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Optimization of Solar Cell Parameters: A Theoretical Approach

Vijay Aithekar*[1], Dr. Amit Saxena[1], Vinay Marmat[1], Gajendra Upadhayay[1]

[1]Department of science. "Oriental University, Indore (M.P.), India

Correspondence Author:

Email ID: vijayaithekar@gmail.com

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ABSTRACT

The generation of conventional electricity using fossil fuels is a significant factor in the pollution of the global environment. The need for energy sources that are less polluting and more long-lasting has grown more pressing as a result of the rapid depletion of fossil fuel reserves and the negative effects these fuels have on the environment. Solar photovoltaic (PV) cells directly generate electricity by utilizing solar energy, a plentiful and renewable resource. However, the cost-effectiveness of solar power generation is ultimately affected by a number of operational and environmental factors that have a significant impact on the efficiency, output, productivity, and lifespan of solar PV cells. The effects of environmental and operational parameters on solar PV cell performance are reviewed in this study. The accumulation of dust, soiling, temperature, and humidity have all been identified as significant contributors to decreased efficiency. Wind-driven dust and sand particles further exacerbate these difficulties in remote areas. A sticky layer forms on the PV modules when dust accumulates in humid conditions. The benefits and challenges of advanced strategies to mitigate these effects are examined in this paper. In addition, it discusses the influence of various solar power generation parameters and their function in efficiency optimization. Solar PV technology's semiconductor materials' efficiency and energy conversion capabilities are also examined. Last but not least, the paper emphasizes the overall advantages of solar PV energy, highlighting its potential as an essential option for producing power in a sustainable manner

Keywords: *Solar PV Efficiency, Renewable Energy, Performance Analysis, Environmental Impact, Semiconductor Materials*

1. INTRODUCTION

Natural energy sources like the sun, the wind, and the ocean replenish energy reserves. Renewable energy is becoming increasingly important due to environmental damage and shifting crude oil costs. PV has the ability to generate conventional power. In deserts and rural areas, solar photovoltaics' immediate conversion to solar power is advantageous. [1]. Cellular photons power charge transporters. The junction's electric field generates electromotive force by separating electrons in the depletion zone from photogenerated holes [2, 3]. Due to fundamental semiconductor characteristics, system efficiency may decrease by 15 to 20 percent. [4].

PV system efficiency is influenced by the environment and other factors. How dirtiness affects solar panel power and performance was investigated in studies on environmental wind, temperature, and soil deposition [5]. PV cell efficiency decreased by 0.485% [6] when the surface temperature of photovaltic panels was increased from 25°C. M. Benghanem [7] says that the monthly ideal slope angle loses 8% more solar energy than the annual average fixed angle does. Temperature affects solar panel efficiency and fill factor, as shown by Ehsan F. [8]. He demonstrates that cooling increases solar panel voltage by 11.8%. Panels that are dirty make less power available. The PV panel is subjected to natural pollution as a result. Using statistical analysis, Bhattacharya T. et al. [9] investigated how wind velocity and air temperature affect the efficiency of solar cell panels. Dincer F. et al. [10] examined cell temperature and solar radiation direction as efficiency factors for solar cells. Costs for photovoltaic models were reduced and efficiency was improved by Tans et al. [11]. The tops of solar panels performed better when they were watered [12, 13]. Environmental contamination had a 92% impact on empirical photovoltaic output [14]. According to Qais M, temperature decreases power production. [15]. Module-specific output decreases with temperature in experience testing: Polycrystalline > Copper indium gallium. In Kirkuk, Iraq, the purpose of this study is to investigate how the performance of solar panels is affected by good tilt angles and the weather. The experiment made use of five identical solar panels. one model of reference. In terms of performance, it has been compared to modules that pollute solar panel tops.

The following can be used to estimate the maximum power:

Pmax = Ipm * Vpm (1)

Additionally, the open circuit voltage and short circuit current (Isc) can be used to estimate final output [18, 19].

Pmax = FF (Voc *Isc) (2)

Where, Isc is short circuit current, FF is fill factor; Voc is open-circuit voltage.

In the I-V curve of the modules, M denotes the highest power point. Due to the semiconductor's predominant electrical characteristics being dominated by thermally excited electrons, open-circuit voltage and fill factor decrease significantly with temperature. The short-circuit current also goes up a little [20]. where FF is the fill factor of the PV panel. The ratio of transparent rectangular regions in Figure 1 depicts the quality of solar panels.

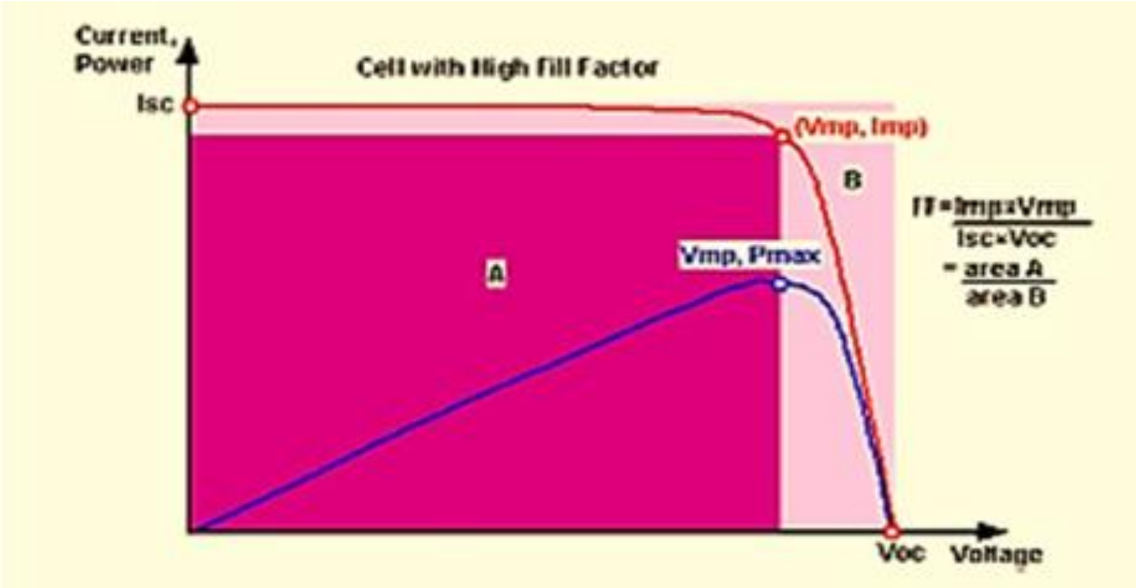

Fig 1. Maximum power and the standard current-voltage curve.

