Sustainable Energy Research

REVIEW

Open Access

Effect of various parameters on the performance of solar PV power plant: a review and the experimental study

Feroz Shaik[1*], Syam Sundar Lingala[1] and Punnaiah Veeraboina[2]

Abstract

One of the biggest causes of worldwide environmental pollution is conventional fossil fuel-based electricity generation. The need for cleaner and more sustainable energy sources to produce power is growing as a result of the quick depletion of fossil fuel supplies and their negative effects on the environment. Solar PV cells employ solar energy, an endless and unrestricted renewable energy source, to generate electricity directly. The optimum output, energy conversion efficiency, productivity, and lifetime of the solar PV cell are all significantly impacted by environmental factors as well as cell operation and maintenance, which have an impact on the cost-effectiveness of power generation. This article presents an analysis of recent research on the impact of operational and environmental factors on the performance of solar PV cells. It has been discovered that temperature and humidity, combined with dust allocation and soiling effect, have a significant impact on the performance of PV modules. In addition, particularly in the lonely places, the wind itself carries a lot of dust and sand particles. The situation gets worse when dust builds up in humid circumstances and produces tenacious, sticky mud on the PV cell, which lowers power output by up to 60–70%. This paper covers cutting-edge methods for reducing these elements' effects, along with their proportional benefits and difficulties. This paper also explains about the parameters which involved in the solar power production and their influence on the efficiency analysis. The efficiency and energy conversion capacity of the semi conducting materials for power production is also discussed. It is also discussed about the general benefits of the solar PV power generation.

Keywords Solar PV cell efficiency, Renewable energy, Parameter estimation, Environment

Introduction

Due to the enormous energy needs of the planet, it is necessary to rely on solar energy, which is abundant and renewable. As the main energy source at the moment, conventional fossil fuels such as oil, coal, and natural gas are widely used. However, their availability is constrained, and their extraction, transportation, and use pose a threat to the environment. Approximately 66% of the world's emissions of carbon dioxide and other greenhouse gases (GHGs) come from fossil fuels (Wang et al., 2017). Solar energy, in particular, is the most suited form of renewable energy, because it is readily accessible, environmentally friendly, and pollutant-free. According to the International Energy Agency (IEA), solar PV (PV) systems may supply 11% of all renewable energy globally, which is comparable to a significant 2.3 Gigaton (Gton) decrease in carbon dioxide (CO_2) emissions year.

Solar radiation comes from the sun, which provides 1367 W/m^2 to the atmosphere (Liu, 2009). The amount of solar energy that is now being absorbed globally is close

*Correspondence:
Feroz Shaik
fshaik@pmu.edu.sa; ferozs2005@gmail.com
[1] Department of Mechanical Engineering, Prince Mohammad Bin Fahd University, Al-Khobar 31952, Saudi Arabia
[2] Electrical Engineering Section, Department of Biotechnology, Centre for DNA Fingerprinting and Diagnostics, Ministry of Science & Technology, Hyderabad, India

to 1.8×10^{11} MW (Shah et al., 2015), which is sufficient to supply all of the world's current energy needs is 580 million terajoules (MTJ) (Wengenmayr and Bührke, 2009). Figure 1 shows that solar energy generation capacity has grown dramatically over the past 11 years, and extrapolation shows that its potential future growth might reach 1700 Gigawatt (GW) by 2030 (Nobuo, 2010). Solar PV systems still struggle with inefficient operation, despite the possibility that they could replace fossil fuels as a sustainable alternative.

Although the highest efficiency of 29% is theoretically achievable in commercial PV, this figure actually only achieves a maximum of 26% (Dewi et al., 2019). The loss of PV panel efficiency is caused by a number of internal and external causes, including environmental, constructional, installation, operational, and maintenance factors. The environmental elements continue to present a significant obstacle despite gradual improvements in PV constructional factors and their installation processes.

PV modules can efficiently receive the intensity and spectrum of solar energy. However, the quantity of solar irradiation that the module receives might be decreased by dust, snow, or any other type of natural or man-made shadowing. Humid air also absorbs dust and air pollutants, which leads to soiling on the module and reduced irradiance, which results in low PV power generation. The direct light exposure causes PV panels to heat up. The quantity of light that is absorbed by the module's components besides the solar cells causes the module to heat up, which lowers the bandgap energy and lowers power production. A specific height is used to attach solar panels to release the extra heat energy.

By including ventilation, fans, or cooling devices to help the air move around the panels, the PV module output power can be enhanced. Naturally, forced convection heat transfer in PV module cooling can benefit places with strong wind flow rates. Although the wind helps to cool the PV panel, it also brings sand and dust particles, which lowers the PV panel's ability to produce power. Therefore, in some instances, some operational and maintenance tasks are necessary to reduce the adverse environmental effect. Because of this, a thorough analysis that takes into accounts all the environmental, operational, and maintenance aspects and how they affect PV performance is necessary.

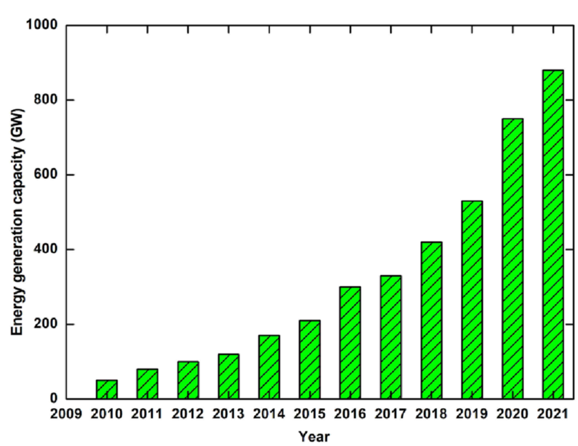

Fig. 1 Photovoltaic energy generation capacity over the years (Dewi et al., 2019)

Numerous studies addressing various elements that affect the performance of solar PV panels have already been published. Kazem et. al. (2020) conducted a thorough study of the literature on dust deposition and cleaning techniques, for instance. They claimed that due to dust buildup, the desert regions experience high power losses (up to 80%). In a different paper, Chanchangi et. al. (2020) reviewed the literature on the impact of dust on the performance of PV modules under Nigerian climatic conditions and suggested that, further conduct comprehensive research on the effects of dust in all geopolitical regions in Nigeria to acquire data that can be used for designing the PV module system considering the most suitable technique in reducing or preventing the effects of soiling in each specific area. Song et. al. (2021) provide a thorough study of the effects of air pollution and soiling on the performance of PV modules and its techno-economic performances.

These evaluation studies, however, primarily concentrate on the dust accumulation and their mitigation strategies. The current study takes one step further by evaluating the operational and maintenance aspects, as well as various environmental conditions such as dust and soiling that have an impact on the performance of PV modules. Fouad et. al. (2017) evaluate research on the effects of various environmental, PV system installations, financial, and other unrelated factors on the performance of PV. The operational and maintenance elements are not investigated, despite the fact that installations, environmental factors, and other random factors are all thoroughly addressed in their study.

The direct solar energy conversion into electric energy using photovoltaic (PV) cells is known as solar cells. The current–voltage (I–V) characteristic, which is non-linear in nature and can be unpredictable, since it varies with solar radiation and temperature, is crucial for the usage of solar cells in power generation. The material is outstanding for solar cell manufacturing, since it produces electricity from solar radiation that is received directly. Semiconductor materials have the potential to convert thermal energy into electrical energy.

The single crystal silicon (Si) is the promising semiconductor material in the earlier 1950, which was first built by United States (US) and tested its efficiency and found 5–6% (Green, 2005). Due to the demand and necessity of improving the efficiency of solar cell, in the earlier 2002, the first type Cadmium telluride (CdTe) material based solar cell and found its efficiency of 16.3% (Wesoff, 2015). The cost of single crystalline material is reached to \$1.00/W (Morris, 2014), and in the year 2020, its cost is reduced to < \$0.3/W (Breyer & Gerlach, 2013).

The performance of solar PV model accuracy in power generating system and its economical aspect are needful (Chauhan & Saini, 2014; Muhsen et al., 2017). The analysis of solar PV module parameters is necessary, because it involves in the power generation and economics. Based on the literature (Jordehi, 2016), there are variety of analyses are used to identify the parameters involved in the solar PV module and those are mostly analytical based at standard test conditions (STCs). The analytical method is simple, reliable and fast to analyze the parameters of solar PV module (Lo Brano & Ciulla, 2013). However, these techniques can give the significant percentage difference between simulated and actual performance of the solar PV cell (Davis et al., 2003; King et al., 2004).

Even though many academics have written extensively about specific issues, there hasn't been much research on how PV modules work. The environment, operations, and maintenance are some of these factors. The performance of solar PV modules is influenced by a wide range of environmental, operational, and maintenance factors, all of which are thoroughly examined in the current study. The research also offers cutting-edge strategies for lessening the influence of the elements causing the decline in solar PV productivity. Researchers and decision-makers may find use for the review report to increase electricity generation and make it economically viable. This review report took into account a number of factors when analyzing a solar PV module. The review also extended to the available semi-conducting materials and their efficiency. The photovoltaic energy generation capacity with respect to the years (Dewi et al., 2019) is mentioned in Fig. 1.

Solar PV cell technology

The first photovoltaic effect was noticed by Alexander-Edmond Becquerel (Yadav & Kumar, 2015) in the year 1839. Meanwhile, the Solar PV Cell made with silicon material identified by Russel Ohl (Castellano, 2010) in the year 1946. The different silicon materials used in the solar cells are single-crystal, amorphous-silicon and multi-crystalline (Fahrenbruch & Bube, 1983; Grisham, 2008; McEvoy et al., 2012; National Energy Education Development Project [NEED], 2015), cadmium telluride (CdTe) (Fahrenbruch & Bube, 1983; McEvoy et al., 2012), copper–indium–gallium–selenide (CIGS) (Bertolli, 2008; Fahrenbruch & Bube, 1983; McEvoy et al., 2012) and copper–indium–gallium–sulfide (Bagher et al., 2015; Srinivas et al., 2015). In light of these materials used in the PV cell manufacturing is indicated in Fig. 2.

First generation PV cell

The first generation solar PV cell is based on the silicon wafers, which is the popular technology because of its high efficiencies. Mostly, the silicon wafers are divided into two types, (i) Monocrystalline silicon solar cell, it is also called as Czochralski process, and (ii) Multicrystalline silicon solar cells, it contains various crystals, coupled with each other.

Second generation PV cell

When compared to silicon wafer solar cells from the first generation, second generation solar cells are more

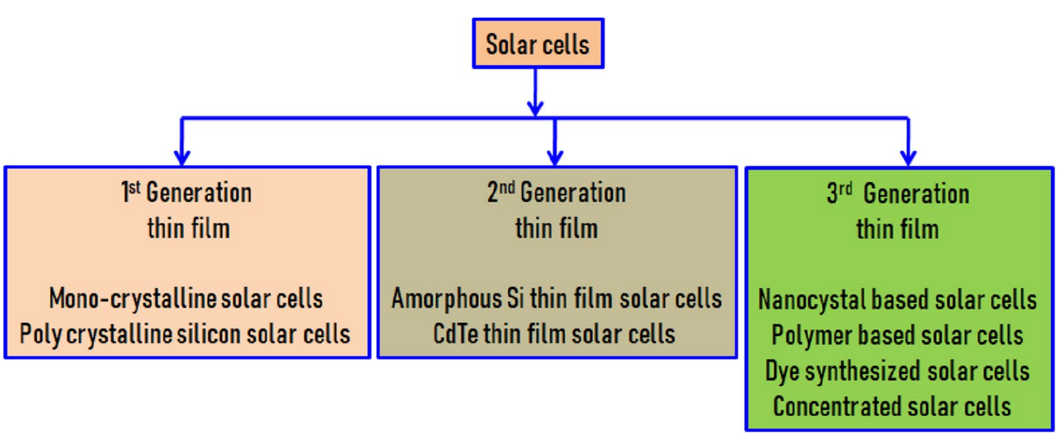

Fig. 2 Various types of solar PV cell technologies and current trends of development (Shruti et al., 2015)

cost-effective. Thin film solar PV cells feature extremely thin light absorbing layers, often of the order of 1 μm thickness, compared to silicon-wafer cells, which have light absorbing layers up to 350 μm thick. Amorphous silicon thin film (a-Si) solar cells, copper–indium–gallium–di-selenide (CIGS) solar cells, and cadmium–telluride (Cd–Te) solar cells are the three types of thin film solar cells.

Third generation PV cell

The third generation of photovoltaic cells includes polymer-based, nanocrystalline, dye-sensitized, and concentrated solar cells. Generally used materials are cadmium telluride and copper–indium–di-selenide for PV module. These materials based solar cells give more efficiency than the silicon based solar cells (Soteris, 2009). Various generations of solar cells are shown in Fig. 3. Various solar PV cells are: (a) copper–zinc–tin–sulphite (CZTS) PV cell, (b) organic solar cell, (c) polymer PV cell, (d) hybrid solar cell, (e) buried contact solar cell, (f) concentrated PV cell (CPV), (g) luminescent solar concentrator (LSC) cell, (h) multifunction solar cell (MJ), (i) nanocrystal solar cell, quantum dot solar cell, (j) dye-sensitized solar cell (DSSC), and (k) photo-electro-chemical cell (PEC).

