American Journal of Energy Engineering
2023; 11(4): 127-133
http://www.sciencepublishinggroup.com/j/ajee
doi: 10.11648/j.ajee.20231104.14
ISSN: 2329-1648 (Print); ISSN: 2329-163X (Online)

A New Approach to Sizing PV Modules While Accounting the Effect of Temperature

Jacques Marie Ilboudo[1], Dominique Bonkoungou[2, *], Zacharie Koalaga[3]

[1]Institute of Research in Applied Sciences and Technologies, Ouagadougou, Burkina Faso
[2]Departement of Applied Science, University of Thomas Sankara, Ouagadougou, Burkina Faso
[3]Departement of Applied Science, University of Joseph Ki-Zerbo, Ouagadougou, Burkina Faso

Email address:
ilboudojacquesmarie@gmail.com (Jacques Marie Ilboudo), dominique.bonkoung@gmail.com (Dominique Bonkoungou), zackkoalaga@gmail.com (Zacharie Koalaga)
[*]Corresponding author

To cite this article:
Jacques Marie Ilboudo, Dominique Bonkoungou, Zacharie Koalaga. (2023). A New Approach to Sizing PV Modules While Accounting the Effect of Temperature. *American Journal of Energy Engineering*, *11*(4), 127-133. https://doi.org/10.11648/j.ajee.20231104.14

Received: November 9, 2023; **Accepted**: November 30, 2023; **Published**: December 8, 2023

Abstract: This manuscript details a study focusing on determining the appropriate size for photovoltaic (PV) modules. The research involves creating a mathematical model that considers how temperature impacts the energy output of PV modules. This model, derived from empirical data, correlates sunlight and the highest ambient temperature to establish what's termed as "temperature-induced efficiency" in PV module performance. This correlation can be incorporated into the standard PV array sizing formula. The set of mathematical expressions provided facilitates calculating the dimensions of PV modules by factoring in sunlight, temperature, and other relevant variables. The slight discrepancy of 0.85 percent between data obtained through our equation and experimental data suggests a low level of error. These findings indicate that the formulated equation effectively predicts temperature-induced efficiency in PV modules. Furthermore, applying this equation along with NASA's sunshine and ambient temperature data allows for calculating the efficiency induced by temperature for specific cities. For instance, in Ouagadougou, Peking, Paris, Brasilia, and Washington, the temperature-induced efficiencies are calculated as 0.9, 0.95, 0.96, 0.93, and 0.98, respectively.

Keywords: Effect of Temperature, Photovoltaic Energy, Sizing of PV Modules

1. Introduction

The primary goal of research into renewable energy (RE) technologies is to convert RE resources into electrical energy to power consumer loads. However, because they are installed in an outdoor environment, continuous exposure to harsh climatic conditions such as sunlight, precipitation, wind, and so on may have an impact on the PV system's effectiveness [1]. A PV system, like any other industrial process, can experience faults and anomalies that cause performance to suffer. Daily monitoring of PV system status is critical for identifying the causes that impede desired performance [2-4].

To advance solar photovoltaic technology and enable the efficient harnessing of solar energy, experimental research must be conducted to supplement existing theoretical knowledge. In this context, our research has revealed that, despite its negative impact on the technology's electrical production, most PV array sizing formulas do not account for the influence of temperature [4, 5]. To improve the competitiveness of PV systems, it is critical that PV array sizing incorporates all relevant parameters, including those related to temperature effects.

The primary goal of this study is to develop a mathematical expression that can be incorporated into the standard PV array formula to account for temperature influence. The study presented in this paper does not focus on the direct effects of temperature on the operation of individual PV cells or modules. Instead, it seeks to develop a mathematical expression that can be seamlessly incorporated into the standard PV array formula, accounting for temperature as an important parameter.

The following is how the paper is structured:

Section 2 details the materials and methods. Section 3 is devoted to the interpretation of the results, and Section 4 is devoted to the conclusion.

2. Materials and Methods

This section delves into the various aspects of the methodology used in this study. Using the PV cell's two diodes model, we combine experimentation and simulation. Indeed, the two diodes model take into account various parameters which are necessary in this study, as compared to the single diode model [6].

2.1. Theoretical Study

In this section, we will explore the two diodes model of the PV cell and the PV module. We also use various expressions related to the modeling of the PV module to determine its energy production.

