ELKHA : Jurnal Teknik Elektro, Vol. 15 No.1, April 2023, pp. 73 - 83
ISSN: 1858-1463 (print), 2580-6807 (online)

Assessment of Solar Energy Resource for PV Plant Development Using a Low-Cost PV Monitoring System

Alfeus Sunarso[1*)], Devi Andriani[2)], Dovian Iswanda[3)], Nurhaidah[4)], Tri Pratomo[5)], Halasan Sihombing[6)], Yunita[7)], Wendhi Yuniarto[8)], and Rusman[9)]

[1,2,3,4,5)] Dept. Mechanical Engineering, Politeknik Negeri Pontianak, Pontianak, Indonesia
[6,7,8,9)] Dept. Electrical Engineering, Politeknik Negeri Pontianak, Pontianak, Indonesia
[*] Corresponding Email: [*)] sunarso@dosen.polnep.ac.id

Abstract – **In this work, we propose the use of a low-cost PV monitoring system for providing accurate and comprehensive data required in the development of efficient and reliable solar PV plants. The system is developed based on an open-source Arduino platform with the capability to monitor solar irradiance, and electric outputs and temperature of multiple solar panels, which should enable the accurate assessment of solar energy resource, as well as electrical energy produced by PV plant under real operating conditions. To demonstrate its applicability, the system has been installed at the campus of Politeknik Negeri Pontianak in Pontianak City, and the data collected by the system is used to assess solar energy resource at the location. Data collected by the system from August 2020 to September 2021 shows that the values of solar irradiation are in the range of 2.9 – 4.1 kWh/m^2 per day, and electric energy produced by commercial solar panels are in the range of 0.30 – 0.46 kWh/m^2 per day, correspond to the monthly averaged efficiencies of 8% – 13%. The values of solar irradiation are 15 – 40 % lower than those obtained from the space-averaged satellite data which are in the range of 4.1 – 5.8 kWh/m^2 per day. This shows the significant effects of local conditions, and confirms the advantage of assessment using the low-cost monitoring system that directly accounts for the effects of local conditions without the need of simulation using complex model and sophisticated software that required in the assessment using satellite-derived data.**

Keywords: Automatic data acquisition, Monitoring system, Solar energy resource, PV plant development, Performance of solar panel.

I. INTRODUCTION

The increasing use of renewable energy globally is not only related to the limited resources of fossil fuels but also tightly related to the global warming issue. It is considered that the use of renewable energy, in combination with rapidly improving energy efficiency, forms the cornerstone of a viable climate solution [1]. Currently, the renewable energy supply is dominated by hydropower and biomass. However, the development of new solar PV plants shows a consistently increasing trend, and therefore solar PV is expected to be a major renewable energy source in the future [1]–[3]. The massive development of solar PV plants should contribute to the efforts to achieve the sustainable development goals (SDG) set by the United Nations (UN), i.e. ensuring access to affordable, reliable, sustainable, and modern energy for all [4].

For massive deployment of solar energy, sound knowledge of solar energy resources including its constituents (direct and diffuse radiation) and variations across time scales is a prerequisite [5]. Comprehensive information on energy resources can be obtained from satellite-derived data which is publicly accessible from some organizations such as NASA [6], World Bank [7], and Copernicus [8]. The satellite-derived data can be used in a preliminary study to assess the potential of solar energy and to determine suitable sites for the deployment of large-scale solar PV plants [9]–[13]. However, as the project development moves forward, ground-based measurements are desirable to provide an increased level of confidence [14], as the spatial resolution of satellite-derived data is relatively low. For satellite-derived data of solar radiation, even at the highest resolution, a data point represents an averaged value over an area of 50 km by 50 km [15]. The coarse spatial resolution may result in a significant discrepancy between satellite-derived data and ground-measured data. Furthermore, the effects of local conditions such as the shading of high building may amplify the discrepancy [16]. Therefore, for the design of efficient and reliable solar PV plants, the assessment of PV potential based on ground-measured data is required. As most of previous works on the assessment of PV potential rely on satellite-derived data, further research on the assessment of PV potential based on ground-measured data would play an important role in development of efficient and reliable solar PV plants.

Ground measurement of the solar energy resource, which is usually expressed in terms of incoming solar power per square meter area or solar irradiance, is commonly performed using a pyranometer [17]–[20]. Recently, the use of PV reference cells as a lower-cost alternative for the measurement of solar energy resources has been investigated [21]–[24]. It should be noted that only a part of incoming solar power can be converted into electrical power. The ratio of produced electric power and the received solar power is known as efficiency, which depends on the material and fabrication technology of the solar panel, as well as the operating conditions.

Manuscript received 2023-03-21; revised 2023-04-14; accepted 2023-04-16

The efficiency of various solar panels under standard conditions has been well documented [25]. However, the efficiency of the solar panels will vary under real operating conditions, as the efficiency is affected by air temperature and humidity [26]–[29], wind speed [28], [30], or surface coverage by dust or snow [31]–[33]. Performance comparison of solar panels with different technologies under different climate conditions shows that solar panels with a specific technology may deliver superior performance under a specific climate condition, but under other climate conditions, they may deliver inferior performance [34]. Therefore, in addition to the data of incoming solar power, the data of the electrical power produced by solar panels under real conditions should be important for the development of efficient and reliable solar PV plants.

The data of incoming solar energy and electrical energy produced by solar panels can be obtained using a PV monitoring system, which is commonly used to investigate the effect of the environment on the performance of the solar panel. The system measures various parameters including solar irradiance, voltage and current produced by solar panel, the temperature of ambient air and surface of solar panel, air humidity, wind speed, and rain precipitation. The early PV monitoring system has been developed and used to monitor the performance of PV plants in Europe [17]. To ensure the accuracy and reliability of measured data, a standard procedure for PV monitoring has been proposed [35], [36]. Based on the guideline, an outdoor testing station to accurately measure the current and voltage curve (I-V curve) of a solar panel has been developed by Imenes et al. [19], [31]. Unfortunately, the system proposed by Imenes et al. uses relatively expensive proprietary hardware and software, which limits its use in common applications. To overcome the problem, a low-cost PV monitoring system using open-source hardware and software based on the Arduino platform has been proposed by Fuentes et al. [20]. Furthermore, a more flexible and powerful open-source system has been proposed by Erraissi et al. [37], but the cost is much higher than that proposed by Fuentes et al. [20].

As an effort to provide accurate and comprehensive data for the development of efficient and reliable solar PV plants, we propose the application of a low-cost PV monitoring system for the assessment of PV potential. Most of the previous works [17], [19], [20], [31], [37] deal with the development and evaluation of PV monitoring system, but the application of the system for assessing PV potential is not addressed yet. Therefore, the application of a low-cost PV monitoring system for the assessment of PV potential presented in this work should give a new insight on the capability of the system in providing comprehensive and accurate data for the design of efficient solar PV plants.