Electrical characteristics of PV cell

The electrical characteristics of solar PV cell are important, because the light absorbing capacity depends on the technology, which are used in the manufacturing of the cell. Using the Micromorph Tandem solar cell, the initial and stable efficiencies were 12.3% and 10.8%, respectively (Meier et al., 2004). The current–voltage (*I–V*) curve of Micromorph Tandem solar cell is indicated in Fig. 4. The *I–V* curve of n+pn+ cells and n+pp+ cells is shown in Fig. 5 and

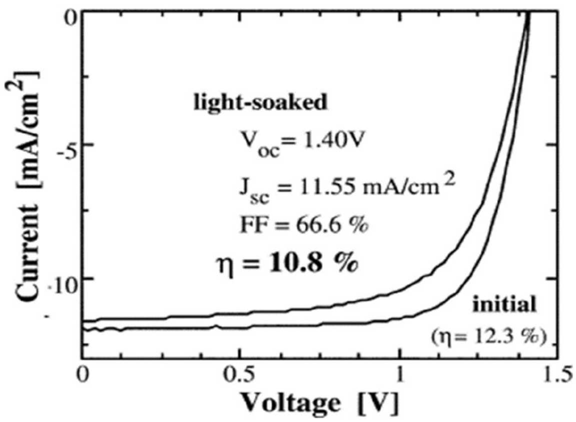

Fig. 4 *I–V* a micromorph tandem test's cell properties (Meier et al., 2004)

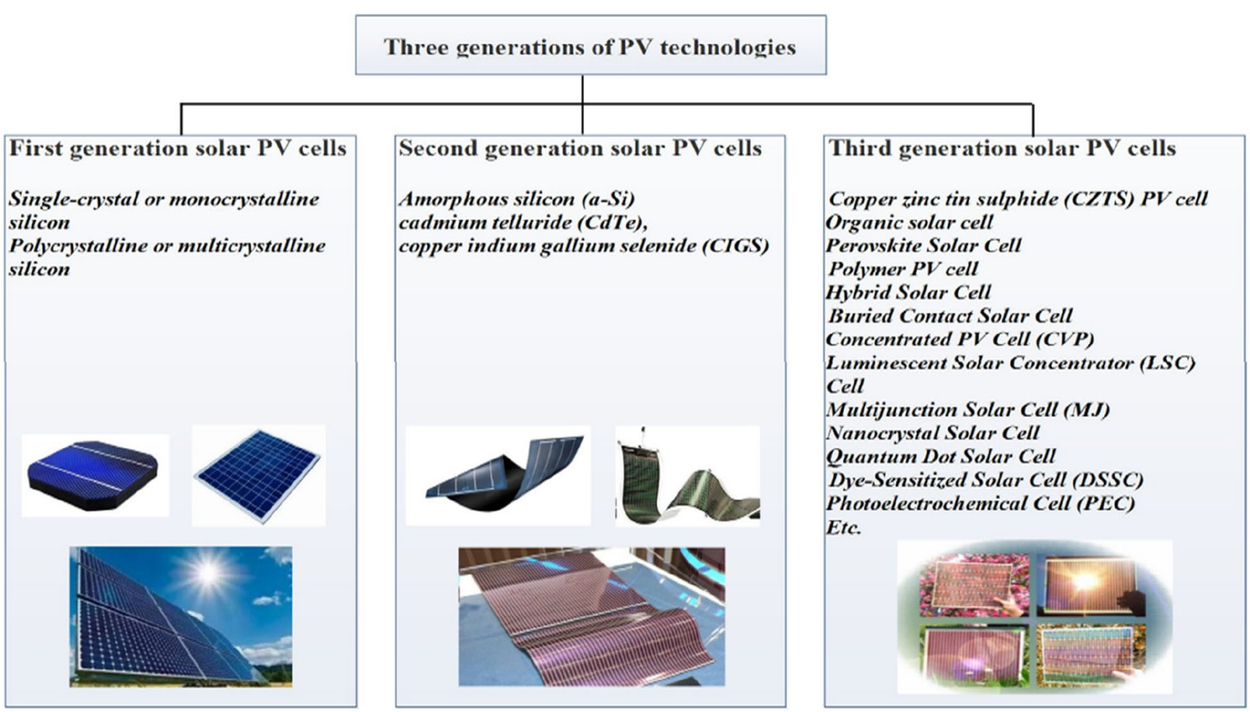

Fig. 3 Three generations of solar PV(PV) cells (Shukla et al., 2016)

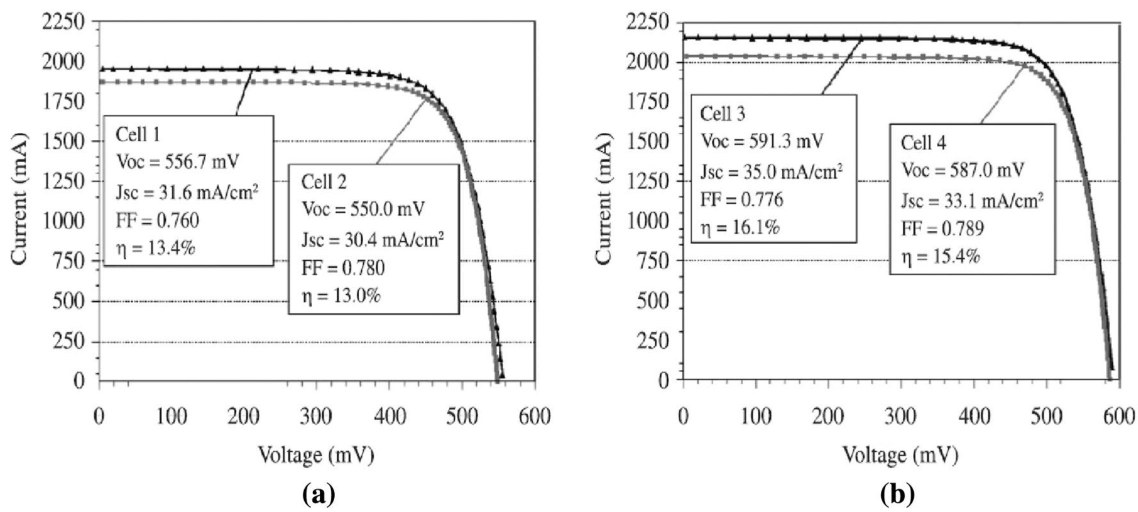

Fig. 5 Electrical characteristics of **a** n+pn+ and **b** n+pp+ solar PV cells (Adriano & Izete, 2012) at standard conditions

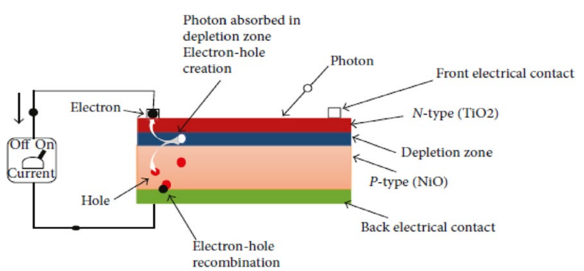

Fig. 6 Power generation using solar cell (Kingsley et al., 2018)

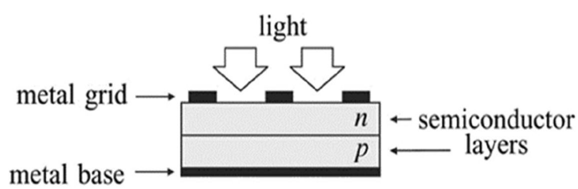

Fig. 7 Physical structure of PV cell (Villalva & Gazoli, 2009a)

noticed that their efficiencies are 16.1% and 13.4% (Adriano & Izete, 2012).

The NiO/TiO_2 P–N hetero-junction solar cell (Kingsley et al., 2018) is fabricated and validated and the sketch is provided in Fig. 6. Using the modeling tool, the NiO material voltage and performance was analyzed. Based on the initial conditions of temperature of 350 °C, illumination of 1000 W/m^2 and achieved output voltage of $V_{OC} = 0.1445$ V, $J_{SC} = 247.959195E^{-6}$ mA/cm^2, and FF = 37.87%. This analysis has been given the design of thin film based NiO solar cells.

Models related to solar PV cell

The different models for the analysis of PV cells are identified; mainly those will give electrical behaviors of PV cell (physical) (Almonacid et al., 2009, 2010; Balzani & Reatti, 2005; Fathabadi, 2013; Piliougine et al., 2015). Using artificial neural networks also the solar cell behavior is modeled (Chegaar et al., 2001; Dash et al., 2015; Kajihara & Harakawa, 2005; Vergura, 2015).

Ideal PV cell model

Usually, two different types of semi-conducting materials, the solar cell are designed and the junctions of P–N are influenced by solar radiation (Chin et al., 2015), which is shown in Fig. 7.

The Shockley (Chin et al., 2015) equation of the solar PV cell with P–N junction diodes and its I–V curve, Eq. (1) is used:

$$I_D = I_S\left[\exp\left(\frac{qV_D}{\alpha KT}\right) - 1\right]. \quad (1)$$

In Eq. (1), the terms simplified as; Boltzman constant is K, saturation current is I_S, current of the diode is I_D, voltage of diode is V_D, charge in of the electron is q, and Kelvin is the temperature units.

The ideal solar cell is indicated in Fig. 8. The P–N junction in the solar cell attracts light photons and produce electron hole pair. This electron hole pair creates potential difference between the junctions and produces an electric circuit that means photocurrent (I_{PV}) (Chin et al., 2015). The current verses voltage curves are shown in Fig. 9. In the figure, the current (I) is superposition of I_{PV} and I_D, but these values can be given by the cell manufacturer. Equation (2) shows the generated I_{PV}

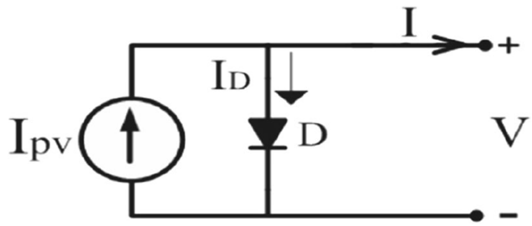

Fig. 8 Ideal model of solar cell

(photocurrent) and it is very sensitive in the environmental conditions:

$$I_{PV}(T,G) = I_{PV,STC} + K_I(T - T_{STC})\left(\frac{G}{G_{STC}}\right). \quad (2)$$

The terms in Eq. (2) are: STC is the standard test condition; that means at a temperature of 25 °C, the photocurrent at STC is I_{PV}, T_{SCT} is the temperature at STC, G_{STC} is the solar radiation is 1000 W/m^2, and K_I is the photocurrent temperature coefficient.

The diode current is neglected because of photovoltaic current and short circuit current are nearly equal (approximately). The term I_{SC} is short circuit current. The ideal PV cell model, Eq. (3), is presented below:

$$I = I_{PV} - I_S\left[\exp\left(\frac{q}{\alpha KT}\right) - 1\right]. \quad (3)$$

The open circuit voltage (V_{OC}), the maximum voltage (V) and current (I) are related to the solar radiation and temperature (Rajasekar et al., 2013; Soon & Low, 2012) are provided below:

$$V_{OC}(T,G) = V_{OC,STC} + K_V(T - T_{STC}) + V_t \ln\left(\frac{G}{G_{STC}}\right), \quad (4)$$

$$V_{mp}(T,G) = V_{mp,STC} + K_V(T - T_{STC}) + V_t \ln\left(\frac{G}{G_{STC}}\right), \quad (5)$$

$$I_{mp}(T,G) = I_{mp,STC} + K_I(T - T_{STC})\left(\frac{G}{G_{STC}}\right). \quad (6)$$

The terms are, temperature coefficient of voltage (K_V) and temperature coefficient of current (K_I), maximum power voltage $\left(V_{mp}\right)$, maximum current power $\left(I_{mp}\right)$ and thermal voltage is (V_t). The relation between all the terms in Eq. (3) is presented in Fig. 10.

Resistance R_S model single-diode based

Actually, the single diode ideal model is not used to simulate the PV cell, but this is used to understand the concepts of PV cell (Ciulla et al., 2014; Lim et al., 2015). The single diode-based resistance model is commonly used and reliable model for solar PV cell based on the resistance of silicon, electrode surfaces and resistance.

The schematic diagram of single diode resistance model is shown in Fig. 11. It contains, I_{PV}, α, q, I_S and R_S terms, and the I–V behavior is presented in Eq. (7). The single diode resistance model is improved model when compared with ideal PV cell model:

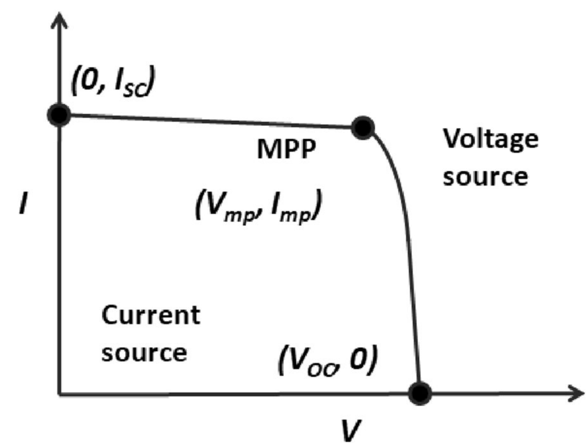

Fig. 10 *I–V* patterns of PV cell (Chin et al., 2015) for V_{oc}, I_{sc}, V_{mp} and I_{mp}

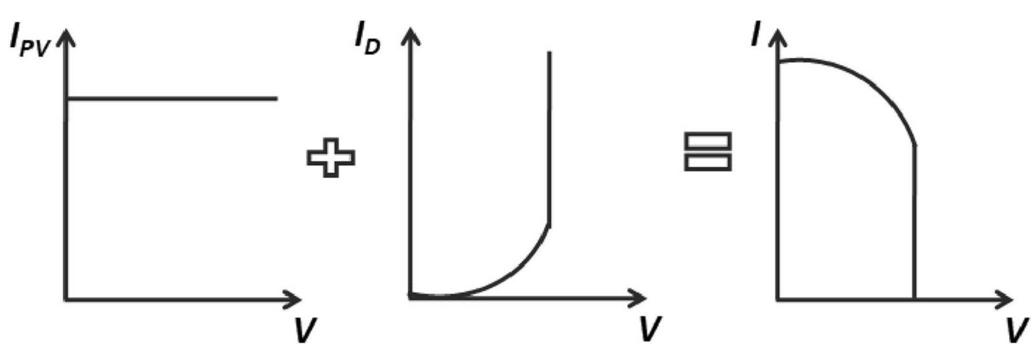

Fig. 9 *I* as superposition of I_{PV} and I_D (Chin et al., 2015)

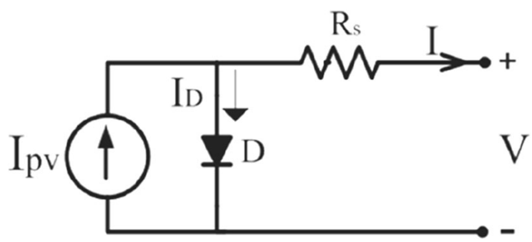

Fig. 11 Single diode R_S model

$$I = I_{PV} - I_S\left[\exp\left(\frac{q(V+R_SI)}{\alpha KT}\right) - 1\right]. \tag{7}$$

Single diode R_P model

The single diode R_P model layout diagram is noticed in Fig. 12 and it contains the parameters of I_{PV}, α, q, I_S, R_S and R_P and the I–V behavior is shown in Eq. (8). By considering the leakage current of P–N junction, the shunt resistance (R_P) is applied to the single diode PV (photovoltaic) model:

$$I = I_{PV} - I_S\left[\exp\left(\frac{q(V+R_SI)}{\alpha KT}\right) - 1\right] - \frac{V+R_SI}{R_P}. \tag{8}$$

The parameter characteristics of the solar PV cell are mostly related to the ambient conditions. The photocurrent is related to the ambient conditions which can be analyzed by Eqs. (2) and (4) is also related to the other PV cell parameters:

$$I_S(T,G) = I_{S,STC}\left(\frac{T}{T_{STC}}\right)^3 \exp\left(\frac{E_g}{K}\left(\frac{1}{T_{STC}} - \frac{1}{T}\right)\right), \tag{9}$$

$$R_S(T,G) = R_{S,STC}\left(\frac{T}{T_{STC}}\right)\left(1 - 0.217\ln\left(\frac{G}{G_{STC}}\right)\right), \tag{10}$$

$$R_P(G) = R_{P,STC}\left(\frac{G}{G_{STC}}\right), \tag{11}$$

$$\alpha(T) = \alpha_{STC}\left(\frac{T}{T_{STC}}\right). \tag{12}$$

The terms are: energy bandgap of material (E_g), diode's ideal factor is α_{STC}, series and shut resistance is $R_{S,STC}$ and $R_{P,STC}$, and diode's saturation current is $I_{S,STC}$.

