

Computational and analysis of thermoelectric cooling for photovoltaic solar panels/PV Panel.

Deepak Rajput, Raghvendra Singh, Samir Kumar Mishra

Faculty of Engineering & Technology, Rama University Uttar Pradesh Kanpur 209217

Email Id: deepak87nk@gmail.com

Abstract:

Solar photovoltaic panels are a crucial component of generating power from renewable sources, providing a secure and sustainable source of energy to address power shortages in any nation. Prior to installing a solar photovoltaic (PV) generator in anywhere, it is crucial to approach, simulate, and analyse its performance. This process allows for a better understanding of the generation's behaviour and features under actual weather conditions at the particular spot. This study presents a simplified model of a solar PV module using a single diode comparable circuitry. The design is simulated in a step-by-step manner using Matlab/Simulink. The I-V and P-V graph of a solar PV module offer a comprehensive insight to researchers, producers, and social societies. The accuracy of the modelled outcome generated by the PV module is confirmed by comparing it with the manufacturer's data-sheet of the JAP6-72-320/4BB modules. The greatest relative error percentage is determined to be 1.65%, indicating a strong agreement with both the manufacturer's values and the simulated results. Furthermore, the PV module demonstrates favourable performances when exposed to actual meteorological conditions, including irradiance and temperature. Furthermore, it is regarded as a robust instrument for assessing the efficiency of solar photovoltaic cells.

Keywords: Photovoltaic solar, Modeling of renewable power, Metrological information.

1.0 Introduction

Accessibility to inexpensive and reliable electricity is a key prerequisite for the prosperity, technological advancement, and societal advancement of each nation. India's requirement for electricity is steadily increasing as a result of industrialisation and urbanisation (Kanchan and Kumarankandath, 2015). India's total installed power capacity has grown from 1.362 GW in 1947 to 326.849 GW as of March 31, 2017, according to the Central Electricity Authority (2017a). Undoubtedly, coal and lignite have been the primary sources of electricity for the nation since its independence. Conventional power generators cause significant human deaths due to the emission of massive quantities of toxic gases and heavy metals from their exhaust stacks (Shahzad Baig and

Yousaf, 2017; Geonka and Guttikunda, 2012). Figure 1 illustrates the distribution of electrical sources in India's total installed capacity, expressed as a percentage. As of October 31, 2017, India has a total operational power generation capacity of 331.117 GW. Out of this, thermal power accounts for 66.27%, renewable energy accounts for 18.17%, nuclear power accounts for 2.05%, and hydro energy accounts for 13.52% (Central Electricity Authority, 2017b). The primary source of energy for use in the Indian electrical system is coal-based authority, accounting for 58.42% of the total share. Coal has been the primary source of electricity since independence.

The reliance on traditional energy sources can be diminished by the integration of numerous renewable energy sources as well as technologies for storing electricity, which are crucial in addressing power fluctuations (Hemmati and Saboori, 2016). Currently, the power distribution system of any country regards energy storage as a crucial component (Saboori et al., 2017). The reason for this is that it can strengthen the stability of the grid, improve the efficiency of the system, boost the penetration of renewable energy, and aid to reduce environmental and health implications by conserving fossil fuels (Amrouche et al., 2016; Aneke and Wang, 2016). Furthermore, the implementation of battery energy storage system technology might lead to a decrease in the operational expenses of the power distribution network (Hemmati, 2018). Therefore, the combination of solar energy and energy storage technology enhances rural energy availability, leading to increased economic growth in every nation (Kim and Jung, 2018).

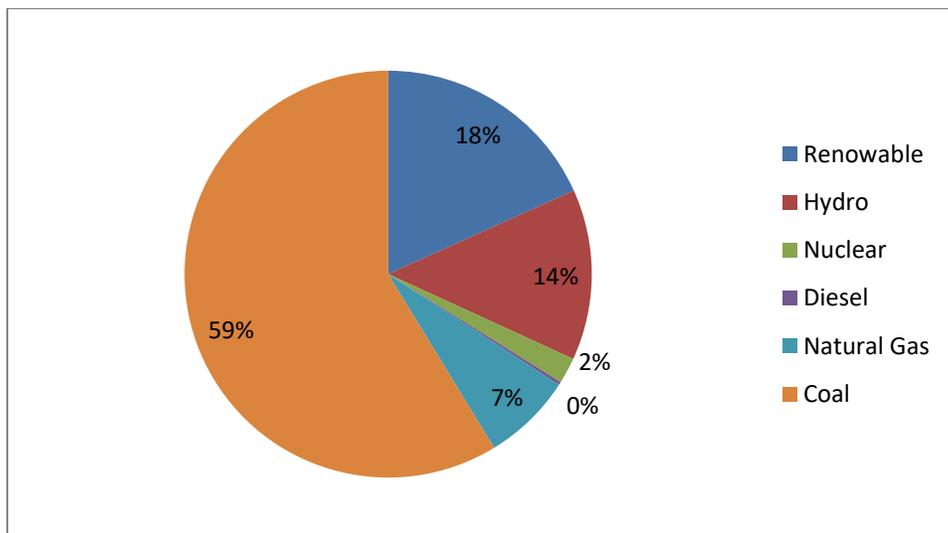
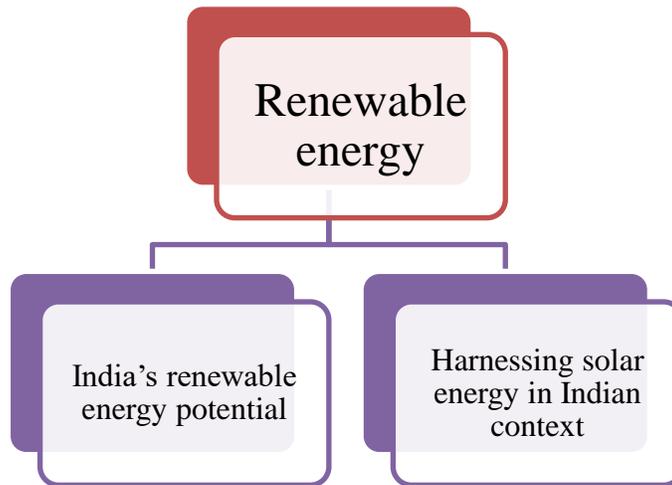


Figure 1 depicts the total installed capacity for electricity in the nation of India, organised by supplier.

Table 1 Renewable energy installed capacity

Renewable energy sources	Installation capacity (MW)	Share (%)
Small hydro power	4389.55	7.29
Wind power	32700.64	54.35
Bio-power	8295.78	13.79
Solar power	14771.69	24.55
Total	60 157.66	100



1.1. India's renewable energy potential

The Indian government recently unveiled a proposed initiative called "24X7 Electricity for All" with the aim of providing affordable and environmentally sustainable electricity to the population of India by March 2019. The source of this information is the Ministry of New and Renewable Energy (MNRE), in the year 2017. Renewable energy will serve as a sustainable and environmentally friendly power source to meet India's electricity needs and support its development. This will also contribute to the fulfilment of the objectives set by the 'Paris Agreement' on climate change. By 2030, the Indian government aims to ensure that a minimum of 40% of its power is generated from renewable sources (Gould, 2015). As of September 30, 2017, the combined capacity of green energy via a number of sources is 60.157 GW, according to Table 1 (Central Electricity Authority, 2017b).

The Indian government has established a lofty objective of producing 175 gigawatts of environmentally friendly electricity by 2022. India has an estimated potential of around 900 GW of renewable energy, which can be derived from various sources. These options include small hydro

(20 GW), wind power (102 GW with an 80-meter mast height), biomass energy (25 GW), and solar power (750 GW, taking into account 3% wasteland in the country). This information is based on data from the Ministry of New and Renewable Energy (MNRE), which was published in 2017. Based on the aforementioned facts, solar power has become a significant and environmentally-friendly source of renewable energy. Its adoption will have a transformative impact on the growth of the country and propel the Indian electrical sector to new levels of achievement.

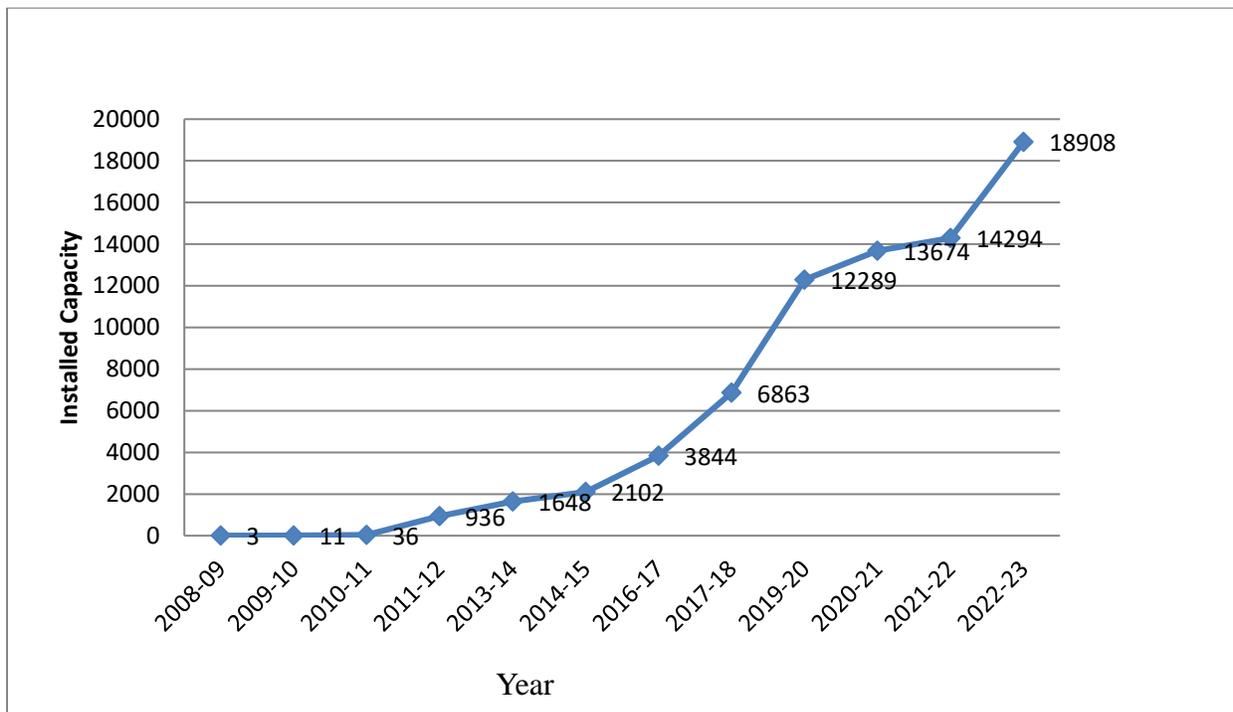


Figure 2 illustrates the progression of solar energy utilisation in India.

