Solar Energy 199 (2020) 521–529

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Robust code-based modeling approach for advanced photovoltaics of the future

C. Ogbonnaya[a,c,*], A. Turan[a], C. Abeykoon[b]

[a] Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester, M13 9PL, UK
[b] Aerospace Research Institute, Department of Materials, The University of Manchester, Oxford Road, M13 9PL, UK
[c] Faculty of Engineering and Technology, Alex Ekwueme Federal University Ndufu-Alike Ikwo, P.M.B. 1010, Nigeria

ARTICLE INFO

Keywords:
Photovoltaic systems
Photovoltaic tools
Code-based modeling
Block-based modeling
Simulation

ABSTRACT

Modeling and simulation of photovoltaics help to reduce development costs, design turnaround time and facilitates better techno-economic decisions. However, there is a current need to generate new theories, algorithms, applications and software in order to increase the contribution of solar energy to the global energy supply. For future advancements in the field of photovoltaics, robust techniques for PV modeling, simulation, visualisation and design are required to overcome the limitations of the current approaches. This study proposes the Code-Based Modeling (CBM) approach as a potent approach to facilitate the study of PV technologies. Experimental data were synthesised and used for coding and training of the code-based (CB) model; followed by a validation of the trained model using commercial PV modules. Results clearly show that the model can repeatedly and reliably predict the short circuit current, maximum power point, open circuit voltage with 0%, < 2% and < 10% deviations, respectively. Furthermore, instances of the applicability of the CBM approach in the study of the thermodynamics of PV, solar cell materials characterisation, PV systems design and power monitoring were presented. Above all, CBM approach accepts user-defined functions and therefore presents new opportunities for scientists and engineers to advance model-based investigations of the photovoltaics beyond the current state-of-the-art.

1. Introduction

Research is actively being carried out on how photovoltaics can be applied as a clean source of energy because it does not emit greenhouse gases during operation (Bukar and Tan, 2019; Ogbonnaya et al., 2019a). The Renewables 2019 Global Status Report (GSR) (REN21, 2018) indicates that solar photovoltaic (PV) constitutes around 100 GW out of 2378 GW global renewable power capacity installed in 2018; which represents 55% of the renewable capacity additions in the year, followed by wind power (28%) and hydropower (11%). Apart from direct power generation with PV systems, PV could also become a primary power subsystem in integrated systems in the future. For instance, PV modules have been studied for integration with electrolysers, fuel cells and batteries for reliable power generation (Lehman and Chamberlin, 1991; Meurer et al., 1999; Özgirgin et al., 2015). Also, PV modules have been integrated with thermal absorbers to create photovoltaic-thermal (PV/T) systems to supply electricity and hot water (Avezov et al., 2011; Michael et al., 2015). The present trends in integrating PV as a power source; or as a subsystem of a hybrid system, suggest that the demand for software including PV models would increase in the future. As an example, the possibility of integrating a maximum power point tracking (MPPT) algorithm with an automotive-based software to optimise solar energy harvesting was designed and verified by (Cheddadi et al., 2018). Kolhe et al. (2019) also experimented with the use of PV systems for power ventilation system of electric cars. It is expected that more application-based studies would be facilitated by robust modeling and simulation approaches; howbeit, complemented by theoretical models and experimental results.

Presently, manufacturers provide limited information on the electrical and thermal characteristics of PV modules whilst omitting other useful information such as bandgap energy, photon-generated current, diode reverse saturation current, shunt resistance and ideality factor of the semiconductors (Villalva et al., 2009). So, in order to generate more information on the module, an accurate, repeatable and reliable computational model is required. Here, PV modeling approaches are classified into block-based modeling (BBM) (Bellia et al., 2014; El Hassouni et al., 2017; Krismadinata et al., 2013; Motahhir et al., 2018; Patel and Sharma, 2013; Zainal and Yusoff, 2016), code-based modeling (CBM)

* Corresponding author at: Department of Mechanical, Aerospace and Civil Engineering, The University of Manchester, M13 9PL, UK.
E-mail address: chukwuma.ogbonnaya@manchester.ac.uk (C. Ogbonnaya).

https://doi.org/10.1016/j.solener.2020.02.043
Received 22 June 2019; Received in revised form 29 November 2019; Accepted 10 February 2020

Nomenclature

A	ideality constant
BB	block-based
BBM	block-based modeling
CB	code-based
CBM	code-based modeling
E_g	bandgap energy
I_0	output current of PV module
I_s	saturation current of PV module
I_{sc}	short circuit current of PV module
k	Boltzmann's const. (1.38×10^{-23} J/K)
MPP	maximum power point
N_s	number of solar cells in series
N_p	number of modules in parallel
P_0	output power of PV module
PV	photovoltaic
q	electron charge (1.602×10^{-19}C)
STC	standard test condition (25 °C, 1000 W/m^2, AM 1.5)
T	temperature
V_0	output voltage of the PV module
V_{oc}	open circuit voltage

Greek symbols

Θ_1	solar cell material constant
Θ_2	solar cell material constant

Subscripts

cell	solar cell
mpp	at maximum power point
ph	photon
pv	photovoltaic
ref	reference

(Lo Brano et al., 2010), electrical circuit modeling (ECM) (Fernandes et al., 2016) and Numerical modeling (NM) (Elkholy et al., 2010; Leuchter et al., 2010). Regardless of the modeling approach adopted, implementing the model in a computer iteratively is basic because of the transcendental nature of the PV model.

Contextually, a computational model of the PV is predictive if it shows how the power generation characteristics are affected by variations in the solar cell material, operating or environmental parameters. The predictive capability of a PV model can help designers study the feasibility of a PV system before installation (Ciulla et al., 2014). Secondly, a PV model is prescriptive if it allows designers to generate PV design scenarios for effective decision making. These two desirable features of a PV model are germane for deepening the current understanding of solar cell physics; and for analysing existing PV systems as well as developing new ones. Researchers select the parameters to be included in the model based on the purpose of their investigation. For instance, five-parameter model including shunt resistance (R_{sh}), series resistance (R_s), diode quality factor (n), reverse saturation current (I_o), photocurrent (I_L) for parametric study of a PV module has been proposed (Lo Brano et al., 2010). Also, the use of open circuit voltage (V_{oc}), short circuit current (I_{sc}), output current (I_0), and voltage at maximum power point (V_{mpp}) for modeling PV characteristics has been proposed (Gupta et al., 2012).

The progress made so far in developing modeling and simulation tools has helped in the advancement PV generations and their hybrids. As an example, the National Renewable Energy Laboratory (NREL) developed System Advisor Model (SAM) based on C++ for techno-economic modeling, simulation and analysis of renewable energy systems; and the software facilitates decision making on the financial, technological and performance of renewable energy systems such as photovoltaics, wind, biomass, solar water heating, geothermal and concentrated solar power plants (Gilman, 2015; Gilman et al., 2018). University of Wisconsin Madison (Solar Energy Laboratory, 2009) developed a transient system simulation (TRNSYS) programme which has

Table 1
Photovoltaic modeling and simulation approaches.