Using the previous explanation and Figure (2), the FF is:

$$FF = \frac{area\ A}{area\ B} = \frac{I_{mp} \times V_{mp}}{I_{sc} \times V_{oc}} \quad (3)$$

PV panel area and solar radiation decline. Mode efficiency may be estimated by:

$$\eta = \frac{P_{max}}{G \times A_c} \quad (4)$$

SOLAR PV CELL TECHNOLOGY

In 1839, Alexander Edmond Becquerel made the discovery of photovoltaics. In 1946, Russel Ohl made the silicon-based Solar PV Cell. Materials such as copper–indium–gallium–selenide (CIGS), single-crystal, amorphous, and multi-crystal cadmium telluride (CdTe), and copper per–indium–gallium–sulfide silicon are utilized in solar cells. Materials for making PV cells are depicted in Fig. 2 [21].

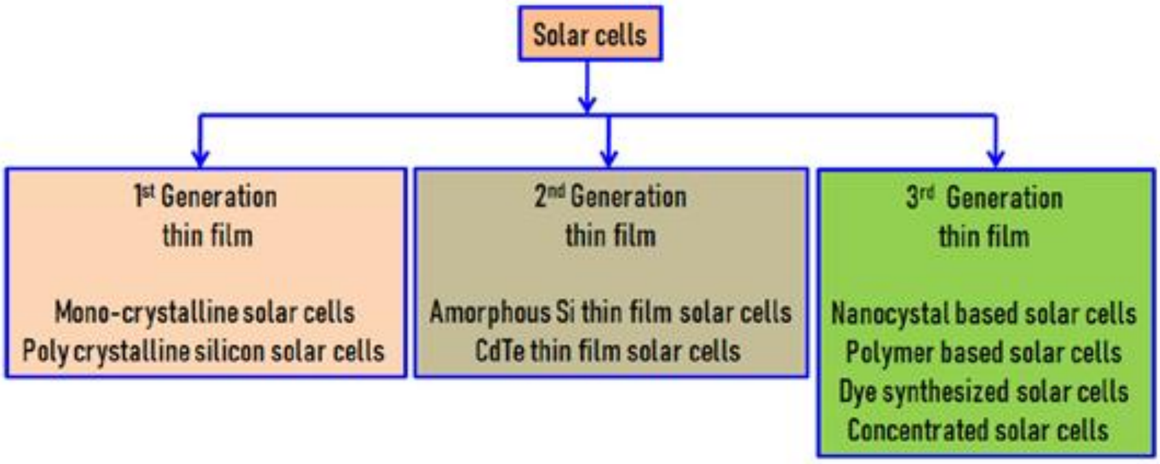

Fig. 2 Technologies and trends in solar PV cell development

First generation PV cell

Due to their high efficiency, silicon wafers are a popular technology for first-generation solar PV cells. The two main kinds of silicon wafers are monocrystalline silicon solar cells, also known as the Czochralski process, and multicrystal line silicon solar cells, which have many crystals [22].

Second generation PV cell

First-generation silicon wafer solar cells are more expensive than second-generation ones. Solar PV cells, in contrast to silicon wafer cells, have thin film layers that are typically one millimeter thick. Amorphous silicon (a-Si), copper–indium–gallium–di-selenide (CIGS), and cadmium–tel luride (Cd–Te) are examples of thin film solar cells [23].

Third generation PV cell

Nanocrystalline, concentrated, dye-sensitized, and polymer-based solar cells make up the third generation of photovoltaic cells. PV modules frequently make use of copper–indium–di-selenide and cadmium telluride. Solar cells based on materials perform better than silicon-based ones. Generations of solar cells are depicted in Figure. 3. Organic, hybrid, buried contact, concen trated, luminescent, multifunction, nanocrystal, quantum dot, dye-sensitized, and photo-electrochemical solar PV cells are all examples of solar PV cells [24].

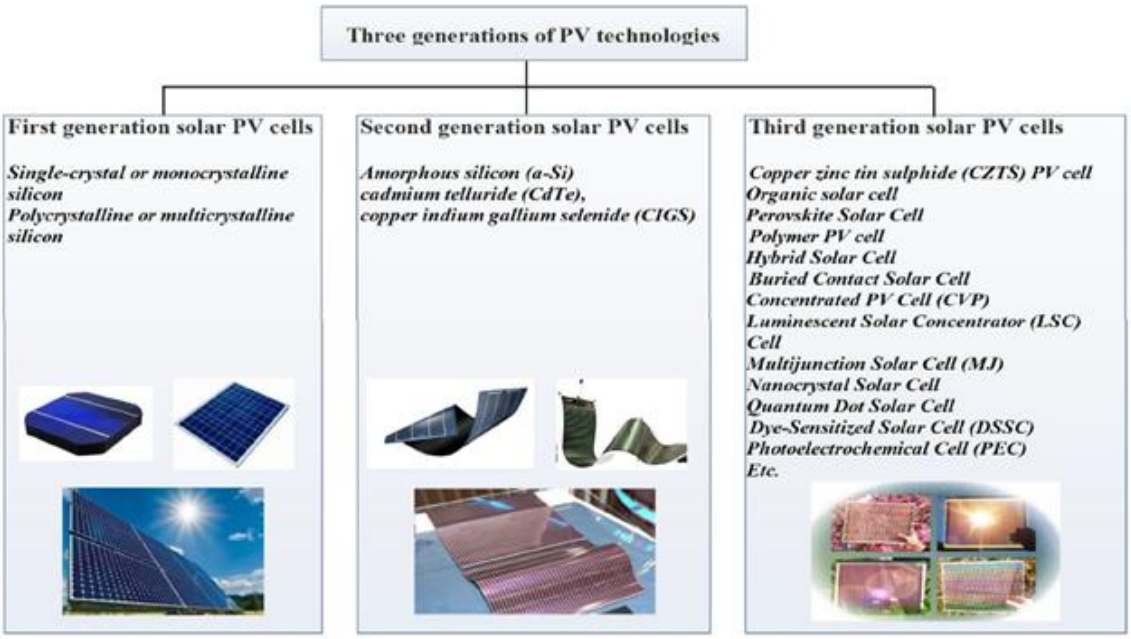

Fig. 3 Solar PV (PV) cells span three generations.

MODELS RELATED TO SOLAR PV CELL

Models of PV cell analysis that place an emphasis on electrical activity are found. Artificial neural networks also simulate the behavior of solar cells [25].

Ideal PV cell model

In Figure, it is shown that solar radiation has an effect on the P–N junctions in solar cells made of two semiconducting materials. 6.