1.2. Utilising solar power in an Indian environment

The nation's population makeup classifies it as a tropical country, characterised by high levels of irradiation and an important opportunity for solar energy. The typical yearly radiation from the sun decline ranges from 4 to 7 kWh/m², based on a study by Kirmani et al. (2015), which also reported 300 bright days per year. The Indian prime minister, in 2014, increased the target for renewable energy installation from 20 GW to an ambitious aim of 100 GW by 2022 (Nathan, 2014). As of March 31, 2017, the cumulative installed capacity of solar power in India is 12.28 GW. This indicates that India possesses a significant untapped opportunity for harnessing solar energy

without generating greenhouse gases. Figure 2 depicts the progression of installed solar power capacity from 2008 to 2017. The capacity started at 3 MW in 2008-09 and increased to 12288.83 MW by the end of the financial year 2017, according to the Central Electricity Board (2017a) and the Ministry of New and Renewable Energy, or MNRE, (2017). India has significantly increased its solar energy production since the year 2008.

The nation's power generation capacity is projected to increase to 746 GW through 2030, according to Gould (2015). India's population makeup positions it as a country with vast solar power resources, with an anticipated potential for approximately 750 GW, according to the Ministry of Renewable and New Energy, or MNRE, in 2017. Thus, the sun's rays can meet every energy demand of the nation.

1.3. Literature review

sunlight photovoltaic panels is crucial in meeting the nation's electrical deficit by providing clean and environmentally friendly energy in the field of producing electricity from renewable sources. Over the past ten years, multiple researchers have conducted studies that model solar energy using different methods and assess multiple variables using a range of simulation software. Some of these studies include those conducted by Amrani and Rekioua (2006), Rekioua and Matagne (2012), and Pendem and Mikkili (2018).

Damo et al. (2011) created the IP10P solar PV model through the creation of PV panel assessment tools using Matlab and Labview software. These tools were used to calculate and monitor the modelling parameters and evaluate the model's performance in a summer outdoor environment. Banu and Istrate (2012) conducted a study where they analysed the I-V and P-V characteristics of solar PV modules using empirical data and a curve fitting technique. The drawback of this technique is its inability to collect sufficient data in the absence of an experimental apparatus. Hence, it is challenging to construct and simulate characteristic curves. Rekioua and Matagne (2012) demonstrated the implementation of different photovoltaic (PV) models using the Matlab/Simulink software. These models provide a comprehensive analysis of the operational and behavioural aspects of PV generators, and comprehensively examine the experimental results in comparison with the simulation outputs. Patel and Sharma (2013) and Krismadinata et al. (2013) introduced a circuit-based solar photovoltaic (PV) model in Matlab and conducted simulations using various radiation and temperature values. These publications simply provide a description of the final model, but they do not include a detailed analysis of a subsystem inside the final solar PV

model. Mohammedi et al. (2013) provided a mathematical description of the photovoltaic (PV) models to accurately assess different model parameters. Additionally, they conducted a comprehensive comparison between the experimental and simulated results of the PV models. Authors also created and assessed the efficiency of a photovoltaic-powered water pumping system. Rahman et al. (2014) created a model of a polycrystalline photovoltaic (PV) module provided by the National Institute of Standards and Technology. The purpose was to assess the output power of the module by comparing it to the measured output power. In their 2015 study, Yatimi and Aroudam utilised Matlab to mathematically model a solar PV module and conducted simulations under real climatic circumstances in Tetouan, Northern Morocco. However, the authors did not include a full description of the PV model's modelling process in this work. In their study, Yıldırım and Tacer (2016) utilised Matlab/Simulink to create a solar PV model based on fundamental equations. They successfully compared the simulated results with the manufacturer data. However, they did not provide a complete step-by-step model of the PV module in their research. The study conducted by Abdullahi et al. (2017) involved the creation of a model for a monocrystalline PV module using Matlab/Simulink. The model was then compared to actual outside findings, and the comparison showed good agreement. However, the study did not provide a detailed explanation of the step-by-step process used to construct the PV modelling. Mendalek and Al-Haddad (2017) utilised the mathematical governing equation to create a PV module script in Matlab. They then determined the model parameters of the commercial PV module KC200GT and conducted simulations using different irradiation and temperature values. AbdelHady (2017) and Fara and Craciunescu (2017) developed a model of a photovoltaic (PV) module using Matlab/Simulink. They determined the characteristics curve of the module by changing the levels of irradiation and temperature. In their 2018 study, Pendem and Mikkili focused on modelling and simulating the KC200GT PV module using the Matlab/Simulink application. They also provided a detailed analysis of the partial shading effect on the PV module's characteristics. However, they did not provide a step-by-step explanation of the development of the PV module model, which makes it challenging for readers to simulate and comprehend the model. Based on the observations made in the aforementioned investigations, it is evident that there is a significant potential for modelling, simulating, and analysing solar modules.

Considering the perpetual influence of solar energy on the societal progress of any nation, it can be confidently stated that solar power is a prominent and promising remedy for electricity scarcity

(Sindhu et al., 2016). It is crucial to comprehend the level of attainability based on the available resources and infrastructure. Several obstacles hinder the effective implementation of solar energy in the country. These include the absence of an evaluation of solar resource data, the need for user-friendly computation and simulation tools to analyse solar generator systems, and the requirement for accurate sizing of photovoltaic systems (Fara and Craciunescu, 2017). In order to overcome obstacles and gain a comprehensive understanding of the actual system behaviour, it is necessary to utilise software packages for model authentication. Several software packages exist for modelling, simulating, and analysing PV systems, such as Solar Pro, PV-Design Pro, PV-Spice, and PV CAD. However, these packages have certain drawbacks, including high cost, limited availability for commercial use only, difficulties in interfacing with electronic power systems, and proprietary nature (Fara and Craciunescu, 2017; Sharma et al., 2014). In order to address the aforementioned limitations, the Matlab/Simulink programme can be employed. These packages are known for their user-friendly interface, flexibility, ability to create precise models, simulate intricate systems, and offer a wide range of applications in power electronics, solar PV systems, and other engineering fields. This package is readily accessible in academic, industrial, and research laboratories (Fara and Craciunescu, 2017; Pandiarajan and Muthu, 2011; Qi and Ming, 2012).

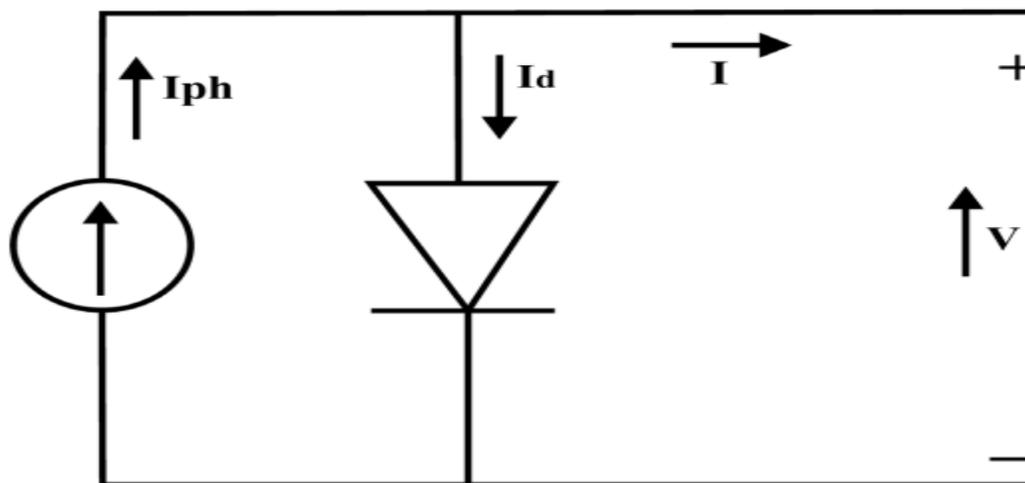


Fig. 3. Simplified equivalent circuit of PV panel.

Prior to installing a photovoltaic (PV) system at any place, it is crucial to approach, simulate, and analyse the PV generation. This process allows for a better knowledge of the actual behaviour and features of the system's components under real climatic circumstances at that specific location

(Meflah et al., 2017). In the past ten years, researchers have extensively studied the modelling and simulation of solar PV modules in order to get valuable insights. Multiple techniques can be employed for modelling and optimising solar PV modules, including analytical approaches, the linearization techniques machine learning methods, numerical techniques, neural networks, fuzzy methods, and genetic algorithms (Lyden et al., 2012; Rekioua and Matagne, 2012). The following part explores the simulation and modelling of a PV paradigm.

2. Methodology for solar PV module

It intended to develop a precise and theoretical model of a single diode equivalent photo-generator component utilising analytical techniques within the Simulink or Mat environment. In order to build a solar PV component, a systematic technique of modelling and simulation is used. The modelling process takes into account the manufacturing data associated with the JAP6-72-320/4BB solar PV component, namely the information provided in the documentation from JA Solar. It could readily assess the attributes of a solar photovoltaic (PV) cell/module. The computer model's manufacturing data sheet findings are validated by comparing them with the results of the simulation.

3. Mathematical formulation of solar PV module

A cell made of sunlight is a basic device that converts sunlight into clean electricity. When multiple solar cells are linked together in both parallel and series configurations, they constitute a photovoltaic (PV) module. In order to construct photovoltaic arrays, these modules are connected in both series and parallel configurations, which are responsible for generating environmentally friendly electricity. A solitary solar cell can be depicted as a constituent of an electrical circuit. The device consists of a p-n junction, known as a diode, which generates a photocurrent in response to light. Additionally, there are two resistors, one connected in parallel or the other connected in parallel, which contribute to the phenomenon known as the Joule effect and recombine losses. The combination of diodes described here is referred to as a single diode solar cell model (Rekioua and Matagne, 2012; Rahman et al., 2014; Mohammedi et al., 2013; Yildiran and Tacer, 2016; Fara and Craci unescu, 2017; Pendem and Mikkili, 2018; Altas and Sharaf, 2007; Villalva et al., 2009). The modelling of a solar PV module follows the same process as that stated for the modelling of solar cells. Figure 3 depicts a streamlined wiring model of a solar power system.