2.1.1. Modeling of the PV Cell

Several mathematical models were developed based on the internal structure of the PV cell to translate its behavior. The mathematical models with one diode, two diodes, and Bishop are the most commonly used [7-11].

Because it better matches the experimental curves of PV cells, the advanced two-diode model is widely used. The model can describe the breakdown region at high negative voltages for PV cells that are driven in the negative voltage range. This must be considered when researching PV cells that are partially shaded and are part of a PV module. Using the simple diode model, Bishop [28] proposed an equation in which the avalanche effect is expressed as a nonlinear multiplication factor that affects the shunt resistance current term.

Figure 1 depicts the PV cell equivalent circuit.

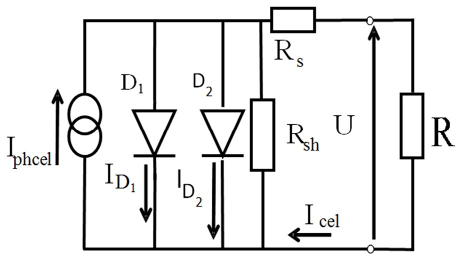

Figure 1. *PV cell electronic model.*

Kirchhoff's first law carries the following relationship between PV cell current and voltage:

$$0 = f(V, I) = I_{PVcel} - I_{D1} - I_{D2} - I_{shcel} - I \quad (1)$$

Then, the photon-current generated can be calculated using Eq. (2), which describes the I-V characteristics of a PV cell [6]:

$$I = I_{PVcel} - I_{01}\left[exp\left\{\frac{q(V+R_S I)}{a_1 V_T}\right\} - 1\right] - I_{02}\left[exp\left\{\frac{q(V+R_S I)}{a_2 V_T}\right\} - 1\right] - \left(\frac{V+R_S I}{R_{Sh}}\right) \quad (2)$$

Where $V_T = {}^{kT}/_{q}$ is the thermal voltage, I_{PV} is the current generated by the incident light, q is the electron charge, $k$is the Boltzmann constant, $T$is the temperature of the p-n junction,R_S is the series resistance, $R_{Sh}$is the shunt resistance, I_{01} and I_{02} are the reverse saturation currents of diode 1 and diode 2 respectively. I_{phcel} is the photocurrent of the PV cell. We can determine it using the following equation (3) [11, 14, 15]:

$$I_{\text{phcel}} = \frac{G_g}{G_{gréf}}\left[I_{\text{phcelref}} + \mu_{Icc} \times (T_{\text{cel}}\text{-}T_{\text{celref}})\right] \quad (3)$$

G_g is the global solar radiation. $G_{gréf}$, $I_{phcelréf}$ and T_{celref} are respectively the global solar radiation, the photo-current and the temperature of the PV cell under standard reference conditions (G_{gref} = 1000 W / m^2, T_{celref} = 25°C). μ_{Isc} is the short-circuit temperature coefficient and T_{cel} represents the junction temperature of the PV cell and its value is determined from the following relation (3) [17, 18]:

$$T_{cel} = T_a + \frac{NOCT-20}{800} \times G_g \quad (4)$$

NOCT is the nominal operating temperature of the PV cell defined in the particular operating conditions of the PV cell relating to the solar distribution spectrum AM1.5, solar radiation of 800 W/m^2, an ambient temperature of 20°C and a wind speed at 1 m/s. Ta is the ambient temperature [19].

In equation (1), q is the charge of the electron ($q=1.6\times10^{-19}$ C), k the Boltzmann constant ($k = 1.38\times10^{-23}$ J / K), n the ideality factor of the diode and I_{scel} is the saturation current of the diode D. I_{scel} is also expressed as a function of the junction temperature of the PV cell by the relation (4) [11, 20]:

$$I_{scel} = I_{scelréf} \times \left(\frac{T_{cel}}{T_{celréf}}\right)^3 \times exp\left[\frac{q\times E_g}{n\times k} \times \left(\frac{1}{T_{celréf}} - \frac{1}{T_{cel}}\right)\right] \quad (5)$$

$I_{scelref}$ represents the saturation current of the PV cell diode under standard conditions and E_g is the gap energy whose value for crystalline silicon at 0 K is 1.12 eV.