References	Modeling type	Software used	Description/Remarks
Vinod et al. (2018)	BBM	Simulink	Used a single diode equivalent circuit model to model and simulate irradiation and temperature of PV module
Gilman (2015)	CBM	SAM	Used for techno-economic modeling for decision making by project managers and engineers, policymakers, developers and researchers
Fatehi and Sauer (2014)	CBM	PVSys	Modelled the temperature and irradiance dependence of photovoltaic modules
Aryal and Bhattarai (2018)	CBM	PVSys	Modelled and simulated 115.2 kWp grid-connected PV system
Abdulkadir et al. (2012)	BBM	Simulink	Simulated the effect of solar radiation and temperature on 36 W PV module
Keles et al. (2013)	BBM	Simulink	Studied the current and voltage potential of PV module for a given solar radiation and temperature
Motahhir et al. (2018)	BBM	Simulink	Studied the effects of parameters on photovoltaic generation using modified incremental conductance algorithm
Fernandes et al., 2016	circuit	PSPICE	Evaluated the effect of shading on characteristics of power generated by different string layouts
Lo Brano et al. (2010)	CBM	Visual Basic Application	Proposed and determined PV panel characteristics using five parameters
Gupta et al. (2012)	BBM	MATLAB/Simulink	Used four parameters to model photovoltaic module characteristics
Morshed et al. (2015)	–	HOMER, PVsys, SolarMAT	Designed and modelled 2 kW stand-alone PV system using three different approaches
Mohammed et al. (2011)	CBM	TRNSYS	Modelled and verified direct solar water heating system
Tan et al. 2004)	BBM	Simulink	Proposed a model for dynamic simulation of photovoltaic power system
El Hassouni et al. (2017)	BBM	Simulink	Designed and modelled 4.2 kW PV generator for agricultural pumping station
Leuchter et al. (2010)	Numerical	MATLAB	Modelled the temperature dependence of photovoltaic panels and maximum power point
Chenni et al. (2007)	Numerical	–	Modelled the effect of temperature and irradiance on solar cells based on four parameters
Elkholy et al. (2010)	Numerical	Simulink/Excel	Modelled photovoltaic modules and arrays
Pagrut et al. (2017)	BBM	Simulink	Studied the effects of environmental factors on PV
Mahmood and Selman (2016)	BBM	Simulink	Studied four parameters that can be used in modeling photovoltaic generation
Krismadinata et al. (2013)	BBM	Simulink	Studied effect of temperature and irradiations on power generation
Acakpovi and Ben Hagan (2013)	BBM	Simulink	Studied the effect of irradiations and temperature variations on power generation
Tsai (2010)	BBM	Simulink	Modelled PV power generation using ambient temperature and irradiation as inputs

been applied for modeling and simulation of the performance of integrated systems as a function of time (Shrivastava et al., 2017). TRNSYS allows user-defined inputs for components of the integrated system. Also, a building integrated photovoltaic systems at Fraunhofer Institute for Solar Energy Systems was simulated to determine the energy yield using computer simulation chain based on two-diode model (Sprenger et al., 2016).

PVsyst, based on single diode module model, is another software package for modeling the PV systems. Sentaurus Technology computer-aided design (TCAD) is useful for simulating the wafer fabrication, operation and reliability of semiconductor devices (Wu et al., 2017). There are other modeling and simulation tools for modeling different aspects of solar energy systems. Such programmes or software include EnergyPlus (US Department of Energy), RETScreen (Natural Resources Canada), SolDesigner(DreSys Germany), SolarPro (SolarPro, USA), T*SOL (Valentin Software, Germany), WATSUN (University of Waterloo), Polysun (Solar consulting USA) and F-Chart (Shrivastava et al., 2017). PV Lighthouse (PVLIGHTHOUSE, 2019) provides a platform where PV calculators and other resources can be accessed. The approaches that accept user defined functions (UDF) appear to be more robust because they allow the users to input customised equations. An example of such software is TRNSYS. The BBM approach has issues of complexity and difficulty in tracing the lines connecting the building blocks. As an example, in the integrated block-based (BB) model, there are multiple lines linking formulas, variables and constants; and this could be confusing and time-consuming to trace. Although, researchers solved the challenge of traceability by grouping the blocks into subsystems, the problem of accessibility of variables particularly during parametric studies still remains.

Here, we argue that a PV model that can easily accept UDF is crucial for further improvement of the physics and applications of the photovoltaics. Consequently, the motivation of this study is driven by the need to demonstrate the applicability of the CBM approach for the advancement of the science and engineering of photovoltaics. Some applications of the proposed approach are demonstrated across the spectrum; from theory to applications of photovoltaics. It is expected that this paper would facilitate the adoption the CBM approach by other researchers and developers using object-oriented languages such as C++, MATLAB, FORTRAN or Python. The review of the state-of-the-art of the approaches and software is presented in Table 1. It shows different studies and associated approaches that have been applied to model and simulate different aspects of PV module or system.

The photovoltaic process converts solar to electrical energy using semiconductor materials; hence, the existing PV modeling approaches tend to focus on the electrical energy dimension of the PV while the application software packages focus on design, parametric analysis and financial analysis. Nevertheless, there are other dimensions such as solar cell physics, electrochemistry, photochemistry, material characteristics and thermodynamics that should be modelled and studied in order to improve the conversion efficiency of the photovoltaics. Therefore, the overarching aim of this study is to demonstrate the predictive and prescriptive capabilities of CBM approach in order to provide an efficient and effective novel approach for the design, modeling, simulating and visualising for PV-led technologies. In order to achieve this aim, the specific objectives of this study are to:

1. Create a code-based (CB) model of photovoltaic module in MATLAB;
2. Validate the model using commercial PV module;
3. Demonstrate instances where the CBM approach can be applied in the science and engineering of photovoltaics.

The CB model in this study uses inputs such as number of solar cell strings in series (N_s), number of modules in parallel (N_p), reference temperature (T_{ref}), operating temperature (T), reference solar radiation (G_{ref}) and operating solar radiation (G), ideality factor (A), short circuit current (I_{sc}), band gap energy at 0 K (E_{go}), material constants (Θ_1 and Θ_2) and temperature coefficient (K_i). It also uses codes to integrate the equations containing the physics of the solar cell thereby making it easier for users to script-in new equations for investigation.

The major contribution of this study is to introduce a more robust and accurate approach for modeling a PV by demonstrating how the UDF feature of the proposed CBM approach could help overcome the limitations of the extant approaches (i.e. BBM, CBM, ECM and NM). The proposed approach focuses on how new theoretical models and algorithms for solar cells material, PV power generation, thermo-photovoltaic, photothermoelectrical models, designs, parametric analysis can be facilitated in order to enrich the existing PV modeling and simulation tools/software or develop new ones. The use of this approach provides an opportunity to reduce system development costs, implementation time and experimental risks. The proposed approach requires that the developer, scientist, engineer or researcher builds the computational model of the physical system using codes; and then subject the model to further investigations based on the research or design objectives. This study, therefore, is a methodological contribution for the advancement of PV modeling, simulation, design, visualisation and applications. Onward, Section 2 presents the overall approach adopted in order to achieve the objectives. Section 3 presents the processes of validating the CB model; while Section 4 discusses the instances where CBM approach can be applied. Finally, the conclusion of the study is presented in Section 5.

2. Research methods and approach

Since this study focuses on methodological development, this section presents how the code-based model was created in the MATLAB. Table 2 presents the equations included in the CB model. The equations include the relationship between bandgap and temperature (Eq. (1)); the relationship between photocurrent and solar radiation (Eq. (2)); the relationship between saturation current with bandgap and temperature (Eq. (3)); the output voltage as a function of the number of cells in series and parallel (Eq. (4)); and the power output equation (Eq. (5)). The terms of the equations are defined in the nomenclature and Table 3.

The flow chart for creating the CB model using MATLAB is shown in Fig. 1.

3. Validation of the code-based model

The synthesised data in Table 3 are from peer-reviewed literature; and they were used for training the PV model. Afterwards, the model was validated with commercial Solarex MSX-60 (Motahhir et al., 2018) and Shell S140 (Shell Solar, 2003) to examine how accurate it predicts the parameters stated by the Manufacturers. A common approach for validating a PV model is to compare the model-predicted characteristics with the manufacturers' stated values (Chenni et al., 2007; Gupta et al., 2012; Lo Brano et al., 2010; Pagrut et al., 2017).

In this study, the maximum power point (MPP), short circuit current and the open circuit voltage of the two PV modules were predicted and compared with the values stated by the manufacturers (see Table 4).

Table 2
Fundamental equations for CBM approach.

References	Equations	Equation Number
Ünlü (1992)	$E_g(T) = E_g(0) - \frac{\Theta_1 T^2}{T + \Theta_2}$	(1)
Bellia et al. (2014)	$I_{ph} = (I_{sc} + K_i\ (T_{cell} - T_{ref}).\frac{G}{G_{ref}}$	(2)
Muhammad et al. (2017)	$I_s = I_{s,ref}\left[\frac{T_{cell}}{T_{ref}}\right]^3 \exp\left[\frac{1}{k}\left(\frac{E_g}{T_{ref}} - \frac{E_g}{T_{cell}}\right)\right]$	(3)
Zeitouny et al. (2017)	$I_0 = I_{ph}N_p - I_sN_p\left[\exp\left(\frac{qV_0}{AN_skT}\right) - 1\right]$	(4)
Power output equation	$P_o = I_o x V_o$	(5)

Table 3
Parameters and operating conditions for training the CB model.