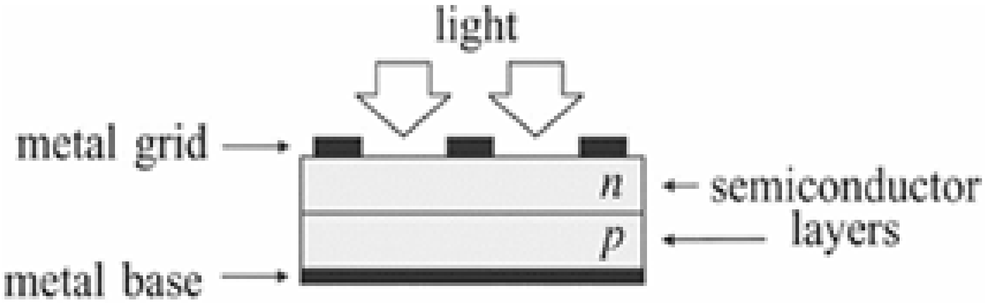

Fig. 4 Physical structure of PV cell

Eq. (1) is the Shockley equation for the solar PV cell's I–V curve and P–N junction diodes:

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

The electron charge is q, the diode voltage is VD, the Boltzmann constant is K, the saturation current is IS, the diode current is ID, and the temperature units are Kelvin in equation (1)[26]. Figure 5 shows the ideal solar cell. Solar cells use photons at the P–N junction to create electron-hole pairs. A photocurrent circuit is created when the electron hole pair creates a potential difference between the connections. The voltage-current curves are depicted in Fig. 6 [27]. The graphic shows current (I) as IPV and ID superimposed, despite the fact that the cell manufacturer may provide these numbers. Equation 2 depicts the photocurrent (IPV), which is influenced by the environment around it:

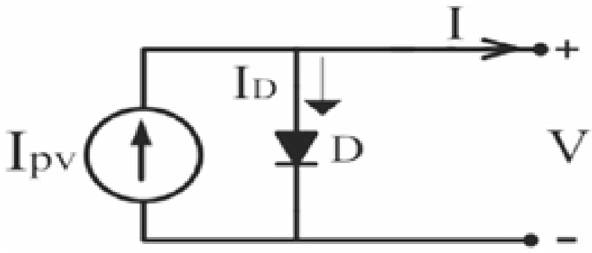

Fig. 5 Ideal solar cell model

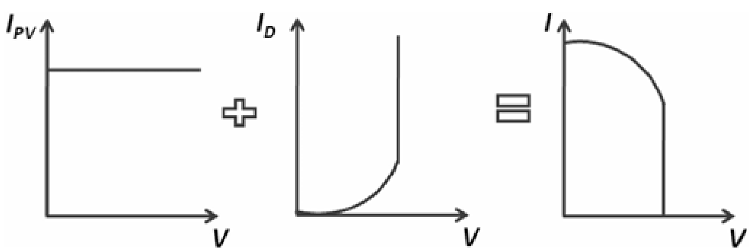

Fig. 6 I as a combination of ID and IPV

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

The IPV is the standard test condition (STC) at 25 °C, the temperature is called TSCT, the GSTC is called 1000 W/m2, and the photo current temperature coefficient is called Kl in Equation 2 [28]. Because photovoltaic and short circuit currents are nearly identical, diode current is ignored. Short for "short circuit current," ISC stands for Equation 3 depicts the ideal PV cell model as follows:

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

The open circuit voltage (VOC), maximum voltage (V), and current (I) are linked to solar radiation and temperature:

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

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

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

Maximum power voltage (Vmp), maximum current power (Imp), temperature coefficients of voltage and current (Kl), and thermal voltage (Vt) are the terms. Figure depicts the relationship between all of the terms in Equation (3). 7 [29].

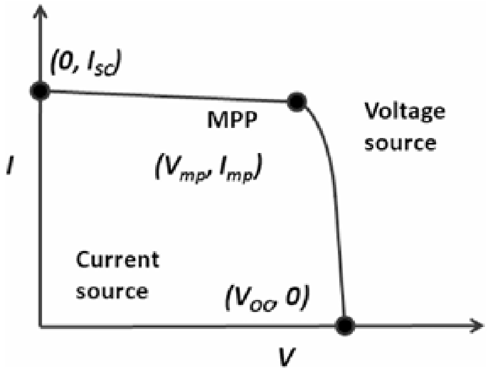

Fig. 7 I–V patterns of PV cell for Voc, Isc, Vmp and Imp

Resistance RS model single-diode based

Instead of simulating PV cells, the single diode ideal model is made to understand their concepts. For solar PV cells, the silicon, electrode surface, and resistance-based single diode-based resistance model is dependable and widely used [30]. Figure depicts the single diode resistance model's design. 8. It has terms for IPV, q, IS, and RS, and the I-V behavior is shown in Eq. (7). The ideal PV cell model is inferior to the single diode resistance model [31]:

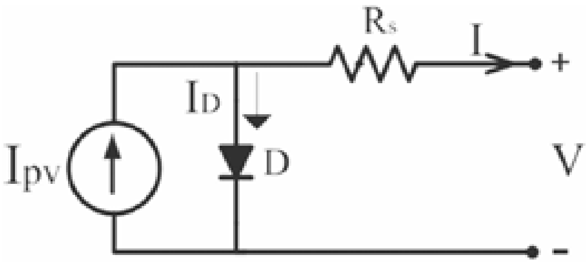

Fig. 8 Model RS with one diode

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

Single diode RP model

The single diode RP model layout diagram is depicted in Fig. 11, and it shows the I–V behavior in Eq as well as the IPV,, q, IS, RS, and RP parameters. (8)[32].To account for the leakage current at the P–N junction, the single diode PV model uses shunt resistance (RP):

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

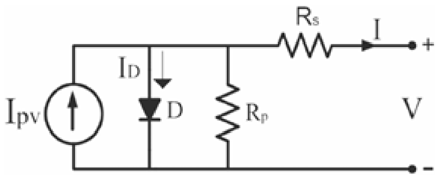

Fig. 9 Single diode RP model

The parameters of solar PV cells are primarily determined by the surrounding conditions. Equations (2) and (4) demonstrate that additional PV cell parameters are influenced by the surrounding environment [33].

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

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

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

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

Material energy bandgap diodes, for example, have a saturation current of IS,STC, a series and shut resistance of RS,STC, and a maximum factor of STC [34].

Two diode model

The two-diode model, which works well with low solar exposure, is depicted in Fig. 10. The second diode (D2) is used to account for current loss in the PV solar cell model. The I–V behavior of IPV, RS, RP, a, IS (first diode), and IS (second diode) is shown in Equation 13:

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

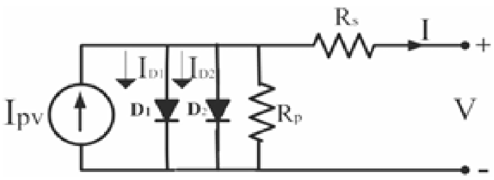

Fig. 10 Two diode RP model

PV cell thermal and other models

The single-diode model with capacitance, three-diode model, modified two-diode model, drift–diffusion model, and multi-dimension-diode model are just a few of the models that can be used to study solar PV cells[35].

