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A study on photovoltaic parameters of mono-crystalline silicon solar cell with cell temperature

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ABSTRACT

In this study, the effect of cell temperature on the photovoltaic parameters of mono-crystalline silicon solar cell is undertaken. The experiment was carried out employing solar cell simulator with varying cell temperature in the range 25–60 °C at constant light intensities 215–515 W/m^2. The results show that cell temperature has a significant effect on the photovoltaic parameters and it controls the quality and performance of the solar cell. The open circuit voltage, maximum power, fill factor and efficiency are found to be decreased with cell temperature. The reverse saturation current increases with cell temperature and a slight increment is observed in the short circuit current. The temperature coefficient of the open-circuit voltage, fill factor and maximum output power is found to be negative while positive for the short circuit current. The relative change study of photovoltaic parameters with temperature is also undertaken. The relative changes are found from −0.0022/°C to −0.0025/°C, 0.002/°C, −0.0013/°C and −0.002/°C for open circuit voltage, short circuit current, fill factor and maximum output power respectively. The results are in good agreement with the available literature.

1. Introduction

The solar energy is one of the most important renewable energy due to its easy availability, cleanness and cheap energy resources. Now days, a number of solar energy approaches are in progress and solar cells have paid more attention due to rapidly developing technology and potential applications to cater the energy demands of the developing world and the society. The solar cell is a device which directly converts electrical energy from the solar radiation which is based on the photovoltaic effect. Mono-crystalline silicon (mc-Si) solar cell is a part of silicon solar cell family and one of the first developed and mostly used solar cells because it has a number of advantages like low maintenance cost, high reliability, noiseless and eco-friendly (Cuce et al., 2013; Cai et al., 2012; Singh and Ravindra, 2012; Solanki, 2013; Fesharaki et al., 2011; Radziemska, 2003; Amouche et al., 2012; Sharma et al., 2014). The overall performance of mc-Si solar cell strongly depends on the environmental parameters such as light intensity or irradiance, tracking angle and cell temperature (Khan et al., 2010; Skoplaki and Palyvos, 2009; Chegaar et al., 2013). Though the photovoltaic parameters like open-circuit voltage, short circuit current, maximum output power, fill factor and efficiency are generally affected with cell temperature yet maximum influence is recorded in the open circuit voltage. So, the open circuit voltage of solar cell is highly sensitive to the cell temperature. The open-circuit voltage, fill factor and maximum output power decrease with temperature while short circuit current increases with temperature therefore temperature coefficient of the open-circuit voltage, fill factor and maximum output is negative as well as positive for the short circuit current. Kim et al. (2013) reported the effect of surface texturing process on the crystalline silicon solar cells using saw-damage etching and concluded that there was no difference between the morphologies and reflectance for each surface condition after one hour of texturing process. A study of electrical characteristics of crystalline silicon cell diodes with cell temperature and frequency was undertaken by Choi et al. (2012). They found that the ideality factor was decreased in space-charge region with temperature and increased in quasi-

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Nomenclature

I	Current
I_0	Reverse saturation current
q	Electron charge (1.602×10^{-19} Coulomb)
V	Voltage
R_s	Series resistance
n	Ideality factor
k	Boltzmann's constant (1.381×10^{-23} J/K)
T	Temperature
R_{sh}	Shunt resistance
I_L	Light generated current
I_{sc}	Short circuit current
V_{oc}	Open circuit voltage
$P_{\max}$	Maximum power point
FF	Fill factor
η	Efficiency
$I_{0\,\max}$	Maximum reverses saturation current
E_g	Energy band gap
$V_{\max}$	Maximum voltage
$I_{\max}$	Maximum current
P_{in}	Input power
$I(t)$	Light intensity or irradiance
A	Surface area of silicon solar cell