2.1.2. Modeling of the PV Module

A PV module is a grouping of PV cells that are connected in series or parallel to increase the required electrical power. The I-V characteristic of series-connected PV cells is derived by adding the induced voltages at the same output current. In the case of parallel-connected PV cells, however, the induced currents are added at the same terminal voltage [28]. The parameters to be added will theoretically be a multiple of one parameter and the number of cells, assuming identical PV cells. Experience has taught us that this assumption is not always correct. Although the PV cells have the same specifications, there are minor differences in manufacturing points under the same insolation level. This phenomenon is known as mismatched operation of PV cells. Thus, the model described in Section 2.1.1 for a PV cell can be extended to a PV module consisting of Ns series PV cells and Np parallel PV cells [28]. The numerical equation for the current I of a PV module arranged in N_P parallel and N_S series PV cells becomes:

$$I = N_P I_{PV} - N_P I_{01}\left[exp\left\{\frac{q(V+\gamma R_S I)}{N_S.a_1 V_T}\right\}-1\right] - N_P I_{02}\left[exp\left\{\frac{q(V+\gamma R_S I)}{N_S a_2 V_T}\right\}-1\right] - \left(\frac{V+\gamma R_S I}{\gamma R_{Sh}}\right) \quad (6)$$

Where $\gamma = {}^{N_S}/_{N_P}$

2.1.3. Impact of the Temperature and Solar Radiation on the Productivity of a PV Module

When exposed to the Sun, the PV module is directly affected by solar radiation and temperature. These two climatic parameters thus influence its electrical performance [9, 12, 16, 23, 24].

Indeed, the characteristic (I-V) of an illuminated photovoltaic (PV) cell or a PV module varies with temperature, according to M. Libra and V. Poulek of the manuscript [23]. The phenomenon is explained by solid-state physics theory. The lower the open circuit voltage and the higher the short circuit current, the higher the temperature. The band theory of solid-state physics is used to explain this behavior. In the case of solar radiation, the higher the intensity, the more photons arrive on the PV cell or module, resulting in large electron-hole pairs that induce the electric current.

Figure 2 shows the short circuit current (I_{SC}) and open-circuit voltage (V_{OC}) in relation to the time of day [24]. It is obvious that I_{SC} and V_{OC} increase in proportion to time, reaching their peak levels in about 12 hours. The V_{OC}, on the other hand, varies in a logarithmic fashion, whereas the I_{SC} is directly proportional to the intensity of the incoming light The V_{OC} curve shows a slight decrease around 12 hours and 15 minutes, which could be attributed to factors such as the high temperatures at this time of day. Figure 2 depicts how the effectiveness of solar PV modules decreases as irradiance increases. When extreme temperatures are not considered, combined with a significant variation in irradiance, it can lead to under-sizing of PV systems, which can result in losses or failure of the PV system [24].

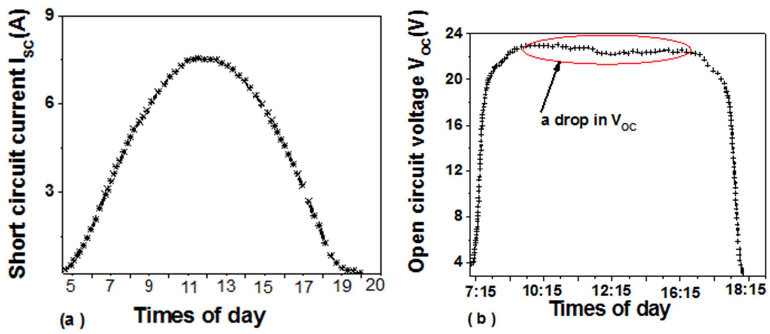

Figure 2. *Impact of temperature on I_{SC} and V_{OC} [24].*

2.1.4. Formula for Sizing a PV Module Field Currently Used

The goal of PV module sizing is to determine the total number of PV modules or their total peak power required to meet the energy needs of a given set of electrical equipment. The following formula is used to dimension a PV module field (7) [25-27]:

$$P_c(Wc) = \frac{E_j}{K_p \times H} \quad (7)$$

with

$$E_j = \sum_{k=1}^{n} P_k \times t_k \quad (8)$$

where Ej denotes the amount of electrical energy to be supplied to electrical appliances. H stands for solar insolation.

P_k is the electrical power of the electrical equipment and t_k the operating time of the electrical device.

Kp is the overall yield and is calculated using the yields of each electronic device in the solar energy production chain. It is expressed in terms of relation (9).

$$K_p = \prod_{k=1}^{n} \eta_k \quad (9)$$

where η_k is the efficiency of each electronic device inserted in the photovoltaic energy production chain.