Parameters	Values	Units	References
Open circuit Voltage(V_{oc})	21.1	V	Motahhir et al. (2018)
Short circuit current(I_{sc})	3.8	A	Motahhir et al. (2018)
Saturation current(I_s)	5.39×10^{-5}	A	Meyer (2017)
Maximum Power Point(P_{mp})	60	Watts	Motahhir et al. (2018)
Maximum Voltage Point(V_{mp})	17.1	V	Motahhir et al. (2018)
Maximum Current Point(I_{mp})	3.5	A	Motahhir et al. (2018)
Ideality factor (A)	2.83		Meyer (2017)
Band gap (Silicon) at 0 K	1.1557–1.295	eV	Shi and Kioupakis (2015); Varshni (1967)
Solar cell material constant (Ó¨$_1$)	7.021×10^{-4}		Varshni (1967)
Solar cell material constant (Ó¨$_2$)	1108		Varshni (1967)
Reference Temperature(T_{ref})	25	°C	Villalva et al. (2009)
Temperature Coefficient at I_{sc} (K_i)	0.065	%/°C	Motahhir et al. (2018)
Temperature Coefficient at V_{oc} (K_v)	−0.38	%/°C	Motahhir et al. (2018)
Number of cells in series(N_s)	36		Motahhir et al. (2018)
Number of cells in parallel (N_p)	1		
Reference Insolation(G_{ref})	1000		Villalva et al. (2009)
Boltzmann constant (k)	1.38×10^{-23}	J/K	constant
Electron Charge (q)	1.602×10^{-19}	C	constant

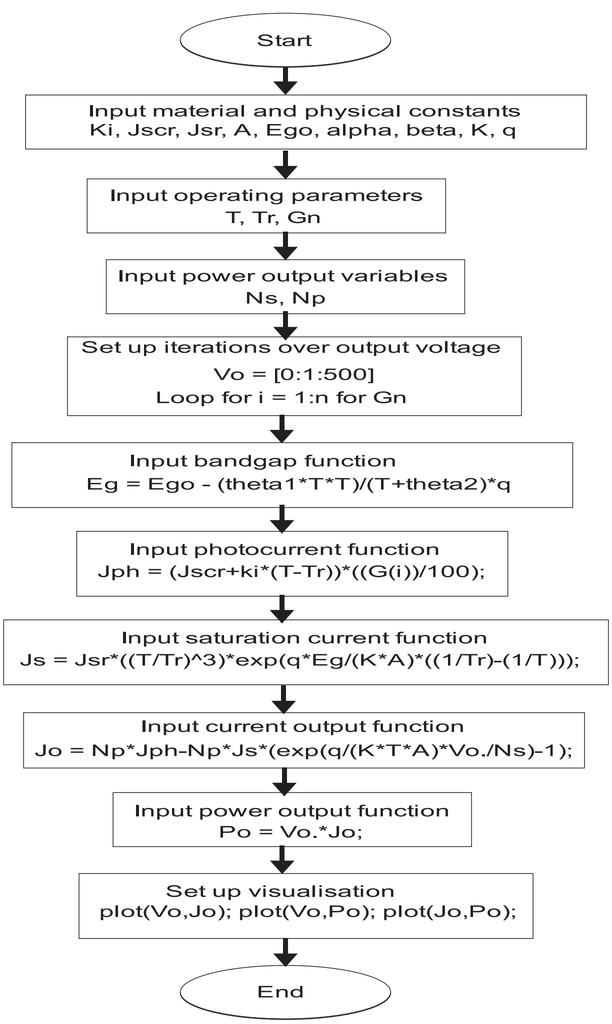

Fig. 1. Flowchart for creating CB model of PV in MATLAB.

The positive '+' sign indicates where the output values of the model are greater than the stated values in the manufacturers' information sheet; negative '−' sign indicates the opposite. The proposed model predicts theI_{sc} with 100% accuracy. The percentage deviation in the maximum power point (MPP) for the two cases was less than 2% while the deviation in the prediction of the V_{oc} is less than 10%. Fig. 2(a) and (b) compare the model and manufacturers' values for Solarex MSX-60 and Shell S140 PV modules. Evidently, the CB model is able to predict the Manufacturers' stated parameters with a significant accuracy.

3.1. Comparison between block-based and code-based models and modeling approaches

In this study, two tests are designed to establish the robustness of the proposed approach. The first test compares the prediction accuracy of the CB model with one of the models listed in Table 1. The second test shows the extent to which the CBM as an approach to model-based system engineering can implement investigations which are computationally difficult with the other approaches.

To implement the first test, the MPP of four commercial PV modules are predicted with CB and BB models of a PV at standard test conditions (25 °C, 1000 W/m^2, AM 1.5) as presented in Fig. 3. The reason for comparing the CB model with the BB model is because both models can be implemented in the MATLAB software (MATLAB, 2016); and this removes biases on the type of software used. Clearly, from Fig. 3, there is no significant difference between the predictions of the two approaches. This means that the CB model is equally as accurate as the prevalent BB model that has been used by many researchers (see Table 1). While the first test is necessary in order to compare the accuracy of the proposed CB model with the BB model, the second test provides sufficient grounds for the claim of robustness of the CBM approach over the BBM approach. Notably, the robustness of the CBM approach is intertwined with the flexibility of the CB model to accommodate additional code-based functions as would be highlighted in Section 4.1. More explicitly, although either CBM or BBM approach can be applied for parametric analysis of PV modules, the structure and algorithm of the CB model bestows on it a "virtual experimentation" capability, which is where new theories, models and applications can be innovated. The concept of "virtual experimentation" embodies a type of modeling and simulation approach in which the model of a PV module/system is first created and validated before subjecting it to different test conditions by either altering its key parameters or adding a new function. The added function may be a function of solar cell material properties, meteorological variables, system cost, etc. as illustrated in Fig. 4. Most modeling and simulation approaches reported in Table 1 are at the level of the PV module model. Thus, deeper understanding of the photovoltaic physics and applications can be enhanced if more functional or decision-making models are integrated with the PV module model using CBM approach.

From here on, discussions on the predictive and prescriptive applications of the proposed CBM approach are further instantiated in order to substantiate the notion of the robustness of the proposed CBM approach.

4. Discussion of results generated using the CBM approach

This section focuses on the results generated from the CB model and the CBM approach using the "virtual experimentation" paradigm. Thermodynamic analysis, PV module characterisation, PV system design and a potential application of the approach for power monitoring of PV generation are presented.

4.1. Thermophotovoltaic modeling using CBM approach

The negative effect of thermalisation of electrons at the quantum level reduces the conversion efficiency of PV (Nelson, 2003); and

Table 4
Percentage deviation of the model from Manufacturers' specifications.