neutral region. Tsuno et al. (2005) investigated the dependence of temperature and irradiance on current–voltage characteristics of different solar cells using linear interpolation method and observed that the physical validity of the linear interpolation for the temperature was based on the current–voltage characteristics of the p–n junction devices. Gandia et al. (2001) suggested a new procedure to evaluate the spectral mismatch parameter as a function of light intensity for the accurate indoor measurement of current–voltage characteristics of solar cells. They analyzed that there was no need to use similar reference and test cells for the measurement of current–voltage characteristics of solar cells. Sabry and Ghitas (2008) reported the influence of temperature on series resistance of silicon solar cells and found that the series resistance was varied with temperature and illuminations. The cell temperature is the key parameter to decide the quality and performance of crystalline silicon solar cell (Dubey et al., 2013; Arjyadhara et al., 2013; Reich et al., 2009; Lammert and Schwarts, 1997; Saran et al., 2013; Coello et al., 2004). The current–voltage characteristic of a crystalline silicon solar cell (Khan et al., 2010).

$$I = I_0\left[\exp\left(\frac{q\,(V - IR_s)}{nkT}\right) - 1\right] + \left(V - \frac{IR_s}{R_{Sh}}\right) - I_L. \quad (1)$$

Here, I_0 is the reverse saturation current, q is electron charge, n is the ideality factor of diode, k is Boltzmann constant, T is the temperature, R_s is the series resistance, R_{sh} is the shunt resistance and I_L is the light generated current of the silicon solar cell. To control the quality and determine the performance of a solar cell, an accurate knowledge of environmental parameters is required. The environmental parameters always play a significant role on the performance characteristics of silicon solar cells. Hence, there is a need to study such parameters with accuracy and to bridge this gap, a study on the influence of cell temperature on photovoltaic parameters of mc-Si solar cell employing solar cell simulator is undertaken in this paper. The experiment was carried out with cell temperature in the range 25–60 °C at constant light intensities between 215–515 W/m^2. The relative change in photovoltaic parameters with temperature is also calculated.

Table 1
The variation of light intensity of two Halogen lamps with different glass plates and filters.

Status	Light intensity (W/m^2)
Without any glass/filter	515
With clear glass	400
With frosted glass	280
With filter (First)	215

2. Experimental details

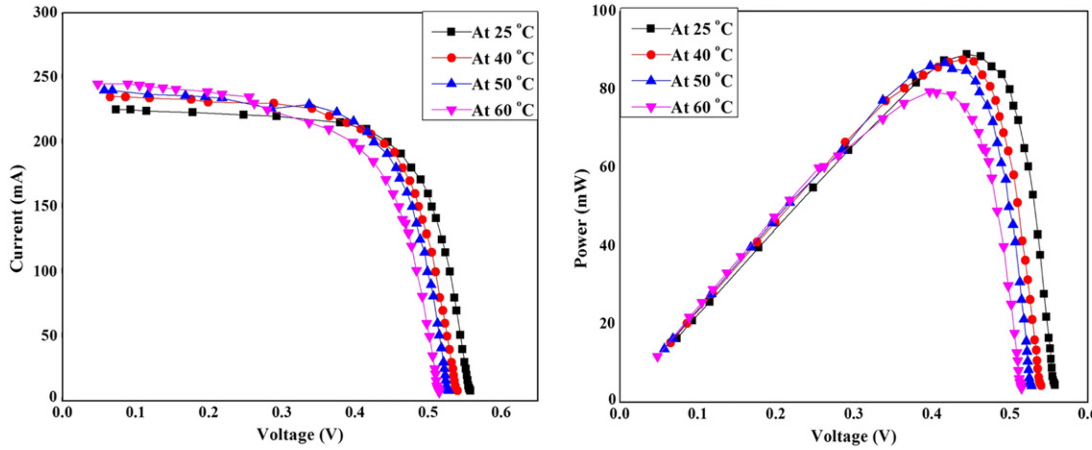
A mono-crystalline silicon solar cell of (4 × 4) cm^2 area was used and the experiment was undertaken employing solar cell simulator with cell temperature in the range 25-60 °C at constant light intensities 215–515 W/m^2 of simulated two quartz Halogen lamps (OSRAM 50 W, 230 V each). The light intensity or irradiance of Halogen lamps was measured by solar power meter. To reduce the intensity of these lamps, various types of glass plates and a number of gray filters were introduced between assembly of lamps and lower chamber of the solar cell simulator. The light intensity of Halogen lamps with different glass plates and filters is illustrated in Table 1. The frosted glass plate helps to diffuse the light and to make it uniform especially if perforated metal plates are used as light attenuators to reduce the light intensity. An exhaust fan was used to cool the solar cell simulator during the entire period of acquisition of the experiment and a temperature control unit was also used to vary the cell temperature. The temperature control unit comprises a heater and temperature sensor to stabilize the required temperature of mc-Si solar cell and it controls the temperature from room temperature to 80 °C. The mc-Si solar cell was used as a power source, current–voltage and power–voltage characteristics were taken into account and photovoltaic parameters were calculated. The relative changes in photovoltaic parameters with cell temperature were also calculated.