Two diode model

The two-diode model schematic representation is provided in Fig. 13 and this model gives the appropriate results at low solar radiation. Considering the loss in current the second diode ($D2$) is applied to the PV solar cell model. It contains the terms of I_{PV}, R_S, R_P, a, I_S (first diode), a, and I_S (second diode) and the I–V behavior is presented in Eq. (13) (Chowdhury et al., 2007; Gow & Manning, 1996; Gupta et al., 2012):

$$\begin{aligned} I =& I_{PV} - I_{S1}\left[\exp\left(\frac{q(V+R_SI)}{\alpha 1KT}\right) - 1\right] \\ &- I_{S2}\left[\exp\left(\frac{q(V+R_SI)}{\alpha 2KT}\right) - 1\right] - \frac{V+R_SI}{R_P}. \end{aligned} \tag{13}$$

PV cell thermal and other models

The other models such as: (i) single-diode model with capacitance (Suskis & Galkin, 2013), (ii) three-diode model (Nishioka et al., 2007), (iii) modified two-diode models (Kurobe & Matsunami, 2005; Mazhari, 2006), (iv) drift–diffusion model (Lumb et al., 2013) and (v) multi dimension-diode model (Soon et al., 2014) can be used to analyze the solar PV cell.

Parameters estimation of PV cells

Various models are available to evaluate the performance of solar PV cell and those are divided into three types, the first type gives the information about the I–V pattern, the secondary is the conversion PV cell model and identifying the optimized condition and the third is hybrids of Metaheuristics and analytical approaches.

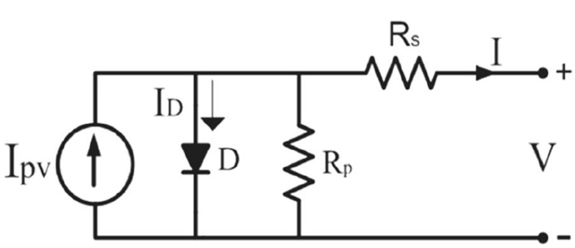

Fig. 12 Single diode R_P model

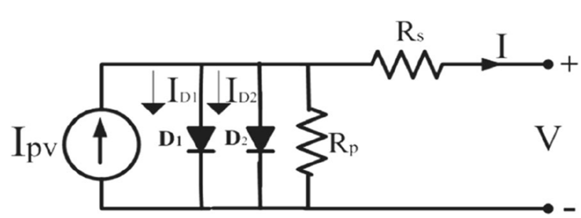

Fig. 13 Two diode PV cell model

Table 1 Comparison of the parameter outcomes that the CS algorithm provided with those of other SDM algorithms

	CS	CPSO (Burden & Faires, 2010)	GA (Huang et al., 2011)	PS (Joseph et al., 2001)
I_{PV}	0.7607	0.761	0.7612	0.7615
I_O	3.25E−07	4.10E−07	8.19E−07	9.88E−07
n	1.4814	1.5103	1.581	1.621
R_S	0.0365	0.0356	0.0289	0.0314
R_P	53.618	59.112	42.368	61.16
RMSE	0.0011	0.00141	0.0192	0.0145

Radiation level evaluation

The identified data of solar PV cell were located in R.T.C France (Ogliari et al., 2013) and the values are provided in Table 1. The values of various parameters are obtained based on the CS algorithm (AlHajri et al., 2012) and compared with various approaches of CPSO (Easwarakhanthan et al., 1986), GA (Huang et al., 2011), and PS (Joseph et al., 2001). The other algorithms of MATLAB (Yang 2023), PSO model (http://www.mathworks.com/products/optimization/index.html) and N–R (Newton–Raphson) method (Birge 2006) are implemented to evaluate the solar cell parameters.

Ambient conditions evaluation

The CS algorithm is used on KC200GT PV module at various environmental conditions. Table 2 shows the SDM and ISDM parameters. The purpose of identifying those parameters is to evaluate the I–V characteristics for design purposes. The SDM parameters identification is important to understand the measured experimental at test condition. From the analysis of PSIM (Al Hajri et al., 2012), the solar PV dimensions of the SDM are evaluated. The experiment is conducted at 1000 W/m^2, 800 W/m^2, 600 W/m^2, 400 W/m^2, and 200 W/m^2 and three different temperature levels (25 °C, 50 °C, and 75 °C) and the I–V curves are drawn and the ISDM data are fitted (Powersim, 2001).

Parameter estimation of PV cell methods

The analytical methods have been used in large number of researches works to extract model parameters of solar cells. Research works are categorized based on the used solar cell model and its analysis is explained in this section.

Single diode R_S model

It is clearly mentioned that, the single diode R_s model has four parameters, i.e., I_{PV}, q, α, I_S, and R_S. For extracting the values of these four parameters, four equations are required (Ma et al., 2013; Ulapane et al., 2011). Typically, PV manufacturers publicize the values of V_{OC}, I_{SC}, V_{mp}, I_{mp}, KI, and KV in their data sheets. The important equations provided in the following two ways i.e., using Eqs. (19)–(21), and Eq. (25), or using Eqs. (19)–(21), and Eq. (26), respectively:

$$O = I_{PV} - I_S\left[\exp\left(\frac{q(V_{oc})}{\alpha KT}\right) - 1\right], \tag{14}$$

$$I_{PV} = I_S\left[\exp\left(\frac{q(V_{oc})}{\alpha KT}\right) - 1\right]. \tag{15}$$

Based on Eq. (7), at short circuit point

$$I_{SC} = I_{PV} - I_S\left[\exp\left(\frac{qR_SI_{SC}}{\alpha KT}\right) - 1\right], \tag{16}$$

$$I_{PV} = I_{SC} + I_S\left[\exp\left(\frac{qR_SI_{SC}}{\alpha KT}\right) - 1\right]. \tag{17}$$

From Eqs. (15) and (17), we have

$$I_S\left[\exp\left(\frac{q(V_{oc})}{\alpha KT}\right) - 1\right] = I_{SC} + \left[\exp\left(\frac{qR_SI_{SC}}{\alpha KT}\right) - 1\right]. \tag{18}$$

Table 2 Values of KC200GT PV module noticed from CS algorithm (Al Hajri et al., 2012)

(a) SDM parameters (extracted by the CS algorithm)						
I_{PV}	I_O	n	R_S	R_P		
8.1715	4.24E−10	1.0089	0.2655	140.58		
(b) Based on the CS code the obtained ISDM parameters						
I_{PVM}	I_{ON}	n	R_{SN}	R_{PM}	K_i	Egn
8.184	5.12E−10	1.010	0.257	117.92	0.002	1.247

The saturation currents as a model can be computed by

$$I_S = \frac{I_{SC}}{\exp\left(\frac{q(V_{oc})}{\alpha KT}\right) - \exp\left(\frac{qR_S I_{SC}}{\alpha KT}\right)}. \tag{19}$$

By plunging Eq. (19) into Eq. (17), photocurrent can be computed by

$$I_{PV} = I_{SC} + \left[1 + \frac{I_{SC}\exp\left(\frac{qR_S I_{SC}}{\alpha KT}\right) - 1}{\exp\left(\frac{qV_{oc}}{\alpha KT}\right) - \exp\left(\frac{qR_S I_{SC}}{\alpha KT}\right)}\right], \tag{20}$$

$$I_{mp} = I_{PV} - I_S\left[\exp\left(\frac{q(V_{mp} + R_S I_{mp})}{\alpha KT}\right) - 1\right], \tag{21}$$

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = V\frac{dI}{dV} + I = 0, \tag{22}$$

$$\frac{dI}{dV} = \frac{-I_{mp}}{V_{mp}}. \tag{23}$$

After differentiating the current (I) with effect to voltage (V) in Eq. (7), we will get

$$\frac{dI}{dV} = \frac{\left[\frac{qI_S}{\alpha KT} \times \exp\left(\frac{q(V+R_S I)}{\alpha KT}\right)\right]}{\left[\frac{qR_S}{\alpha KT} \times \exp\left(\frac{q(V+R_S I)}{\alpha KT} - 1\right)\right]}. \tag{24}$$

From Eqs. (23) and (24), we extract, Eq. (25):

$$\frac{\left[\frac{qI_S}{\alpha KT} \times \exp\left(\frac{q(V_{mp}+R_S I_{mp})}{\alpha KT}\right)\right]}{\left[\frac{qR_S}{\alpha KT} \times \exp\left(\frac{q(V_{mp}+R_S I_{mp})}{\alpha KT} - 1\right)\right]} = \frac{-I_{mp}}{V_{mp}}. \tag{25}$$

It is possible to obtain another equation from the slope of the I–V curve at a short circuit location:

$$\frac{\left[\frac{qI_S}{\alpha KT} \times \exp\left(\frac{q(R_S I_{SC})}{\alpha KT}\right)\right]}{\left[\frac{qR_S}{\alpha KT} \times \exp\left(\frac{q(R_S I_{SC})}{\alpha KT} - 1\right)\right]} = \frac{-1}{R_{SO}}. \tag{26}$$

Required four associated terms in single diode, R_S model is provided in Table 3.

Single diode R_P model

The single diode R_P model has five parameters; I_{PV}, a, I_s, and R_s (Bellini et al., 2009). The extraction of model parameters is done using five of the following equations. In some instances, the Ideality Factor (IF) of the diode in the range [1, 2.5] is selected at random:

$$0 = I_{PV} - I_S\left[\exp\left(\frac{q(V_{oc})}{\alpha KT}\right) - 1\right] - \frac{V_{OC}}{R_P}. \tag{27}$$

Therefore, we can write

$$I_{PV} = I_S\left[\exp\left(\frac{q(V_{oc})}{\alpha KT}\right) - 1\right] + \frac{V_{OC}}{R_P}. \tag{28}$$

From Eq. (8), the short circuit point we get is

$$I_{SC} = I_{PV} - I_S\left[\exp\left(\frac{q(R_S I_{SC})}{\alpha KT}\right) - 1\right] - \frac{R_S I_{SC}}{R_P}. \tag{29}$$

Therefore, we can have

$$I_{PV} = I_{SC} + I_S\left[\exp\left(\frac{q(R_S I_{SC})}{\alpha KT}\right) - 1\right] + \frac{R_S I_{SC}}{R_P}. \tag{30}$$

By equating (28) and (30), we can have

$$\begin{aligned} I_S\left[\exp\left(\frac{q(V_{oc})}{\alpha KT}\right) - 1\right] + \frac{V_{OC}}{R_P} &= I_{SC} \\ + I_S\left[\exp\left(\frac{q(R_S I_{SC})}{\alpha KT}\right) - 1\right] &+ \frac{R_S I_{SC}}{R_P}. \end{aligned} \tag{31}$$

Therefore, we have

$$I_S = \frac{\left[I_{SC} + \frac{R_S I_{SC}}{R_P} - \frac{V_{OC}}{R_P}\right]}{\left[\exp\left(\frac{q(V_{oc})}{\alpha KT}\right) - \exp\left(\frac{q(R_S I_{SC})}{\alpha KT}\right)\right]}. \tag{32}$$

Then, inserting Eq. (32) in Eq. (28), we have

Table 3 Paths to extract the equations in single diode R_S models

References	Equations (SC: short circuit, OC: open circuit)
Yang (2023), Birge (2006)	In (Wang et al., 2017), the ideality factor of the diode, the slope of the *I–V* curve at the OC point, and the SC point are all picked at random
Huang et. al. (2011)	Maximum power point, SC point, OC point, and maximum power point's power derivative with respect to voltage are all set to zero
Burden and Faires (2010)	The derivative of power with respect to voltage at maximum power point is 0 at the SC point, OC point, and maximum power point
Huang et. al. (2011)	Maximum power point, SC point, OC point, and the derivative of power with respect to voltage there are all set to zero

$$I_{PV} = \frac{\left(I_{SC} + \frac{R_S I_{SC}}{R_P} - \frac{V_{OC}}{R_P}\right)\left[\exp\left(\frac{q(V_{oc})}{\alpha KT}\right) - 1\right]}{\exp\left(\frac{q(V_{oc})}{\alpha KT}\right) - \exp\left(\frac{q(R_S I_{SC})}{\alpha KT}\right)} - \frac{V_{OC}}{R_P}. \tag{33}$$

Based on Eq. (8), I_{mp} is given as

$$I_{mp} = I_{PV} - I_S\left[\exp\left(\frac{q\left(V_{mp} + R_S I_{mp}\right)}{\alpha KT}\right) - 1\right] - \frac{V_{mp} + R_S I_{mp}}{R_P}. \tag{34}$$

After differentiating I with V in Eq. (8), we get

$$\frac{dI}{dV} = \frac{-\left[\frac{qI_S}{\alpha KT} \times \exp\left(\frac{q(V+R_S I)}{\alpha KT}\right) + \frac{1}{R_P}\right]}{\left[\frac{R_S I_S}{\alpha KT} \times \exp\left(\frac{q(V+R_S I)}{\alpha KT}\right) + \frac{R_S}{R_P} + 1\right]}. \tag{35}$$

Using Eq. (23), at the maximum power point, we get

$$\frac{-\left[\frac{qI_S}{\alpha KT} \times \exp\left(\frac{q(V+R_S I)}{\alpha KT}\right) + \frac{1}{R_P}\right]}{\left[\frac{R_S I_S}{\alpha KT} \times \exp\left(\frac{q(V+R_S I)}{\alpha KT}\right) + \frac{R_S}{R_P} + 1\right]} = \frac{-I_{mp}}{V_{mp}}. \tag{36}$$

By using R_{so} (Short circuit point) in the slope of I–V curve, we can derive another equation:

$$\frac{-\left[\frac{qI_S}{\alpha KT} \times \exp\left(\frac{q(V+R_S I)}{\alpha KT}\right) + \frac{1}{R_P}\right]}{\left[\frac{R_S I_S}{\alpha KT} \times \exp\left(\frac{q(V+R_S I)}{\alpha KT}\right) + \frac{R_S}{R_P} + 1\right]} = \frac{-1}{R_{S0}}. \tag{37}$$

Similar to this, another equation can be derived using the slope of the I–V curve at the open circuit point (RPLO):

$$\frac{-\left[\frac{qI_S}{\alpha KT} \times \exp\left(\frac{q(V+R_S I)}{\alpha KT}\right) + \frac{1}{R_P}\right]}{\left[\frac{R_S I_S}{\alpha KT} \times \exp\left(\frac{q(V+R_S I)}{\alpha KT}\right) + \frac{R_S}{R_P} + 1\right]} = \frac{-1}{R_{P0}}. \tag{38}$$

In some cases, R_P and R_{PO} have been assumed equal (Chouder et al., 2012; Orioli & Gangi, 2013).