In this work, we develop our monitoring system based on an open-source Arduino platform, similar to the system proposed by Fuentes et al. [20], but differs in hardware configuration to allow the monitoring of multiple solar panels. This feature enables the assessment of electric power generated by solar panels with different materials and production technologies under real working conditions, which is required in the design of efficient and reliable solar PV plants. To show the capability of the system in assessing the PV potential, we use the PV monitoring system to collect solar irradiance and PV electrical outputs for assessment of PV potential in a one year period, and the data obtained from the system is compared with publicly accessible satellite-derived data provided by NASA [6]. Despite our main contribution is on the use of the system for the assessment of PV potential, the design and implementation of the system is also presented such that our work can be replicated easily.

II. Material and methods

A. Low-cost PV monitoring system

We propose a monitoring system to assess PV potential on a specific location by measuring the power of solar radiation and the power produced by solar panels periodically in a long-time span. As the performance of solar panels with different materials and fabrication technology is important in the assessment of PV potential, the proposed system should be able to simultaneously measure voltage and current produced by multiple solar panels. The system also should be able to measure incoming solar power, and temperature of solar panels and ambient air, as reference for the analysis of solar panel performance. The data of those parameters should be obtained periodically, and then shown in a display, as well as stored with a timestamp in a storage media.

To keep the cost of the monitoring system as low as possible, we use open-source hardware and software based on the Arduino platform. Fuentes et al. [20] have proposed a low-cost PV monitoring system using Arduino Uno microcontroller, but the number of solar panels that can be monitored is very limited due to limited ports (6 analog and 14 digital pins) for input/output devices and limited size of memory (32 kB) for programming. To overcome the problem, especially the limited size of memory for programming, we use the Arduino Mega2560 microcontroller that provides 16 analog pins, 54 digital pins, and 256 kB programming memory (8 times of Arduino Uno programming memory). Furthermore, we use different sensors and sensor connection interfaces to maximize the number of solar panels that can be monitored by our system.

We use components listed in Table 1, which are to be connected as a system according to the wiring diagram shown in Figure 1. The main component of the system is an Arduino Mega2560 micro controller that periodically reads raw data from input devices such as sensors, converts the data into physically meaningful data, shows data on an LCD, and stores the data into a memory card. The power of solar panels is obtained by measuring their current and voltage using the INA219 sensor, while the power of solar radiation is measured using Kipp & Zonen SP Lite 2 pyranometer that connected to an ADC module to amplify its signal. The temperature of ambient air and surface of solar panel is measured using the DS18B20 temperature sensors. For measurement of solar panel temperature, the sensors are attached at the back side of solar panels. To mark the time of processes such as displaying or storing data, a DS3231 module is used as the real-time clock (RTC) of the system. As shown in Table 1 and illustrated in Figure 1, most of the input and output devices are connected using the I2C communication protocol. In principle, multiple devices can be connected to an I2C bus without conflict if each device has a unique address. Usually, devices with different types have different addresses, so they can be connected to the I2C bus without conflict. Multiple devices of the same address are connected through TCA9548 multiplexers.

The system will be used to measure power produced by different solar panels with a rated peak power of 20 W. These solar panels have an open-circuit voltage of about 22 V and a short circuit current of about 1.2 A. The voltage and current are measured using INA219 with a measurement range of 0 to 32 V for voltage and 0 to 3.2 A for current, which covers the maximum voltage and current generated by the solar panel. INA219 has a 12 bits A/D converter which enables measurement with a resolution of 1/4096 or 0.024%, which complies with the IEC standard [35].

All components listed in Table 1 were purchased at a relatively low-cost, and then were connected to the microcontroller according to the wiring diagram shown in Figure 1. To ensure each device works properly, a diagnostic code that checks and reports the state of each device was uploaded into the microcontroller, such that each time a device has connected to the system, we can verify whether it works properly or not. For systematic verification, first, we must connect the LCD to the microcontroller such that we can show the state of other devices or other processing information to the LCD. Subsequently, we can add RTC, memory card module, TCA9548 multiplexer, ADS1115 A/D converter, pyranometer, temperature sensors, and INA219 power sensors that are connected to solar panels.

Table 1. List of components of the Arduino-based automatic data acquisition system for assessment of PV potential.

No.	Component and Specification	Type and Function
1	Microcontroller (Arduino Mega2560): 16 MHz processor speed, 16 analog pins, 54 digital pins, 256 kB programming memory.	Processor: read data from various input devices, manipulate data, show and store data into output devices.
2	Power sensor (INA 219): digital connection, I2C communication (16 unique addresses), measurement limit of 3.2 A and 32 V, 12-bit A/D conversion (0.8 mA and 8 mV resolution).	Input: measure the current and voltage generated by the solar panel. The generated power is calculated by multiplying current and voltage.
3	Solar irradiance sensor (Kipp & Zonen SP Lite 2): silicon pyranometer, analog connection, sensitivity of 74.2 $\mu V/(W/m^2)$.	Input: measure power per square meter of solar radiation.
4	Temperature sensor (DS18B20): one wire connection, 48 bits unique serial numbers, -55 to +125°C measurement range, ±0.5 °C accuracy for -10 to +85°C, 9-12-bit resolution.	Input: measure the temperature of ambient air and surface of solar panels.
5	Analog to digital converter / ADC (ADS1115): digital connection, I2C communication (4 unique addresses), 4 analog channels, 16-bit resolution.	Signal converter: convert analog signals from pyranometer into digital signals.
6	Multiplexer (TCA9548): digital connection, I2C communication (8 unique addresses), 8 channels for I2C devices.	Input selector: select a specific input device to connect from a pool of multiple devices.
7	Real-time clock (DS3231): digital connection, I2C communication.	Input: mark the time of processes such as displaying or storing data.
8	Memory card module: digital connection, SPI communication, maximum capacity of 16 GB.	Output: store data of measurements.
9	LCD module: digital connection, I2C communication, 16 columns x 2 lines of characters.	Output: display various information such as processes or data of measurements.

The flow of the monitoring process is shown in Figure 2, which is translated into a programming code that is uploaded into the memory of microcontroller. When the microcontroller is turned on, it will first reserve memory for the declared variables and execute the set-up process, and then execute the loop of the data acquisition process. In the set-up process, all input and output devices are initiated, and the states of each device are displayed on the LCD, such that we can verify if each device works properly.

When all devices have been initiated, the process goes into the loop of data acquisition, in which the microcontroller first reads time information from RTC, and then checks the value of the current day. If the value of the current day is different from the value in a variable used to record the last day of data saving, a new file name to store data is generated, and the variable of saving day is updated with the value of the current day. This process is skipped if the above condition is not fulfilled. In the next process, the microcontroller reads data from all sensors and converts the data into physical meaningful values. For measurement of power produced by solar panels, the microcontroller accesses all INA219 sensors one by one using TCA9548 and then reads the values of voltage and current. To measure the power of solar radiation, an analog voltage signal from SP Lite 2 pyranometer is converted into a digital value using the ADS1115 ADC and then converted into the power of solar radiation by multiplying the value of voltage with a coefficient of sensor sensitivity. For measurement of temperature, the microcontroller reads the data from DS18B20 sensors in the form of digital values that have been calibrated to temperature values in centigrade.