2.2. Experimental Investigation

The availability of experimental data is a requirement for conducting an experimental investigation on the dimensioning of a field of PV modules while taking temperature into account. As a result, we employ one year of experimental data on solar radiation and PV module temperature. These data were collected using the data acquisition system installed in the 85 kWp photovoltaic power plant connected to the electricity network of Burkina Faso's Ministry of Environment. Figure 3 depicts the data measurement system, which consists primarily of:

1. a data acquisition system called Sunny web box;
2. Sensors for ambient temperature, PV module temperature, and solar radiation. These sensors are linked to the Sunny web box by a device known as the Sunny sensor box.

Figure 3 shows the measuring device.

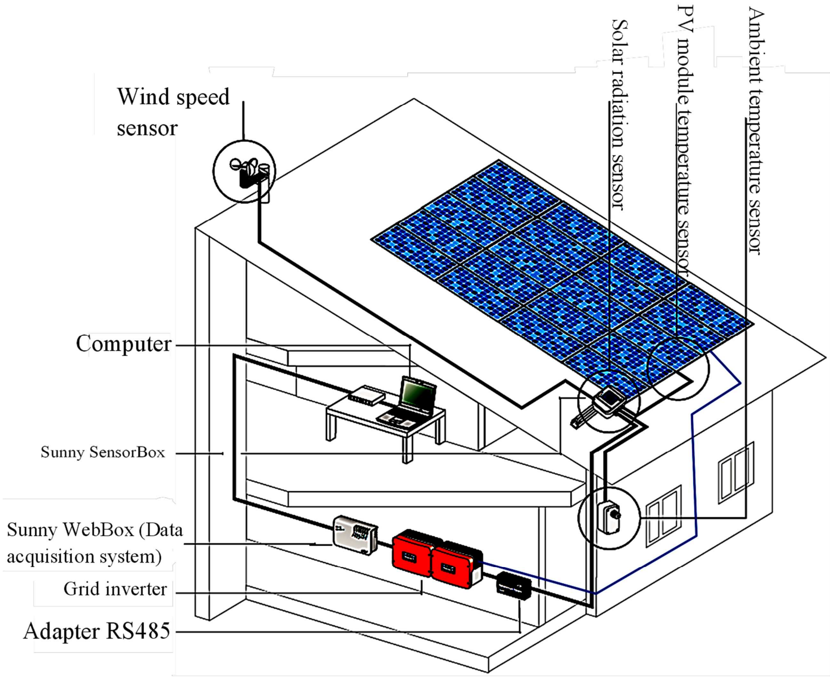

Figure 3. *Experimental devices for monitoring the behavior of a PV system connected to the national grid.*

3. Results and Discussion

The research conducted in this document enabled us to obtain the results that we will present in this section.

3.1. Energy Production of a PV Module at Standard and Real Temperatures

In this section, the energy production of a PV module at 25°C is compared to the energy production of the PV module at the temperature in real-world climatic conditions. To do so, we use equation 8 to calculate the daily energy production of a 225 Wp PV module.

The calculation of the real daily energy production is performed using data from the solar radiation (W/m^2) and the temperature of the PV module obtained in real climatic conditions at the Ministry of the Environment's PV plant. In addition, we simulate the energy production of the same PV module with the same measured solar radiation data but at a temperature of 25°C in this study. The obtained results cover a one-year period and are represented by the curves in figure 4.