3. Results and discussion

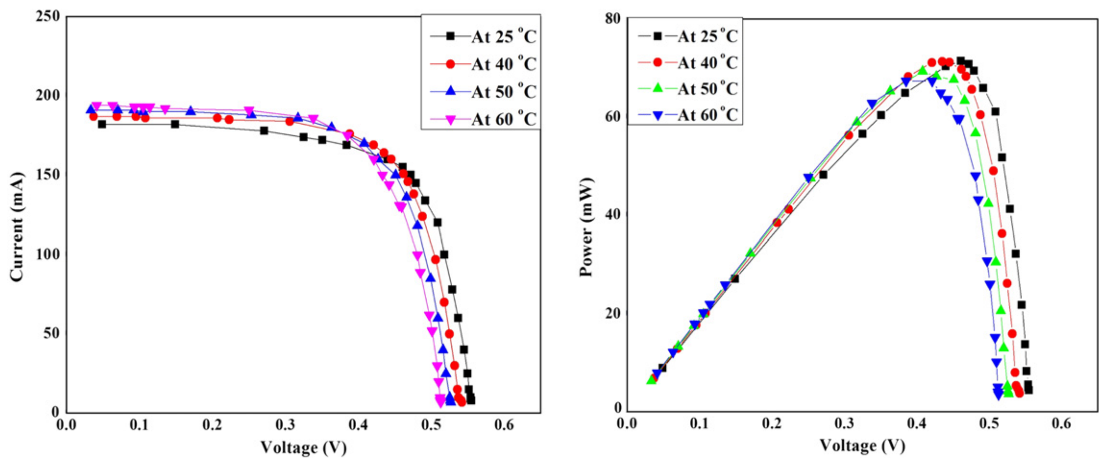
The current–voltage and power–voltage characteristics of mc-Si solar cell with cell temperature at constant light intensity are presented in Fig. 1. The observations were undertaken for cell temperatures 25 °, 40 °, 50 ° and 60 °C at the constant light intensities 215, 280, 400 and 515 W/m^2.

It is clearly visible in Fig. 1(a)–(d) that the current–voltage and power–voltage characteristics depend on the cell temperature. In the current–voltage characteristics, it is observed that the current is maximum as well as almost constant in the lower voltage range and varies with cell temperature in the range 100–120 mA, 125–140 mA, 170–190 mA and 220–240 mA at constant light intensities 215 W/m^2, 280 W/m^2, 400 W/m^2 and 515 W/m^2 respectively. The characteristics estimation follows the order of cell temperature as the successive higher underestimates the lower one. The trend is reversed about voltage 0.3 V, 0.375 V, 0.385 V and 0.4 V for intensities 515 W/m^2, 400 W/m^2, 280 W/m^2 and 215 W/m^2 respectively. Thereafter, the current is found to be decreased rapidly and reached to minimum in the range 6–8 mA with voltage between 0.5–0.58 V and the characteristics corresponding to successive lower cell temperature are existed beyond the higher.