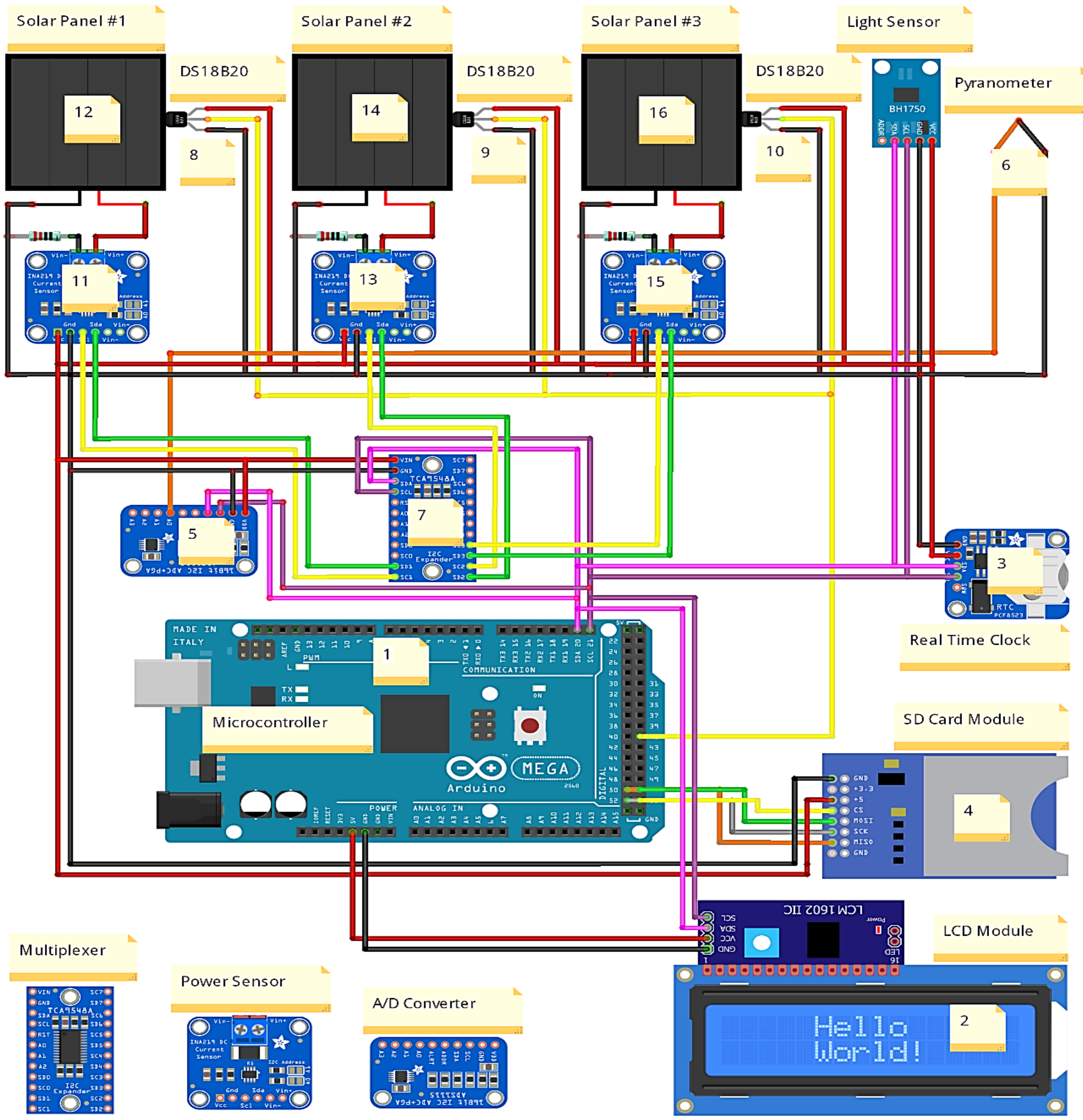

Figure 1. Wiring diagram of Arduino-based automatic data acquisition system for assessment of PV potential.

After data from all sensors have been processed, the microcontroller computes the elapsed time from the last time of data were displayed. This is done by computing the difference of the current value of millis() function (a function that records time elapsed from the time microcontroller was powered on in milliseconds) and the value saved in a variable (millisDisplay) to mark the last time of data were shown. If the time is equal to or larger than the display interval (1000 ms), then the data are shown on the LCD, and the variable to mark the time of data shown is updated with the value of millis() function. If the time span is less than the display interval, the data displaying process is skipped. As the LCD can only show characters in 2 rows with 16 columns per row (total of 32 characters), it cannot show all the data once at a time. To overcome this problem, only the data of one solar panel (current, voltage, and surface temperature) are shown at a time, and each time the data are displayed, they are taken from different solar panels.

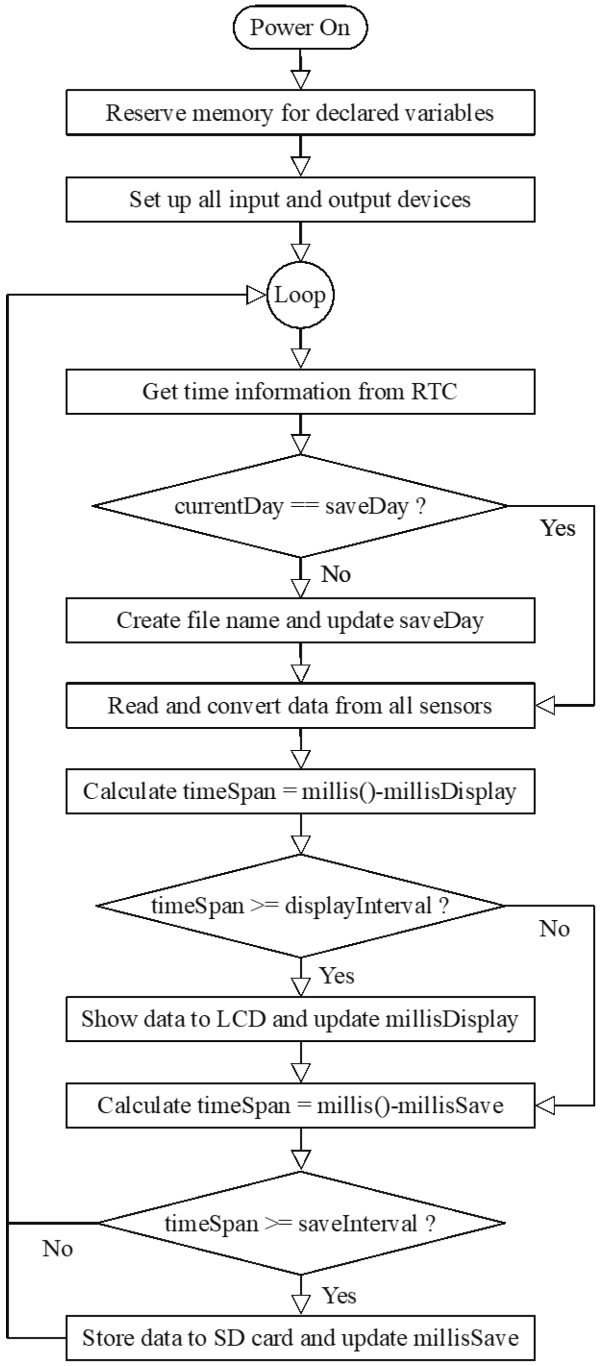

Figure 2. Flow chart of the data acquisition process in the monitoring system.