PV Module	MPP (W) (Manuf.)	MPP (W) (Model)	% deviation	I_{sc} (A) (manuf.)	I_{sc} (A) (model)	% deviation	V_{oc} (V) (manuf.)	V_{oc} (V) (model)	% deviation
Solarex MSX-60	60.0	59.00	−1.7	3.8	3.8	0.00	21.1	23.1	+9.4
Shell S140	40.0	39.51	−1.2	2.68	2.68	0.00	23.3	22.6	−3.0

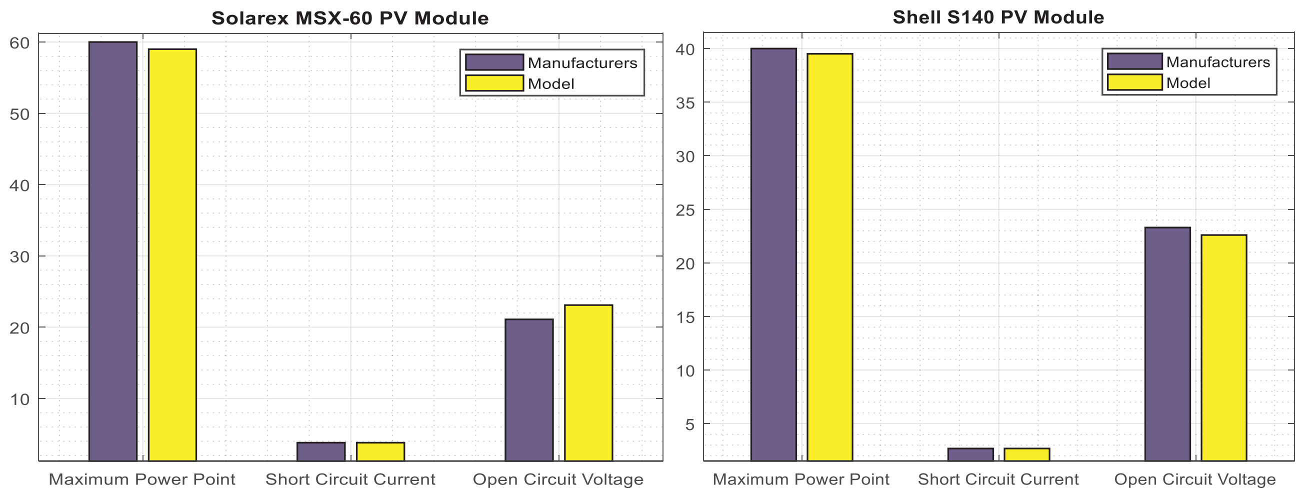

Fig. 2. Comparison between Manufacturers' and model predicted values. (a). Solarex MSX-60 (b) Shell S140.

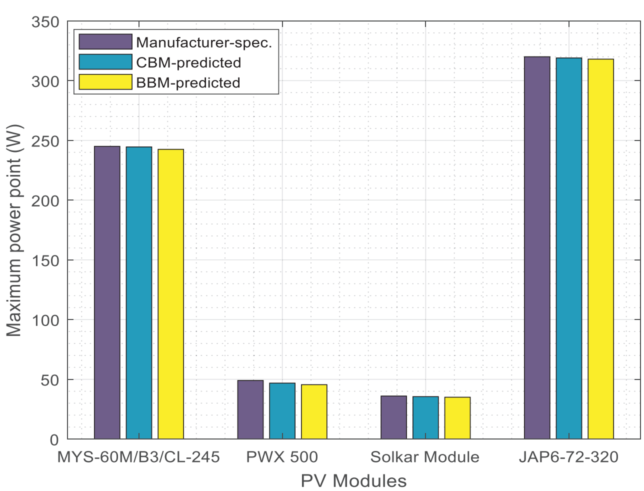

Fig. 3. Comparison between manufacturers', code-based model and block-based model predictions of the MPP of commercial PV modules.

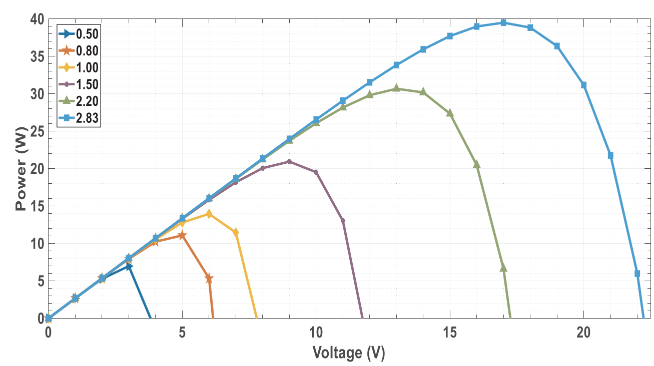

Fig. 5. Code-based model predicted P - V curves for solar cell ideality factors.

strategies to reduce the heat generation or recover it for useful low temperature thermal work is a subject of much active research today. The authors integrated the solar, electrical and thermal exergies of a PV module using CBM approach (published in *Solar Energy* journal (Ogbonnaya et al., 2019d)). The integrated thermophotovoltaic model is expressed in Eq. (6). The novel thermophotovoltaic model predicts

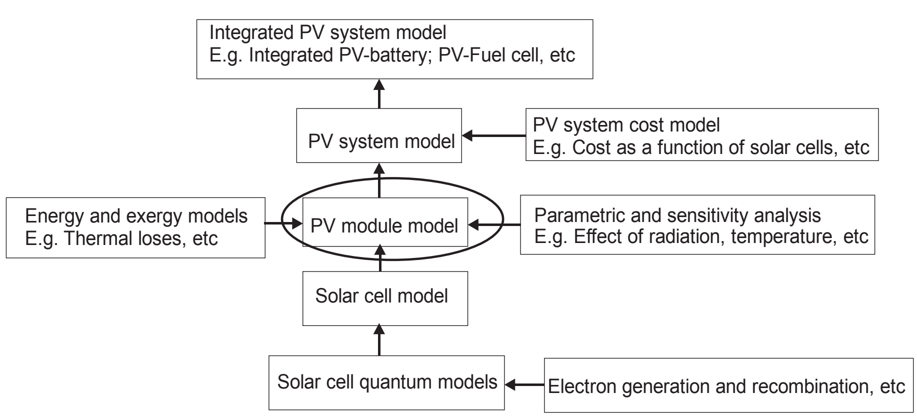

Fig. 4. Spectrum of applications of the CBM approach.

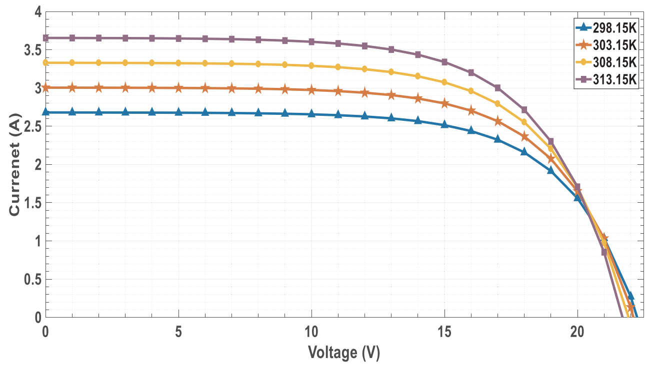

Fig. 6. Code-based model predicted I - V curves for 15 °C increment over reference temperature at 5 °C intervals.

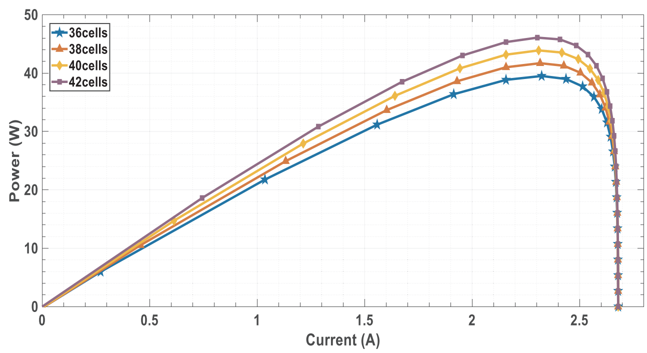

Fig. 7. Code-based model predicted P - I curve for a module design with 36, 38, 40 and 42 solar cell strings in series.

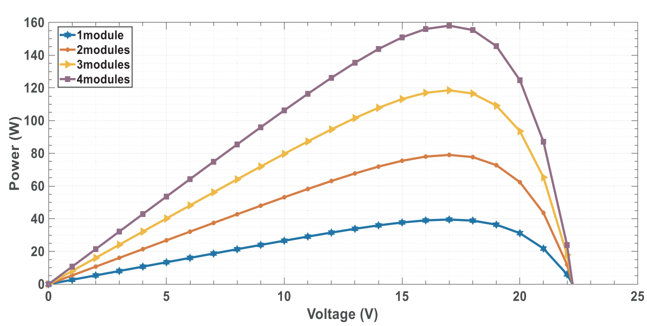

Fig. 8. Code-based model predicted P - V curves for PV modules in arrays.