PARAMETER ESTIMATION OF PV CELL METHODS

Numerous studies have utilized analytical techniques to extract model characteristics of solar cells. Research is categorized and analyzed in this area according to the solar cell model.

Single diode RS model

The four parameters are IPV, q, IS, and RS. Four equations can be used to calculate these four parameters. In their data sheets, PV manufacturers frequently include VOC, ISC, Vmp, Imp, KI, and KV. Significant equations can be presented using either Eqs. (19)–(21) and Eq. (25) or Eqs. (19)–(21) and Eq. (25) alone. (26):

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

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

According to (7), the short circuit point is

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

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

We have from Equations (15) and (17)

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

As a model, the saturation currents can be calculated by

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

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

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

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

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

$$\frac{dI}{dV} = \frac{-I_{mp}}{V_{mp}}. \quad (23)$$

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

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

We take the following equation, Eq. (25):

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

The slope of the I–V curve at a short circuit point yields another equation:

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

The RS model is presented in Table 1 and requires four associated terms for a single diode.

Table 1 ways to get the equations from RS models with just one diode

Key Concepts	**Details**
Ideality factor, I-V curve slope at OC and SC points	Factors chosen at random.
Ideality factor, I-V curve slope at OC and SC points	Factors chosen at random.
SC point, OC point, maximum power point, power derivative at maximum power	All points and derivatives are marked as zero.
Zero-voltage, one-current, and maximum-power points; power-voltage derivative	Power-voltage derivative is zero at zero-voltage, one-current, and maximum-power points.
SC point, OC point, maximum power point, power derivative at maximum power	Power derivative, maximum power point, SC point, and OC point are set to zero.

Single diode RP model

The single diode RP model is made up of is, Rs, IPV, and an. Model parameters are obtained through five equations. Sometimes, the range of diode ideality factors (IFs) [1, 2.5] is chosen at random:

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

As a result, we can write.

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

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

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

As a result, we can have

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

We can have by equating (28) and (30).

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

Therefore, we have

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

After adding Equation (32) to Equation (28), we now have

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

Based on Equation Eighth, Imp is defined as

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

We get after separating I from V in Equation (8).

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

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

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

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

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

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

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

RP and RPO are sometimes considered equivalent.

The five essential equations are derived from the data in Table 2, and the reference equations in single diode RP models depend on the slope of the I–V curve at the short circuit (SC) and open circuit (OC) points [36].

Table 2 single-diode RP models for equations

Variables Studied	**Details**
Voc, Isc, dP/dV = 0, Rpo, Rso	Focus on open circuit voltage (Voc), short circuit current (Isc), power derivative, and resistances.
Citation	Research referenced in the context of Voc and Isc studies.
Citation	Cited in context of Voc, Isc, Vmp, Imp, Rso, and Rpo studies.
Voc, Isc, Vmp, Imp, Rso, Rpo	Comprehensive analysis of voltage, current, and resistances.
Voc, Isc, Vmp, Imp, Rso, Rpo	Detailed study of electrical parameters.
Voc, Isc, Vmp, Imp, Rso, Rpo	Explored voltage, current, and resistance parameters.

Voc, Isc, Vmp, Imp, Rpo, dP/dV = 0	All parameters, including the derivative of power, were set to zero.
Voc, Isc, Vmp, Imp, Rso, Rpo	Comprehensive investigation of system variables.
Voc, Isc, Vmp, Imp, Rso	Focus on voltage, current, and series resistance (Rso).
A = 1, Voc, Isc, Vmp, Imp = 0	Set variables and conditions for specific scenarios.

FACTORS EFFECT ON THE EFFICIENCY OF THE PV CELL

Environmental factors

PV modules need sunlight all the time. PV module performance and efficiency are thus affected by environmental factors such as irradiance, temperature, dust dispersion, soiling, wind, shadow, humidity, and others. The subsequent sections [37] discuss these factors' effects.

Solar irradiance

The energy that enters a horizontal area at a specific wavelength and time is called the irradiance. PV panel output is affected by solar power or irradiance because of its volatility. Time resolution has an impact on sub second variability, which increases with resolution. The weather, seasonality, location, time of day, and position of the sun all have an impact on irradiance. With height, the position of the sun changes throughout the day. Overcast conditions, as depicted in Figure 11, result in varying IR values [38].

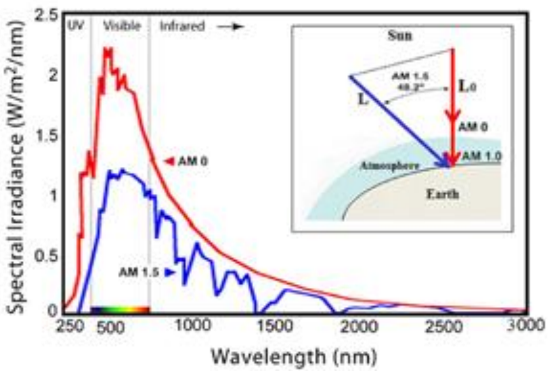

Fig. 11 Variation in the values of spectral irradiation

PV modules receive diffused light from the ground, the sky, and nearby objects in addition to direct sunlight (Fig. 12). It's important to be in direct sunlight. It is more difficult to calculate incident irradiance when adjacent objects cast shadows or reflect sunlight onto PV modules. The solar panel must be oriented toward the sun in order to receive the most sunlight. The ideal tilt angle is determined by the latitude. The tilt angle deviates from the latitude angle by approximately 15 degrees during the summer and winter [39].

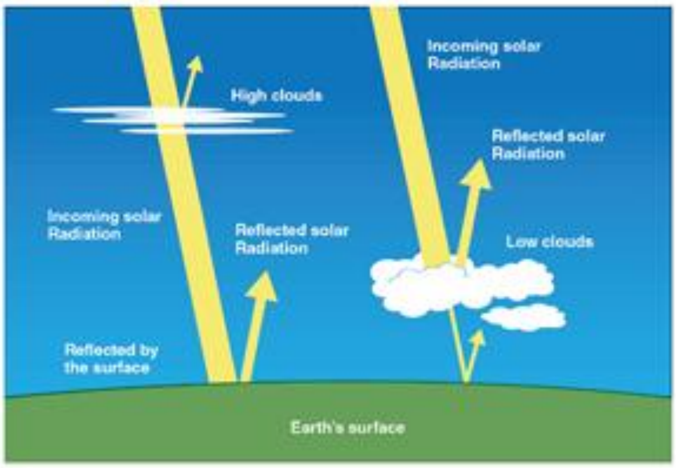

Fig. 12 Incoming solar radiation

Numerous solar tracking techniques are used to align PV panels with direct sunlight. One degree south azimuth loss results in a 0.08 percent decrease in irradiance. PV module production is boosted by irradiation [40]. Irradiance can be determined by the PV module using the linear G–P (sun radiation–output maximum power) curve. Due to the linear relationship between module current and irradiance, it is challenging to determine the proportion of solar irradiance that influences PV panel performance [41].