Subsequent process after data displaying process is data saving process. To check if the data saving process is required, the microcontroller computes elapsed time span from the last time data were saved using millis() function and the variable (millisSave) to mark the last time of data were saved. If the time span is equal to or larger than the save interval (10,000 ms), then the data are stored into an SD card, and the variable to mark the time of data saved is updated with the value of millis() function. Otherwise, the process loops back to the beginning of the data acquisition process. To save the data, a file is opened, and then time information obtained from RTC and data acquired from all sensors are written into the file in a single line. Data saving is completed by closing the file, and then the process loops back to the beginning of the data acquisition process.

Figure 1 shows the wiring diagram of the system with 3 solar panels to be monitored. As all sensors attached to the solar panels (INA219 and DS18B20 sensors) are connected using the I2C interface, the system can be easily extended to monitor more than 3 solar panels. Considering the hardware aspects, the number of solar panels that can be monitored should be limited by number of INA219 sensors that can be connected to the I2C bus. Noting that INA219 sensors are connected to I2C bus through TCA9548 multiplexers, while the number of TCA9548 multiplexers that can be connected to I2C bus is limited to 8 modules (8 channels per modules), the number of INA219 sensors that can be connected to the I2C bus is limited to 64 units. From the software aspect, the number of solar panels that can be monitored should be limited by the memory size of the microcontroller. As a verification, we created and compiled programs to monitor multiple solar panels and checked the memory required by the programs. A program to monitor 12 panels uses 37022 bytes (14%) of program storage space (253952 bytes) and global variables use 2783 bytes (33%) of dynamic memory (8192 bytes), while a program to monitor 18 panels uses 42836 bytes (16%) of program storage space and global variables use 3329 bytes (40%) of dynamic memory. Based on the data, a program to monitor 64 panels is predicted to occupy 87410 bytes (34%) of program storage space and the global variables occupy 7515 bytes (92%) of dynamic memory. Therefore, the proposed system should be able to monitor up to 64 solar panels simultaneously.

The values obtained from INA219 sensors have been already expressed in the physical meaningful values of current and voltage, and thus calibration is not required for the sensor. However, to verify the reliability of measurement, we compared the values of voltage and current measured using INA219 sensors with the values of voltage measured using a multi-meter. Similarly, the digital values obtained from DS18B20 sensors have been already expressed in the physical meaningful values of temperature in centigrade, and thus no further calibration is required. To verify the reliability of measurement, we compared the values of temperature measured using DS18D20 sensors with the values of temperature measured using a commercial temperature measurement device. For the analog sensor (pyranometer) connected to ADC ADS1115, the generated digital signal should be converted into physical variables.

As noted previously, the digital signal corresponds to the analog voltage of the pyranometer can be converted into the power of solar radiation by multiplying the voltage with a sensitivity coefficient, which is specific for each device. In our case, we use Kipp & Zonen SP Lite 2 pyranometer with sensitivity coefficient of 74.2 $\mu V/(W/m^2)$. The sensitivity coefficient was obtained from the calibration performed by the manufacturer, and therefore no further calibration is required for the pyranometer.

Table 2. Costs of Arduino-based PV monitoring system.

No	Components	Quantity	Unit Cost (IDR)	Total Cost (IDR)	Total Cost (USD)
1.	Mega 2560 + Extension Board	1	400,000	400,000	26.7
2.	LCD I2C 16x2	1	40,000	40,000	2.7
3.	RTC DS3231	1	40,000	40,000	2.7
4.	SD Card Module + 16GB Card	1	90,000	90,000	6.0
5.	ADC ADS1115	1	90,000	90,000	6.0
6.	Multiplexer TCA9548	1	50,000	50,000	3.3
7.	Temperature Sensor DS18B20	4	20,000	80,000	5.3
8.	Power Sensor INA219	3	45,000	135,000	9.0
	Cost of data acquisition system			*925,000*	*61.7*
9.	Enclosure Box	1	350,000	350,000	23.3
10.	Supporting Structure	1	1,500,000	1,500,000	100.0
11.	Solar Charger	1	300,000	300,000	20.0
12.	Battery	1	200,000	200,000	13.3
	Cost of supporting system			*2,350,000*	*156.7*
12.	SP Lite 2 Pyranometer	1	8,000,000	8,000,000	533.3
13.	Solar Panel 20W	4	300,000	1,200,000	80.0
Cost of solar energy receiving devices				*9,200,000*	*613.3*
	Total cost			**12,475,000**	**831.7**

After a careful testing to confirm that all components of the monitoring system have worked properly, the system is installed in the field. The costs of the system are summarized in Table 2, while the picture of the installed system is shown in Fig.3. The components of the system are purchased from Indonesian market, thus the costs are expressed in thousands Indonesian Rupiah (kIDR) and converted into United State Dollar (USD) with the assumption of 1 USD = 15 kIDR.

The lists in Table 2 cover the costs of data acquisition system, supporting system, and solar energy receiving devices. By using the open-source Arduino platform, the cost of data acquisition system developed in this work is about 62 USD, and there is no additional cost for data acquisition software and data acquisition control device (computer). The cost of our data acquisition system is comparable to a low-cost portable data logger developed by Fuentes et al. [20], and is much lower than the cost of the proprietary data acquisition systems. For example, a proprietary datalogger used by Imenes et al. [31], i.e. Campbell Scientific Datalogger CR1000 costs around 3,000 USD. If we account for the costs of data acquisition system, supporting system, and solar energy receiving devices, the total cost of our system is about 832 USD, which is still much lower than the cost of a proprietary datalogger without supporting system, and solar energy receiving devices.

B. Data processing for assessment of PV potential

To evaluate the performance of the system, the system was used to monitor the power of solar radiation and the power produced by 3 different solar panels that commonly available in the market. Data collected from continuous monitoring are processed to calculate daily and monthly potential and produced energies. In addition, by comparing the real power produced by solar panels and potential power from solar radiation, we can obtain the efficiency of each solar panel.

The power produced by a solar panel is calculated from the measured current and voltage. If the current and voltage produced by the solar panel are expressed in terms of I_p and V_p, respectively, the power produced by the solar panel (P_p) can be calculated as follows:

$$P_p = V_p I_p \tag{1}$$

Here, I_p is in ampere (A), V_p is in volt (V), and then P_p is in watt (W). However, to be consistent with the unit of power of solar radiation or solar irradiance (W/m^2) in the calculation of efficiency, the produced power of solar panel should be expressed in terms of power per square meter, which is known as power intensity. If a solar panel has an effective area of A_p, the power intensity produced by solar panel $P_{p/A}$ is:

$$P_{p/A} = P_p / A_p \tag{2}$$

Daily energy produced by a solar panel of 1 m^2 can be obtained by integrating the instantaneous values of power intensity over the available solar radiation in one day. If the measurement is performed every Δt in second (s), the daily energy produced by a solar panel with an area of 1 m^2 ($E_{p/A}$) can be calculated using the following equation:

$$E_{p/A} = \sum_{i=1}^{N} (P_{p/A} \Delta t) \tag{3}$$

Please note, Δt is 10 s for our system, i and N refer to sequence and total number of data respectively. To get the comprehensive and accurate data, Δt should be chosen as small as possible. In this work, Δt of 10 s is chosen such that rapid change in various parameters due to fluctuation in solar irradiance can be captured (see Figs. 4-6), while the size of the saved data is still in the acceptable range. The unit of $E_{p/A}$ calculated from equation (3) is in J/m^2. We can convert the unit into a commonly used unit of Wh/m^2 by dividing the value of $E_{p/A}$ by 3,600.