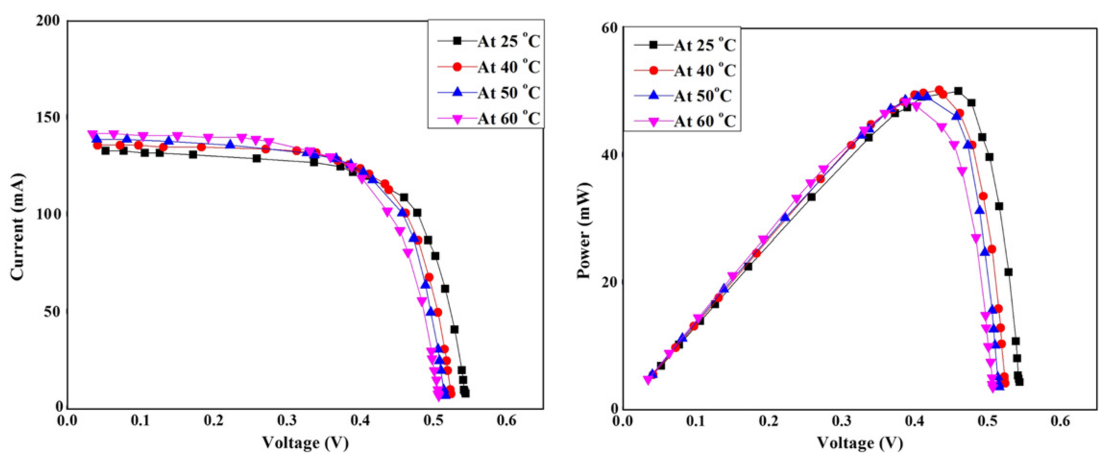
Similarly, the power–voltage characteristics estimation follows the same trend to the current–voltage characteristics. The power is started from the range 2–8 mW for all temperature and constant light intensities. It is observed to be increased and found almost linear with cell temperature at low voltage range, reached to maximum in the range 35–90 mW for the all constant light intensities. Thereafter, it is found to be decreased rapidly at higher voltage range owing to the increasing rate of photon generation with cell temperature which revealed the rapid increment in the



(a) Light intensity at 515 W/m^2.



(b) Light intensity at 400 W/m^2.



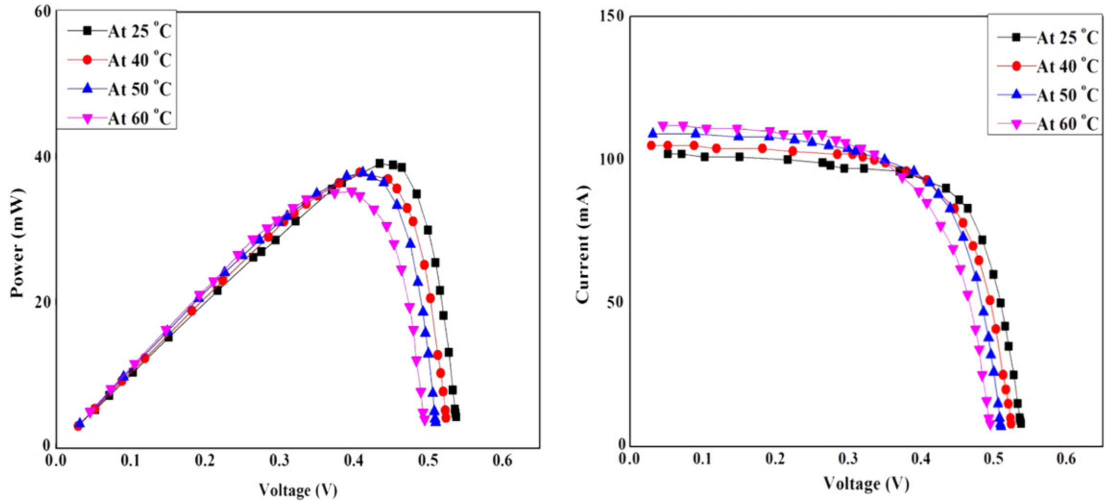
(c) Light intensity at 280 W/m^2.