Table 4 References are used for single diode R_p models in preparation of useful equations

Ref.	Equations
Arab et. al. (2004)	V_{oc}, I_{sc}, $dP/dV=0$, R_{po}, R_{so}
Bai et. al. (2014)	V_{oc}, I_{sc}, V_{mp}, I_{mp}, R_{po}, R_{so}
Mares et. al. (2015)	V_{oc}, I_{sc}, V_{mp}, I_{mp}, R_{so}, R_{po}
Arab et. al. (2004)	V_{oc}, I_{sc}, V_{mp}, I_{mp}, R_{so}, R_{po}
De Blas et. al. (2002)	V_{oc}, I_{sc}, V_{mp}, I_{mp}, R_{so}, R_{po}
Brano et. al. (2010)	V_{oc}, I_{sc}, V_{mp}, I_{mp}, R_{so}, R_{po}
Orioli and Gangi (2013)	V_{oc}, I_{sc}, V_{mp}, I_{mp}, R_{po}, $dP/dV=0$
Sera et. al. (2007)	V_{oc}, I_{sc}, V_{mp}, I_{mp}, R_{so}, R_{po}
Chouder et. al. (2012)	V_{oc}, I_{sc}, V_{mp}, I_{mp}, R_{so}
Adamo et. al. (2009)	V_{oc}, I_{sc}, V_{mp}, I_{mp}, $dP/dV=0$, a is set as 1

The five necessary equations are extracted from Table 4 using data, and the reference equations in single diode R_P models are described (Arab et al., 2004; Bai et al., 2014) requires the slope of the I–V curve at the short circuit (SC) and open circuit (OC) points in terms of the availability of the necessary data.

Two-diode model

I_{pv}, R_S, R_P, a and I_s of the first diode, and a and I_s of the second diode are the first two of the two diode model's seven parameters. These seven parameters must be identified using seven equations. Three equations are generated by applying the I–V characteristic of Eq. (13), at short circuit point, open circuit point, and maximum power point, from the slope of the I–V curve at short circuit point and open circuit point. The sixth equation can be obtained by setting the derivative of power with respect to voltage at maximum power point to zero. Ultimately, the seventh equation can be obtained by setting the sum of the ideality factors of two diodes to 3 (Belhaouas et al., 2013; Elbaset et al., 2014; Villalva & Gazoli, 2009b).

Efficiency of solar PV cells

A DC is produced when a solar cell is exposed to light; it is a p–n junction semiconductor. Numerous benefits are provided by photovoltaics, including great dependability, cheap maintenance costs, little environmental contamination, and no noise (Ishaque et al., 2011). Due to the massive use of fossil fuels, there is a huge interest in using renewable energy sources, including solar energy. In the past 10 years, photovoltaic power has grown rapidly, making it an established technology (Patel et al., 2008).

Factors effect on the efficiency of the PV cell

Environmental factors

The PV modules must be exposed to the environment in full sunshine. Therefore, environmental parameters including irradiance, temperature, dust distribution, soiling, wind, shade, humidity, etc. have a significant impact on the performance and efficiency of the PV module. The effects of these elements are discussed in the following sections.

Solar irradiance

The quantity of energy that enters a specific horizontal region at a given wavelength and time is known as irradiance (Santbergen et al., 2017). Solar power or solar irradiance has a significant impact on the output of the PV panel due to the great unpredictability of the solar resource (Mondol et al., 2007). At the sub-second level, the amount of variability is affected by time resolution, and it rises with increasing time resolution (Bright et al.,

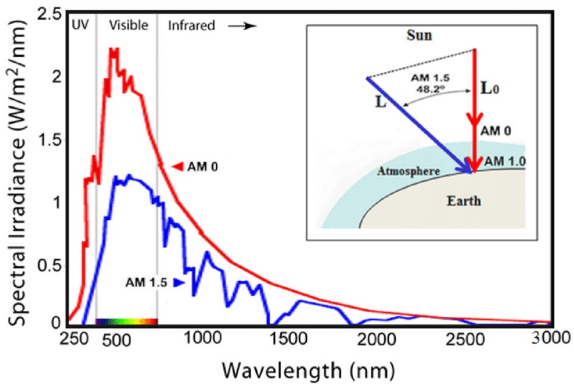

Fig. 14 Variation of spectral irradiation values (Wang et al., 2020)

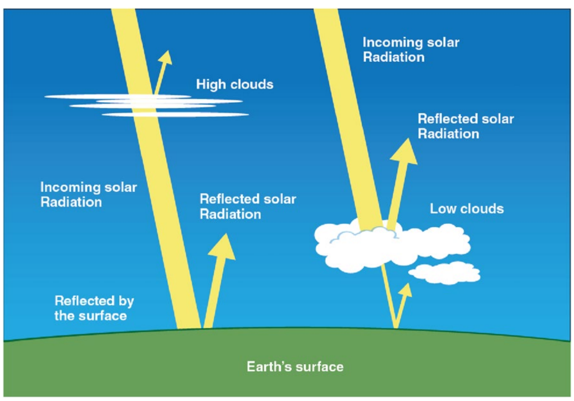

Fig. 15 Incoming solar radiation (Santbergen et al., 2017)

2017). Irradiance is impacted differently by the following factors: weather, seasonal variations, place, time of day, and solar position in the sky (Prema & Uma, 2015). According to changes in its height, the sun's position changes throughout the day (Fouad et al., 2017). Figure 14 shows that the main cause of the fluctuating irradiance values is cloudy situations (Wang et al., 2020).

The PV modules get both direct-sunlight from the sun and dispersed light from the sky, ground, and nearby objects (Santbergen et al., 2017) (Fig. 15). Direct sun exposure does, however, play a significant role (Fouad et al., 2017). It is more challenging to calculate the incident irradiance when nearby objects cast shadows or reflect sunlight onto the PV modules. The solar panel would need to be oriented and towards the sun to receive the most solar irradiance. The optimal tilt angle is determined by the location's latitude angle. The tilt angle deviates from the latitude angle in the summer and by around 15° in the winter (Viitanen, 2015).

Several solar tracking techniques are used to align PV panels with the direct component of solar irradiance. A one-degree azimuth deviation from the south causes an irradiation loss of 0.08% (Chanchangi et al., 2020). The output of the PV module increases as the irradiation does (Zogou, 2011). The PV module can utilize the G–P (sun radiation–output maximum power) curve to calculate irradiance, because it is essentially linear (Salim et al., 2013). The literature states that it is impossible to calculate the impact of solar irradiance on the performance of the PV panel by a precise percentage, because there is a linear relationship between the module current and the irradiance value (Fouad et al., 2017).

Temperature on photovoltaic cell performance

The quantity of power generated by photovoltaic cells will be impacted by the variation in solar cell efficiency that occurs with temperature changes (PV modules). The temperature has a big impact on the voltage. Temperature and voltage are inversely related. The output of a PV

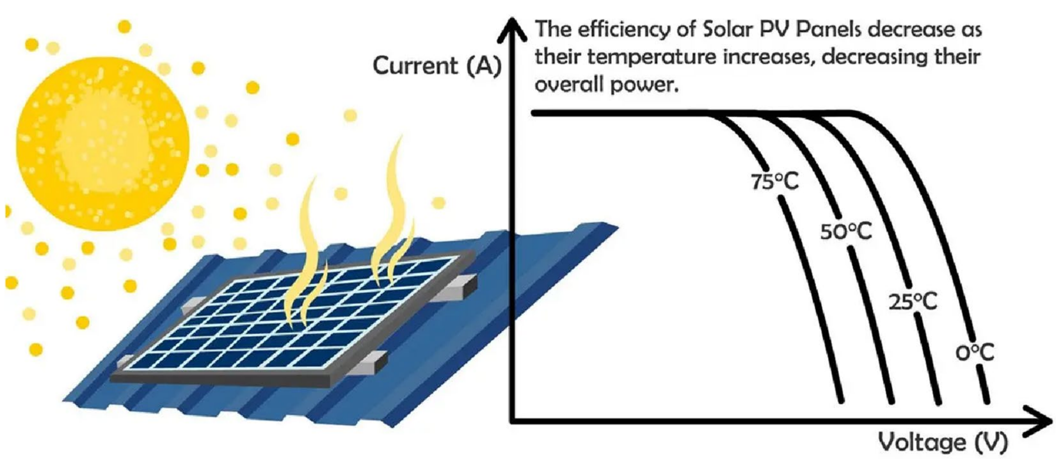

Fig. 16 Effect of panel temperature (Fesharaki et al., 2011)

power system is influenced by a variety of environmental factors. Module temperature is a factor that significantly affects how a PV system behaves, because it modifies system efficiency and energy output as well as atmospheric parameters (such as ambient temperature, irradiance level, dirt, and dust), as well as specific installation conditions such as rooftop, on floor, or on water bodies (Fesharaki et al., 2011) (Fig. 16).

The efficiency of a single crystal silicon solar cell is significantly influenced by its operating temperature. At an operating temperature of 56 °C and a 1000 W/m^2 radiation level, the solar cell's efficiency decreases by 3.13% (Rahman et al., 2015). Nižetić et. al. (2016) research shows that panel efficiency is reduced by 69% at 64 °C and, additionally, efficiency decreases to 5% when the module temperature increases from 43 to 47 °C, illustrating the effect of wind speed on the rate of temperature rise.

In the absence of cooling, every 1 °C increase in solar cell temperature causes a 0.03–0.05% drop in electrical efficiency (Odeh & Behnia, 2009). The thermal dissipation and absorption properties of the encapsulating or covering materials have an impact on the PV performance (Said et al., 2018).

Dust accumulation

The effectiveness of the PV modules is decreased when debris, water vapor, air molecules, and other pollutants in the atmosphere prevent sunlight from penetrating the PV panel. Sunlight can be refracted by airborne dust particles bigger than the wavelength of the sun's incoming beam, lowering solar irradiance (Mani & Pillai, 2010) (Fig. 17). On the surface of the PV module, a thick layer of dust may also accumulate. A dust layer's optical characteristics can be changed to improve light reflection, absorption, and reduce surface transmissibility, which in turn boosts the output of PV modules (Said et al., 2018). Dust accumulation is influenced by environmental factors such as wind speed, humidity, rainfall, dust source, particle type, PV module technology, and PV module surface coverage.

Fig. 17 Dust accumulation on the PV cell (Mani & Pillai, 2010)

It gets worse in desert areas, where there is a lot of dust and little rain. The typical rate of efficiency decline, according to research done in Saudi Arabia, is 6–7% every month (Said, 1990; Said & Walwil, 2014) and might increase to 13% in 6 weeks without cleaning (Said et al., 2015). The output power generation could even decrease to 50% of its maximal level in the absence of cleaning (Adinoyi and Said 2013). Elminir et. al. (2006) estimate that Egypt's output power is decreasing by about 17.4% each month. The problem is made worse by air pollutants, toxic gases, suspended particles, and dust that lower PV energy output by more than 60% (Asl-Soleimani et al., 2001). Dust gathers on module covers as a result of gravity (Mastekbayeva & Kumar, 2000).

When exposed to humid air conditions, these particles transform into adhesive and sticky mud at the surfaces (Yilbas et al., 2016a). Dust collection for 45 days reduces the overall glass cover transmittance by 20%, according to Said et. al. (2015). The impact of rain on dust deposition is clear. When Egypt receives 18 to 50 mm of precipitation per year, PV power generation drops to 60–70%. Studies (Mohandes et al., 2009) and (Touati et al., 2013) conducted in the UAE and Qatar, which receive 80–90 mm and 70–75 mm of precipitation per year, respectively, have revealed a lower (10%) reduction in PV power generation than Egypt.

Soiling

Furthermore, a dust accumulation could render the PV module unclean. In humid environments, dust particles drop on PV surfaces and gather up water from the surrounding atmosphere to generate mud (Yilbas et al., 2017). The air humidity has a substantial impact on the force of adhesion between dust particles and PV surfaces (Jing et al., 2009) which results the dust accumulation grows as absolute humidity rises. In addition, the vapor condensation in the solar PV module forms capillary bridges between the particles and the surface. Large meniscus forces are generated, improving particle and surface adhesion and promoting dust formation (Barkhouse et al., 2012; Ghazi et al., 2013).

Soiling shades the PV panel on both its soft and hard sides, reducing its power production. Smog in the atmosphere causes soft shading, but soil mass or muck on the panel causes hard shading. Solar irradiance still reaches the cells that are not hard shaded, therefore, even though severe shadowing on some PV module cells lowers module voltage, the current is unaffected. PV power loss from soiling varies geographically similar to dust deposition, because different forms of dust have varied effects on light transmission.

In some cases, the amount of soiling and PV power loss has a linear connection (Maghami et al., 2016; Verma et al., 2011). Since the surface is already quite dusty, new dust particles that may accumulate on older ones due to an increase in soil mass do not further obstruct light. Studies show that after 40 days of exposure, coated glass transmittance falls by 30% and uncoated glass by 37% in Saudi Arabia. 55 According to measurements made in Belgium with a 35° tilt angle and typical rainfall intervals, transmission loss varies based on the type of glass used, such as multilayer (ML) (0.85%), self-cleaning (SC) (1.30%), anti-reflection (AR) (1.75%), and standard glass (2.63%).

It reveals that panels with a flatter orientation or a smaller tilt angle are more vulnerable to the effects of soiling (Shaju & Chacko 2018). The amount of dust that accumulates at the panel's surface is decreased and transmittance is increased by increasing the hydrophobicity. The surface energy and roughness are changed to achieve this (Yilbas et al., 2016b). Rainfall can naturally fix the soiling problem, while fluids or water can also mechanically fix it.

Wind velocity

The amount of electricity a photovoltaic module produces depends on the wind's characteristics, including wind speed and direction. A number of variables, including module temperature, surface structure, and dust deposition, are used to characterize how wind affects PV performance. Utilizing convective heat transfer by natural wind movement as much as feasible is the most economical cooling approach (Vasel & Iakovidis, 2017) (Fig. 18). PV cell temperature increases are far more influenced by wind speed than wind direction (Griffith et al., 1981). Convection cooling of PV panels is clearly impacted by surface form and structure. Glass cover surfaces with structure and grooves may function in colder climates with higher wind speeds.

However, for the flat surface at low wind speed, the cooling impact is significantly greater (Duell et al., 2010). According to studies conducted in the USA, a glass cover with grooves can lower the operating temperature by 3.5 °C for winds of 10 m/s. In addition, the temperature in Slovenia can be reduced to half of its operating temperature with a wind speed of 12 m/s and by up to 10 °C in the KSA. 88 In addition, the wind clears the PV module's surface of dust particles and lowers dust deposition (Assi & Chaar, 2008). For instance, a study conducted in Egypt demonstrates that, at a specific tilt angle, blowing wind causes a reduction in dust deposition from the module. The desert region, where wind itself transports a substantial amount of dust and sand particles, is adversely affected (Mekhilef et al., 2012). Due to the movement of the air wind in Libya, dust builds up over the PV surface quickly and at a high rate (O'Hara et al., 2006).

Shading

The blockage in the direction of light that hits the PV panel is known as shading. The PV power output was reduced by the shadowing effect. There are many different types of shading, including self-shading, hard shading, and soft shading. Hard shading develops as a result of the buildup of debris, such as leaves, bird droppings, snow, and dust. In addition, a distinct and definite shape of sunlight is also blocked by poles, trees, and buildings. PV module output is greatly reduced by partial or total shade, which depends on module position, array configuration, and shading scenario. A PV module's output is substantially impacted by partial shading, since the shaded cells are unable to produce any current.