Figure 3. Installed low-cost PV monitoring system.

Similarly, if the measured solar irradiance is expressed in $P_{s/A}$ (in W/m^2), the daily energy from solar radiation on a surface of 1 m^2 or known as solar irradiation can be calculated as follows:

$$E_{s/A} = \sum_{i=1}^{N} (P_{s/A} \Delta t) \quad (4)$$

By accumulating the daily energy during one month and divide it by the number of days in the month, we can obtain the monthly averaged daily energy of the solar panel $\bar{E}_{p/A}$ and solar radiation $\bar{E}_{s/A}$. The daily energy and monthly averaged daily energy produced by solar panels can be used to assess the PV potential. Furthermore, from the data, the efficiency of solar panel η_p can be obtained by comparing the power intensity of solar panel and solar radiation as follows:

$$\eta_p = 100 \times P_{p/A} / P_{s/A} \quad (5)$$

The efficiency obtained from equation (5) is an instantaneous efficiency. The average efficiency in a day ($\bar{\eta}_p$) can be obtained by comparing the daily energy produced by solar panel $E_{p/A}$ and daily energy received from solar radiation $E_{s/A}$, such that:

$$\bar{\eta}_p = 100 \times E_{p/A} / E_{s/A} \quad (6)$$

III. RESULTS AND DISCUSSION

As shown in Fig. 3, the monitoring system has been installed on the top of a building at the Mechanical Engineering Department of Politeknik Negeri Pontianak in West Kalimantan – Indonesia, which is located at latitude of 0.056°S and longitude of 109.346°E. The system has been used to measure solar radiation and power generated by solar panels from August 2020 to September 2021. The power of solar radiation, current and voltage generated by solar panels, as well as temperature of ambient air and surface of solar panels are measured and stored in a memory card every 10 s. The measurement was performed every day from 6 in the morning to 18 in the afternoon. The data obtained from the system has been processed and used for the assessment of PV potential at the location of measurement.

A. Performance of solar panels under real conditions

Figure 4 shows the sample of daily raw data of voltage and current of solar panels on August 1, 2020. The values of voltage are plotted with the scale on the left vertical axis, while the values of current are plotted with the scale on the right vertical axis. Using the data of voltage and current obtained from the monitoring system, the power produced by each solar panel can be calculated using equation (1), and then converted into power per square meter (power intensity) using equation (2).

The plots of the calculated values of power intensity generated by the solar panels and the measured values of solar irradiance are shown in Fig. 5. It can be observed that the current and voltage, as well as the power generated by the solar panels, vary in a way that follows the variation in solar irradiance. This confirms the validity of the measurement, as the generated power computed from current and voltage represents a part of solar irradiance that is converted into electric power by the solar panels. As shown in Figs. 4 and 5, the curves of voltage, current, and power generated by the different solar panels show the similar patterns with slight difference in absolute values due to the difference in solar panel efficiencies. It is also confirmed that the values of measured parameters are in the range of corresponding sensors, which ensure the reliability of the acquired data. For example, the maximum values of parameters at a relatively clear weather condition presented in Figs. 4 and 5, are 1100 W/m^2 for solar irradiance, 19 V for voltage and 0.9 A for current, which are below the measurement limits of SP Lite 2 pyranometer (2000 W/m^2) and INA219 sensor (32 V for voltage and 3.2 A for current). The voltage and current of solar panels increase with the increase in solar irradiance, but the values would not exceed the open-circuit voltage of around 22V and short-circuit current of around 1.3A. The maximum values of solar panel temperatures, as shown in Fig. 6, are around 60°C, which are below the limit of DS18B20 sensor (125°C).

The power generated by the solar panels fluctuates significantly according to the fluctuation of solar irradiance which depends on the weather conditions, as shown in Fig. 5. To investigate the performance of solar panels under the fluctuating solar irradiance, the efficiency of solar panels, which is calculated from equation (5), is plotted along with the solar panel surface temperature as shown in Fig. 6. It can be confirmed that solar irradiance affects the surface temperature and efficiency of the solar panels. When the solar irradiance increases, the heat generated on the surface of solar panels also increases, and consequently the temperature of the solar panel surface increases.

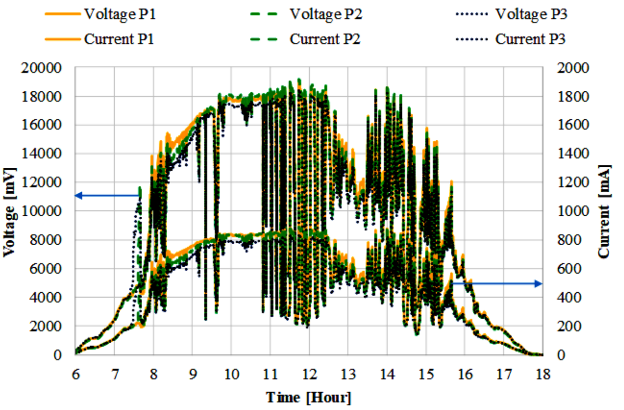

Figure 4. Sample of daily raw data obtained from the monitoring system.

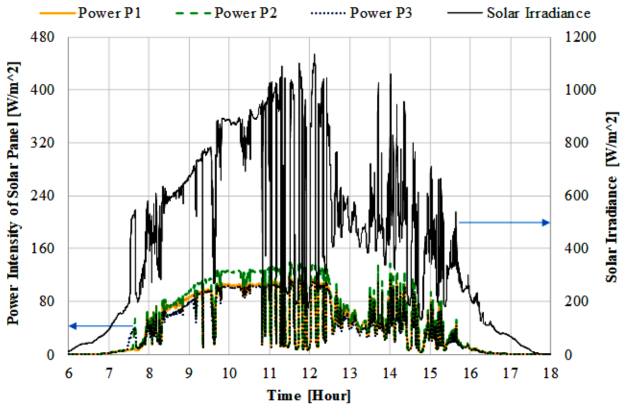

Figure 5. Power of solar radiation and power produced by solar panels.