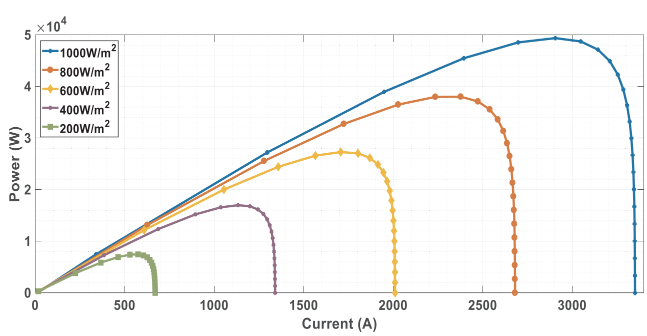

Fig. 9. Code-based model predicted P - I curves for large-scale power generation (50 kW).

the amount of heat generated from a PV module, as a function of temperature and solar radiation. Furthermore, the energy and exergy efficiency enhancement analysis of the PV and PV/T systems were also studied based on the flexibility of the CBM approach (Ogbonnaya et al., 2019b).

$$\dot{Q}_{loss} = \left[GxA_{cell}x\tau_{glass}\left(1-\frac{4}{3}\frac{T}{T_{sun}}+\frac{1}{3}\left(\frac{T}{T_{sun}}\right)^{4}\right)\right]-\left(I_{ph}N_p-I_sN_p\left[\exp\left(\frac{qV_{pv}}{AN_skT}\right)-1\right]\right)xV_{pv} \quad (6)$$

where $\dot{Q}_{loss}$ is the heat generation rate in the module; τ_{glass} is the transmissivity of the PV glass surface; T_{sun} is the temperature of the sun while other terms are already defined in Table 3 or in the nomenclature.

These novel applications of the CBM approach allowed a liberal investigation into the thermodynamics of the photovoltaic module particularly how the heat generated can be reduced in PV or recovered for application in PV/T systems. Implementing the novel thermo-photovoltaic model would probably be beyond the reach of the prevalent approaches because the integration involved additional UDFs (thermal and solar exergies) apart from the power generation model of the PV module. The existing PV modeling and simulation software that allow UDF still constrains the user to implement in-built pre-defined algorithm; while, the CBM approach allows the user to determine the algorithm of the modified CB model. The CBM approach therefore appears well positioned for implementing UDF at micro- and macro-levels (illustrated in Fig. 4) since it allows the user to direct the implementation of the CB model.

4.2. PV module characterisation using CBM approach

The CBM approach, like other PV modeling and simulation approaches, can be used for modeling and simulating the characteristics of solar cell materials and modules. To demonstrate this, ideality factor (A) which describes how the solar cell matches the Shockley or an ideal forward-biased diode has been simulated. The ideality factor stated by the Manufacturer for a 40 W PV module is 2.83. This was varied from 0.5 to 2.83 to observe the effects on the model prediction accuracy. From Fig. 5, the accuracy of prediction increases as the ideality factor increases from 0.5 to 2.83 with constant number of iteration at 500. It was also observed that the accuracy of prediction did not improve after the number of iterations reached 500; although the computing time proportionally increased with the number of iterations.

There are two implications of these results. First, the output current of the PV relates with the ideality factor based on Eq. (4). The short circuit current, representing the current when the PV is not delivering current to the load is related with the conversion efficiency by (Eq. (7)) (Nelson, 2003).

$$\eta_{pv} = \frac{I_{sc}V_{oc}FF}{GxA_{cell}} \quad (7)$$

The fill factor (FF) describes the rectangularness of the current - voltage curve of the PV module. FF could be affected by the resistances in series and the shunt resistance in the solar cells (Kiermasch et al., 2019). The closer the FF of a solar cell is to unity, the higher the conversion efficiency based on Eq. (7). Thus, the use of materials with low resistivity would ultimately increase the power efficiency of the solar cell because the Ohmic losses would be reduced; and ultimately increase the ideality factor. The second implication of the results is that the number of iterations influences the computational time of the model. So, limiting the number of iterations above the saturation point would not jeopardise the precision of the output; rather it would save time and power for PV-led algorithms.

Again, the effect of temperature variations on the open circuit voltage is critical to the PV conversion efficiency as shown in Eq. (7). The degradation of the performance of the PV by temperature increase has been reported by Dupré et al. (2017) and Chenni et al. (2007). Since, electrical efficiency of a solar cell varies inversely with the operating

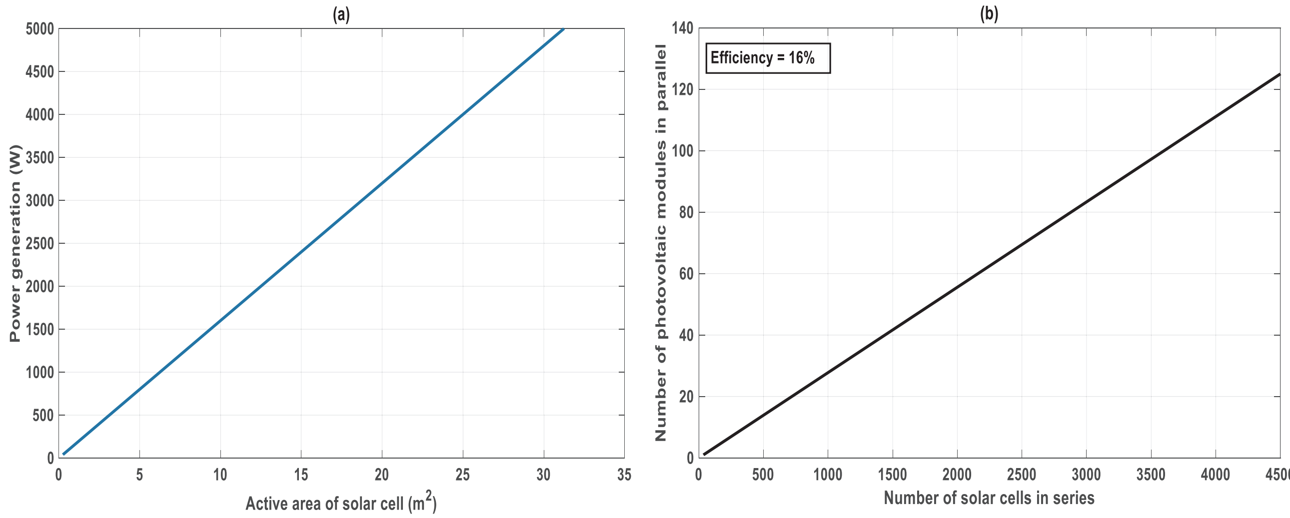

Fig. 10. Photovoltaic generation of 5 kW systems at STC (a) Relationship between power generation and active area of solar cell. (b) Relationship between the solar cells in series in the module and the number of PV modules.

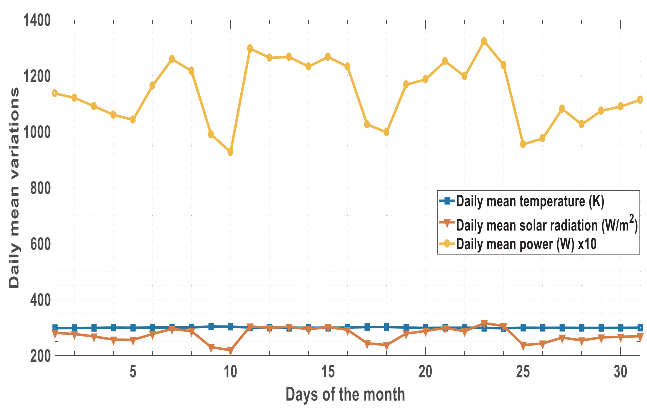

Fig. 11. Code-based model predicted power output based on mean daily solar radiation and temperature.

temperature (Brinkworth et al., 1997; Lee and Tay, 2012), high temperature solar cell (HTSC) that could withstand generation and recombination of electrons (without theV_{oc}degrading) might be worth investigating based on the implications of the results presented in Fig. 6. HTSC may require a tuning of the heat capacity of solar cell materials to withstand the degradation effects of increasing temperature. This agrees with Varshni's relationship between bandgap and temperature (Varshni, 1967) in Eq. (1). Bandgap engineering could also increase the proportion of solar spectrum utilised; and also reduce the degradation of the V_{oc} due to the thermalisation of electrons (Bünzli and Chauvin, 2014) that were not collected as electricity in the valence-conduction bands.