As a result, the current generated in cells that are not shaded flows into cells that are shaded, causing the latter to operate in a zone of negative voltage and lose energy rather than produce it. In addition, the maximum power point tracker (MPPT) in shaded areas may change from

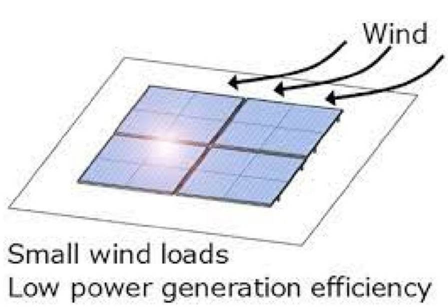

Fig. 18 Wind velocity on the solar PV cell (Vasel & Iakovidis, 2017)

Fig. 19 Shading on the solar PV cell (Lavado Villa et al., 2013)

the global maximum power point (MPP), resulting in less energy being produced. To lessen the losses brought on by full or partial shading numerous researchers have studied the losses and created technical solutions (Ahmad et al., 2017; Lavado Villa et al., 2013) (Fig. 19).

Humidity

The accumulation of minute water droplets and water vapor on solar panels from the atmosphere is influenced by the relative humidity, which is one of the factors. Sunlight that has been refracted, reflected, or diffracted away from solar cells by water droplets is less likely to directly hit those cells and generate electricity. 90 Because smaller water vapor particles have larger scattering angles, the radiation intensity also varies nonlinearly with humidity (Gwandu & Creasey, 1995). Due to moisture intrusion into the solar cell, prolonged exposure to a humid environment corrodes PV modules. In addition, the preservation of moisture in the module housing raises the material's electrical conductivity and leakage currents (Ndiaye et al., 2013) (Fig. 20).

In addition, increasing corrosion rates caused by water condensation at the interface between the components of the encapsulant and the solar cell materials raise the possibility of encapsulant delamination (Ndiaye et al., 2013). A suitable hermetic seal or an encapsulant loaded with desiccant with a very low diffusivity can be used to prevent performance degradation in the module (Kempe, 2006). Furthermore, the high relative humidity (RH) causes sticky and adhesive dust layers to accumulate on PV surfaces (Sala et al., 2009), which could lead to soiling and a reduced power output. As the relative humidity drops from 60 to 48%, the efficiency of solar cells rises from 9.7 to 12.04%. A 20% increase in relative humidity results in a 3.16 W reduction in power production.

According to another study, PV power output falls by 40% during the rainy season at a relative humidity of 76.3% and by 45% during the overcast season at a relative humidity of 60.5% (Gupta et al., 2019). Although the loss of irradiance caused by moisture is a natural one, dust adhesion loss on the surface of the module can be regained with the use of the right cleaning techniques (Ndiaye et al., 2013).

Operation and maintenance factors

Over time, the photovoltaic module deteriorates. However, some operational and maintenance aspects might lessen PV module deterioration and increase their economic viability. Some of these factors are covered in the section that follows.

Panel degradation

Panel degradation is the phrase used to describe the slow deterioration of a PV system's properties, which might affect how much power it can produce. A panel is considered deteriorated, according to manufacturer recommendations, when its power falls below 80% of its starting power (Munoz et al., 2011). PV panels deteriorate over time due to a variety of conditions, including temperature, humidity, radiation, and mechanical shock (Waqar Akram et al., 2020). Hotspot formation is also a problem, since cells may be damaged by high temperatures (Gosumbonggot & Fujita, 2019) (Fig. 21). Hotspot heating is caused by series-connected cells that are partially shadowed, damaged, or mismatched. Studies revealed certain hotspot mitigation techniques. Using hotspot detection, Jerada et. al. (2016) provided an accurate and

Fig. 20 Humidity on solar PV cell

Fig. 21 Solar PV panel degradation (Gosumbonggot & Fujita, 2019)

Fig. 22 Natural cleaning on solar PV cell

quick reaction. The undesirable power generating losses can be eliminated with proper management of all these problems.

Cleaning methods

Reduced glass transmittance and overall PV power generation are the results of dust accumulation and soiling. According to studies, its effectiveness can be increased with the right cleaning system and regular cleaning. When the PV module is exposed to desert conditions, the study also advised a cleaning frequency of about 20 days (Kazem & Chaichan, 2019). Particulate matter (PM) from the combustion of fossil fuels is one of the main contaminants that is deposited on the PV (Zorrilla-Casanova et al., 2011). Researchers looked into the damage effect, cleaning substance, and cleaning technique. However, the model pattern, PV capacity, and power generation should all be taken into consideration while designing the best and most suitable cleaning procedure.

Natural cleaning Figure 22 depicts the natural cleaning of a solar PV panel. In the natural PV cleaning method, rain and wind are primarily responsible for cleaning PV panels. Panels are typically tilted at an angle to allow rainwater falling on the panel's surface to wash away dust particles, facilitating the natural cleaning process. However, this process frequently leaves behind dust that has been moistly adhered to the panels, and it takes a lot of rain to wash it away. The effectiveness of such a method to wash off the deposited soil is questioned when there is excessive soiling and minimal rainfall.

According to reports, when the rain stops during dry seasons due to dust accumulation, daily PV performance reductions of more than 20% may occur (Paudyal & Shakya, 2016). Paudyal and Shakya (2016) investigated the impact of dust buildup on PV modules and Kathmandu's seasonal rains. Jiang et al. (2018) simulated the suspension of dust particles with sizes ranging from 0.1 to 100 mm and found that dust particles bigger than 1 m in diameter are easily dispersed by wind to assess the effects of using natural cleaning of PV module by air movement at a speed of 0.23–57.56 m/s.

Water cleaning This method requires a lot of water running continuously at a high pressure to wash away any soiling PM that has clung to the PV panel surface. Pressurized water can be used to cool down PV panels in semi-arid and desert regions, and it is occasionally mixed with a specific cleaning solution to wipe away dust particles. Figure 23 mentions water cleaning on solar PV cell (Moharram et al. 2013; Saha 2014). According to the findings of the experimental inquiry using water spraying, the surface temperature of the headboard was lowered by 45.5%, while the surface temperature of the back was reduced by 39%.

Over the course of the testing, the cleaned and cooled panel's efficiency was 11.7% as opposed to the non-cleaned and non-cooled panel's 9% (Elnozahy et al., 2015). The results of a study conducted in Egypt showed that using the natural water flow, the PV efficiency decreased by 50% after 45 days (Gürtürk et al., 2018).

Manual cleaning To avoid scratching the surface of the PV module, dust is removed manually using specialized brushes with bristles. In terms of returning the solar panel surface to its initial condition, it is far more effective than rain cleaning. To increase PV efficiency, Al Shehri et al. (2017) carried out an empirical study to determine the most efficient cleaning methods using silicone rubber, nylon, and cotton brushes. Pure water does not leave a residue on the PV surface, as demonstrated by Al Shehri et al. (2017). Therefore, pure water is superior to other chemically active substances such as detergent, network water, and liquid soap as a cleaning agent. Based on the results of the experiment, the authors suggested various cleaning instruments, including a glass razor, squeegee, chamois, velour, and sponge. Energy, exergy, and power

Fig. 23 Water cleaning on solar PV cell

Fig. 24 Mechanical cleaning on solar PV cell

conversion efficiency are all reduced by the squeegee by a maximum of 17.87%, 19.37%, and 19.62%, respectively.

Mechanical cleaning Cleaning with an automated and mechanical water system (Fig. 24) is more effective than cleaning with rain and air from the atmosphere. A robotic water spray cleans and cools the PV panel, increasing the PV module efficiency by 15%, claims a study (Mazumder et al., 2011). Mani and Pillai (2010) suggested cleaning the panel once per week during dry seasons and every day during periods of excessive dust accumulation. Their study uses automation for the cooling technique, with a microcontroller and sensors to manage the system. In this instance, it is a labor-saving technique for cleaning panel surfaces, even though it uses extra electricity to function.

Forced air-flow cleaning Assi et. al.'s (2012) method of cleaning dust from solar panels in the UAE climate involved forcing air from air-conditioning fans to flow directly on the panels. A model was developed by Alqatari et. al. (2015) to examine the effects of three dust removal techniques—EDS, highly hydrophobic nanocoating, and air-blowing mechanisms—on the performance of PV modules in six different Saudi Arabian locations.

Self-cleaning material The surface of a PV module can self-clean thanks to hydrophobic or hydrophilic properties that disperse or repel water. A clean surface is produced when a waterfall falls over a hydrophobic surface, because the water simply flows away and sweeps away any dirt that sticks to the top (Isbilir et al., 2018). The purpose of this method is to coat the PV surface with a hydrophobic coating and a thin barrier layer to stop water from clinging to it. It is also referred to as "active cleaning", since water moves over the surface and picks up the dirt as it does so. TiO_2 nanofilm is chemically combined with the PV surface to create a super hydrophilic surface. TiO_2 is often utilized in coatings on cover glass surfaces to create surfaces that can be cleaned by themselves.

Battery maintenance

In a solar PV system, batteries are used to store extra electrical energy produced by the PV cell and provide it when sunlight is not available. In addition, battery aids in supplying consistent electrical power in opposition to variable PV system output features. Lead-acid batteries are frequently utilized in stand-alone power systems, because they provide the best price/capacity ratio (Chumchal & Kurzweil, 2017). The optimal charging and discharging cycle of a battery depends on the water level in each cell. Consequently, watering the batteries frequently may be necessary to maintain a safe water level. However, both excessive and inadequate watering might shorten the battery life.

Batteries are also periodically discharged and recharged, and when charging, a portion of the water is used by the battery. The liquid levels in the cells must thus be monitored, and if necessary, water should be given to depleted cells in accordance with the manufacturer's instructions. According to Quansah et. al. (2017), when batteries are charged in conjunction with PV modules, the rate of PV deterioration is 1.3% per year and 0.8% per year. In a different study, Rajput et. al. (2016) discovered that when an outdated battery-charging technique is deployed alongside PV, it degrades at a rate of 1.9%/year. A battery bank should ideally have enough capacity to provide 5 days of autonomy under overcast conditions. Battery life will be shortened if the battery bank's capacity is less than 3 days, since it will frequently cycle profoundly. When used in a PV system, batteries need to be placed in a room with moderate temperatures and enough ventilation.

Performance analysis of PV module

In the above section, we discussed about the influence of various parameters to evaluate the performance of solar PV cell. To fully understand the performance of solar PV cell an experimental analysis was conducted. A 500 KWp solar power generating unit was installed in Center for Diagnostics and Finger Printing campus, Hyderabad, India. The solar panels were purchased from sunlight solar systems and each panel size is 2.25 m^2 area, made with polycrystalline silicon material. Based on the standard test conditions (STC), the efficiency of the solar module is 17.52% and the capacity of 315–340 W range. To generate 500 KWp, the solar panels used are 1516 units. The silicon is the promising material for solar cell material and it is occupied 48% solar cell market (Liu et al.,

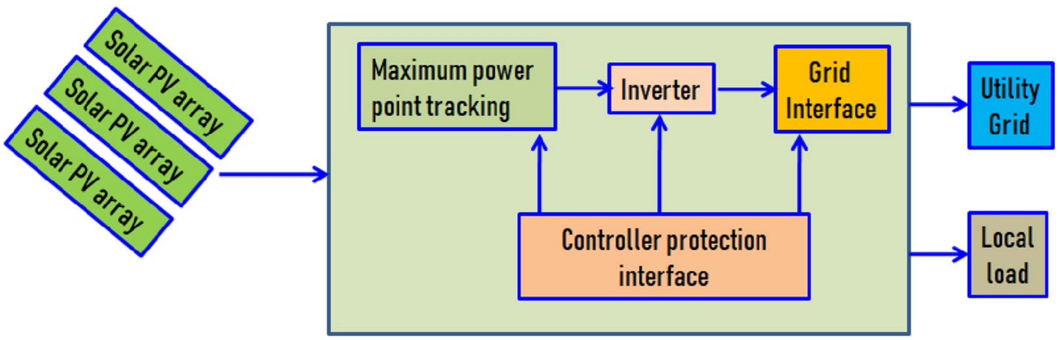

Fig. 25 Sketch of solar PV generation and utility

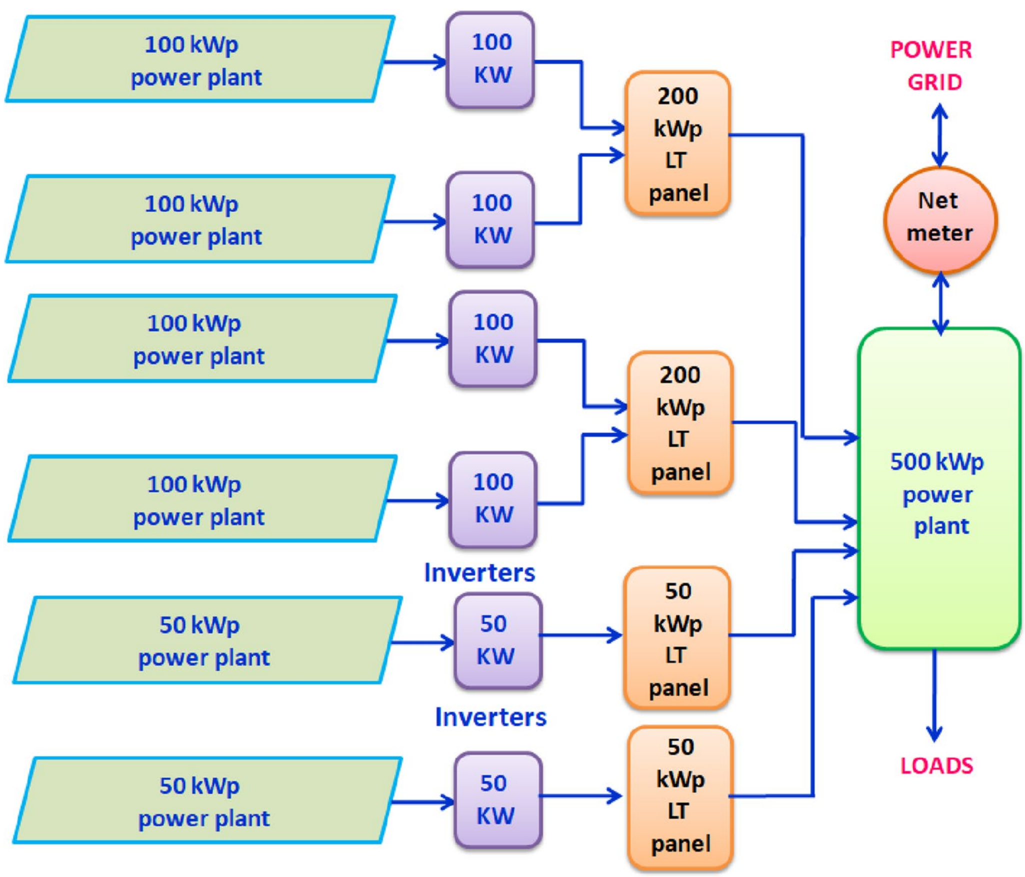

Fig. 26 Block diagram of various accessories and its assembly for 500 kWp solar PV generating system

2010). In general, the monocrystalline solar cell manufacturing is cheap, but its efficiency is very less ~ 12–14% (Saga, 2010). Hence, in the present study, polycrystalline silicon material-based solar cells are used.