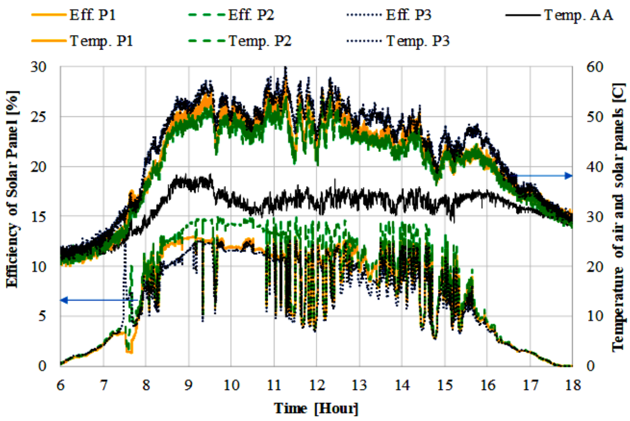

Figure 6. Instantaneous temperature and efficiency of solar panels.

An increase in solar panel temperature decreases its efficiency [26]–[29]. For silicon solar cells, the efficiency will decrease by 0.4% per °C for mono-crystalline solar cells and 0.45% per °C for multi-crystalline solar cells [26]. Under standard conditions (25°C), the maximum efficiency of the mono-crystalline silicon solar cell is 26.7%, while the maximum efficiency of the multi-crystalline silicon solar cell is 22.3% [25]. Fig. 6 shows the variation temperature and efficiency of solar panels under the real operating conditions. In the legend, suffixes P1, P2, P3 stand for panel 1, panel 2, and panel 3, respectively, while suffix AA stands for ambient air. It can be observed, the temperature of the solar panels exceeds 50°C, and the maximum efficiency of the solar panels drops to a maximum value of 15% for the mono-crystalline solar panel (panel 2) and 13% for multi-crystalline solar panels (panels 1 and 3).

Figures 5 and 6 show that the instantaneous efficiency of solar panels fluctuates following the fluctuation of solar irradiance. The efficiency increases with the increase in solar irradiance, and reversely, the efficiency decreases with the decrease in solar irradiance. Therefore, even though the higher solar irradiance will result in the higher temperature of the solar panel, the overall efficiency averaged over the daily data will be higher for the days with a high level of solar irradiance as compared to the days with a low level of solar irradiance. It is also interesting to note that, when the value of solar irradiance exceeds a specific value (around 800 W/m^2), the increase in solar irradiance would not increase the efficiency of the solar panels. A similar phenomenon was confirmed in the research performed by Hamou et al. [38].

B. Assessment of PV potential

To assess the PV potential, the daily energies received from solar radiation and produced by the solar panels were calculated using equations (3) and (4). As an example, Fig. 7 shows the plot of data in August 2021. It is shown that the daily energy produced by the solar panels varies in the pattern that follows the variation of the received solar energy (solar irradiation) calculated from the data of the pyranometer. The variation in daily energy is consistent with the variation instantaneous power, where the variation of power intensity of solar panels follows the variation of solar irradiance.

It has been noted previously, publicly accessible satellite-derived data can be used for a preliminary study to assess the potential of solar energy and to determine suitable sites for the deployment solar PV plants. However, for the design of efficient and reliable PV plants, more accurate data obtained from ground measurements are required. Therefore, in Fig. 7, the solar irradiation obtained from local measurement using Kipp & Zonen SP Lite 2 pyranometer is compared with solar irradiation obtained from satellite-derived data provided by NASA POWER SSE [6], which is extracted based on the location of the installed monitoring system, i.e. latitude of 0.056°S and longitude of 109.346°E. In general, the daily variation of solar irradiation obtained from local measurement is similar to that obtained from satellite-derived data. However, we can observe a significant difference between the values of local measurement and satellite-derived data. In most cases, the values of solar irradiation obtained from local measurement are lower than the values of satellite-derived data.

To clarify the effects of solar radiation level on the efficiency of solar panels, the solar irradiation is plotted along with the daily averaged efficiency in Fig. 8. It can be confirmed that the daily averaged efficiency of solar panels is higher at relatively high solar irradiation as compared to that at relatively low solar irradiation. The values of the daily averaged efficiency of the solar panels are ranging from 5% to 12%. In addition, it can be confirmed that the daily averaged efficiency of a mono-crystalline solar panel (panel 2) is higher than that for poly-crystalline solar panels (panel 1 and 3).

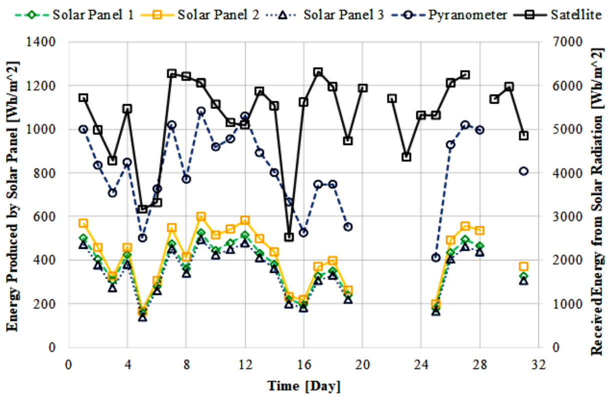

Figure 7. Daily energy received from solar radiation and produced by solar panels.

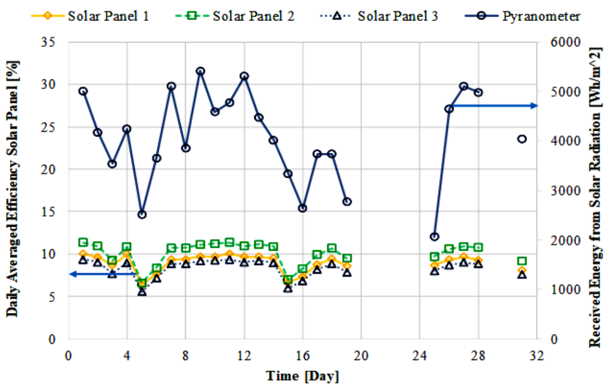

Figure 8. Daily energy of solar radiation and daily averaged efficiency of solar panels.

For a more comprehensive demonstration of the use of the monitoring system in assessing the solar PV potential, the daily data of energy received from the solar radiation and energy produced by solar panels are monthly averaged and the results are presented in Table 3. The values of solar irradiance obtained from satellite data and measurement using pyranometer, as well as the difference between the two sets of data are presented in columns labelled with "Received Energy", while the values of energy generated by solar panels and the efficiency of solar panels are presented in columns labelled with "Produced Energy" and "Efficiency", respectively. The efficiency of solar panels is computed from energy produced by solar panels and solar radiation measured using pyranometer. Incomplete data due to unattended system errors in June and July 2021 are not included in the table. As shown in Table 2, the values of received energy measured using a pyranometer are 15% – 40% lower than the values obtained from satellite-derived data. It should be noted that the monitoring system is installed at a site with high building at the west side, and therefore the lower values of local measurement should be related to the shading effects of the high building. Ideally, solar PV plants should be installed at locations that free of shading effects. However, for rooftop solar PV plants, the choice of location is usually limited, thus the shading effect of surrounding building should be considered carefully. To account for the building shading effects in the estimation of energy generation of PV system based on satellite data, modelling software with 3D CAD capability (Ecotec, PVsyst) is required, while the generic modelling software (HOMER, RETScreen, Hybrid2) over estimates the PV outputs by more than 100% [16]. Therefore, the use of a low-cost PV monitoring system would help the designer of solar PV plants as it provides accurate data of solar energy resource and the energy generated by PV plants without employing sophisticate modelling software.