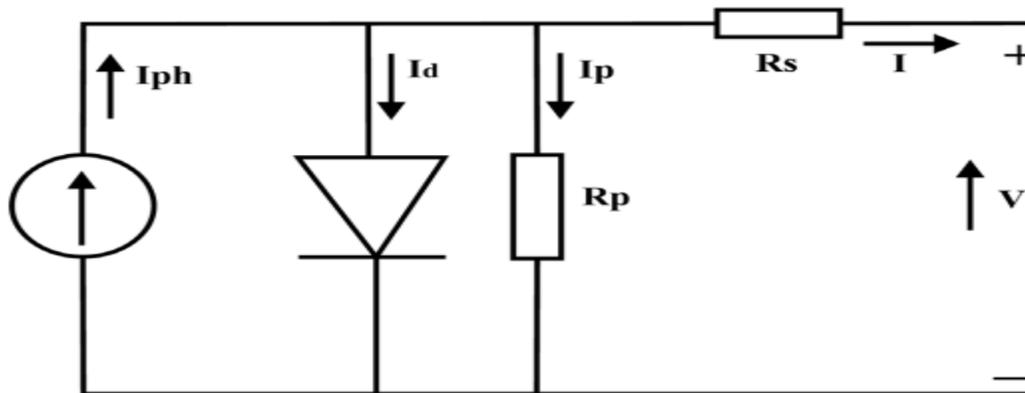


Fig. 4. Equivalent circuit of real model for PV panel.

3.1. The mathematical modeling of perfect solar cells.

The sunlight-generating photovoltaic (PV) technology can be modelled as a perfect crystalline silicon solar cell with an electric current source (I_{ph}) connected concurrently to the diode, as shown in Figure 3. By applying Kirchhoff's first equation, the current at the output of an idealised photographic cell can be characterised utilising Equation (1).

$$I = I_{PH} - I_d \quad (1)$$

The I-V properties of a PV photovoltaic cell are described by Shockley's diodes present the formula, which is a foundational algebraic formula derived from the concept of semiconductor (Sera et al., 2007; Bellini et al., 2009). The formula for this equation is represented by Eq. (2).

$$I_d = I_s \left[\exp \left(\frac{qV_{oc}}{N_s K A T_o} \right) - 1 \right] \quad (2)$$

Substituting the given number of the I_d in Equation (1) yields the resultant output current, I , of a desirable solar cell as defined in Equation (3).

$$I = I_{ph} - I_s \left[\exp \left(\frac{qV_{oc}}{N_s K A T_o} \right) - 1 \right] \quad (3)$$

In a perfect world, a solar cell offers a highly accurate estimation of the current created by photons, which is precisely corresponding to the intensity and absorbance of the illumination. Several variables that aren't accounted for in the ideal case model have a significant impact on the output of a photovoltaic (PV) device in real-world scenarios (Bellini et al., 2009; Villalva et al., 2009; Sera et al., 2007). The following subsection illustrates the improved model for just one diode in an actual scenario.

3.2. Mathematical model of a PV cell (real/practical cell case)

Figure 4 depicts an electrical model for a photovoltaic cell that is more exact and closely resembles reality. This is commonly referred to as the genuine single diode approach, which includes a series impedance (R_s) and a pair of parallel impedance (R_p). In an ideal scenario, the resistances R_s and R_p would be disregarded. However, in the real world, it is not feasible to ignore these parasitic resistances as they have an impact on the efficiency of the PV solar cell. This has been demonstrated by various studies (Villalva et al., 2009; Pandiarajan and Muthu, 2011; Rekioua and Matagne, 2012; Lyden et al., 2012; Mohammedi et al., 2013; Sera et al., 2007). The suitable model is depicted in Figure 4. The series resistance (R_s) is a component in the current route that is responsible for losses caused by the Joule effect. It is mostly attributed to metallic lines, semiconductor components, the collection bus, and the links between them. R_p refers to parallel resistances that are connected mitigating the seepage of energy caused by factors like as the layer thickness of the cell and surface effects. These resistances are also known as shunt impedance. The impact of R_s is significant since it results from the expansion of the conductivity between cells in the solar power system, in contrast to R_p . The impact of R_p is solely

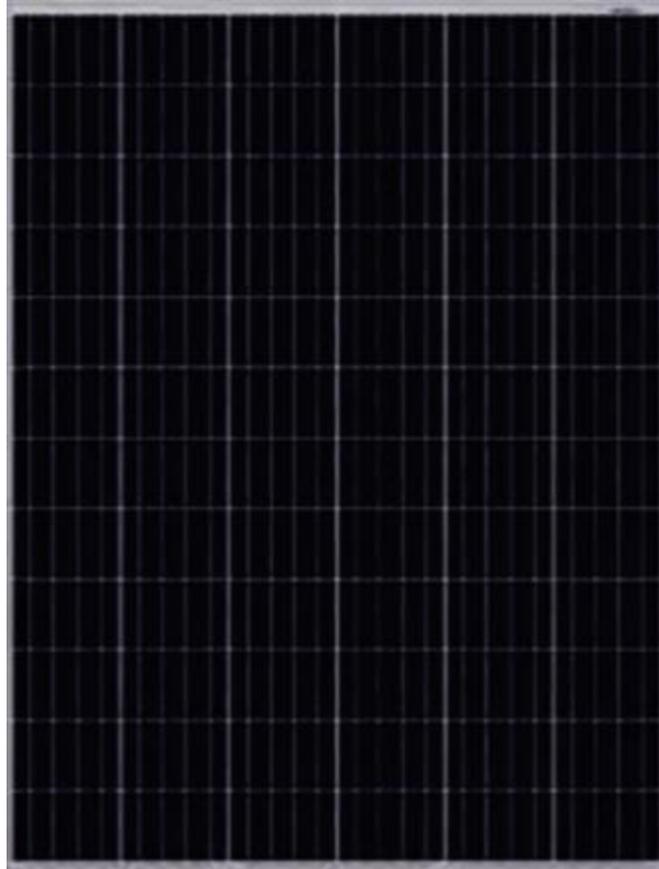


Fig. 5. Solar PV module

The issue of visibility becomes apparent when a significant quantity of PV modules are included in a solar energy system (Bellini et al., 2009; Villalva et al., 2009; Qi and Ming, 2012; Lyden et al., 2012; Sera et al., 2007). When considering the values of R_s and R_p , R_s are taken as a factor while R_p is assumed to be unlimited. As a result, the equation for diode up-to-date Eq. (2), is adjusted to Eq. (4).

$$I_d = I_s \left[\exp \left(\frac{q(V + IR_s)}{N_s K A T_0} \right) - 1 \right] \quad (4)$$

Once the value of R_s was considered, it had an effect on the modification of Equation (3) and controlled Equation (5).

$$I = I_{ph} - I_s \left[\exp \left(\frac{q(V + IR_s)}{N_s K A T_0} \right) - 1 \right] \quad (5)$$

When the photovoltaic cells are connected in a series-parallel configuration and the current through their outputs I is calculated, then Equation (5) can be changed and represented by Equation (6) as shown below:

$$I = N_p * I_{ph} - N_p * I_s \left[\exp \left(\frac{q(V + IR_s)}{N_s K A T_0} \right) - 1 \right] \quad (6)$$

Given the equations given above for PV cell modelling, however are a few variables that must be chosen for the modelling process. The selection of the PV module model will influence these variables (Bellini et al., 2009). In this model, we need to calculate I_{ph} , I_{rs} , and I_s , which can be determined using the formulas that follow. The photocurrent (I_{ph}) is directly proportional to the incident flux and is not affected by the voltage (V) or series resistance (R_s). It is directly correlated with the rays from the sun and is also impacted by temperature, as described by equation (7).

$$I_{ph} = [I_{sc} + K_i (T_0 - T_r)] * \frac{G}{G_{ref}} \quad (7)$$

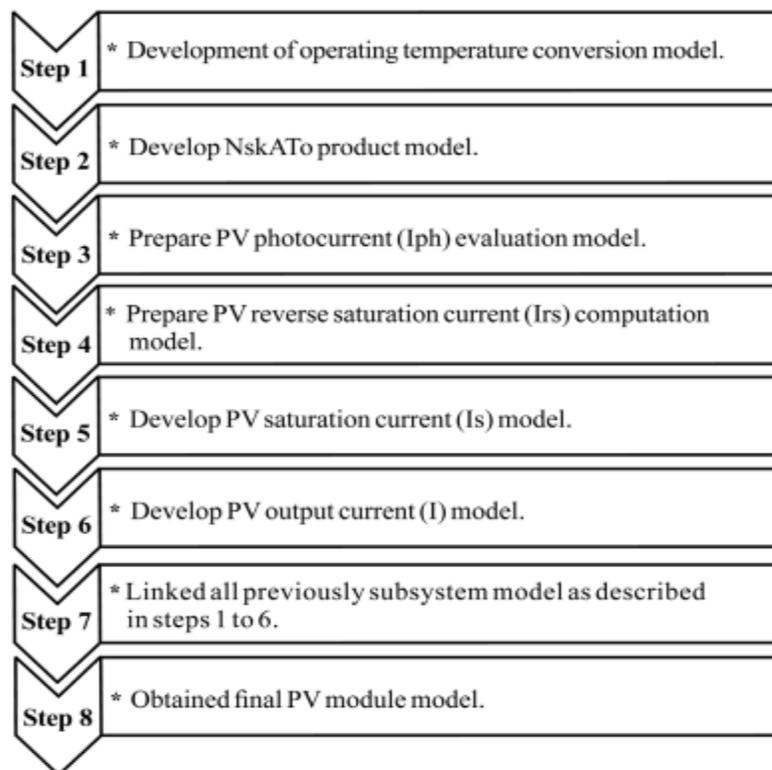


Fig.6. Photovoltaic modeling steps involved in Simulink.