The sketch of solar PV power generation system is shown in Fig. 25 and the block diagram of various accessories and its assembly for 500 kWp solar PV generating system is shown in Fig. 26. The entire plant solar PV generating system connected with 6 Inverters, out of which 100 kVA each connected to 100 kWp each module, and 2 numbers of 50 kVA Inverter is connected to 50 kWp modules. The total number of strings is 61 units for 400 kWp, and the number of modules in each string is 20 units. The number of stings for each 50 kWp is 8 units and 19 units in each sting, which is connected to 50 kVA Inverters. 500 kWp solar PV generations is connected to the main LT panel, which is connected to loads and excess power generation if any is export to the Grid

Fig. 27 Photograph of solar PV plant installations

through a net metering system. The output of the AC load is connected to the Main electrical LT DB. The generated power is utilizing the existing load requirements and, if any excess load produces, will be supplied to the power grid through a net metering system. The consumer will pay the bills on the net units based on the import and export units of the system. Solar PV generation plants in MWp scale can be connected to the electric grid, which is known grid-connected solar plants. Smaller capacity PV plants work separately and those are named as autonomous PV systems (Jayakumar, 2009; Reca et al., 2016). The assembled 1516 solar modules image is indicated in Fig. 27. Each module was located at a height of 7 ft through steel structure. The power conditioning device may include the MPPT (Maximum power point tracking), inverter, grid interface, as well as the controller protection interfacing.

The power generated by solar PV cell was monitored for a period of 5 months and the value is 301,361 kWh, with an average power generation per month is 60,272 kWh. Based on the power generated by the solar PV cell, the cost analysis was made. The capital cost of the erection of the 500 kWp solar power generating unit is 19,500,000 INR and the income generated by the plant per month is 427,484 INR. The generated kWh power (60,272 INR) multiplied by the government unit kWh cost will give the income generated by the plant. From this analysis, the cost will recover for the period of 3.8 year, which is the payback period.

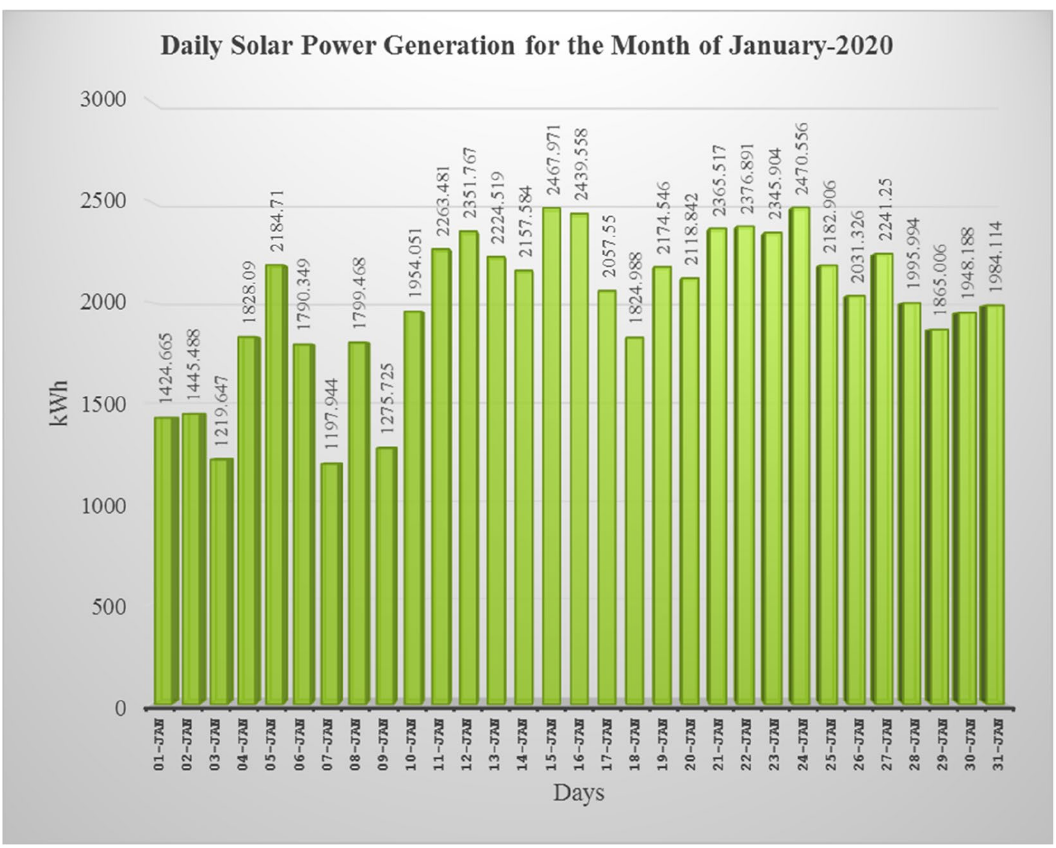

Fig. 28 Solar PV generation for the month of January-2020

The total generated power for the month of January 2020 is 62009 kWh and the data are indicated in Fig. 28. Based on the Indian metrological department data, the solar irradiation for the January month is 149.8 kWh/m^2:

$$\text{Performance ration}(PR) = \frac{\text{Energy generated(kWh)} \times 100}{\text{Irradiation } \left(\text{kWh}/m^2\right) \times \text{Total area of solar modules}\left(\text{m}^2\right) \times \text{module efficiency}}, \quad (39)$$

$$\text{PR for 330 Wp} = \frac{62009 \text{ kWh} \times 100}{149.8\left(\text{kWh/m}^2\right) \times 2941.57 \text{ m}^2 \times 0.17} = 82.77\%. \quad (40)$$

The performance ratio is 82.77% which means the power generated by the used solar PV modules is in excellent conditions. However, this performance factor of the solar PV module will decrease over the period of time which is called as degradation. The degradation rate depends on the environmental conditions and the technology of the module used in the PV generation. In the process of manufacturing of solar PV cells, there are several hazardous chemicals, such as HCL (Hydrochloricacid), H_2SO_4 (Sulfuric acid), HNO_3 (Nitric acid), HF (Hydrogen fluoride) and C_3H_6O (acetone), are used to clean and purify the semiconductor surface depend on the size of silicon dust and cleaning needed.

Future work

- Making the best use of water will increase the efficiency of cooling technology, enhancing PV module performance and cost-effectiveness. To create the ideal hybrid cooling technology that can lower pumping power and water usage, more research is required. It is possible to design automatic cooling and cleaning solutions with suitable sensor systems.
- Additional research can be done to create artificially intelligent models that can forecast dust buildup on PV surfaces. The researcher will benefit from this expected model to create suitable cooling and cleaning technologies.
- More research is needed to identify the proper nanomaterials that will shield PV modules from dust and contamination in humid and arid environments.

Conclusions

In recent years, there has been a noticeable increase in both the stand-alone deployment of solar PV and its integration into the current grid network. However, the weather and climatic factors have the biggest impact on the PV panel's performance indicator. The various elements affecting a PV module's output of electricity have been successfully identified in this article. The latest research has also revealed cutting-edge ways to lessen the impact of the many elements that contribute to the performance decline of solar PV systems. The following are draw from the study:

- The amount of solar energy that is accessible and falls directly on the module has a major impact on the output of PV systems; for every degree that the direct solar irradiance component deviates, there is a 0.08% loss in output. By continually orienting the PV panel towards the sun, this can be reduced. The fixed tilt angle can be calculated by $\phi \pm 15^{\circ}$.
- As module temperature rises, PV module performance suffers. Efficiency drops by 0.03–0.05% for every 1 °C increase in temperature without cooling, and it can drop by as much as 69% while operating at 64 °C. The PV panel's cooling indicates an increase in energy gain of 18%, 15%, and 2.5%, respectively, through thermoelectric cooling, active water cooling, and natural ventilation.
- In 45 days without cleaning, glass transmittance falls by 20%. Tilt angle, rainfall, wind, and other environmental factors can all cause a decrease in dust density. The PV panel becomes soiled when dust accumulates in humid conditions and generates tenacious, sticky mud. After 40 days of exposure in the Kingdom of Saudi Arabia, the soiling impact can lower transmittance by 30% for coated glass and 37% for uncoated glass. Pure water has the highest cleaning and cooling properties and can boost productivity by 15% when used with a robotic sprayer.
- There are advantages and disadvantages to environmental wind speed. In the USA, a wind speed of 10 m/s might result in a 3.5 °C drop in operating temperature. However, a 10 °C reduction at 2.8–5.3 m/s wind flow is feasible in a warm location like KSA.
- The materials should be carefully chosen to withstand humid conditions, because moisture intrusion causes corrosion of the PV panel in humid environments.
- The cheap cost of operation and maintenance makes modern PV systems a cost-effective renewable energy source, despite their relatively high installation costs. As a result, the energy payback period and the total life cycle cost are as short as possible. Given that this study took into account the most recent papers, the

literature review it presents will be useful for engineers, academics, designers, and policymakers in identifying the issues and potential solutions related to PV systems.

- The various solar cell material types and circuit models for evaluating solar PV cell performance are covered. The sole element that determines how successfully solar energy is converted is the material used in solar cells. The conversion efficiency of silicon-based materials can reach 17%, and semiconductor-based solar cells made of quantum dots in nanocrystals have the potential to have a conversion efficiency of 60%.
- Using multi-junction cells with different bandgaps is another way to increase cell efficiency. A performance ratio of 82.77% was discovered through experimental examination of 500 kWp of solar PV power generation. The performance of the solar PV cell will be impacted by the production of dust in the surrounding area. Solar PV cells need to be chemically cleaned once a month to function more effectively.

Acknowledgements
Not applicable.

Author contributions
All the authors contributed in preparation of this research work and preparation of this manuscript. All authors read and approved the final manuscript.

Funding
No funding involved for this research work.

Availability of data and materials
Not applicable.

Declarations

Ethics approval and consent to participate
This research work is not based on human beings or living organisms. No need for ethics approval and consent to participate.

Consent for publication
I, Dr. Feroz Shaik (the corresponding author), on behalf of all authors give our consent for the publication this paper in the journal Sustainable Energy Research.

Competing interests
The authors do not have any competing interests.

Received: 4 December 2022 Accepted: 16 March 2023
Published online: 10 April 2023

References

Adamo, F., Attivissimo, F., Di Nisio, A., Lanzolla, A., & Spadavecchia, M. (2009). Parameters estimation for a model of photovoltaic panels. In: *XIX IMEKO world congress fundamental applied metrology. Lisbon, Portugal* (Vol. 9, pp. 6–11).

Adinoyi, M. J., & Said, S. A. (2013). Effect of dust accumulation on the power outputs of solar photovoltaic modules. *Renewable Energy, 60*, 633–636.

Adriano, M., & Izete, Z. (2012). Development of silicon solar cells and photovoltaic modules in Brazil: Analysis of a pilot production. *Materials Research, 15*(4), 581–588.

Ahmad, R., Murtaza, A. F., Ahmed Sher, H., Tabrez Shami, U., & Olalekan, S. (2017). An analytical approach to study partial shading effects on PV array supported by literature. *Renewable and Sustainable Energy Reviews, 74*, 721–732. https://doi.org/10.1016/j.rser.2017.02.078

AlHajri, M. F., El-Naggar, K. M., Al Rashidi, M. R., & Al-Othman, A. K. (2012). Optimal extraction of solar cell parameters using pattern search. *Renewable Energy, 44*, 238–245.

Almonacid, F., Rus, C., Hontoria, L., Fuentes, M., & Nofuentes, G. (2009). Characterization of Si-crystalline PV modules by artificial neural networks. *Renewable Energy, 34*, 941–949.

Almonacid, F., Rus, C., Hontoria, L., & Muñoz, F. (2010). Characterization of PV CIS module by artificial neural networks. A comparative study with other methods. *Renewable Energy, 35*, 973–980.

Alqatari, S., Alfaris, A., & De Weck, O. L. (2015). Cost and performance comparative model of dust mitigation technologies for solar PV in Saudi Arabia. *Journal of Environmental Science, 4*, 1–7.

Al Shehri, A., Parrott, B., Carrasco, P., Al Saiari, H., & Taie, I. (2017). Accelerated testbed for studying the wear, optical and electrical characteristics of dry cleaned PV solar panels. *Solar Energy, 146*, 8–19. https://doi.org/10.1016/j.solener.2017.02.014

Arab, A. H., Chenlo, F., & Benghanem, M. (2004). Loss-of-load probability of photovoltaic water pumping systems. *Solar Energy, 76*, 713–723.

Asl-Soleimani, E., Farhangi, S., & Zabihi, M. S. (2001). The effect of tilt angle, air pollution on performance of photovoltaic systems in Tehran. *Renewable Energy, 24*(3–4), 459–468. https://doi.org/10.1016/S0960-1481(01)00029-5

Assi, A., & El Chaar, L. (2008). Effect of wind blown sand and dust on photovoltaic arrays. In *The 23rd European photovoltaic solar energy conference*.

Assi, A., Hassan, A., Al-Shamisi, M., & Hejase, H. (2012). Removal of air blown dust from photovoltaic arrays using forced air flow of return air from air conditioning systems. In *2012 international conference on renewable energies for developing countries (REDEC) 2012*. https://doi.org/10.1109/REDEC.2012.6416699

Bagher, A. M., Vahid, M. M. A., & Mohsen, M. (2015). Types of solar cells and application. *American Journal of Optics and Photonics, 3*, 94–113.

Bai, J., Liu, S., Hao, Y., Zhang, Z., Jiang, M., & Zhang, Y. (2014). Development of a new compound method to extract the five parameters of PV modules. *Energy Conversion and Management, 79*, 294–303.

Balzani, M., & Reatti, A. (2005). Neural network based model of a PV array for the optimum performance of PV system. *Research in microelectronics and electronics (Ph.D.)* (pp. 123–126). IEEE.

Barkhouse, D. A. R., Gunawan, O., Gokmen, T., Todorov, T. K., & Mitzi, D. B. (2012). Dust-induced shading on photovoltaic modules. *Progress in Photovoltaics: Research and Applications, 20*, 6–11. https://doi.org/10.1002/pip.1160

Belhaouas, A., Cheikh, A., & Larbes, C. (2013). Suitable Matlab-Simulink simulator for PV system based on a two-diode model under shading conditions. In *Proceedings of the 3rd international conference on systems and control (ICSC 2013)* (pp. 7276). IEEE.

Bellini, A., Bifaretti, S., Iacovone, V., & Cornaro, C. (2009). Simplified model of a photovoltaic module. In *Applied electronics, 2009 (AE 2009)* (pp. 47–51). IEEE.

Bertolli, M. (2008). *Solar cell materials. Course: Solid state II*. Department of Physics, University of Tennessee.

Birge, B. (2006). Particle swarm optimization toolbox. http://www.mathworks.com/matlabcentral/fileexchange/7506-particleswarm-optimization-toolbox

Brano, V. L., Orioli, A., Ciulla, G., & Di Gangi, A. (2010). An improved five-parameter model for photovoltaic modules. *Solar Energy Materials and Solar Cells, 94*, 1358–1370.