In addition to the data of solar radiation, the accurate data of electrical energy produced by PV panels should be important in the planning of efficient and reliable solar PV plants. As shown in Table 2, under real operating conditions at the top of a building at the Mechanical Engineering Department of Politeknik Negeri Pontianak - Indonesia, the commercial PV panels produce electrical energy of 300 – 460 Wh/m^2 per day, which corresponds to the monthly averaged efficiencies of 8% – 13%. It is also shown that the efficiency of mono-crystalline solar panel is around 1% higher than the efficiency of multi-crystalline solar panels. This should be related to the single crystal structure in the monocrystalline solar cells, which provides the electrons that generate a flow of electricity more room to move.

It should be noted that the efficiencies of solar panels operating under tropical weather conditions of are much lower than the maximum efficiency of solar panels tested under standard conditions with an ambient temperature of 25°C, i.e. 26.7% for the mono-crystalline silicon solar panels and 22.3% for the multi-crystalline silicon solar panels [25]. If the energy generated by PV plant is to be assessed based on satellite-derived data and efficiency of PV under standard conditions, its values would be in the range of 982 – 1298 Wh/m^2 for PV plant with multi-crystalline silicon solar panels and 1176 – 1555 Wh/m^2 for PV plant with mono-crystalline silicon solar panels, which are about 3 – 4 times higher than the real values obtained by local measurement. These results confirm that data of local measurements are highly required, and the proposed low-cost PV monitoring system should provide a promising solution for the demands of accurate and comprehensive data in the design of reliable and efficient solar PV plants. In the case of Indonesia where massive development of PV plants is planned, but the accurate and comprehensive data of PV potential is still lack, the replication and installation of the low-cost PV monitoring system in many locations would provide a solution for the problem. In the future, further research on integration of the low-cost PV monitoring system with a web-based data acquisition system should be important the promote the development of ground measurement network across the country.

Table 3. Monthly averaged daily energy received from solar radiation and produced by solar panels.

No	Year/ Month	Received Energy [Wh/m^2]			Produced Energy [Wh/m^2]			Efficiency [%]		
		Sat	Pyr	Dev	P 1	P 2	P 3	P 1	P 2	P 3
1	2020/08	5292	4074	-23%	372	419	347	9.2	10.4	8.6
2	2020/09	4888	4144	-15%	379	427	351	9.1	10.3	8.5
3	2020/10	4502	3685	-18%	345	377	313	9.4	10.2	8.5
4	2020/11	4161	3397	-18%	304	340	277	8.6	9.6	7.8
5	2020/12	4724	3468	-27%	347	385	312	9.9	10.9	8.8
6	2021/01	4404	2930	-33%	281	311	253	9.3	10.3	8.4
7	2021/02	5823	3800	-35%	410	460	378	10.8	12.1	10.0
8	2021/03	5267	3363	-36%	330	359	297	9.8	10.7	8.8
9	2021/04	5711	3412	-40%	403	445	371	11.8	13.0	10.9
10	2021/05	5114	3249	-36%	373	408	344	11.5	12.6	10.6
11	2021/08	4642	3268	-30%	324	384	311	9.9	11.8	9.5
12	2021/09	5013	3463	-31%	335	404	327	10.2	12.3	9.9

IV. Conclusion

A low-cost Arduino-based monitoring system has been developed and its use for the assessment of PV potential has been demonstrated. The system has been installed at the top of a building at the Mechanical Engineering Department of Politeknik Negeri Pontianak – Indonesia, and the acquired data in the period of August 2020 to September 2021 have been used to assess the PV potential at the location. It has been shown that the values of solar irradiation obtained from local measurement using the system differ by 15 – 40 % from the values of satellite-derived data that averaged over wide areas. Furthermore, the obtained data show that the values of electrical energy produced by commercially available solar panels installed at the corresponding location are in the range of 300 – 460 Wh/m^2 per day, which are much lower than those predicted based space-averaged satellite data and efficiency of solar panels under standard conditions. These results confirm the advantage of assessment of solar energy resources using the low-cost PV monitoring system, as the system can provide accurate and comprehensive data required in the design of reliable and efficient solar PV plants without the need of simulation using complex model and sophisticated software that required in the assessment using satellite-derived data.

Acknowledgments

This research is supported by the Institutional Research Grant of Politeknik Negeri Pontianak.

References

[1] IRENA, *Global Energy Transformation: A Roadmap to 2050*. Abu Dhabi: International Renewable Energy Agency, 2018.

[2] REN21, *Renewables 2019 Global Status Report*, vol. 8, no. 3. Paris: REN21 Secretariat, 2019.

[3] DNV-GL, *Energy transition outlook 2019: a global and regional forecast to 2050*. Høvik, Norway: DNV GL AS, 2019.

[4] United Nations, “Transforming our world: the 2030 agenda for sustainable development,” 2016. doi: 10.1201/b20466-7.

[5] IEA, *Solar Energy: Mapping the Road Ahead*, no. October. France: International Energy Agency, 2019.

[6] NASA, “Prediction Of Worldwide Energy Resource,” 2017. https://power.larc.nasa.gov/ (accessed May 01, 2020).

[7] World Bank, “Solar Resource and Photovoltaic Potential in Indonesia,” Washington, D.C., 2017. [Online]. Available: https://www.esmap.org/node/58032.

[8] European Commission, “Copernicus Atmosphere Monitoring Service,” 2017. https://atmosphere.copernicus.eu/ (accessed May 17, 2017).

[9] M. L. Sabo, N. Mariun, H. Hizam, M. A. Mohd Radzi, and A. Zakaria, “Spatial energy predictions from large-scale photovoltaic power plants located in optimal sites and connected to a smart grid in Peninsular Malaysia,” *Renew. Sustain. Energy Rev.*, vol. 66, pp. 79–94, 2016, doi: 10.1016/j.rser.2016.07.045.

[10] A. Alami Merrouni, F. Elwali Elalaoui, A. Ghennioui, A. Mezrhab, and A. Mezrhab, “A GIS-AHP combination for the sites assessment of large-scale CSP plants with dry and wet cooling systems. Case study: Eastern Morocco,” *Sol. Energy*, vol. 166, no. March, pp. 2–12, 2018, doi: 10.1016/j.solener.2018.03.038.

[11] Y. Zhang, J. Ren, Y. Pu, and P. Wang, “Solar energy potential assessment: A framework to integrate geographic, technological, and economic indices for a potential analysis,” *Renew. Energy*, vol. 149, pp. 577–586, 2020, doi: 10.1016/j.renene.2019.12.071.

[12] A. Sunarso, K. Ibrahim-Bathis, S. A. Murti, I. Budiarto, and H. S. Ruiz, “GIS-based assessment of the technical and economic feasibility of utility-scale solar PV plants: Case study in West Kalimantan province,” *Sustainability*, vol. 12, no. 15, pp. 1–12, 2020, doi: 10.3390/su12156283.