Temperature on photovoltaic cell performance

Photovoltaic cell power generation is affected by the temperature-dependent variation in solar cell efficiency. Voltage is strongly affected by temperature. Inverse relationship between voltage and temperature. PV power system output is affected by the environment. PV system efficiency, energy output, atmospheric parameters like temperature, irradiance level, dirt, and dust, as well as installation conditions like rooftop, floor, or water bodies are all affected by module temperature (Fig. 14)[42].

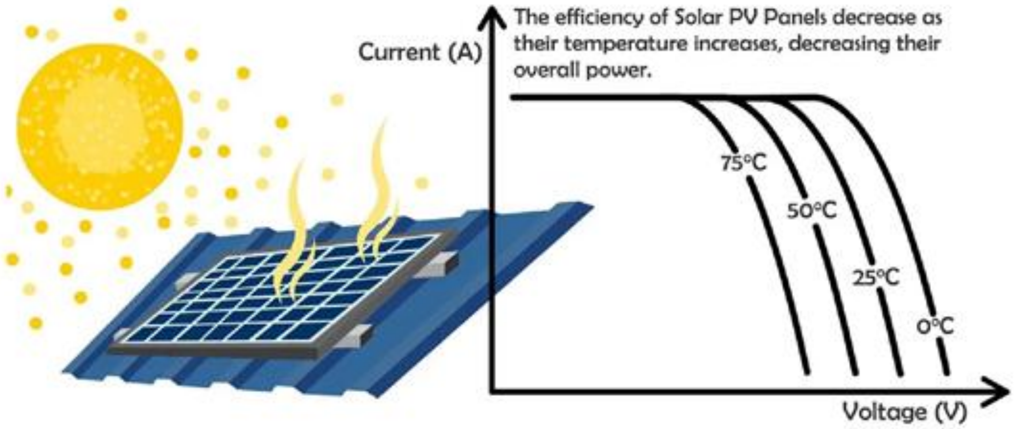

Fig. 13 Effect of panel temperature

Single crystal silicon solar cell efficiency is strongly impacted by operating temperature. At 56 °C and 1000 W/m2 radiation, the solar cell loses 3.13 percent of its efficiency. The fact that panel efficiency decreases by 69% at 64 °C and by 5% when the module temperature rises from 43 to 47 °C[43] demonstrates the effect of wind speed on temperature rise. For every 1 °C increase in solar cell temperature without cooling, electrical efficiency decreases by 0.03–0.05%. PV performance is affected by encapsulating or covering materials' heat absorption and dissipation.

Dust accumulation

Debris, water vapour, air molecules, and other atmospheric pollutants prevent sunlight from reaching PV modules, reducing their efficiency. Solar irradiance is decreased when airborne dust particles larger than the sun's beam reflect sunlight (Fig. 14). The PV module might get covered in a lot of dust. Dust layer optical properties can be altered to increase PV module output by enhancing surface transmissibility, light reflection, and absorption. The speed of the wind, humidity, rainfall, dust source, particle type, PV module technology, and surface coverage all have an impact on dust accumulation[44].

Fig. 14 Dust accumulation on the PV cell

It gets worse in dry deserts with a lot of dust. A study conducted in Saudi Arabia found a monthly efficiency decrease of 6–7%, which could reach 13% after six weeks without cleaning. Egypt's monthly power output is estimated to have decreased by 17.4 percent due to a lack of cleaning. PV energy production is reduced by approximately 60% due to air pollution caused by ants, poisonous gases, suspended particles, and dust. Gravity causes dust to accumulate on module covers [45]. When exposed to humid air, these particles produce sticky mud on surfaces. The transmittance of the glass cover decreases by 20% after 45 days of dust accumulation. Rain clearly affects dust deposition. When Egypt receives 18-50 millimeters of precipitation annually, PV power production drops to 60-70%. The UAE and Qatar, which receive 70–75 millimeters and 80–90 millimeters of precipitation annually, have a 10% lower PV power generation decline than Egypt[46].

Soiling

PV modules may also be tainted by dust. Mud forms when dust on PV surfaces collects water from the air in humid conditions. Dust particles stick to PV surfaces, so dust deposition increases with absolute humidity. Capillary bridges between particles and surfaces are also created as a result of solar PV module vapor condensation. Meniscus forces increase both the production of dust and the adhesion of particles [47]. Soil obscures the soft and hard surfaces of PV panels, reducing power. Panel soil mass or muck, in contrast to air haze, shades hard. While some high-shading PV module cells reduce voltage, unshadow cells receive solar irradiation, so current is unaffected. Because different kinds of dust alter the way light is transmitted, PV power loss from soiling varies by location [48]. PV power loss and certain soiling are inextricably linked. The mass increase of new soil dust particles does not block light because the surface is already dusty. After 40 days, coated glass transmittance decreases by 30% and uncoated glass by 37%, according to Saudi Arabian research. 55 With a tilt angle of 35 degrees and average rainfall intervals, transmission loss varies by type of glass in Belgium: self-cleaning (1.30%), anti-reflection (1.75%), standard (2.63%), and multilayer (0.85%)[49]. Panels become dirtier at angles of flattened tilt. Hydrophobicity improves transmission and reduces panel dust. By adjusting roughness and surface energy, this is made possible. Soil can be rebuilt by water and rain [50].

Wind velocity

Wind speed and direction have an impact on a solar module's power output. Wind's effect on PV performance is measured using module temperature, surface structure, and dust deposition[51]. Convective heat transfer caused by wind movement is the most cost-effective cooling method (Fig. 15). PV cell temperature rises more quickly with wind speed than with wind direction. Surface structure and shape affect PV panel convection cooling. Structured and grooved glass cover surfaces may be useful in areas with lower temperatures and higher wind speeds [52].