The reverse saturating current, also known as I_{rs} , and the current of saturation are two related terms. The calculation is performed using equations (8) and (9).

$$I_{rs} = I_{sc} / \left[\exp \left(\frac{qV_{oc}}{N_s K A T_o} \right) - 1 \right] \quad (8)$$

$$I_s = I_{rs} [T_o/T_r]^3 \exp \left[\left(\frac{qE_g}{AK} \right) \left(\frac{1}{T_r} - \frac{1}{T_o} \right) \right] \quad (9)$$

An ideal conditions coefficient A and energy band gap E_g are derived using the chosen model provided by the creator of the chosen component.

3.3. Standard Framework for Modelling

The JAP6-72-320/4BB photovoltaic (PV) module was chosen for the purpose of developing the modelling and conducting a simulation of a solar cell design. This module is illustrated in Figure 5. The module comprises of 72 polycrystalline silicon solar cells that are interconnected in a series configuration. This module minimises resistance in a sequence of cells caused by the interconnectors placed back to back. These interconnectors provide excellent efficiency when converting. The specifics of this module may be found in Table 2.

4. Simulation model

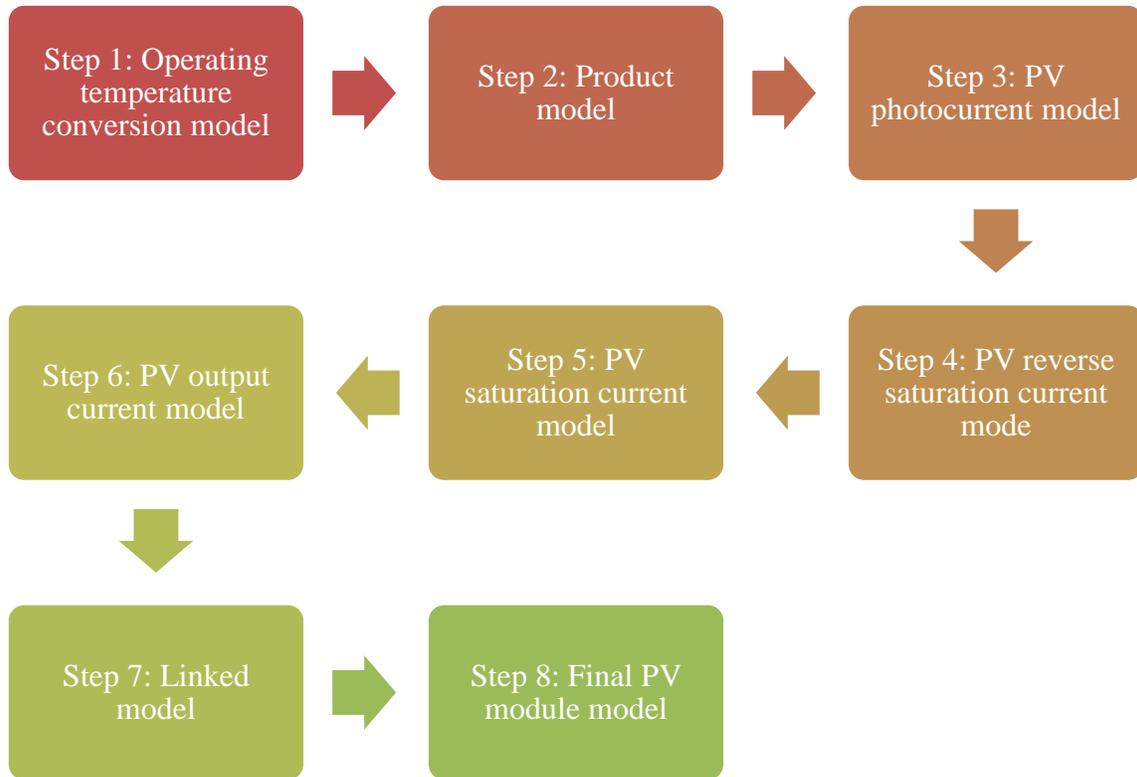
A mathematical representation of a photovoltaic panel (PV) is produced utilising essential components such as a current source, diode, series resistances, and parallel resistance. The model is created in an organised manner within the Matlab/Simulink system, utilising the equations (1)–(9) mentioned above. Figure 6 illustrates the sequential procedures of photovoltaic (PV) modelling. The PV model being sought consists of interconnected subsystems that have been established and connected to each other (Kharb et al., 2013; Rekioua and Matagne, 2012; Meflah et al., 2017; Pendem and Mikkili, 2018).

Table 2 Electrical parameters of JAP6-72-320/4BB solar PV module.

S. No.	Parameters	Variables	Values
1.	Maximum power at STC (P_m)	P_m	320 W
2.	Maximum power voltage (V_{mp})	V_m	37.38 V
3.	Maximum power current (I_{mp})	I_m	8.56 A
4.	Open circuit voltage (V_{oc})	V_{oc}	46.22 V
5.	Short-circuit current (I_{sc})	I_{sc}	9.06 A
6.	Total series cells	N_s	72
7.	Total parallel cells	N_p	1
8.	Ideality factor of diode	A	1.3
9.	Cell short circuit current temperature coefficient of I_{sc}	K_i	0.058%/°C
10.	Reference temperature	T_{ref}	25 °C
11.	Solar Irradiance	G_{ref}	1000 at STC

The JAP6-72-320/4BB PV solar module has been chosen as the reference model for simulation and will be used to provide the input settings for modelling. The datasheet for the JAP6-72-

320/4BB module from JA Solar will be used as a reference. The ultimate PV cell model converts solar energy into electricity and generates curves with characteristics based on supplied temperatures and radiation inputs.



Step 1: Operating temperature conversion model

In the case of a solar photovoltaic (PV) system the ambient temperature is a parameter that is measured in degrees Celsius, respectively. However, when developing PV models, the temperature used in the mathematical equations is in Kelvin. Therefore, all temperature information must be converted to Kelvin. This conversion is shown in Figure 7 and is an essential component of the solar photovoltaic (PV) modelling a component.

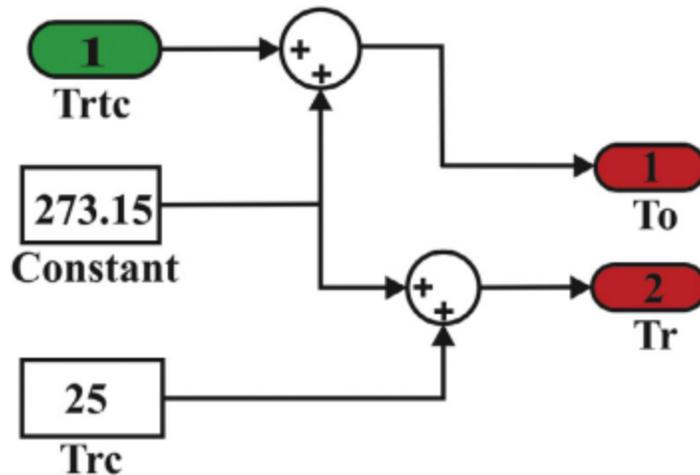


Fig. 7: temperature of operation the conversion concept

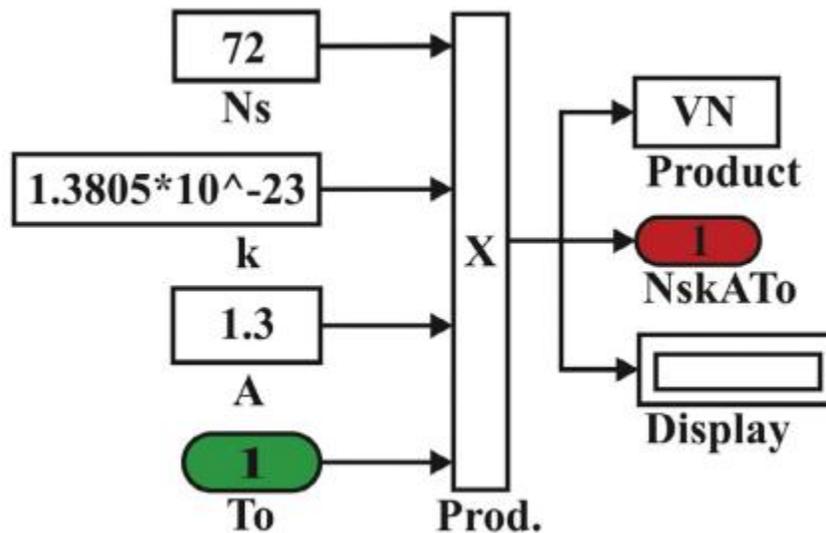


Figure 8 illustrates an example model for NskATo.

Step 2: Product model

The mathematical modelling of the PV Modules, as shown in the section prior to this one, includes the NskATo equations (3) to (8), which need the temperature that is used to be in Kelvin. Hence, a model in Simulink for the NskATo product is created to compute its value and incorporate it as a subsystem in the final PV model (Kharb et al., 2013; Salem, 2014). Figure 8 displays the goods architecture.

Step 3: PV photocurrent model

The PV the photocurrent framework serves as a component within the solar PV approach, and is constructed using Equation (7) in Simulink. The photo current has an inverse relationship with solar irradiation and is also affected by the temperature at which it works (Rekioua and Matagne, 2012; Meflah et al., 2017). Figure 9 illustrates the comprehensive implementation of I_{ph} in the Simulink environment, including its subsystem and the impact of external variables such as sun irradiation (G) and temperatures (T_o) as the parameters that are entered.

Step 4: PV reverse saturation current mode

The backwards saturation current model shown in Fig. 10 is constructed utilising Equation (8) within the Simulink platform. The computational model is developed using variables from the manufacturer's data sheet (Pandiarajan and Muthu, 2011; Meflah et al., 2017).

Step 5: PV saturation current model

Equation (9) denotes the saturation current (I_s), which is dependent on the temperature of the cell. A mathematical representation for this relationship is constructed in the Simulink environment. The reversible saturation current component model, depicted in Figure 10, is utilised as input, together with the energy bands gap, electrons the driver's seat benchmark humidity, as well as the operational temperature of the module (Kharb et al., 2013; Abdulkadir et al., 2012). The simulated model depicted in Figure 11 assesses the saturation point of the flow.