4.3. PV system modeling and design using CBM approach

PV systems can be designed to produce high voltage or high current depending on the end-users' requirements (Masters, 2004). This section demonstrates how the solar cells string design and modular configurations affects power generation of the PV. The PV module designs with 36, 38, 40 and 42 solar cells were simulated with the CB model as shown in Fig. 7. The current flowing through the modules is constant while the voltage across the cells in series increased (i.e. $V_{module} = V_1 + V_2 + \cdots + V_n$); where n is the number of solar cells in series inside the module. This is a predictive application of the CB model because it predicts the MPP of different solar cell strings configuration.

The predictive feature of the CB model can also aid the design of large-scale PV system as exemplified by our recent study involving a virtual deployment of a 5 MW PV system at six different locations in

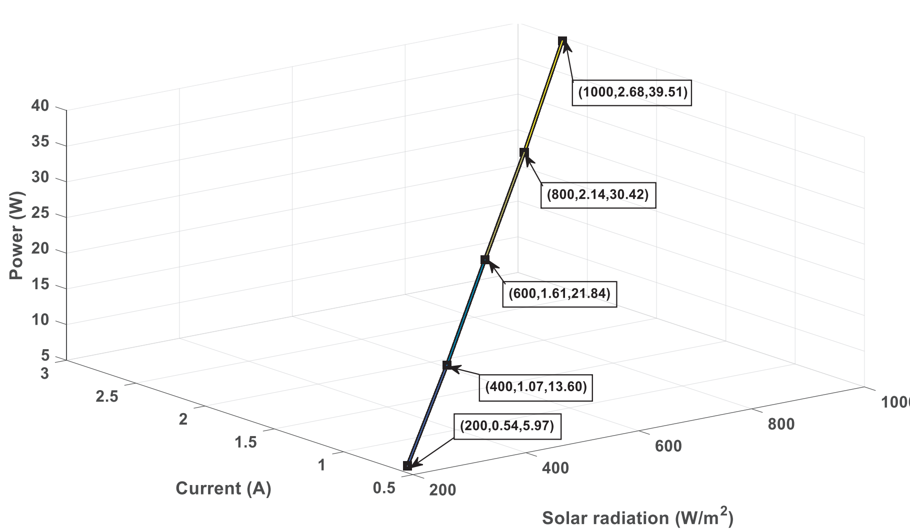

Fig. 12. Model predicted Power - current - radiation trajectory between 200 and 1000 W/m^2.

order to determine the optimal location (Ogbonnaya et al., 2019c). The voltage output of the array (V_{array}) is constant while the current output of the modules adds up (i. e. $I_{array} = I_1 + I_2 + \cdots + I_n$) to give the overall current of the photovoltaic array. Eq. (8) can be used to predict the number of PV modules, of equal power rating, that can be used for constructing large-scale PV system.

$$P_{system} = P_{Pv} + P_{Pv}(N_P - 1) \tag{8}$$

where P_{system} is the power output of array, P_{Pv} is the power output of the PV module and N_P is the number of PV modules in parallel connection.

For instance, Fig. 8 shows a PV array with 160 W constructed with four PV modules rated 40 W each; and designed using the CBM approach. It can be seen that the output voltage is constant while current varies proportionally with the number of modules added to the array.

The CB model can also predict PV performance based on the environmental factors. Fig. 9 shows the effect of variation of solar radiation on a 50 kW PV generation based on "virtual experimentation". The PV array was first designed at STC using a total of 1,250 PV modules composed of 45,000 solar cells covering an area of 312.5 m^2. After the design process, the PV array was simulated at different solar intensities. This result agrees with Eq. (2) and other results reported in the literatures in Table 1. Simulation results with actual radiation data of a location using the CB model can help designers to estimate the storage system that can be combined with the PV at the design stage. This would be discussed further in Section 4.4.

Fig. 10(a) shows the relationship between the power output and solar cell active area; Fig. 10(b) shows the relationship between the number of solar cells in series and the number of PV modules. Because the power output depends on the conversion efficiency of solar cell, the relationships between the efficiency, solar cell active area, number of solar cells and PV modules can aid the process of predicting the parameters for any scale of PV system based on Eq. (8). The use of the CBM approach for establishing design scenarios constitutes a prescriptive application since the choice to either use higher number of solar cells per module in order to reduce the number of modules; or use lower number of solar cells and higher number of modules can be made for various scales of PV systems. Again, suppose that a total cost function including cost of materials for PV module (e.g. solar cell, glass top, ethylene–vinyl acetate, frame, wiring, etc) is incorporated into Eq. (8), the cost of any scale of the PV system can be modelled and computed.

4.4. Using CBM approach for monitoring the PV power performance

Fig. 11 shows daily mean power generation using mean temperature and solar radiation based on the CBM approach. In Sections 4.2 and 4.3, the effect of only one input variable on power characteristics was simulated. Here, the effect of two input variables based on actual meteorological data from January 1 to 31, 2016 for Enugu city sourced through the Nigerian Meteorological Agency, Abuja have been simulated for the 50 kW PV system in Fig. 8. These results appear to make the CBM approach more dynamic than the BBM approach since there has not been a previous study involving a simultaneous simulation of solar radiation and temperature to visualise the power performance of the PV system. This feature can give insights into sizing of PV system and storage capacity since it can show upper and lower limits of power generation based on two critical meteorolgical variables for PV generation. If appropriate sizing is achieved, it could improve system reliability as sufficient power would be generated, and could also reduce system cost as the number of modules to generate the required power can be predicted at the design stage. Another possible application of the CBM approach is for modeling and simulation of a large-scale photovolatic power generation (LSPPG) system with actual solar radiation and temperature data in order to establish an optimum location for the LSPPG deployment; for a case where a location must be selected from multiple locations (Ogbonnaya et al., 2019c).

Moreover, Fig. 12 shows a visualisation of power generated from a commercial module rated 40 W for insolation between 200 and 1000 W/m^2. The trajectory shows the corresponding power, current and voltage at different solar radiations. Unlike the MPPT algorithms that focuses on the MPP of generation (Gheibi et al., 2011; Saravanan and Ramesh Babu, 2016), the CBM approach could facilitate the expression of transient power output in terms of current and voltage. This feature, which can be applied in PV power monitoring devices, can be achieved by including a sub-routine that divides power output with photocurrent to get the voltage as shown in Fig. 12.

From the foregoing discussions, the process of creating CB model in MATLAB has been presented. The validation of the created model has been presented as well. A discussion of the instances where the CBM approach could facilitate model-based studies involving PV have been discussed including an application of actual data for potential power monitoring application. Overall, the three objectives presented at the introduction section of this study have been achieved.

5. Conclusion

This study presents code-based modeling (CBM) approach as a potent approach that can enable model-based investigations that could advance the state-of-the-art of the photovoltaics. First, the CBM was coded in the MATLAB and trained with synthesized data from some pieces of peer-reviewed literature. Then, it was validated using commercial PV modules. The validation of the code-based model shows that the proposed model repeatedly and reliably predicted the short circuit current, maximum power point, open circuit voltage with 0%, $< 2\%$ and $< 10\%$ deviations, respectively. Then, the potential applications of CBM approach in studying the thermodynamics of the PV, solar cells material characterisation, PV systems design and PV power monitoring are discussed based on results generated from the proposed CBM approach. It can therefore be stated that the CBM approach, demonstrated in this study, exhibits robustness beyond the capability of the current PV modeling approaches; and should be explored by scientists and engineers for theoretical and application-based investigations involving user-defined equations and algorithms.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work is supported by a scholarship of the Petroleum Technology Development Fund (PTDF) Nigeria number PTDF/ED/PHD/OC/1078/17. The Nigerian Meteorological Agency, Abuja is appreciated for providing raw solar radiation and temperature data for the study.