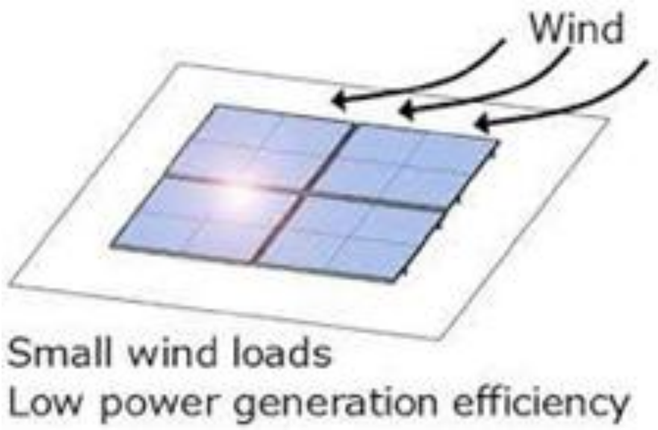

Fig. 15 Wind velocity on the solar PV cell

However, flat surfaces cool more when the wind is at a lower speed. According to US studies [53], a glass cover with grooves could lower the operating temperature by 3.5 °C for winds of 10 m/s. With a wind speed of 12 m/s, Slovenia could cut its operational temperature by half and cut the KSA by 10 °C. Additionally, 88 Wind reduces dust deposition on PV modules. An Egyptian study found that wind reduces module dust at a specific tilt. Because the wind blows a lot of sand and dust into the desert, it suffers. Libya's breeze accelerates dust accumulation on PV surfaces [54].

Shading

Shade is a PV panel that blocks light. Shadowing reduced PV power generation. Self-shading, harsh shading, and soft shading are all types of shades. Debris like snow, leaves, bird droppings, and dust provide hard shading. In some way, poles, buildings, and trees all block sunlight. Depending on the module's location, array configuration, and shade, PV module output is significantly reduced by a partial or complete shadow. PV module production is decreased by partial shadowing because shaded cells are unable to generate current [55]. Shaded cells lose energy as a result of the current that comes from nonshaded cells into them. In darkened areas, the maximum power point tracker (MPPT) may differ from the global MPP, resulting in lower energy production. Numerous researchers have investigated and developed technological means of reducing shading losses in full or in part (Fig. 16)[56].

Fig. 16 shading on the solar PV cell

Humidity

The accumulation of tiny water droplets and water vapor on solar panels is affected by the air's relative humidity. Solar cells lose power when water droplets scatter, reflect, or refractive sunlight away from them. Since smaller water vapor particles scatter more, humidity changes radiation intensity nonlinearly. Because the solar cell allows moisture in, PV modules corrode when exposed to humidity for an extended period of time. Module housing moisture also increases electrical conductivity and leakage currents (Fig. 17)[57].

Fig. 17 Humidity on solar PV cell

Water condensation at the encapsulant-solar cell interface may also increase corrosion rates, resulting in delamination. A desiccant hermetic seal or encapsulant with a low diffusivity may prevent module performance degradation. High relative humidity (RH) also causes sticky and adhesive dust layers to form on PV surfaces, which can lead to soiling and a decrease in power output. Solar cell efficiency rises from 9.7 to 12.04 percent when relative humidity drops from 60 to 48%. Power generation is reduced by 3.16 W by increasing relative humidity by 20%[58]. Another study found that at 76.3% relative humidity during the rainy season, PV power production decreases by 40%, while at 60.5% relative humidity during the gloomy season, PV power production decreases by 45%. Moisture reduces irradiance, but dust adhesion loss on the module surface can be restored with proper cleaning.

OPERATION AND MAINTENANCE FACTORS

Modules for photovoltaic systems degrade over time. However, operational and maintenance factors may reduce degradation and increase the economic viability of PV modules. Below, we'll go over a few of these issues [59-61].

Panel degradation

Panel degradation is the gradual deterioration of a PV system that may affect its power output. A panel is considered degraded when its power falls below 80% of its initial power, according to manufacturer guidelines. Mechanical trauma, radiation, temperature, and humidity all cause damage to PV panels. Another issue is the development of hotspots because cells are damaged by high temperatures (Fig. 18). Series-connected cells that are partially shaded, damaged, or misaligned cause hotspot heating. Methods for reducing hotspots were identified by studies. Hotspot detection made it possible to respond quickly and precisely. By addressing these issues, losses in power generation can be avoided [62].

Fig. 18 Solar PV panel degradation

Cleaning methods

Dust and soiling reduce PV power generation and glass transmittance. According to studies, regular cleaning and the right method of cleaning might make it work better. In desert conditions, the research suggested cleaning the PV module every 20 days. Particulates produced by burning fossil fuels are a significant PV contaminant. The researchers looked into the damage, the cleaning method, and the cleaning agent. When devising the ideal cleaning strategy, model pattern, PV capacity, and power generation should all be taken into consideration [63].

- **Natural cleaning** Figure 21 depicts the natural cleaning of solar PV panels. The elements of wind and rain naturally clean PV panels. The tilted panels make it possible for rainwater to remove dust particles, which encourages natural cleaning. However, this method frequently leaves panels covered in damp dust that needs a lot of rain to get rid of. When there is a lot of soiling and not enough rain, this method might not be able to remove the soil. Simulated the suspension of dust particles from 0.1 to 100 mm and discovered that dust particles larger than 1 m are readily dispersed by wind to analyze the impacts of natural PV module cleaning by air movement at 0.23–57.56 m/s[64]. reports say dust deposition during dry seasons may impede rain, reducing PV effectiveness by more than 20%.

Fig. 19 Natural cleaning on solar PV cell

- **Water cleaning** Using constant high-pressure water, this method removes PM from PV panels that are contaminated. PV panels can be cooled and cleaned by mixing presaturated water with a cleaning solution in semi-arid and desert climates. Figure 20 depicts how solar PV cells clean water. The experimental study that used water spraying found that the back surface and headboard surface temperatures dropped by 39% and 45.5%, respectively. The cleaned and cooled panel performed better in tests than the uncleaned and uncooled panel, which performed less well by 9%. Egyptian researchers found that natural water flow reduced PV efficiency by 50% after 45 days.
- **Manual cleaning** Dust is manually removed from PV modules with bristle brushes to prevent scratches. It restores the surfaces of solar panels more effectively than rain washing. Investigated methods for cleaning nylon, cotton, and silicone rubber in order to increase PV efficiency. Al demonstrated that PV does not remain in pure water. Consequently, pure water cleans better than detergent, network water, or liquid soap. Following the trial, the authors suggested using a sponge, velour, chamois, glass razor, and squeegee. The efficiency of power conversion is affected by squeegees by 19.62%, 19.37%, and 17.87%, respectively.
- **Mechanical cleaning** Better than rain and air, an automated and mechanical water system (Fig. 20) cleans. A study found that cleaning and cooling PV panels with robotic water spray increased efficiency by 15%. During dry seasons, panel cleaning should be done once a week, and during dusty ones, it should be done every day. Their research automates cooling using sensors and a microcontroller. Cleaning panel surfaces takes less time, despite the fact that it requires power.