Breyer, C., & Gerlach, A. (2013). Global overview on grid-parity. *Progress in Photovoltaic Research Applications, 21*, 121–136.

Bright, J. M., Babacan, O., Kleissl, J., Taylor, P. G., & Crook, R. (2017). A synthetic, spatially decorrelating solar irradiance generator and application to a LV grid model with high PV penetration. *Solar Energy, 147*, 83–98. https://doi.org/10.1016/j.solener.2017.03.018

Burden, R. L., & Faires, J. D. (2010). *Numerical analysis*. Cengage Learning.

Castellano, R. (2010). *Solar panel processing*. Old City Publishing Inc.

Chanchangi, Y. N., Ghosh, A., Sundaram, S., & Mallick, T. K. (2020). Dust and PV performance in Nigeria: A review. *Renewable and Sustainable Energy Reviews, 121*, 109704.

Chauhan, A., & Saini, R. P. (2014). A review on integrated renewable energy system based power generation for stand-alone applications: Configurations, storage options, sizing methodologies and control. *Renewable and Sustainable Energy Reviews, 38*, 99–120.

Chegaar, M., Ouennoughi, Z., & Hoffmann, A. (2001). A new method for evaluating illuminated solar cell parameters. *Solid-State Electronics, 45*, 293–296.

Chin, V. J., Salam, Z., & Ishaque, K. (2015). Cell modeling and model parameters estimation techniques for photovoltaic simulator application: A review. *Applied Energy, 154*, 500–519.

Chouder, A., Silvestre, S., Sadaoui, N., & Rahmani, L. (2012). Modeling and simulation of a grid connected PV system based on the evaluation of main PV module parameters. *Simulation Modelling Practice and Theory, 20*, 46–58.

Chowdhury, S., Taylor, G., Chowdhury, S., Saha, A., & Song, Y. (2007). Modeling, simulation and performance analysis of a PV array in an embedded environment. In *Proceedings of the 42nd international universities power engineering conference, 2007 (UPEC 2007)* (pp. 781–785). IEEE.

Chumchal, C., & Kurzweil, D. (2017). Lead-acid battery operation in micro-hybrid and electrified vehicles. *Lead-acid batteries for future automobiles* (pp. 395–414). Elsevier. https://doi.org/10.1016/B978-0-444-63700-0.00013-1

Ciulla, G., Brano, V. L., Di Dio, V., & Cipriani, G. (2014). A comparison of different one-diode models for the representation of I–V characteristic of a PV cell. *Renewable and Sustainable Energy Reviews, 32*, 684–696.

Dash, S. K., Raj, R. A., Nema, S., & Nema, R. (2015). Development of photovoltaic (PV) cell/module/array and non-uniform irradiance effect based on two-diode model by using PSPICE simulator. In *Proceedings of international conference on nascent technologies in the engineering field (ICNTE 2015)* (pp. 1–6). IEEE.

Davis, M. W., Fanney, A. H., & Dougherty, B. P. (2003). Measured versus predicted performance of building integrated photovoltaics. *Journal of Solar Energy Engineering, 125*, 21–27.

De Blas, M., Torres, J., Prieto, E., & Garcıa, A. (2002). Selecting a suitable model for characterizing photovoltaic devices. *Renewable Energy, 25*, 371–380.

Dewi, T., Risma, P., & Oktarina, Y. (2019). A review of factors affecting the efficiency and output of a PV system applied in tropical climate. *IOP Conference Series: Earth and Environmental Science, 258*, 012039.

Duell, M., Ebert, M., Muller, M., et al. (2010). Impact of structured glass on light transmission, temperature and power of PV modules. In *25th European photovoltaic solar energy conference and exhibition/5th world conference on photovoltaic energy conversion, 6–10 Sept. 2010, Val. Spain* (pp. 3867–3872). https://doi.org/10.4229/25thEUPVSEC2010-4CO.20.2

Easwarakhanthan, T., Bottin, J., Bouhouch, I., & Boutrit, C. (1986). Nonlinear minimization algorithm for determining the solar cell parameters with microcomputers. *International Journal of Solar Energy, 4*, 1–12.

Elbaset, A. A., Ali, H., & Abd-El, S. M. (2014). Novel seven-parameter model for photovoltaic modules. *Solar Energy Materials and Solar Cells, 130*, 442–455.

Elminir, H. K., Ghitas, A. E., Hamid, R. H., El-Hussainy, F., Beheary, M. M., & Abdel-Moneim, K. M. (2006). Effect of dust on the transparent cover of solar collectors. *Energy Conversion and Management, 47*(18–19), 3192–3203. https://doi.org/10.1016/j.enconman.2006.02.014

Elnozahy, A., Rahman, A. K. A., Ali, A. H. H., Abdel-Salam, M., & Ookawara, S. (2015). Performance of a PV module integrated with standalone building in hot arid areas as enhanced by surface cooling and cleaning. *Energy and Buildings, 88*, 100–109. https://doi.org/10.1016/j.enbuild.2014.12.012

Fahrenbruch, A. L., & Bube, R. H. (1983). *Fundamentals of solar cells*. Academic Press Inc.

Fathabadi, H. (2013). Novel neural-analytical method for determining silicon/plastic solar cells and modules characteristics. *Energy Conversion and Management, 76*, 253–259.

Fesharaki, V. J., Dehghani, M., & Fesharaki, J. J. (2011). The effect of temperature on photovoltaic cell efficiency. In *Proceedings of the 1st international conference on emerging trends in energy conservation—ETEC Tehran, Tehran, Iran* (Vol. 11, pp. 20–21).

Fouad, M. M., Shihata, L. A., & Morgan, E. S. I. (2017). An integrated review of factors influencing the performance of photovoltaic panels. *Renewable and Sustainable Energy Reviews, 80*, 1499–1511.

Ghazi, S., Ip, K., & Sayigh, A. (2013). Preliminary study of environmental solid particles on solar flat surfaces in the UK. *Energy Procedia, 42*, 765–774. https://doi.org/10.1016/j.egypro.2013.11.080

Gosumbonggot, J., & Fujita, G. (2019). Global maximum power point tracking under shading condition and hotspot detection algorithms for photovoltaic systems. *Energies, 12*(5), 882. https://doi.org/10.3390/en12050882

Gow, J., & Manning, C. (1996). Development of a model for photovoltaic arrays suitable for use in simulation studies of solar energy conversion systems. https://doi.org/10.1049/cp:19960890

Green, M. A. (2005). Silicon photovoltaic modules: A brief history of the first 50 years. *Progress in Photovoltaics: Research and Applications, 13*, 447–455.

Griffith, J. S., Rathod, M. S., & Paslaski, J. (1981). Some tests of mod Temps_PVSC1981.pdf. In *Proceedings of the 15th IEEE photovoltaic specialists conference* (pp. 822–830).

Grisham, L. R. (2008). *Nuclear fusion in: Future energy, improved, sustainable and clean options for our planet, edited by Trevor M. Letcher* (2nd ed., pp. 291–301). Elsevier Ltd.

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 *Proceedings of Asia-Pacific power and energy engineering conference (APPEEC 2012)* (pp. 1–4). IEEE.

Gupta, V., Sharma, M., Pachauri, R. K., & Dinesh Babu, K. N. (2019). Comprehensive review on effect of dust on solar PVsystem and mitigation techniques. *Solar Energy, 191*, 596–622. https://doi.org/10.1016/j.solener.2019.08.079

Gürtürk, M., Benli, H., & Ertürk, N. K. (2018). Effects of different parameters on energy—Exergy and power conversion efficiency of PV modules. *Renewable and Sustainable Energy Reviews, 92*, 426–439. https://doi.org/10.1016/j.rser.2018.04.117

Gwandu, B. A. L., & Creasey, D. J. (1995). Humidity: A factor in the appropriate positioning of a photovoltaic power station. *Renewable Energy, 6*(3), 313–316. https://doi.org/10.1016/0960-1481(95)00073-S

Huang, W., Jiang, C., Xue, L., & Song, D. (2011). Extracting solar cell model parameters based on chaos particles warm algorithm. In *Proceedings of the international conference on electric information and control engineering (ICEICE '11)* (Vol. 4, pp. 398–402).

Isbilir, K., Lisco, F., Womack, G., Abbas, A., & Walls, J. M. (2018). Testing of an anti-soiling coating for PV module cover glass. In *2018 IEEE 7th world conference on photovoltaic energy conversion (WCPEC) (a joint conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC)* (pp. 3426–3431). https://doi.org/10.1109/PVSC.2018.8547272

Ishaque, K., Salam, Z., & Taheri, H. (2011). Modeling and simulation of photovoltaic (PV) system during partial shading based on a two-diode model. *Simulation Modelling Practice and Theory, 19*, 1613–1626.

Jayakumar, P. (2009). *Solar energy resource assessment handbook*. Renewable Energy Corporation Network for the Asia Pacific.

Jiang, Y., Lu, L., Ferro, A. R., & Ahmadi, G. (2018). Analyzing wind cleaning process on the accumulated dust on solar PV(PV) modules on flat surfaces. *Solar Energy, 159*, 1031–1036. https://doi.org/10.1016/j.solener.2017.08.083

Jiang, Y., Lu, L., & Lu, H. (2016). A novel model to estimate the cleaning frequency for dirty solar PV(PV) modules in desert environment. *Solar Energy, 140*, 236–240. https://doi.org/10.1016/j.solener.2016.11.016

Jing, L., Zhi-Jun, Z., Ji-Lin, Y., & Yi-Long, B. (2009). A thin liquid film and its effects in an atomic force microscopy measurement. *Chinese Physics Letters, 26*(8), 086802. https://doi.org/10.1088/0256-307X/26/8/086802

Jordehi, A. R. (2016). Parameter estimation of solar PV(PV) cells: A review. *Renewable and Sustainable Energy Reviews, 61*, 354–371.

Joseph, A. J., Hadj, B., & Ali, A. L. (2001). Solar cell parameter extraction using genetic algorithms. *Measurement Science and Technology, 12*, 1922–1925.

Kajihara, A., & Harakawa, T. (2005). Model of photovoltaic cell circuits under partial shading. In: *Proceedings of IEEE international conference on industrial technology, (ICIT 2005)* (pp. 866–870). IEEE.

Kazem, H. A., & Chaichan, M. T. (2019). The effect of dust accumulation and cleaning methods on PV panels' outcomes based on an experimental study of six locations in northern Oman. *Solar Energy, 187*, 30–38. https://doi.org/10.1016/j.solener.2019.05.036

Kazem, H. A., Chaichan, M. T., Al-Waeli, A. H. A., & Sopian, K. (2020). A review of dust accumulation and cleaning methods for solar PV systems. *Journal of Cleaner Production, 276*, 123187.

Kempe, M. D. (2006). Modeling of rates of moisture ingress into photovoltaic modules. *Solar Energy Materials and Solar Cells, 90*(16), 2720–2738. https://doi.org/10.1016/j.solmat.2006.04.002

King, D. L., Boyson, W. E., & Kratochvill, J. A. (2004). *Photovoltaic array performance model*. Sandia National Laboratories (SNL).

Kingsley, O. U., Freddie, L. I., & Andrew, C. E. (2018). Fabrication of affordable and sustainable solar cells using NiO/TiO_2 P–N heterojunction. *International Journal of Photo Energy*. https://doi.org/10.1155/2018/6062390

Kurobe, K.-I., & Matsunami, H. (2005). New two-diode model for detailed analysis of multi-crystalline silicon solar cells. *Applied Physics, 44*, 8314.

Lavado Villa, L. F., Ho, T. P., Crebier, J. C., & Raison, B. (2013). A power electronics equalizer application for partially shaded photovoltaicmodules. *IEEE Transactions on Industrial Electronics, 60*(3), 1179–1190. https://doi.org/10.1109/TIE.2012.2201431

Lim, L. H. I., Ye, Z., Ye, J., Yang, D., & Du, H. (2015). A linear method to extract diode model parameters of solar panels from a single I–V curve. *Renewable Energy, 76*, 135–142.

Liu, L. (2009). Comment on 'recent progress in thermodynamics of radiation-exergy of radiation, effective temperature of photon and entropy constant of photon.' *Science in China Series E: Technological Sciences, 52*(6), 1809–1810.

Liu, L. Q., Wang, Z. X., Zhang, H. Q., & Xue, Y. C. (2010). Solar energy development in China—A review. *Renewable and Sustainable Energy Reviews, 14*(1), 301–311.

Lo Brano, V., & Ciulla, G. (2013). An efficient analytical approach for obtaining a five parameters model of photovoltaic modules using only reference data. *Applied Energy, 111*, 894–903.

Lumb, M. P., Bailey, C. G., Adams, J. G., Hillier, G., Tuminello, F., Elarde, V. C., & Walters, R. (2013). Analytical drift-diffusion modeling of GaAs solar cells incorporating a back mirror. In *Proceedings of IEEE 39th photovoltaic specialist's conference (PVSC 2013)* (pp. 1063–1068). IEEE.

Ma, J., Ting, T. O., Man, K. L., Zhang, N., Guan, S. U., & Wong, P. W. (2013). Parameter estimation of photovoltaic models via cuckoo search. *Journal of Applied Mathematics*. https://doi.org/10.1155/2013/362619

Maghami, M. R., Hizam, H., Gomes, C., Radzi, M. A., Rezadad, M. I., & Hajighorbani, S. (2016). Power loss due to soiling on solar panel: A review. *Renewable and Sustainable Energy Reviews, 59*, 1307–1316. https://doi.org/10.1016/j.rser.2016.01.044

Mani, M., & Pillai, R. (2010). Impact of dust on solar PV(PV) performance: Research status, challenges and recommendations. *Renewable and Sustainable Energy Reviews, 14*(9), 3124–3131. https://doi.org/10.1016/j.rser.2010.07.065

Mares, O., Paulescu, M., & Badescu, V. (2015). A simple but accurate procedure for solving the five-parameter model. *Energy Conversion and Management, 2015*(105), 139–148.

Mastekbayeva, G. A., & Kumar, S. (2000). Effect of dust on the transmittance of low density polyethylene glazing in a tropical climate. *Solar Energy, 68*(2), 135–141. https://doi.org/10.1016/S0038-092X(99)00069-9

Mazhari, B. (2006). An improved solar cell circuit model for organic solar cells. *Solar Energy Materials and Solar Cells, 90*, 1021–1033.

Mazumder, M. K., Sharma, R., Biris, A. S., et al. (2011). Electrostatic removal of particles and its applications to self-cleaning solar panels and solar concentrators. In *Developments in surface contamination and cleaning. Methods for removal of particle contaminants* (pp. 149–199). https://doi.org/10.1016/B978-1-4377-7885-4.10005-3

McEvoy, A., Castaner, L., & Markvart, T. (2012). *Solar cells: Materials, manufacture and operation* (2nd ed., pp. 3–25). Elsevier Ltd.