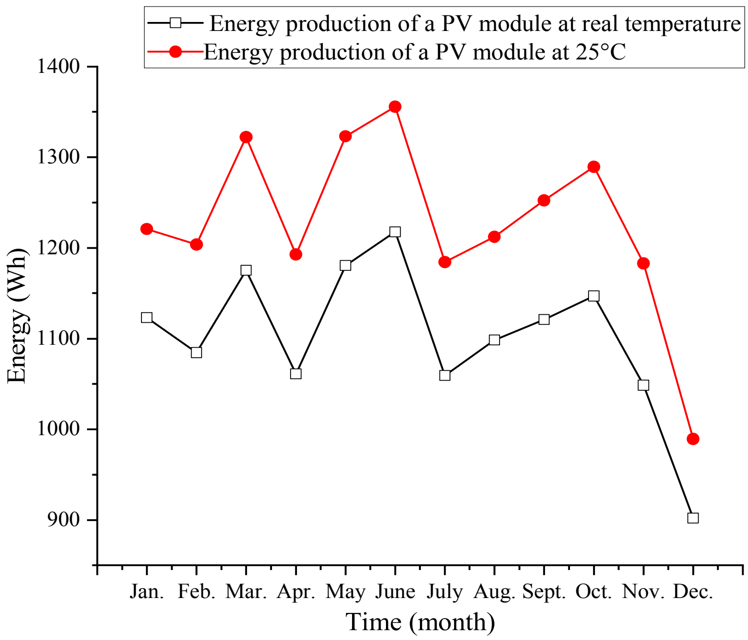

Figure 4. *Monthly average energy production of the PV module field at 25°C and real temperature condition.*

Figure 4 shows that the average energy production of a PV module under real-world temperature conditions is lower than that at 25°C. Remember that a PV module operates in real-world climatic conditions at temperatures that are generally higher than 25°C. The decrease in PV module performance caused by temperature in real-world climatic conditions demonstrates that the impact of temperature is very real and can be attributed to the effect of an energy production efficiency induced by temperature, the value of which is between 0 and 1.

The mathematical expression used in most PV module field sizing takes into account the energy production of the PV field under climatic conditions at a temperature of 25°C. As a result, it is necessary to reformulate the PV module field dimensioning equation by incorporating the effect of temperature. This can be accomplished using the PV system efficiency formula of Equation, which we develop below.

3.2. Mathematical Expression of the Efficiency of a PV Module

The concept of temperature-induced efficiency in the production of a PV module will be used to model the impact of temperature on the performance of PV modules under real-world climatic conditions. This yield is the ratio of a PV module's daily energy production under climatic conditions at real temperature to a PV module's daily energy production under conditions at 25°C temperature with equal sunshine. To calculate this induced yield, we conducted research to develop this mathematical relationship based on the amount of sunlight and the maximum ambient temperature, which translates the effect of temperature on the efficiency of a PV module field.

The research is carried out using a software application whose database is used to create a mathematical expression that links the temperature-induced efficiency to the maximum ambient temperature and sunshine parameters. Temperature-induced efficiency data is obtained using measurements from the Ministry of Environment's PV plant. The sunshine and maximum ambient temperature data used are also obtained from the Ministry of Environment's PV plant.

The mathematical function retained is given by formula (10), which was obtained using software that provides several mathematical expressions. This one produces the best results in terms of reproducing the values of efficiency induced by temperature based on data on sunshine and maximum ambient temperature.

$$\eta_{temp} = A + B \times H + C \times T_{Max} \quad (10)$$

H (kWh/m^2) is the sunshine, T_{Max} (°C) denotes the maximum ambient temperature. Table 1 shows the coefficients A, B, and C.

Table 1. *Coefficients for formula (17).*

Coefficient	Value
A	1.08055
B	-0.00699
C	-0.00381

Figure 5 depicts the curve derived from experimental data on temperature-induced efficiency and that resulting from equation (10).

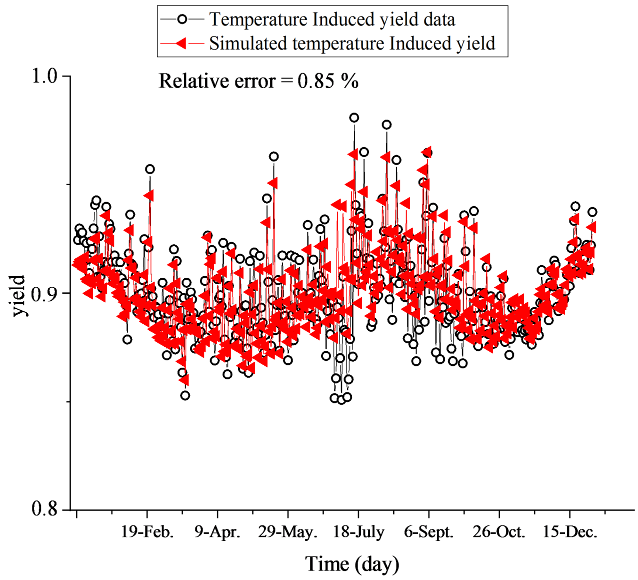

Figure 5. *Temperature-induced yield on PV module production.*

Figure 5 shows that the curve of the mathematical function meets the point clouds of the experimental data at an acceptable level. The relative error obtained from the extracted data using equation 10 and those obtained experimentally is of the order of 0.85 percent, which is considered low. These results show that the developed formula reproduces the temperature-induced efficiency values of a PV module satisfactorily.