Fig. 20 Mechanical cleaning on solar PV cell

- **Self-cleaning** material PV modules can be cleaned on their own if they have hydrophilic or hydrophobic properties. A waterfall on a hydrophobic surface removes debris from the surface. This method coats the PV surface with a hydrophobic coating and a thin barrier layer to prevent water from adhering. "Active cleaning" refers to the process of water picking up debris as it moves across the surface. Due to its chemical bond with the PV surface, the TiO2 nanofilm is highly hydrophilic. Glass is covered with TiO2 coatings to make it self-cleaning.

PERFORMANCE ANALYSIS OF PV MODULE

Above, we talked about how factors affect the performance of solar PV cells. In order to comprehend the performance of solar PV cells, experimental research was carried out. In Hyderabad, India, the Center for Diagnostics and Finger Printing installed a 500 KWp solar power generator. 2.25 m2 polycrystalline silicon solar panels were sold by Sunlight Solar Systems. The solar module has a capacity of 315–340 W at 17.52 percent efficiency under standard test conditions (STC). To produce 500 KWp, 1516 solar panels are required. Silicon appears to be the most promising material for solar cells, accounting for 48 percent of the market. Manufacturing monocrystalline solar cells is cost-effective, but their efficiency is only 12 to 14 percent. As a result, polycrystalline silicon solar cells are utilized in this study [65]. Figure 21 depicts a schematic of a 500 kWp solar PV power generation system and a block diagram of its various components and assembly. 25. Six inverters make up the plant's solar PV production system. Two of them are 50 kVA and connect to 50 kWp modules. There are 61 strings with 20 modules each for 400 kWp. 500 kWp of solar PV production is connected to the main LT panel, which is connected to loads and exports surplus electricity to the Grid via net metering. Each 50 kWp has 8 stings with 19 units each and is connected to 50 kVA inverters. The AC load output is received by the Main electrical LT DB. Electricity generation makes use of the existing load requirements and adds additional load to the power grid through net metering. The customer will pay bills in net units in accordance with the system's import and export units. Grid-connected solar PV facilities up to MWp are possible. In Figure, 1516 solar modules are assembled. Smaller PV plants operate independently. 26. Through the steel frame, each module stood 7 feet tall. Power conditioning devices include MPPT, inverter, grid interface, and controller protection interface.

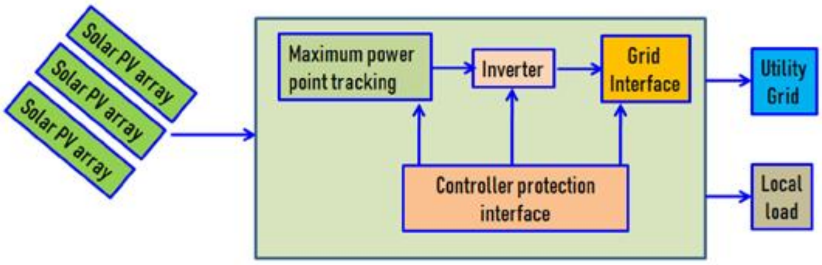

Fig. 21 Sketch of solar PV generation and utility

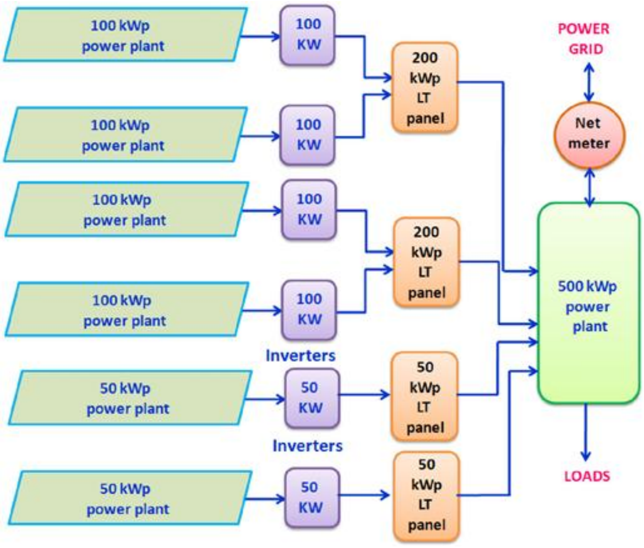

Fig. 21 For a 500 kWp solar PV generation system, a block diagram showing various accessories and their assembly

Fig. 22 Photograph of solar PV plant installations

The solar PV cell power was monitored for five months and was 301,361 kWh, or 60,272 kWh on average per month. The cost was determined using the power of solar PV cells. The 500 kWp solar power plant costs 19,500,000 INR to construct and generates 427,484 INR per month. The government's unit kWh cost is multiplied by the amount of electricity produced (60,272 INR) to determine plant revenue. This study shows that the payback time is 3.8 years. Figure 23 depicts the 62009 kWh of electricity produced in January 2020. The Indian metrological department reports that the irradiation from the sun in January is 149.8 kWh/m2:

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

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

The solar PV modules' performance ratio of 82.77% indicates excellent power generation. The solar PV module's performance deteriorates over time. Both environmental factors and PV module technology have an impact on the rate of deterioration. The hazardous chemicals used to clean and purify the semiconductor surface during the manufacturing of solar PV cells, such as HCL, H2SO4, HNO3, HF, and C3H6O, are determined by the size of the silicon dust and the amount of cleaning required [66].