Step 6: PV output current model

The current output, as described by Equation (6), is generated in Simulink and depicted in Figure 12. This Simulink model allows for the investigation of the output current in relation to the voltage, which is influenced by both temperature and radiation.

Step 7: Linked model

The component model created from step 1 to step 6 within the Simulink, which framework was joined and produced an interconnected model, as depicted in Figure 13.

Step 8: Final PV module model

The final PV sun modules model has been created in the Simulink, which the surroundings, as shown in Figure 14. It takes irradiance (G) and temperature (T_o) as input variables and delivers current (I) and voltage (V) as results for output.

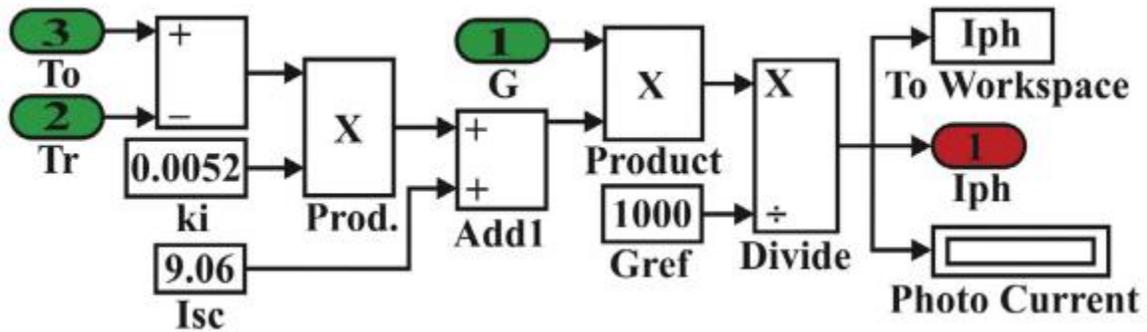


Fig. 9. Photocurrent model.

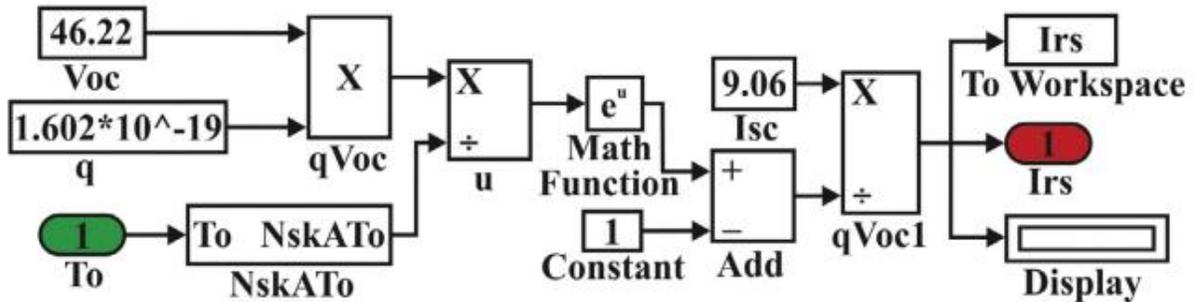


Figure 10: Reverse saturated current concept.

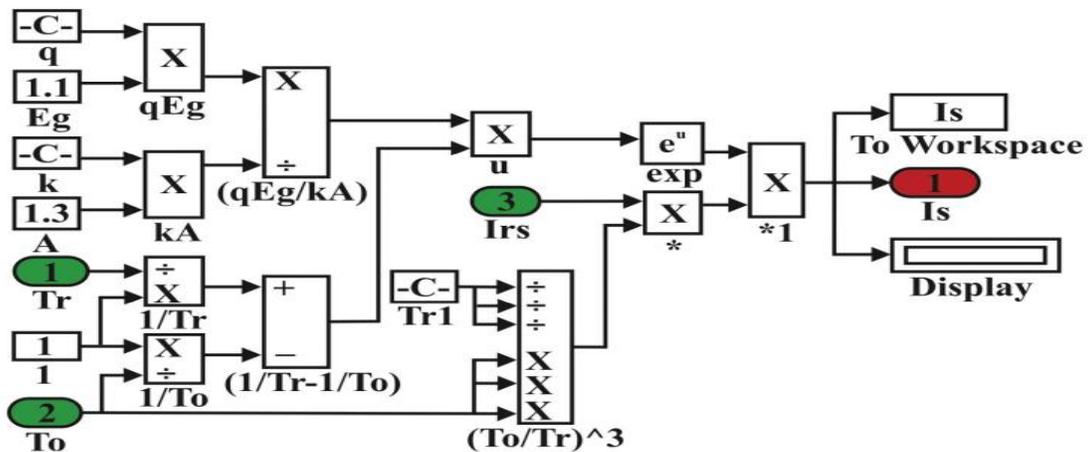


Fig. 11. PV saturation current model

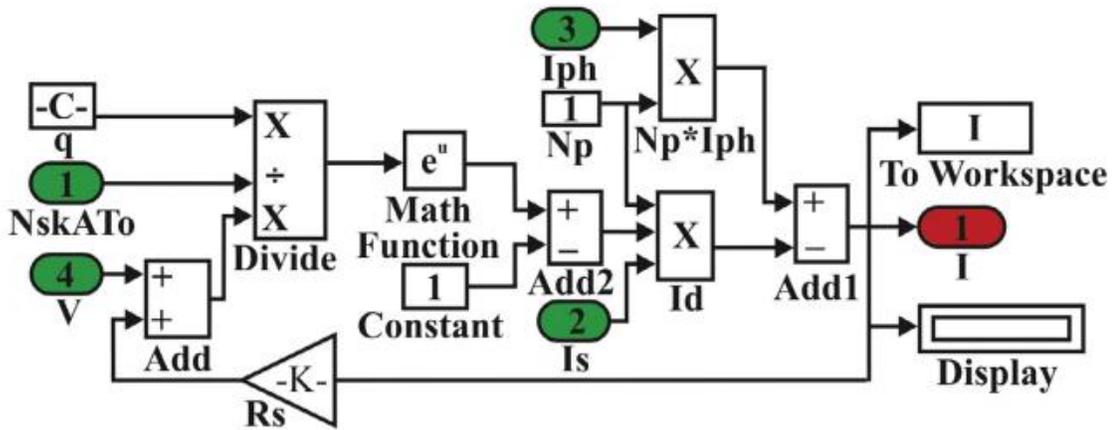


Fig. 12. PV output current model.

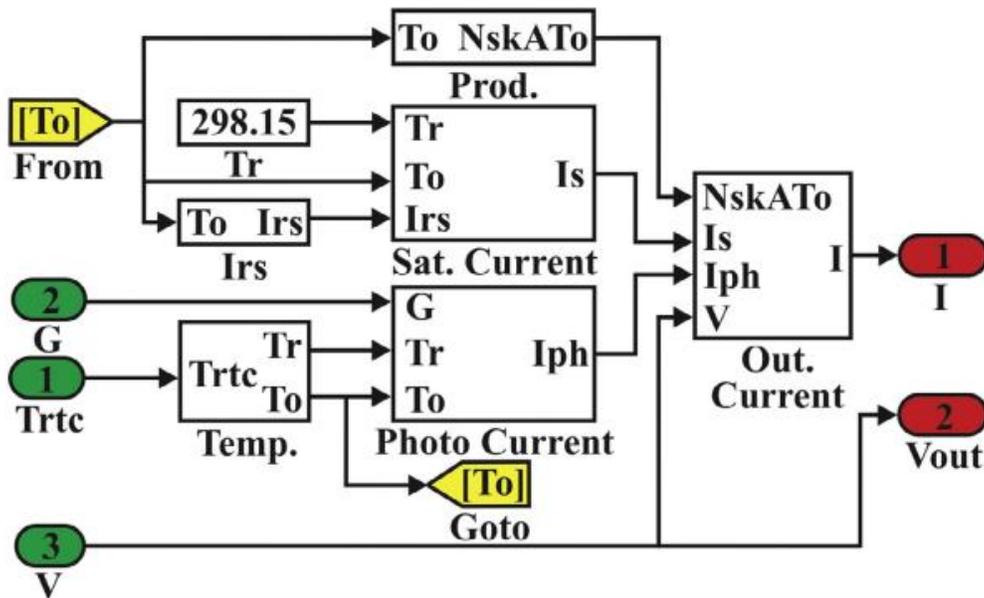


Fig. 13. Linked model of subsystems.

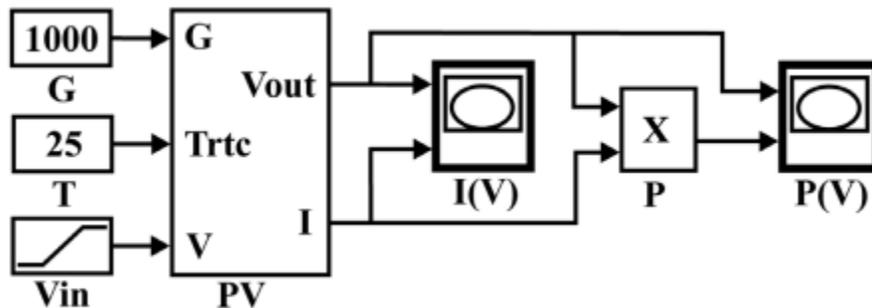


Fig. 14. Final PV module model

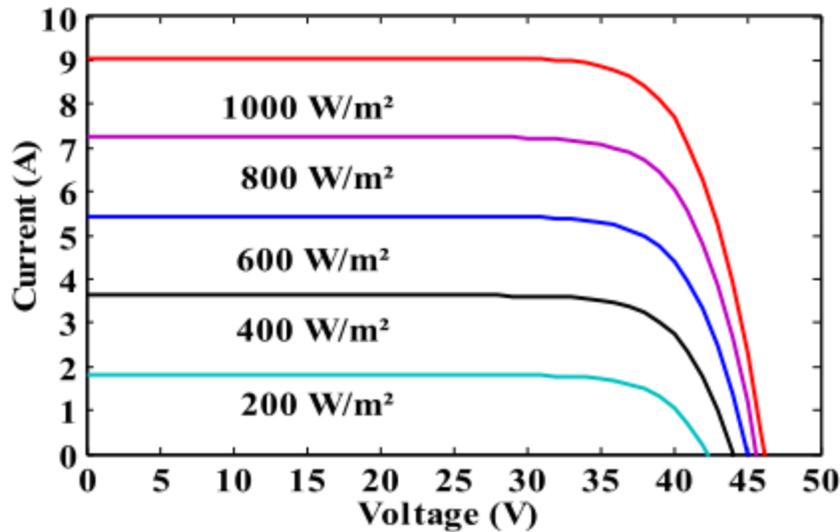


Figure 15 shows I-V characteristics with varied irradiation at a fixed temperature

Table 3 compares the baseline model levels with modelling data at STC.