References

Abdulkadir, M., Samosir, A.S., Yatim, A.H.M., 2012. Modeling and simulation based approach of photovoltaic system in Simulink model. ARPN J. Eng. Appl. Sci. 7 (5), 616–623.

Acakpovi, A., Ben Hagan, E., 2013. Novel photovoltaic module modeling using Matlab/Simulink. Int. J. Comput. Appl. 83 (16), 27–32. https://doi.org/10.5120/14535-2978.

Aryal, A., Bhattarai, N., 2018. Modeling and simulation of 115.2 kWp grid-connected solar PV system using PVSYST. Kathford J. Eng. Manage. 1 (1), 31–34. https://doi.org/10.3126/kjem.v1i1.22020.

Avezov, R.R., Akhatov, J.S., Avezova, N.R., 2011. A review on photovoltaic-thermal (PV-T) air and water collectors. Appl. Solar Energy 47 (3), 169–183. https://doi.org/10.3103/S0003701X11030042.

Bellia, H., Youcef, R., Fatima, M., 2014. A detailed modeling of photovoltaic module using MATLAB. NRIAG J. Astron. Geophys. 3 (1), 53–61. https://doi.org/10.1016/j.nrjag.2014.04.001.

Brinkworth, B.J., Cross, B.M., Marshall, R.H., Yang, H., 1997. Thermal regulation of photovoltaic cladding. Sol. Energy 61 (3), 169–178. https://doi.org/10.1016/S0038-