Meier, J., Spitznage, J., Krolla, U., Buchera, C., Fay, S., Moriarty, T., & Shah, A. (2004). Potential of amorphous and microcrystalline silicon solar cells. *Thin Solid Films, 451*, 518–524.

Mekhilef, S., Saidur, R., & Kamalisarvestani, M. (2012). Effect of dust, humidity and air velocity on efficiency of photovoltaic cells. *Renewable and Sustainable Energy Reviews, 16*(5), 2920–2925. https://doi.org/10.1016/j.rser.2012.02.012

Mohandes, B. M. A., El-Chaar, L., & Lamont, L. A. (2009). Application study of 500 W photovoltaic (PV) system in the UAE. *Applied Solar Energy, 45*(4), 242–247. https://doi.org/10.3103/S0003701X09040057

Moharram, K. A., Abd-Elhady, M. S., Kandil, H. A., & El-Sherif, H. (2013). Influence of cleaning using water and surfactants on the performance of photovoltaic panels. *Energy Conversion and Management, 68*, 266–272. https://doi.org/10.1016/j.enconman.2013.01.022

Mondol, J. D., Yohanis, Y. G., & Norton, B. (2007). The impact of array inclination and orientation on the performance of a grid-connected photovoltaic system. *Renewable Energy, 32*(1), 118–140. https://doi.org/10.1016/j.renene.2006.05.006

Morris, N. (2014). The $1 per watt solar illusion. www.businessspectator.com.au

Muhsen, D. H., Khatib, T., & Nagi, F. (2017). A review of photovoltaic water pumping system designing methods, control strategies and field performance. *Renewable and Sustainable Energy Reviews, 68*, 70–86.

Munoz, M. A., Alonso-García, M. C., Vela, N., & Chenlo, F. (2011). Early degradation of silicon PV modules and guaranty conditions. *Solar Energy, 85*(9), 2264–2274. https://doi.org/10.1016/j.solener.2011.06.011

National Energy Education Development Project (NEED). (2015–2016). Energy from the Sun, student guide. https://issuu.com/theneedproject/docs/energyfromthesunstudentguide_1cc70ae9b951f9

Ndiaye, A., Charki, A., Kobi, A., Kébé, C. M. F., Ndiaye, P. A., & Sambou, V. (2013). Degradations of silicon photovoltaic modules: A literature review. *Solar Energy, 96*, 140–151. https://doi.org/10.1016/j.solener.2013.07.005

Nishioka, K., Sakitani, N., Uraoka, Y., & Fuyuki, T. (2007). Analysis of multi-crystalline silicon solar cells by modified 3-diode equivalent circuit model taking leakage current through periphery into consideration. *Solar Energy Materials and Solar Cells, 91*, 1222–1227.

Nižetić, S., Čoko, D., Yadav, A., & Grubišić-Čabo, F. (2016). Water spray cooling technique applied on a photovoltaic panel: The performance response. *Energy Conversion and Management, 108*, 287–296. https://doi.org/10.1016/j.enconman.2015.10.079

Nobuo, T. (2010). *Technology roadmap: Solar PV energy*. International Energy Agency.

O'Hara, S. L., Clarke, M. L., & Elatrash, M. S. (2006). Field measurements of desertdust deposition in Libya. *Atmospheric Environment, 40*(21), 3881–3897. https://doi.org/10.1016/j.atmosenv.2006.02.020

Odeh, S., & Behnia, M. (2009). Improving photovoltaic module efficiency using water cooling. *Heat Transfer Engineering, 30*(6), 499–505. https://doi.org/10.1080/01457630802529214

Ogliari, E., Grimaccia, F., Leva, S., & Mussetta, M. (2013). Hybrid predictive models for accurate forecasting in PV systems. *Energies, 6*(4), 929–2013.

Orioli, A., & Di Gangi, A. (2013). A procedure to calculate the five-parameter model of crystalline silicon photovoltaic modules on the basis of the tabular performance data. *Applied Energy, 102*, 1160–1177.

Patel, H., et al. (2008). Maximum power point tracking scheme for PV systems operating under partially shaded conditions. *IEEE Transactions on Industrial Electronics, 55*(4), 1689–1698.

Paudyal, B. R., & Shakya, S. R. (2016). Dust accumulation effects on efficiency of solar PV modules for off grid purpose: A case study of Kathmandu. *Solar Energy, 135*, 103–110. https://doi.org/10.1016/j.solener.2016.05.046

Piliougine, M., Elizondo, D., Mora-López, L., & Sidrach-de-Cardona, M. (2015). Modelling photovoltaic modules with neural networks using angle of incidence and clearness index. *Progress in Photovoltaics: Research and Applications, 23*, 513–523.

Powersim. (2001). *PSIM user manual*. Powersim Inc.

Prema, V., & Uma, R. K. (2015). Development of statistical time series models for solar power prediction. *Renewable Energy, 83*, 100–109. https://doi.org/10.1016/j.renene.2015.03.038

Quansah, D., Adaramola, M., Takyi, G., & Edwin, I. (2017). Reliability and degradation of solar PV modules—Case study of 19-year-old polycrystalline modules in Ghana. *Technologies, 5*(2), 22. https://doi.org/10.3390/technologies5020022

Rahman, M. M., Hasanuzzaman, M., & Rahim, N. A. (2015). Effects of various parameters on PV-module power and efficiency. *Energy Conversion and Management, 103*, 348–358. https://doi.org/10.1016/j.enconman.2015.06.067

Rajasekar, N., Kumar, N. K., & Venugopalan, R. (2013). Bacterial foraging algorithm based solar PV parameter estimation. *Solar Energy, 97*, 255–265.

Rajput, P., Tiwari, G. N., Sastry, O. S., Bora, B., & Sharma, V. (2016). Degradation of mono-crystalline photovoltaic modules after 22 years of outdoor exposure in the composite climate of India. *Solar Energy, 135*, 786–795. https://doi.org/10.1016/j.solener.2016.06.047

Reca, J., Torrente, C., López-Luque, R., & Martínez, J. (2016). Feasibility analysis of a standalone direct pumping photovoltaic system for irrigation in Mediterranean greenhouses. *Renewable Energy, 85*, 1143–1154.
Saga, T. (2010). Advances in crystalline silicon solar cell technology for industrial mass production. *NPG Asia Materials, 2*, 96–102.
Saha, K. (2014). Planning and installing photovoltaic system: A guide for installers, architects and engineers. *International Journal of Environmental Studies, 71*(6), 887–898. https://doi.org/10.1080/00207233.2014.951543
Said, S. A. M. (1990). Effects of dust accumulation on performances of thermal and photovoltaic flat-plate collectors. *Applied Energy, 37*(1), 73–84. https://doi.org/10.1016/0306-2619(90)90019-A
Said, S. A. M., Al-Aqeeli, N., & Walwil, H. M. (2015). The potential of using textured and anti-reflective coated glasses in minimizing dust fouling. *Solar Energy, 113*, 295–302. https://doi.org/10.1016/j.solener.2015.01.007
Said, S. A. M., Hassan, G., Walwil, H. M., & Al-Aqeeli, N. (2018). The effect of environmental factors and dust accumulation on photovoltaic modules and dust-accumulation mitigation strategies. *Renewable and Sustainable Energy Reviews, 82*, 743–760. https://doi.org/10.1016/j.rser.2017.09.042
Said, S. A. M., & Walwil, H. M. (2014). Fundamental studies on dust fouling effects on PV module performance. *Solar Energy, 107*, 328–337. https://doi.org/10.1016/j.solener.2014.05.048
Sala, S. A., Campaniello, M., & Bailini, A. (2009). Experimental study of polymers as encapsulating materials for photovoltaic modules. In *2009 European microelectronics and packaging conference, EMPC*.
Salim, M. S., Najim, J. M., Salih, S. M., & Mohammed, S. S. (2013). Practical evaluation of solar irradiance effect on PV performance. *Energy Science and Technology, 6*(62), 36–40. https://doi.org/10.3968/j.est.1923847920130602.2671
Santbergen, R., Muthukumar, V. A., Valckenborg, R. M. E., van de Wall, W. J. A., Smets, A. H. M., & Zeman, M. (2017). Calculation of irradiance distribution on PV modules by combining sky and sensitivity maps. *Solar Energy, 150*, 49–54.
Sera, D., Teodorescu, R., & Rodriguez, P. (2007). PV panel model based on datasheet values. In *Proceedings of IEEE international symposium on industrial electronics, 2007 (ISIE 2007)* (pp. 2392–2396). IEEE.
Shah, A. S. B. M., Yokoyama, H., & Kakimoto, N. (2015). High-precision forecasting model of solar irradiance based on grid point value data analysis for an efficient photovoltaic system. *EEE Transactions on Sustainable Energy, 6*(2), 474–481.
Shaju, A., & Chacko, R. (2018). Soiling of photovoltaic modules-review. *IOP Conference Series: Materials Science and Engineering., 396*, 012050. https://doi.org/10.1088/1757-899X/396/1/012050
Shruti, S., Kamlesh, K. J., & Ashutosh, S. (2015). Solar cells: In research and applications—A review. *Materials Sciences and Applications, 6*, 1145–1155.
Shukla, A. K., Sudhakar, K., & Baredar, P. (2016). A comprehensive review on design of building integrated photovoltaic system. *Energy and Buildings, 128*, 99–110.
Song, Z., Liu, J., & Yang, H. (2021). Air pollution and soiling implications for solar photovoltaic power generation: A comprehensive review. *Applied Energy, 298*, 117247.
Soon, J. J., & Low, K.-S. (2012). Photovoltaic model identification using particle swarm optimization with inverse barrier constraint. *IEEE Transactions on Power Electronics, 27*, 3975–3983.
Soon, J. J., Low, K. S., Goh, S. T. (2014). Multi-dimension diode photovoltaic (PV) model for different PV cell technologies. In *Proceedings of IEEE 23rd international symposium on industrial electronics (ISIE 2014)* (pp. 2496–2501). IEEE.
Soteris, K. (2009). *Solar energy engineering processes and system* (1st ed., p. 30). Elsevier Inc.
Srinivas, B., Balaji, S., Nagendra Babu, M., & Reddy, Y. S. (2015). Review on present and advance materials for solar cells. *International Journal of Engineering Research-Online, 3*(2015), 178–182.
Suskis, P., & Galkin, I. (2013). Enhanced photovoltaic panel model for MATLAB-simulink environment considering solar cell junction capacitance. In *Proceedings of the 39th annual conference of the IEEE industrial electronics society (IECON 2013)* (pp. 1613–1618). IEEE.
The Math Works Inc. Optimization toolbox. http://www.mathworks.com/products/optimization/index.html
Touati, F., Massoud, A., Hamad, J. A., & Saeed, S. A. (2013). Effects of environmental and climatic conditions on PV efficiency in Qatar. *Renewable Energy and Power Quality Journal, 1*(11), 262–267. https://doi.org/10.24084/repqj11.275
Ulapane, N. N., Dhanapala, C. H., Wickramasinghe, S. M., Abeyratne, S. G., Rathnayake, N., & Binduhewa, P. J. (2011). Extraction of parameters for simulating photovoltaic panels. In *Proceedings of the 6th IEEE international conference on industrial and information systems (ICIIS 2011)* (pp. 539–544). IEEE.
Vasel, A., & Iakovidis, F. (2017). The effect of wind direction on the performance of solar PV plants. *Energy Conversion and Management, 153*, 455–461. https://doi.org/10.1016/j.enconman.2017.09.077
Vergura, S. (2015). Scalable model of PV cell in variable environment condition based on the manufacturer datasheet for circuit simulation. In *Proceedings of IEEE 15th international conference on environment and electrical engineering (EEEIC 2015)* (pp. 1481–1485). IEEE.
Verma, L. K., Sakhuja, M., Son, J., et al. (2011). Self-cleaning and antireflective packaging glass for solar modules. *Renewable Energy, 36*(9), 2489–2493. https://doi.org/10.1016/j.renene.2011.02.017
Viitanen, J. (2015). Energy efficient lighting systems in buildings with integrated photovoltaics. https://aaltodoc.aalto.fi/handle/123456789/15265
Villalva, M. G., & Gazoli, J. R. (2009a). Comprehensive approach to modeling and simulation of photovoltaic arrays. *IEEE Transactions on Power Electronics, 2009*(24), 1198–1208.
Villalva, M. G., & Gazoli, J. R. (2009b). Comprehensive approach to modeling and simulation of photovoltaic arrays. *IEEE Transactions on Power Electronics, 24*, 1198–1208.
Wang, F., Xuan, Z., Zhen, Z., et al. (2020). A minutely solar irradiance forecasting method based on real-time sky image-irradiance mapping model. *Energy Conversion and Management, 220*, 113075. https://doi.org/10.1016/j.enconman.2020.113075
Wang, H., Ang, B. W., & Su, B. (2017). A multi-region structural decomposition analysis of global CO_2 emission intensity. *Ecological Economics, 142*, 163–176.
Waqar Akram, M., Li, G., Jin, Y., et al. (2020). Study of manufacturing and hotspot formation in cut cell and full cell PV modules. *Solar Energy, 203*, 247–259. https://doi.org/10.1016/j.solener.2020.04.052
Wengenmayr, R., & Bührke, T. (2009). Renewable energy: Sustainable energy concepts for the future. *Choice Reviews Online, 46*(05), 46–2689.
Wesoff, E. (2015). First solar reaches 16.3% efficiency in production PV modules. https://greentechmedia.com
Yadav, A., & Kumar, P. (2015). Enhancement in efficiency of PV cell through P&O algorithm. *International Journal for Technological Research in Engineering, 2*, 2642–2644.
Yang, X. S. (2023). Cuckoo search algorithm (source code). http://www.mathworks.com/matlabcentral/fileexchange/29809cuckoo-search-cs-algorithm
Yilbas, B. S., Ali, H., Al-Aqeeli, N., et al. (2016a). Characterization of environmental dust in the Dammam area and mud after-effects on bisphenol-A polycarbonate sheets. *Science and Reports, 6*(1), 1–14. https://doi.org/10.1038/srep24308
Yilbas, B. S., Ali, H., Al-Sharafi, A., & Al-Aqeeli, N. (2017). Environmental mud adhesion on optical glass surface: Effect of mud drying temperature on surface properties. *Solar Energy, 150*, 73–82. https://doi.org/10.1016/j.solener.2017.04.041
Yilbas, B. S., Ali, H., Khaled, M., Al-Aqeeli, N., & Al-Sulaiman, F. (2016b). Laser gas assisted texturing of alumina surfaces and effects of environmental dry mud solution on surface characteristics. *Ceramics International, 42*(1), 396–404. https://doi.org/10.1016/j.ceramint.2015.08.123
Zogou, O. (2011). *Experimental and computational investigation of the thermal and electrical performance of a new building integrated photovoltaic concept*. Mechanical Engineering Dept.
Zorrilla-Casanova, J., Piliougine, M., Carretero, J., et al. (2011). Analysis of dust losses in photovoltaic modules. In *Proceedings of world renewable energy congress–Sweden, 8–13 May, 2011, Linköping, Sweden* (Vol. 57, pp. 2985–2992). https://doi.org/10.3384/ecp110572985

Publisher's Note