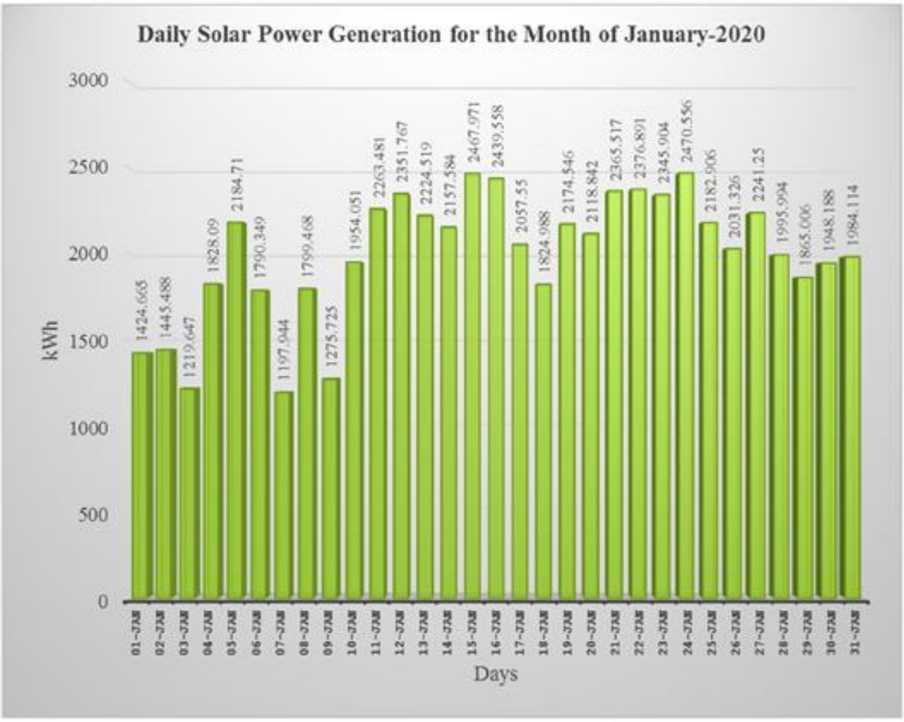

Fig. 23 Generation of solar PV for the month of January in 2020

COMPARATIVE ANALYSIS OF SOLAR PV SYSTEM MODELING AND SIMULATION TECHNIQUES

Solar photovoltaic (PV) systems are influenced by several environmental and operational factors, making their performance analysis crucial for efficiency enhancement. Different techniques have been developed to model, simulate, and estimate solar cell parameters, each with its own advantages and limitations. This comparative analysis draws on recent studies and experimental works from the provided documents to examine various approaches and simulation tools.

Techniques for Parameter Estimation and Modeling

Analytical Methods

Analytical methods are often used for modeling solar cell parameters based on algebraic equations that derive from current-voltage (IV) characteristics. These methods are simple, fast, and suitable for practical applications but lack accuracy due to their reliance on specific points and approximations.

Numerical Methods

Numerical methods use iterative algorithms to solve the diode model equations explicitly. Techniques like the Newton-Raphson and least-squares methods are employed but are prone to local optima issues. In contrast, heuristic approaches like Particle Swarm Optimization (PSO) and Teaching-Learning-Based Optimization (TLBO) are more robust and widely used.

Meta-Heuristic Algorithms

Meta-heuristic methods are increasingly used for parameter estimation in PV systems due to their adaptability and ability to handle complex, non-linear optimization problems. Common techniques include:

- **Genetic Algorithms (GA)**

- **Particle Swarm Optimization (PSO)**
- **Teaching-Learning-Based Optimization (TLBO)**
- **Grey Wolf Optimization (GWO)**
- **Whale Optimization Algorithm (WOA)**

These methods efficiently extract parameters from data, especially when dealing with complex IV curves and non-standard operating conditions.

Experimental Software for Solar PV Analysis

MATLAB/Simulink

Widely used for modelling and simulation, MATLAB/Simulink allows the integration of control strategies and dynamic simulation of PV systems. It is useful for simulating effects of environmental factors like temperature and solar irradiance on PV performance.

SCAPS-1D (Solar Cell Capacitance Simulator)

SCAPS-1D is a powerful tool for analyzing solar cell performance, including IV characteristics, quantum efficiency, and capacitance-voltage behavior. It can simulate multi-layer solar cells and study the effect of temperature variations and material properties.

PVsyst

A software tool dedicated to the design and simulation of PV systems. It offers a detailed analysis of energy production, system losses, and performance ratios. It is particularly useful for large-scale PV installations.

COMSOL Multiphysics

COMSOL provides finite element analysis for solar cells, including multi-physics simulations that combine thermal, electrical, and optical properties. It is suitable for detailed analysis of device physics but can be computationally intensive.

Comparative Analysis of Techniques

Technique	**Advantage**	**Limitation**	**Suitable Software**
Analytical Methods	Fast and straightforward	Prone to inaccuracies	MATLAB, Simulink
Numerical Methods	Better accuracy with iterative solutions	Prone to local optima	MATLAB, SCAPS-1D
Meta-Heuristic Algorithms	Robust and adaptable to various conditions	Computationally demanding	MATLAB, SCAPS-1D, COMSOL
Experimental Simulation	Real-world data integration, dynamic modeling	Hardware and setup cost	PVsyst, COMSOL, MATLAB

Notable Findings from Experimental Studies

- **Impact of Temperature:** Increasing PV panel temperature significantly reduces efficiency due to reduced open-circuit voltage.
- **Dust and Soiling:** Accumulation of dust on PV modules can reduce efficiency by up to 92% in polluted environments.
- **Cooling Strategies:** The use of DC fans to regulate panel temperature has been shown to maintain efficiency under high temperature conditions.
- **Optimization Approaches:** TLBO and PSO are proven effective in parameter extraction, especially in systems where real-time data is incorporated.

Recommendations for Practical Implementation

- **Software Choice:** Use MATLAB/Simulink for early-stage modeling, SCAPS-1D for detailed device simulations, and PVsyst for large-scale energy performance analysis.
- **Algorithm Selection:** Meta-heuristic algorithms (like TLBO and PSO) are preferable for real-time data analysis and parameter extraction.
- **Environmental Considerations:** Integrate cooling mechanisms and dust mitigation strategies into the PV system

design to enhance longevity and efficiency.

Combining analytical, numerical, and heuristic methods allows for a comprehensive approach to solar PV performance analysis. The choice of technique and software should align with the specific application, whether it's system design, real-time monitoring, or degradation analysis.

For more information, refer to the detailed studies and reviews from the uploaded documents:

- Energy Conversion and Management: X.
- International Transactions on Electrical Energy Systems.
- International Journal for Modern Trends in Science and Technology.

2. CONCLUSION

Solar PV technology's efficiency and cost-effectiveness can only be improved by addressing operational and environmental issues, according to a study of the characteristics that affect its performance. The efficiency with which solar cells convert energy and their overall output are harmed in significant ways by factors such as temperature swings, humidity, accumulation of dust, and soiling. Innovative mitigation measures are urgently required due to the multiplicative effects of these factors, particularly in remote or dry locations where performance degradation is exacerbated by wind-borne particles and thick dirt layers. Innovations in cleaning technology, operational efficiencies, and semiconductor materials are essential for overcoming these obstacles.

Solar PV systems that follow these principles may have longer operating lifespans, higher levels of dependability, and improved efficiency. We can reduce our reliance on fossil fuels and our impact on the environment by utilizing solar energy, which is renewable and lasts a long time. The potential of solar photovoltaic (PV) technology as an essential component of long-term, environmentally friendly power systems is further demonstrated by this research. A future with energy that is cleaner and more sustainable is within reach as a result of ongoing research and development that optimizes performance while taking into account the effects on the environment. Producing solar energy will consequently become even more attainable and scalable

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