092X(97)00044-3.
Bukar, A.L., Tan, C.W., 2019. A review on stand-alone photovoltaic-wind energy system with fuel cell: System optimization and energy management strategy. J. Cleaner Prod. https://doi.org/10.1016/j.jclepro.2019.02.228.
Bünzli, J.-C. G., Chauvin, A.-S., 2014. Chapter 261 - Lanthanides in solar energy conversion. In: Including Actinides, vol. 44, pp. 169–281. https://doi.org/10.1016/B978-0-444-62711-7.00261-9.
Cheddadi, Y., Errahimi, F., Es-sbai, N., 2018. Design and verification of photovoltaic MPPT algorithm as an automotive-based embedded software. Sol. Energy 171, 414–425. https://doi.org/10.1016/j.solener.2018.06.085.
Chenni, R., Makhlouf, M., Kerbache, T., Bouzid, A., 2007. A detailed modeling method for photovoltaic cells. Energy 32 (9), 1724–1730. https://doi.org/10.1016/j.energy.2006.12.006.
Ciulla, G., Lo Brano, V., Di Dio, V., Cipriani, G., 2014. A comparison of different one-diode models for the representation of I-V characteristic of a PV cell. Renew. Sustain. Energy Rev. 32, 684–696. https://doi.org/10.1016/j.rser.2014.01.027.
Dupré, O., Vaillon, R., Green, M.A., 2017. Thermal Behavior of Photovoltaic Devices: Physics and Engineering. Springer. https://doi.org/10.1007/978-3-319-49457-9.
El Hassouni, B., Haddi, A., Amrani, A.G., 2017. Modeling and simulation of an autonomous PV Generator dedicated to supply an agricultural pumping station. In: Energy Procedia, vol. 139, pp. 153–160. https://doi.org/10.1016/j.egypro.2017.11.189.
Elkholy, A., Fahmy, F.H., Abu Elela, A., 2010. A new technique for photovoltaic module performance mathematical model. In: ICCCE 2010–2010 International Conference on Chemistry and Chemical Engineering, Proceedings, pp. 6–10. https://doi.org/10.1109/ICCCENG.2010.5560349.
Fatehi, J.H., Sauer, K.J., 2014. Modeling the incidence angle dependence of photovoltaic modules in PVsyst. In: 2014 IEEE 40th Photovoltaic Specialist Conference, PVSC 2014, pp. 1335–1338. https://doi.org/10.1109/PVSC.2014.6925164.
Fernandes, C.A.F., Torres, J.P.N., Gomes, J., Branco, P.J.C., Nashih, S.K., 2016. Stationary solar concentrating photovoltaic-thermal collector - Cell string layout. In: Proceedings - 2016 IEEE International Power Electronics and Motion Control Conference, PEMC 2016, pp. 1275–1282. https://doi.org/10.1109/EPEPEMC.2016.7752179.
Gheibi, A., Mohammadi, S.M.A., maghfoori, M., 2011. Maximum power point tracking of photovoltaic generation based on the type 2 fuzzy logic control method. Energy Proc. 12, 538–546. https://doi.org/10.1016/j.egypro.2011.10.073.
Gilman, P., 2015. SAM photovoltaic model technical reference SAM photovoltaic model technical reference. Sol. Energy 63 (May), 323–333 https://doi.org/NREL/TP -6A20-64102.
Gilman, P., DiOrio, N.A., Freeman, J.M., Janzou, S., Dobos, A., Ryberg, D., 2018. SAM Photovoltaic Model Technical Reference 2016 Update. https://doi.org/10.2172/1429291.
Gupta, S., Tiwari, H., Fozdar, M., Chandna, V., 2012. Development of a two diode model for photovoltaic modules suitable for use in simulation studies. In: Asia-Pacific Power and Energy Engineering Conference, APPEEC, https://doi.org/10.1109/APPEEC.2012.6307201.
Keles, C., Alagoz, B.B., Akcin, M., Kaygusuz, A., Karabiber, A., 2013. A photovoltaic system model for Matlab/Simulink simulations. In: International Conference on Power Engineering, Energy and Electrical Drives, pp. 1643–1647. https://doi.org/10.1109/PowerEng. 2013.6635863.
Kiermasch, D., Gil-Escrig, L., Bolink, H.J., Tvingstedt, K., 2019. Effects of masking on open-circuit voltage and fill factor in solar cells. Joule. https://doi.org/10.1016/j.joule.2018.10.016.
Kolhe, M., Adhikari, S.K., Muneer, T., 2019. Parked electric car's cabin heat management using photovoltaic powered ventilation system. Appl. Energy 233–234, 403–411. https://doi.org/10.1016/j.apenergy.2018.10.012.
Krismadinata, Rahim, N.A., Ping, H.W., Selvaraj, J., 2013. Photovoltaic module modeling using Simulink/Matlab. Proc. Environ. Sci. 17, 537–546. https://doi.org/10.1016/j.proenv.2013.02.069 546.
Lee, Y., Tay, A.A.O., 2012. Finite element thermal analysis of a solar photovoltaic module. Energy Proc. 15, 413–420. https://doi.org/10.1016/j.egypro.2012.02.050.
Lehman, P.A., Chamberlin, C.E., 1991. Design of a photovoltaic-hydrogen-fuel cell energy system. Int. J. Hydrogen Energy 16 (5), 349–352. https://doi.org/10.1016/0360-3199(91)90172-F.
Leuchter, J., Rerucha, V., Zobaa, A.F., 2010. Mathematical modeling of photovoltaic systems. In: Proceedings of EPE-PEMC 2010–14th International Power Electronics and Motion Control Conference, https://doi.org/10.1109/EPEPEMC.2010.5606897.
Lo Brano, V., Orioli, A., Ciulla, G., Di Gangi, A., 2010. An improved five-parameter model for photovoltaic modules. Sol. Energy Mater. Sol. Cells 94 (8), 1358–1370. https://doi.org/10.1016/j.solmat.2010.04.003.
Mahmood, J.R., Selman, N.H., 2016. Four matlab-simulink models of photovoltaic system. Int. J. Energy Environ. 7 (5), 417–426.
Masters, G.M., 2004. Chapter 3 The Electric Power Industry. Renew. Effic. Electr. Power Syst. https://doi.org/10.1002/0471668826.ch3.
MATLAB, 2016. MATLAB. MATLAB. https://doi.org/10.1201/9781420034950.
Meurer, C., Barthels, H., Brocke, W.A., Emonts, B., Groehn, H.G., 1999. PHOEBUS—an autonomous supply system with renewable energy: six years of operational experience and advanced concepts. Sol. Energy 67 (1–3), 131–138. https://doi.org/10.1016/S0038-092X(00)00043-8.
Meyer, E.L., 2017. Extraction of saturation current and ideality factor from measuring Vocand Iscof photovoltaic modules. Int. J. Photoenergy 2017. https://doi.org/10.1155/2017/8479487.
Michael, J.J., Iniyan, S., Goic, R., 2015. Flat plate solar photovoltaic-thermal (PV/T) systems: A reference guide. Renew. Sustain. Energy Rev. 51, 62–88. https://doi.org/10.1016/j.rser.2015.06.022.
Mohammed, M.N., Alghoul, M.A., Abulqasem, K., Mustafa, A., Glaisa, K., Ooshaksaraei, P., Sopian, K., 2011. TRNSYS Simulation of Solar Water Heating System in Iraq. In: Recent Researches in Geography, Geology, Energy, Environment and Biomedicine. Proceedings of the 4th WSEAS International Conference on Engineering Mechanics, Structures, Engineering Geology (EMESEG 2011). Proceedings of the 2nd International Conference on, pp. 153–156.
Morshed, M.S., Ankon, S.M., Chowdhury, M.T.H., Rahman, M.A., 2015. Designing of a 2kW stand-alone PV system in Bangladesh using PVsyst, Homer and SolarMAT. In: 2015 International Conference on Green Energy and Technology, ICGET 2015. https://doi.org/10.1109/ICGET.2015.7315090.
Motahhir, S., Ghzizal, A. El, Sebti, S., Derouich, A., 2018. Modeling of Photovoltaic System with modified Incremental Conductance Algorithm for fast changes of irradiance. Int. J. Photoenergy 2018, 13. https://doi.org/10.1155/2018/3286479.
Muhammad, F.F., Yahya, M.Y., Hameed, S.S., Aziz, F., Sulaiman, K., Rasheed, M.A., Ahmad, Z., 2017. Employment of single-diode model to elucidate the variations in photovoltaic parameters under different electrical and thermal conditions. PloS One 12 (8), e0182925. https://doi.org/10.1371/journal.pone.0182925.
Nelson, J., 2003. The physics of solar cells. In: Properties of Semiconductor Materials, pp. 384. https://doi.org/10.1142/9781848161269_0001.
Ogbonnaya, C., Abeykoon, C., Damo, U.M., Turan, A., 2019a. The current and emerging renewable energy technologies for power generation in Nigeria: a review. Therm. Sci. Eng. Prog. 13 (June), 100390. https://doi.org/10.1016/j.tsep.2019.100390.
Ogbonnaya, C., Turan, A., Abeykoon, C., 2019b. Energy and exergy efficiencies enhancement analysis of integrated photovoltaic-based energy systems. J. Storage Mater. 26. https://doi.org/10.1016/j.est.2019.101029.
Ogbonnaya, C., Turan, A., Abeykoon, C., 2019c. Novel thermodynamic efficiency indices for choosing an optimal location for large-scale photovoltaic power generation. J. Cleaner Prod. https://doi.org/10.1016/j.jclepro.2019.119405. (xxxx).
Ogbonnaya, C., Turan, A., Abeykoon, C., 2019d. Numerical integration of solar, electrical and thermal exergies of photovoltaic module: A novel thermophotovoltaic model. Sol. Energy 185 (April), 298–306. https://doi.org/10.1016/j.solener.2019.04.058.
Özgirgin, E., Devrim, Y., Albostan, A., 2015. Modeling and simulation of a hybrid photovoltaic (PV) module-electrolyzer-PEM fuel cell system for micro-cogeneration applications. Int. J. Hydrogen Energy 40 (44), 15336–15342. https://doi.org/10.1016/j.ijhydene.2015.06.122.
Pagrut, U.P., Sindekar, A.S., Lachure, S.S., Lachure, J.S., 2017. Performance of 125 watt PV module using MATLAB-simulink. In: Proceedings of the 3rd IEEE International Conference on Advances in Electrical and Electronics, Information, Communication and Bio-Informatics, AEEICB 2017, pp. 45–49. https://doi.org/10.1109/AEEICB.2017.7972381.
Patel, J., Sharma, G., 2013. Modeling and simulation of solar photovoltaic module using Matlab/simulink. Int. J. Res. Eng. Technol. 2 (3), 225–228.
PVLIGHTHOUSE, 2019. Photovoltaic software and calculators. Retrieved June 21, 2019, from https://www.pvlighthouse.com.au/.
REN21, 2018. Renewables 2018 Global Status Report (Paris: REN21 Secretariat). Paris: Renewable Energy Policy Network for the 21st Century, pp. 1–324. https://doi.org/978-3-9818911-3-3.
Saravanan, S., Ramesh Babu, N., 2016. Maximum power point tracking algorithms for photovoltaic system - A review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2015.12.105.
Shell Solar, 2003. Product Information Sheet Shell S25 Typical I/V Characteristics.
Shi, G., Kioupakis, E., 2015. Electronic and optical properties of nanoporous silicon for solar-cell applications. ACS Photo. 2 (2), 208–215. https://doi.org/10.1021/ph5002999.
Shrivastava, R.L., Kumar, V., Untawale, S.P., 2017. Modeling and simulation of solar water heater: A TRNSYS perspective. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2016.09.005.
Solar Energy Laboratory, 2009. User Manual: TRNSYS 17 a TRaNsient SYstem Simulation program - Volume 4 - Mathematical Reference. TRNSYS Library, Volume 4 Mathematical Reference, vol. 4, Solar Energy Laboratory, University of Wisconsin-Madison, USA.
Sprenger, W., Wilson, H.R., Kuhn, T.E., 2016. Electricity yield simulation for the building-integrated photovoltaic system installed in the main building roof of the Fraunhofer Institute for Solar Energy Systems ISE. Sol. Energy 135, 633–643. https://doi.org/10.1016/j.solener.2016.06.037.
Tan, Y.T., Kirschen, D.S., Jenkins, N., 2004. A model of PV generation suitable for stability analysis. IEEE Trans. Energy Convers. 19 (4), 748–755. https://doi.org/10.1109/TEC.2004.827707.
Tsai, H.L., 2010. Insolation-oriented model of photovoltaic module using Matlab/Simulink. Sol. Energy 84 (7), 1318–1326. https://doi.org/10.1016/j.solener.2010.04.012.
Ünlü, H., 1992. A thermodynamic model for determining pressure and temperature effects on the bandgap energies and other properties of some semiconductors. Solid-State Electron. 35 (9), 1343–1352. https://doi.org/10.1016/0038-1101(92)90170-H.
Varshni, Y.P., 1967. Temperature dependence of the energy gap in semiconductors. Physica 34 (1), 149–154. https://doi.org/10.1016/0031-8914(67)90062-6.
Villalva, M., Gazoli, J., Filho, E., 2009. Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Trans. Power Electron. 24 (5), 1198–1208. https://doi.org/10.1109/tpel.2009.2013862.
Vinod, Kumar, R., Singh, S.K., 2018. Solar photovoltaic modeling and simulation: As a renewable energy solution. Energy Reports 4, 701–712. https://doi.org/10.1016/j.egyr.2018.09.008.
Wu, Y.-C., Jhan, Y.-R., Wu, Y.-C., & Jhan, Y.-R., 2017. Introduction of Synopsys Sentaurus TCAD Simulation. In: 3D TCAD Simulation for CMOS Nanoeletronic Devices, pp. 1–17. https://doi.org/10.1007/978-981-10-3066-6_1.
Zainal, N.A., Yusoff, A.R., 2016. Modelling of photovoltaic module using Matlab simulink. IOP Conf. Ser. Mater. Sci. Eng. 114 (1), 12137. https://doi.org/10.1088/1757-899X/114/1/012137.
Zeitouny, J., Katz, E.A., Dollet, A., Vossier, A., 2017. Band gap engineering of multi-junction solar cells: Effects of series resistances and solar concentration. Sci. Rep. 7 (1). https://doi.org/10.1038/s41598-017-01854-6.