Parameters	Parameters of JAP6-72/320/4BB datasheet - reference model	Parameters from simulation of the model	Relative error (%)
Pmax (W)	320	319.9996	0.000125
Voc (V)	46.22	46.2063	0.030
Isc (A)	9.06	9.06	0
Vmp (V)	37.38	38	1.63
Imp (A)	8.56	8.421	1.65
Efficiency (η %)	16.51	16.51	0

5. Computation Assessment and Discussion

The Solar PV modules design is created in the Matlab/Simulink framework utilising the formulas for the calculation of photovoltaic cells that have already been explained. The settings of the JAP6-72/320/4BB component, as stated in the the manufacturer's information sheet, are included in the simulation block model and are used as the basis for the unit. The output data of the ultimate photovoltaic (PV) approach, shown in Figure 14, are recreated and generated by varying the input variables including radiation and temperatures. These results include measurements of electrical power, voltage, and current (Adamo et al., 2011; Rekioua and Matagne, 2012).

5.1. Evaluation of model in standard test conditions

The ultimate photovoltaic solar model is assessed under ordinary circumstances (STC). The specified circumstances, as described by Abdullahi et al. (2017), are consistent worldwide. These settings involve an irradiation of 1000 W/m², a temperature of 25 °C, and an atmosphere with a

mass of 1.5. The solar PV simulator generates the I-V and P-V distinctive curves. The operational characteristics of the comparison model and simulated PV model at STC showed a generally satisfactory agreement, as shown in Table 3. The relative inaccuracy for all of the settings of the solar energy production model ranges from 0 to 1.65%.

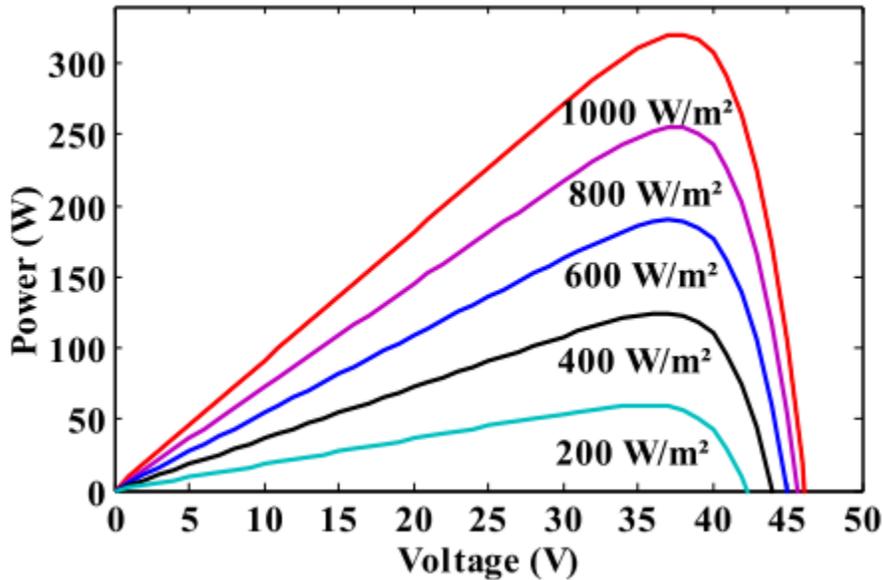


Figure 16: P-V relationships with varied sunlight at a single temperature.

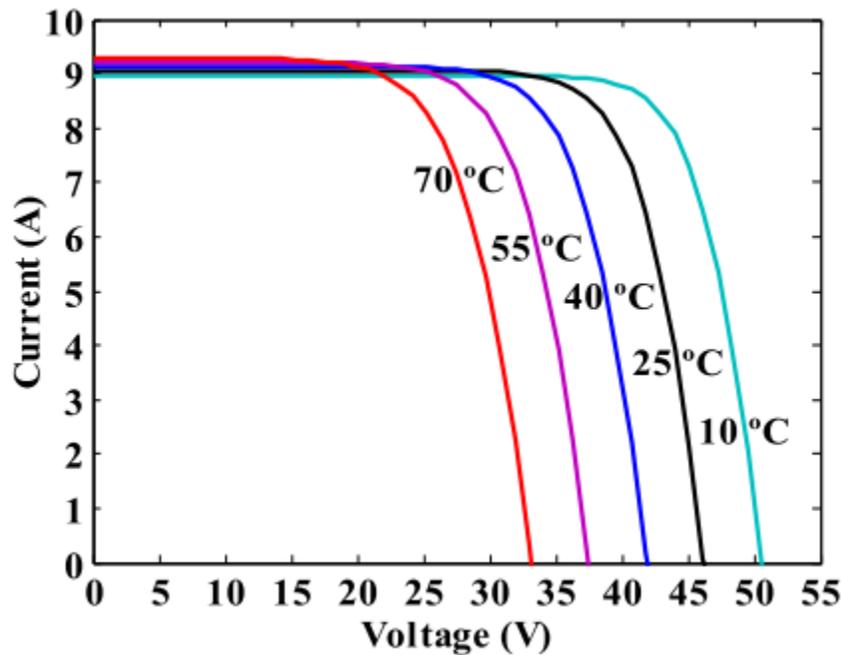


Figure 17 shows the features of I-V at varied temperatures under steady solar light.

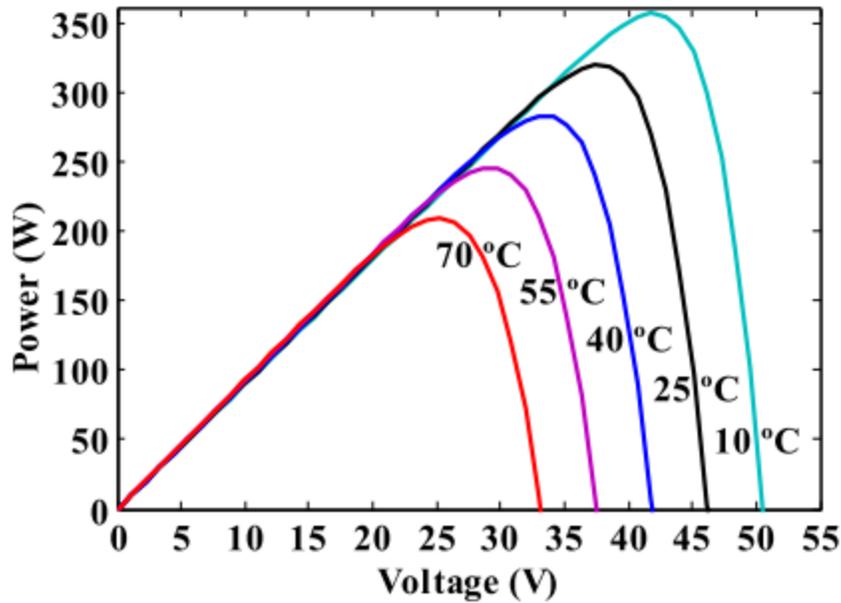


Figure 18 shows P-V relationships at varied temperatures under consistent solar light.

5.1.1. The brightness Impacts on PV Solar Modules

The impact upon the solar photovoltaic (PV) model's I-V & P-V curves of character is illustrated in Figures 15 and 16. This is done by adjusting the intensity of irradiance from 200 W/m² to 1000 W/m² while maintaining a constant temperature of 25 oC. It has been noticed that the current remains equal as the voltage increases up to 30 V, and then it declines. Furthermore, the current exhibits an increase when the amount of light intensity rises.

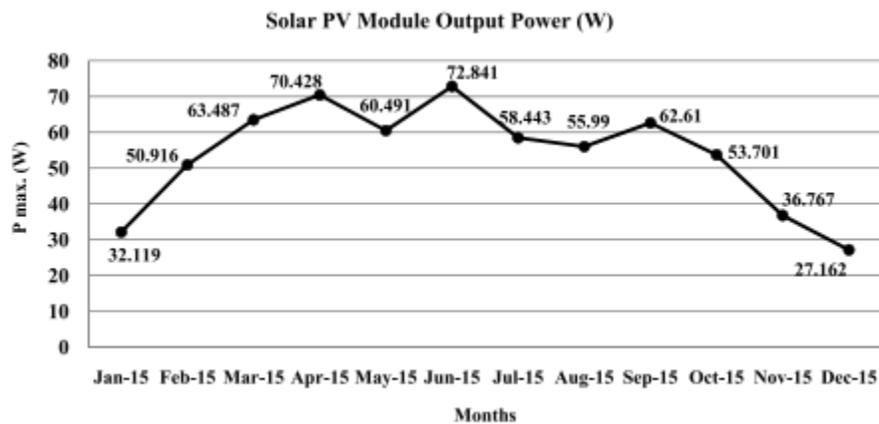


Figure 19 shows the monthly output power (Pmax) of solar PV modules.

This illustrates that the level of irradiance has a significant impact on the short circuit current, while the open circuit voltage is quite low, as depicted in Figure 15. The greatest power indications can be found on power performance curves. The generation of electricity of solar PV models can be enhanced by increasing the intensity of solar irradiation, as depicted in Figure 16.

5.2. Solar PV model validation

The correctness of the solar photovoltaic (PV) model is assessed by calculating the proportion of of variation (RE) between the results of the simulation and the manufacturer datasheet results under standard test circumstances (STC). Table 3 displays the proportion of relative error, which is consistently below 1.70% for all parameters. The manufacturer data parameters and simulated PV solar model results shown a strong consistency. The relative error between the simulated solar PV model and the manufacturer specifications was found to be below 2% for all parameters (Meflah et al., 2017). The study conducted by Hashim and Khazaal (2017) determined the range of relative error in maximum power production for fifteen various types of PV connections to be between 0.1% and 6.76%. The discrepancy between the modelling of PV module results and the results provided by the company's datasheet was determined to be less than 10% (Mohamed Abdullahi et al., 2017). The model demonstrated a strong correlation between the characteristics of curves and the efficacy of the PV sun modules.