We calculated the annual average values of temperature-induced efficiency on PV module production in some cities using equation 10 (our developed formula) equation and NASA maximum ambient temperature and insolation data. Table 2 displays the results.

Table 2. *Annual average values of temperature-induced efficiency on PV module production of some cities.*

Country	City	Value
Burkina Faso	Ouagadougou	0,90
South Africa	Pretoria	0,93
Kenya	Nairobi	0,93
Egypt	Cairo	0,92
Tunisia	Tunis	0,93
Saudi Arabia	Riyadh	0,90
China	Peking	0,95
Sweden	Stockholm	0,98
French	Paris	0,96
Brazil	Brasilia	0,93
USA	Washington	0,98

3.3. Mathematical Model for Sizing the PV Module

The effect of temperature on the daily energy production of PV modules, according to the previous study, induces a yield, which we have modeled using equation 10. Thus, an update is required in equation (7) for sizing the PV module field, which requires the integration of the parameter concerning the efficiency induced by temperature to account for the impact of heat on the performance of solar PV technology. As a result, the new mathematical expression for dimensioning the PV module field is (11):

$$P_c(Wc) = \frac{E_j}{K_p \times H \times \eta_{temp}} \quad (11)$$

where η_{temp} represents the efficiency induced by the temperature on the production of the PV modules.

4. Conclusion

We conducted research in this paper to develop a mathematical function that accounts for the effect of temperature on the electrical production of a field of PV modules and can be integrated into the standard sizing formula for the field of PV modules. Temperature-induced efficiency is the mathematical term for this relationship. It's a linear function with two variables and three constants. The sunshine and the maximum ambient temperature are the variables in the mathematical function.

The combination of the efficiency induced by the temperature function and the standard formula for sizing a PV field of modules provides a complete relationship for calculating the peak power of a PV field while taking sunlight and temperature into account.

ORCID

Dominique Bonkoungou: 0000-0003-3480-0025

Conflicts of Interest

The authors declare no conflicts of interest regarding the publications of this paper.

References

[1] Siva Ramakrishna Madeti, S. N. Singh, A comprehensive study on different types of faults and detection techniques for solar photovoltaic system, Solar Energy, Volume 158, 2017, Pages 161-185, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2017.08.069.

[2] Vaclav B, Tomae Ol, Martin Libra, Vladislav P, Jan S, Minh-Quan D, Igor T, New Monitoring System for Photovoltaic Power Plants' Management Energies, 10.3390/en11102495, 11, 10, (2495), (2018).

[3] Hegazy Rezk, Igor Tyukhov, Mujahed Al-Dhaifallah, Anton Tikhonov, Performance of data acquisition system for monitoring PV system parameters, Measurement, 10.1016/j.measurement.2017.02.050, 104, 204-211, (2017).

[4] Rezk, Hegazy; Tyukhov, Igor; Raupov, A. (2015). Experimental implementation of meteorological data and photovoltaic solar radiation monitoring system. International Transactions on Electrical Energy Systems doi: 10.1002/etep.2053.

[5] Mambrini, T. Caracterisation de panneaux solaires photovoltaïques en conditions réelles d'implantation et en function des différentes technologies. Thesis, Université Paris-sud, France, 2014.

[6] Dominique Bonkoungou, Toussaint Guingane, Eric Korsaga, Sosthène Tassembedo, Zacharie Koalaga, Arouna Darga, François Zougmore, "A Novel Topology to Improve PV Module Efficiency under Partial Shading Conditions", International Journal of Photoenergy, vol. 2022, Article ID 4401187, 19 pages, 2022.

[7] BISHOP, J. W. Computer simulation of the effects of electrical mismatches in photovoltaic cell interconnection circuits. Solar Cells, Italie, 1988.

[8] BONKOUNGOU, D. Étude de l'impact de la variabilité de l'irradiation solaire et des paramètres météorologiques sur la production d'énergie d'une centrale solaire PV alimentant en réseau isolé un village du Burkina Faso. Thesis, UNIVERSITE OUAGA 1 Pr Joseph KI-ZERBO, Burkina Faso, 2016.