[13] H. S. Ruiz Rondan, A. Sunarso, K. Ibrahim-Bathis, S. A. Murti, and I. Budiarto, “GIS-AHP Multi Criteria Decision Analysis for the optimal location of solar energy plants at Indonesia,” *Energy Reports*, vol. 6, pp. 3249–3263, 2020, doi: 10.1016/j.egyr.2020.11.198.

[14] IFC, *Utility-Scale Solar Photovoltaic Power Plants: A Project Developer's Guide*. Washington: International Finance Corporation, 2015.

[15] P. W. Stackhouse *et al.*, "POWER Release 8.0.1 (with GIS Applications) Methodology," 2018.

[16] A. G. Siraki and P. Pillay, "Comparison of PV System Design Software Packages for Urban applications," in *21st World Energy Congress (WEC) 2010*, 2010, p. 12, [Online]. Available: https://www.osti.gov/etdeweb/servlets/purl/21390280.

[17] G. Blaesser, "PV system measurements and monitoring the European experience," *Sol. Energy Mater. Sol. Cells*, vol. 47, no. 1–4, pp. 167–176, Oct. 1997, doi: 10.1016/S0927-0248(97)80008-6.

[18] N. Forero, J. Hernández, and G. Gordillo, "Development of a monitoring system for a PV solar plant," *Energy Convers. Manag.*, vol. 47, no. 15–16, pp. 2329–2336, 2006, doi: 10.1016/j.enconman.2005.11.012.

[19] A. G. Imenes, G. H. Yordanov, O. M. Midtgård, and T. O. Saetre, "Development of a test station for accurate in situ I-V curve measurements of photovoltaic modules in Southern Norway," in *37th IEEE Photovoltaic Specialists Conference (PVSC) 2011*, 2011, pp. 003153–003158, doi: 10.1109/PVSC.2011.6186610.

[20] M. Fuentes, M. Vivar, J. M. Burgos, J. Aguilera, and J. A. Vacas, "Design of an accurate, low-cost autonomous data logger for PV system monitoring using Arduino™ that complies with IEC standards," *Sol. Energy Mater. Sol. Cells*, vol. 130, 2014, doi: 10.1016/j.solmat.2014.08.008.

[21] J. Meydbray, K. Emery, and S. Kurtz, "Pyranometers and reference cells, the difference," *PV Mag.*, no. March, pp. 108–110, 2012.

[22] J. Meydbray, E. Riley, L. Dunn, K. Emery, and S. Kurtz, "Pyranometers and Reference Cells : Part 2 : What Makes the Most Sense for PV Power Plants," 2012. doi: https://doi.org/10.2172/1059158.

[23] L. Dunn, M. Gostein, and K. Emery, "Comparison of pyranometers vs. PV reference cells for evaluation of PV array performance," *Conf. Rec. IEEE Photovolt. Spec. Conf.*, pp. 2899–2904, 2012, doi: 10.1109/PVSC.2012.6318193.

[24] J. Polo, W. G. Fernandez-Neira, and M. C. Alonso-García, "On the use of reference modules as irradiance sensor for monitoring and modelling rooftop PV systems," *Renew. Energy*, vol. 106, pp. 186–191, 2017, doi: 10.1016/j.renene.2017.01.026.

[25] M. Green, E. Dunlop, J. Hohl-Ebinger, M. Yoshita, N. Kopidakis, and X. Hao, "Solar cell efficiency tables (version 57)," *Prog. Photovoltaics Res. Appl.*, vol. 29, no. 1, pp. 3–15, 2021, doi: 10.1002/pip.3371.

[26] G. Makrides, B. Zinsser, M. Norton, and G. E., "Performance of Photovoltaics Under Actual Operating Conditions," in *Third Generation Photovoltaics*, 2012.

[27] G. Makrides, B. Zinsser, A. Phinikarides, M. Schubert, and G. E. Georghiou, "Temperature and thermal annealing effects on different photovoltaic technologies," *Renew. Energy*, vol. 43, no. June 2006, pp. 407–417, 2012, doi: 10.1016/j.renene.2011.11.046.

[28] J. K. Kaldellis, M. Kapsali, and K. A. Kavadias, "Temperature and wind speed impact on the efficiency of PV installations. Experience obtained from outdoor measurements in Greece," *Renew. Energy*, vol. 66, pp. 612–624, 2014, doi: 10.1016/j.renene.2013.12.041.

[29] I. M. Peters, H. Liu, T. Reindl, and T. Buonassisi, "Global Prediction of Photovoltaic Field Performance Differences Using Open-Source Satellite Data," *Joule*, vol. 2, pp. 1–16, 2017, doi: 10.1016/j.joule.2017.11.012.

[30] C. Schwingshackl *et al.*, "Wind effect on PV module temperature: Analysis of different techniques for an accurate estimation," *Energy Procedia*, vol. 40, pp. 77–86, 2013, doi: 10.1016/j.egypro.2013.08.010.

[31] A. G. Imenes, H. G. Beyer, K. Boysen, J. O. Odden, and R. E. Grundt, "Performance of grid-connected PV system in Southern Norway," in *42nd IEEE Photovoltaic Specialist Conference (PVSC) 2015*, 2015, doi: 10.1109/PVSC.2015.7355823.

[32] H. Pedersen, J. Strauss, and J. Selj, "Effect of Soiling on Photovoltaic Modules in Norway," *Energy Procedia*, vol. 92, no. 1876, pp. 585–589, 2016, doi: 10.1016/j.egypro.2016.07.023.

[33] M. R. Maghami, H. Hizam, C. Gomes, M. A. Radzi, M. I. Rezadad, and S. Hajighorbani, "Power loss due to soiling on solar panel: A review," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 1307–1316, 2016, doi: 10.1016/j.rser.2016.01.044.

[34] L. R. do Nascimento, M. Braga, R. A. Campos, H. F. Naspolini, and R. Rüther, "Performance assessment of solar photovoltaic technologies under different climatic conditions in Brazil," *Renew. Energy*, vol. 146, pp. 1070–1082, 2020, doi: 10.1016/j.renene.2019.06.160.

[35] IEC 61724, *Photovoltaic System Performance Monitoring-Guidelines for Measurement, Data Exchange, and Analysis*, 1st ed. Switzerland, Geneva: International Electrotechnical Commission (IEC), 1998.

[36] A. Jagomägi *et al.*, "European Network of PV Outdoor Testing - Steps towards Harmonized Procedures," in *24th EUPVSEC*, 2009, no. September 2016, pp. 3432–3438, doi: 10.4229/24thEUPVSEC2009-4AV.3.44.

[37] N. Erraissi, M. Raoufi, N. Aarich, M. Akhsassi, and A. Bennouna, "Implementation of a low-cost data acquisition system for 'PROPRE.MA' project," *Meas. J. Int. Meas. Confed.*, vol. 117, no. March, pp. 21–40, 2018, doi: 10.1016/j.measurement.2017.11.058.

[38] S. Hamou, S. Zine, and R. Abdellah, "Efficiency of PV module under real working conditions," *Energy Procedia*, vol. 50, pp. 553–558, 2014, doi: 10.1016/j.egypro.2014.06.067.