Table 5 shows solar PV model results parameters based on 2023 metrological information.

Months	Input parameters		Output parameters		
	Avg. value of G (W/m ²)	Avg. value of Amb. T (°C)	Imp (A)	Vmp (V)	Pmax (W)
January	99.52	11.45	0.845	38.001	32.119
February	160.92	17.09	1.376	37.002	50.916
March	203.17	20.22	1.716	36.997	63.487
April	236.31	26.85	2.012	35.003	70.428
May	214.99	32.68	1.833	33.001	60.491
June	250.65	30.08	2.187	33.300	72.841
July	203.28	29.96	1.719	34.018	58.443
August	193.55	28.92	1.647	33.995	55.990
September	215.01	28.79	1.842	33.990	62.610
October	181.58	25.99	1.534	35.007	53.701
November	122.02	20.97	1.021	36.010	36.767
December	87.22	14.84	0.734	37.005	27.162

5.3. Assessing solar PV modules performance using real-world measurements.

The efficiency of a photovoltaic (PV) panel was assessed in Matlab/Simulink using the mean monthly measurements of irradiance and ambient temperature for the year 2015. The assessment was conducted at the Solar Radiation Resource Assessment (SRRA) centre located at Deenbandhu Chhotu Ram University of Science and Technology in Murthal, Sonipat, Haryana. This centre was established by the Ministry of New and Renewable Energy (MNRE) under the Government of India. Table 4 displays the demographic status of SRRA, Murthal station, Haryana, India. The photovoltaic PV model's output figures are displayed in Table 5, utilising the monthly average values of irradiance (G) and temperature (T) as the parameters of input for the period of the month of January to December of the same year.

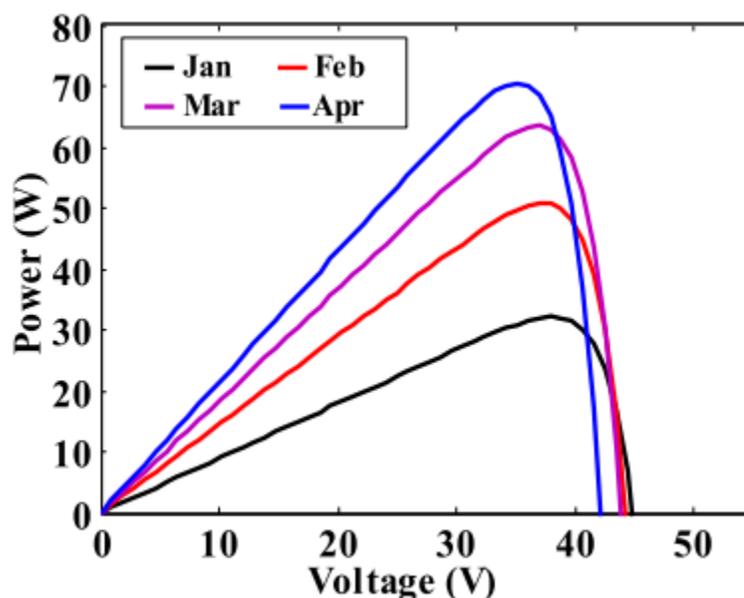


Fig. 20. I-V and P-V graphs for the month

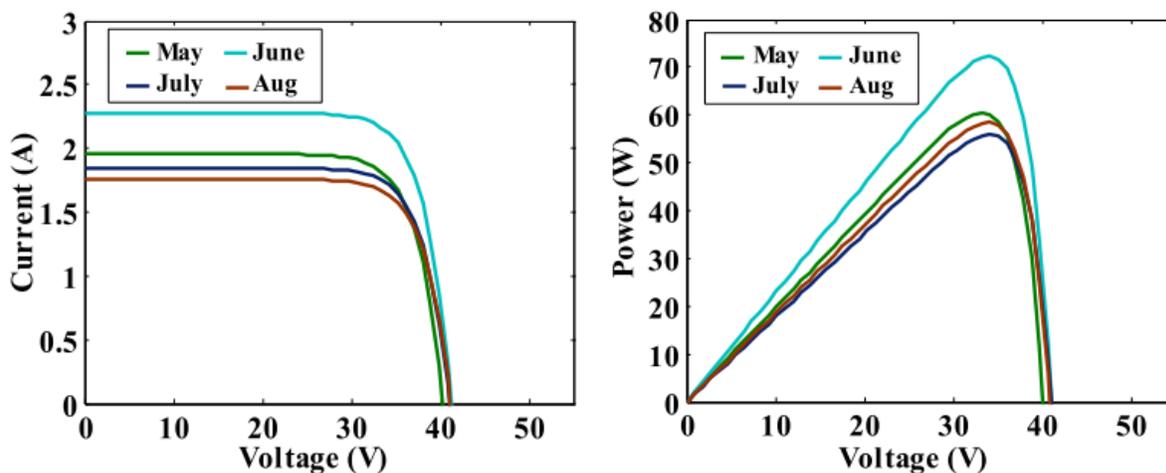


Fig. 21. I-V and P-V graphs for the month

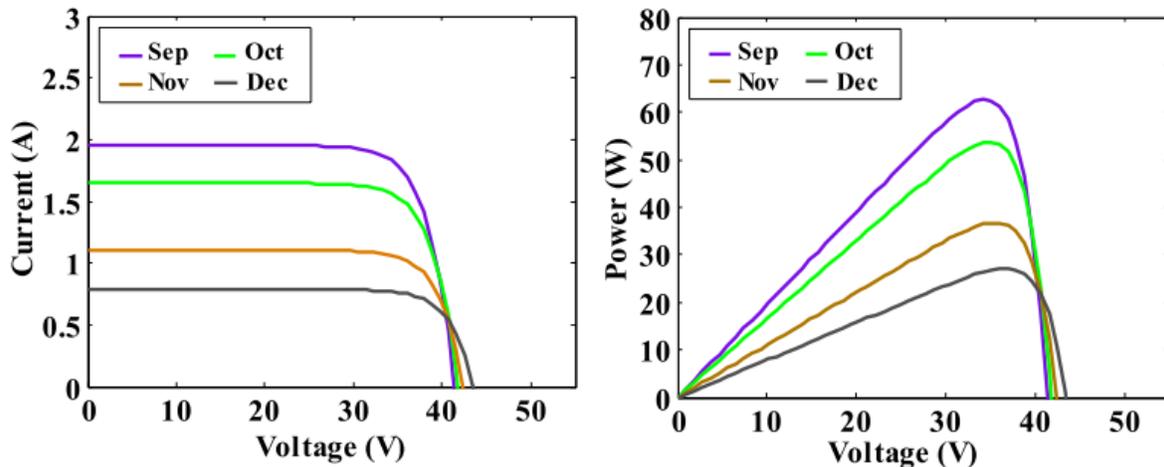


Fig. 22. I–V and P–V graphs for the month

The amount of light emitted ranges from a minimum of 87.22 W/m² to an average of 250.65 W/m², while the temperature fluctuates between a minimum of 11.45 oC and a high of 32.68 oC. The I–V and P–V graphs representing the values from January to December 2015 for the solar PV model are simulated and depicted in Figures 20–22. Consistency is observed in the key aspects of current, voltage, and power for a solar PV model, even when the irradiance and temperature fluctuate. A strong correlation is observed between the current and irradiance intensity. Whenever the irradiance increases, the current of the solar PV model likewise increases, as shown in Figures 20-22.

In December of that year, the lowest power output recorded was 27.162 W, while in June 2015, the highest power production was 72.841 W, as shown in Figure 19. A strong correlation was seen between the rise in irradiance intensity from January to June and the corresponding increase in power output. In the month of May, there is a decline in power output due to a reduction in irradiance intensity and the highest average temperature recorded during this period. There is a noticeable decline in power output from July to December. Additionally, it is disclosed that there is an increase in power output during the month of September, which can be attributed to the higher intensity of irradiation. This demonstrates that as the irradiance increases, the output current also increases, resulting in an upsurge in the generating capacity of the solar PV component.

6. Conclusions

The present article presents a precise model of a PV solar portion, which accurately represents the behaviour of a single diode. An described procedure for modelling a photovoltaic solar module in a Matlab/Simulink environment is provided. This modelling methodology facilitates the comprehension of

the operational performance curves of PV solar modules for researchers, manufacturers, and individuals. The maximum relative error percentage is determined to be 1.65%, indicating a strong correlation between the manufacturer's values and the simulated values. This confirms that the simulation accurately replicates the characteristic curve and performance of the PV solar module. The PV solar module's achievement, based on the metrological information regarding the temperature and irradiance from February to October, yields favourable outcomes. Furthermore, this is considered a robust method to assess the efficiency of photovoltaic cells as well as panels under varying meteorological situations. Therefore, this will support the "Make in India" initiative to the sphere of photovoltaic production.