[9] Salim, J. A., Albaker, B. M., Alwan, M. S., Hasanuzzaman, M. Hybrid MPPT approach using Cuckoo Search and Grey Wolf Optimizer for PV systems under variant operating conditions. Global Energy Interconnection, 2022.

[10] Naeijian, M., Pourmousa, N., Rahimnejad, A., Ebrahimi, S. M., Gadsden, S. A. Parameter estimation of PV solar cells and modules using Whippy Harris Hawks Optimization Algorithm. Energy Reports, 2021.

[11] Saadaoui, D., Elyaqouti, M., Assalaou, K., Ben hmamou, D., Lidaighbi, S. Parameters optimization of solar PV cell / module using genetic algorithm based on non-uniform mutation. Energy Conversion and Management, 2021.

[12] Yaw-Juen Wang, "Po-Chun Hsu an investigation on partial shading of PV modules with different connection configurations of PV cells" Energy 36 (2011) 3069e3078, doi: 10.1016/j.energy.2011.02.052.

[13] Boghdady, T. A., Mohamed, Y. A. Reactive power compensation using STATCOM in a PV grid connected system with a modified MPPT method. Ain Shams Engineering Journal, 2022.

[14] Piccoli, E., Dama, A., Dolara, A., Leva, S. Experimental validation of a model for PV systems under partial shading for building integrated applications. Solar Energy, Italie, 2019.

[15] Dio, V. D., Cascia, D. L., Miceli R., Rando, C. A Mathematical Model to Determine the Electrical Energy Production in Photovoltaic Fields Under Mismatch Effect. IEEE, Italie, 2009.

[16] Aoun, N. Methodology for predicting the PV module temperature based on actual and estimated weather data. Energy Conversion and Management, 2022.

[17] Bi, B. E. B., Gbaha, P., Koffi M. P. E., Koua, K. B. Modélisation Des Composants D'un Système Hybride Panneaux Photovoltaïque – Stockage D'énergie Via L'hydrogène – Batteries. European Scientific Journal, Côte d'Ivoire, 2018.

[18] Guiheneuf, V. Approche multi-physique du vieillissement des matériaux pour application photovoltaïque. Thesis, Université Paris-Est, France, 2017.

[19] Tifidat, K., Maouhoub, N., Benahmida, A., Salah, F. E. A. An accurate approach for modeling I-V characteristics of photovoltaic generators based on the two-diode model. Energy Conversion and Management, 2022.

[20] Sundaram, K. M., Boopathi, C. S., Pandian, A., Kalyan Sagar Kadali, Sathyamurthy, R., Anandhraj, P., Madhu, B. Predator-Prey based firefly optimization for PV Module parameters extraction. Energy Reports 7, 2021.

[21] Motahhir, S., El Hammoumi, A., El Ghzizal, A. Photovoltaic system with quantitative comparative between an improved MPPT and existing INC and P&O methods under fast varying of solar irradiation. Energy Reports, 2018.

[22] Libra, M., Poulek, V. Influence of Temperature on Important Characteristics of Photovoltaic Cells. Green Energy and Technology, 2021.

[23] Shaheen, A. M., El-Seheimy, R. A., Xiong, G., Elattar, E., Ginidi, A. R. Parameter identification of solar photovoltaic cell and module models via supply demand optimizer. Ain Shams Engineering Journal, Egypte, 2022.

[24] Dominique Bonkoungou, Jacques Marie Ilboudo, Abdoulaye Kabre, Zacharie Koalaga. Monitoring and Effectiveness Analysis of a Hybrid PV Battery System in Real Conditions. International Journal of Energy and Power Engineering (in press) 2023.

[25] Bruni, G., Cordiner, S., Mulone, V. Domestic distributed power generation: Effect of sizing and energy management strategy on the environmental efficiency of a photovoltaic-battery-fuel cell system. Energy, 2014.

[26] Soufi, A., Chermitti, A., Triki, N. B. Sizing and Optimization of a Livestock Shelters Solar Stand-Alone Power System. International Journal of Computer Applications, 2013.

[27] Korsaga, E. Etude comparative des dispositifs de stockage de l'énergie applicables aux systèmes photovoltaïques au Burkina Faso. Thesis, UNIVERSITE OUAGA 1 Pr Joseph KI-ZERBO, Burkina Faso, 2019.