References

- [1]. AbdelHady, R., 2017. Modeling and simulation of a micro grid-connected solar PV system. *Water Sci.* 31 (1), 1–10. <http://dx.doi.org/10.1016/j.wsj.2017.04.001>. Abdulkadir, M., Samosir, A.S., Yatim, A.H.M., 2012. Modeling and simulation based approach of photovoltaic system in simulink model. *J. Eng. Appl. Sci. (ARPNS)* 7 (5), 616–623.
- [2]. Abdullahi, N., Saha, C., Jinks, R., 2017. Modeling and performance analysis of a silicon PV module. *J. Renew. Sustain. Energy* 9 (3), 1–11. <http://dx.doi.org/10.1063/1.4982744>.
- [3]. Adamo, F., Attivissimo, F., Di Nisio, A., Spadavecchia, M., 2011. Characterization and testing of a tool for photovoltaic panel modeling. *IEEE Trans. Instrum. Meas.* 60 (5), 1613–1622. <http://dx.doi.org/10.1109/TIM.2011.2105051>.
- [4]. Altas, I.H., Sharaf, A.M., 2007. A photovoltaic array simulation model for MatlabSimulink GUI environment. In: *Clean Electrical Power, 2007. ICCEP. IEEE*, pp. 341–345. <http://dx.doi.org/10.1109/ICCEP.2007.384234>.
- [5]. Amrani, O., Rekioua, D., 2006. Etude et identification des différents modèles Electriques photovoltaïques. In: *International Conference ICEA, Vol. 6*.
- [6]. Amrouche, S.O., Rekioua, D., Rekioua, T., Bacha, S., 2016. Overview of energy storage in renewable energy systems. *Int. J. Hydrogen Energy* 41 (45), 20914–20927. <http://dx.doi.org/10.1016/j.ijhydene.2016.06.243>.
- [7]. Aneke, M., Wang, M., 2016. Energy storage technologies and real-life applications—A state of the art review. *Appl. Energy* 179, 350–377. <http://dx.doi.org/10.1016/j.apenergy.2016.06.097>.
- [8]. Aoun, N., Chenni, R., Nahman, B., Bouchouicha, K., 2014. Evaluation and validation of equivalent five-parameter model performance for photovoltaic panels using only reference data. *Energy Power Eng.* 6 (09), 235. <http://dx.doi.org/10.4236/epe.2014.69021>.
- [9]. Banu, I.V., Istrate, M., 2012. Modeling and simulation of photovoltaic arrays. *Bul. AGIR* 3, 161–166, <http://www.buletinulagir.agir.ro/articol.php?id=1378>. Bellini, A., Bifaretti, S., Iacovone, V., Cornaro, C., 2009. Simplified model of a photovoltaic module. In: *Applied Electronics. IEEE*, pp. 47–51

- [10]. Central Electricity Authority, 2017a. Growth of electricity sector in India from 1947- 2017, pp. 1-83. http://www.cea.nic.in/reports/others/planning/pdm/growth_2017.pdf.
- [11]. Central Electricity Authority, 2017b. All India installed capacity of power stations, pp. 1-7. www.cea.nic.in/reports/monthly/installedcapacity/2017/installed_capacity-10.pdf.
- [12]. Fara, L., Craciunescu, D., 2017. Output analysis of stand-alone PV systems: modeling, simulation and control. *Energy Procedia* 112, 595–605. <http://dx.doi.org/10.1016/j.egypro.2017.03.1125>.
- [13]. Geonka, D., Guttikunda, S., 2012. Coal Kills: An Assessment of Death and Disease Caused by India's Dirtiest Energy Source. Urban Emissions in partnership with the Conservation Action Trust and Greenpeace India. http://www.greenpeace.org/india/Global/india/report/Coal_Kills.pdf.
- [14]. Gould, T., 2015. World energy outlook special report 2015. Paris. In: OECD/International Energy Agency. International Energy Agency, Paris, pp. 1–19, https://www.iea.org/publications/freepublications/publication/IndiaEnergyOutlook_WEO2015.pdf.
- [15]. Hamdi, R.T.A., 2017. Solar cell system simulation using Matlab-Simulink. *Kurdistan J. Appl. Res.* 2 (1), 45–51. <http://dx.doi.org/10.24017/science.2017.1.4>.
- [16]. Hashim, E.T., Khazaal, S.Q., 2017. Modelling and output power evaluation of seriesparallel photovoltaic modules. *Int. J. Comput. Appl.* 158 (8), 35–46. <http://dx.doi.org/10.5120/ijca2017912846>.
- [17]. Hemmati, R., 2018. Optimal design and operation of energy storage systems and generators in the network installed with wind turbines considering practical characteristics of storage units as design variable. *J. Cleaner Prod.* 185, 680–693. <http://dx.doi.org/10.1016/j.jclepro.2018.03.062>.
- [18]. Hemmati, R., Saboori, H., 2016. Emergence of hybrid energy storage systems in renewable energy and transport applications—A review. *Renew. Sustain. Energy Rev.* 65, 11–23. <http://dx.doi.org/10.1016/j.rser.2016.06.029>.
- [19]. Kanchan, S., Kumarankandath, A., 2015. The Indian power sector: Need of sustainable energy access, IPPAI knowledge report, 126-140. http://cdn.cseindia.org/attachments/0.61046700_1505884602_The-Indian-Power-Sector.pdf. Kharb, R.K., Shimi, S.L., Chatterji, S., 2013. Improved maximum power point tracking for solar PV module using ANFIS. *Int. J. Curr. Eng. Technol.* 3 (5), 1878–1885.
- [20]. Kim, H., Jung, T.Y., 2018. Independent solar photovoltaic with Energy Storage Systems (ESS) for rural electrification in Myanmar. *Renew. Sustain. Energy Rev.* 82, 1187–1194. <http://dx.doi.org/10.1016/j.rser.2017.09.037>.
- [21]. Kirmani, S., Jamil, M., Rizwan, M., 2015. Empirical correlation of estimating global solar radiation using meteorological parameters. *Int. J. Sustain. Energy* 34 (5), 327–339. <http://dx.doi.org/10.1080/14786451.2013.826222>.
- [22]. Krismadinata, Rahim, N.A., Ping, H.W., Selvaraj, J., 2013. Photovoltaic module modeling using Simulink/Matlab. *Procedia Environ. Sci.* 17, 537–546. <http://dx.doi.org/10.1016/j.proenv.2013.02.069>.

- Lyden, S., Haque, M.E., Gargoom, A., Negnevitsky, M., Muoka, P.I., 2012. Modeling and parameter estimation of photovoltaic cell. In: Power Engineering Conference, AUPEC. IEEE, pp. 1–6.
- [23]. Meflah, A., Rahmoun, K., Mahrane, A., Chikh, M., 2017. Outdoor performance modeling of three different silicon photovoltaic module technologies. *Int. J. Energy Environ. Eng.* 8 (2), 143–152. <http://dx.doi.org/10.1007/s40095-017-0228-6>.
- [24]. Mendalek, N., Al-Haddad, K., 2017. Photovoltaic system modeling and simulation. In: *Industrial Technology, ICIT*. IEEE, pp. 1522–1527. <http://dx.doi.org/10.1109/ICIT.2017.791592>.
- [25]. Ministry of New and Renewable Energy (MNRE), 2017. Annual Report-MNRE 2016- 2017, 1-224. <http://mnre.gov.in/file-manager/annual-report/2016-2017/EN/index.html>. Mohammedi, A., Rekioua, D., Mezzai, N., 2013. Regular paper experimental study of a PV water pumping system. *J. Electr. Syst.* 9 (2), 212–222.
- [26]. Nathan, H.S.K., 2014. Solar energy for rural electricity in India: A misplaced emphasis. *Econ. Polit. Wkly* 49 (50), 60–67, <http://eprints.nias.res.in/921/1/2015-Kristle%20Nathan-EPW.pdf>
- [27]. Pandiarajan, N., Muthu, R., 2011. Mathematical modeling of photovoltaic module with Simulink. In: *Electrical Energy Systems, ICEES*. IEEE, pp. 258–263. <http://dx.doi.org/10.1109/ICEES.2011.5725339>.
- Patel, J., Sharma, G., 2013. Modeling and simulation of solar photovoltaic module using Matlab/Simulink. *Int. J. Res. Eng. Technol.* 2 (3), 225–228
- [28]. Pendem, S.R., Mikkili, S., 2018. Modeling, simulation and performance analysis of solar PV array configurations (Series, Series-Parallel and Honey-Comb) to extract maximum power under Partial Shading Conditions. *Energy Rep.* 4, 274– 287. <http://dx.doi.org/10.1016/j.egy.2018.03.003>. Qi, C., Ming, Z., 2012. Photovoltaic module Simulink model for a stand-alone PV system. *Phys. Procedia* 24, 94–100
- [29]. Rahman, S.A., Varma, R.K., Vanderheide, T., 2014. Generalised model of a photovoltaic panel. *IET Renew. Power Gener.* 8 (3), 217–229. <http://dx.doi.org/10.1049/iet-rpg.2013.0094>.
- [30]. Rekioua, D., Matagne, E., 2012. Optimization of Photovoltaic Power Systems: Modelization, Simulation and Control. Springer Science & Business Media, <http://dx.doi.org/10.1007/978-1-4471-2403-0>.
- [31]. Saboori, H., Hemmati, R., Ghiasi, S.M.S., Dehghan, S., 2017. Energy storage planning in electric power distribution networks—A state-of-the-art review. *Renew. Sustain. Energy Rev.* 79, 1108–1121. <http://dx.doi.org/10.1016/j.rser.2017.05.171>. Salem, F.A., 2014. Modeling and simulation issues on photovoltaic systems, for mechatronics design of solar electric applications. *IPASJ Int. J. Mech. Eng. IJME* 2 (8), 24–47.
- [32]. Sera, D., Teodorescu, R., Rodriguez, P., 2007. PV panel model based on datasheet values. In: *Industrial Electronics*. IEEE, pp. 2392–2396. <http://dx.doi.org/10.1109/ISIE.2007.4374981>.

- [33]. Shahzad Baig, K., Yousaf, M., 2017. Coal-fired power plants: Emission problems and controlling techniques. *J. Earth Sci. Clim. Change* 8 (404), 1–9. <http://dx.doi.org/10.4172/2157-7617.1000404>.
- Sharma, D.K., Verma, V., Singh, A.P., 2014. Review and analysis of solar photovoltaic software. *Int. J. Curr. Eng. Technol.* 4 (2), 725–731.
- [34]. Sindhu, S., Nehra, V., Luthra, S., 2016. Identification and analysis of barriers in implementation of solar energy in Indian rural sector using integrated ISM and fuzzy MICMAC approach. *Renew. Sustain. Energy Rev.* 62, 70–88. <http://dx.doi.org/10.1016/j.rser.2016.04.033>
- [35]. Villalva, M.G., Gazoli, J.R., Ruppert Filho, E., 2009. Comprehensive approach to modeling and simulation of photovoltaic arrays. *IEEE Trans. Power Electron.* 24 (5), 1198–1208. <http://dx.doi.org/10.1109/TPEL.2009.2013862>.
- [36]. Yatimi, H., Aroudam, E.H., 2015. A Detailed Study and Modeling of Photovoltaic Module under Real Climatic Conditions. <http://dx.doi.org/10.12720/ijeee.3.3.171-176>.
- [37]. Yıldırım, N., Tacer, E., 2016. Identification of photovoltaic cell single diode discrete model parameters based on datasheet values. *Sol. Energy* 127, 175–183. <http://dx.doi.org/10.1016/j.solener.2016.01.024>