Fig. 1. The current–voltage and power–voltage characteristics of mc-Si solar cell with cell temperature at constant light intensities (a) 515 W/m^2, (b) 400 W/m^2, (c) 280 W/m^2 and (d) 215 W/m^2.

reverse saturation current as reported by Arjyadhara et al. (2013). The power–voltage characteristics clearly show a point of maximum power and the voltage at this point is less than the open circuit voltage. Similarly, the current at this point is also less than the short circuit current. The variation in current and voltage is nearly identical at this point for different cell temperatures. These results are similar to the earlier reported work (Fesharaki et al., 2011; Sabry and Ghitas, 2008).

The temperature dependence effect on photovoltaic parameters like open circuit voltage, short circuit current and fill factor with cell temperature in the range 25–60 °C at constant light intensities 215, 280, 400 and 515 W/m^2 is shown in Fig. 2.

It is seen from Fig. 2 that the open circuit voltage (V_{oc}) and fill factor (FF) are found to be decreased with cell temperature while the short circuit current (I_{sc}) is increased slightly. The open circuit voltage, short circuit current and fill factor are varied with



(d) Light intensity at 215 W/m^2.

Fig. 1. (*continued*)

cell temperature in the range 0.495–0.558 V, 112–245 mA and 0.651–0.704 respectively for all constant light intensities. These results are in agreement with the literature (Fesharaki et al., 2011; Arora and Hauser, 1982; Emery and Osterwald, 1987) and their explanation are also given on the basis of Eqs. (2) and (3) those are described in the earlier work (Cai et al., 2012; Singh and Ravindra, 2012; Lammert and Schwarts, 1997). The relative changes study of open circuit voltage, short circuit current, fill factor and maximum power is also calculated and is given by the relations (4)–(6).

The cell temperature dependent open circuit voltage (V_{oc}) is given by the relation concerned (Cai et al., 2012).

$$V_{oc} = \frac{E_g}{q} - \frac{nkT}{q}\left(\ln \frac{I_{0\,\max}}{I_{sc}}\right). \tag{2}$$

Here, E_g is the energy band gap and $I_{0\,\max}$ is the maximum reverses saturation current. The fill factor (FF) is given by the relation concerned (Singh and Ravindra, 2012).

$$FF = \frac{P_{\max}}{V_{oc} \times I_{sc}} = \frac{V_{\max} \times I_{\max}}{V_{oc} \times I_{sc}}. \tag{3}$$

Here, $V_{\max}$ and $I_{\max}$ are the voltage and current respectively corresponding to the maximum output power. The relation for short circuit current is available in the literature (Lammert and Schwarts, 1997). The relative change in the open circuit voltage (V_{oc}), short circuit current (I_{sc}) and the fill factor (FF) with cell temperature were calculated and given by the relations (4)–(6).

$$\frac{1}{V_{oc}}\frac{dV_{oc}}{dT} \approx -\,(0.0022 \text{ to } 0.0025) \text{ per °C} \tag{4}$$

$$\frac{1}{I_{sc}}\frac{dI_{sc}}{dT} \approx 0.002 \text{ per °C} \tag{5}$$

$$\frac{1}{FF}\frac{d(FF)}{dT} \approx -0.0013 \text{ per °C} \tag{6}$$

Eq. (2) concludes that the energy band gap decreases with cell temperature and consequently open circuit voltage is decreased. The short-circuit current (I_{sc}) is proportional to the number of generated charge carriers and their mobility. It strongly depends on the generation rate of charge carriers and diffusion length. The rate of generation of charge carriers increases with cell temperature which causes an increment in the short circuit current as reported by Arora and Hauser (Lammert and Schwarts, 1997). Eq. (3) concludes that the fill factor decreases with cell temperature due to change in corresponding open circuit voltage and short circuit current. The variations in the maximum output power ($P_{\max}$) and efficiency of mc-Si solar cell with cell temperature at constant light intensities 215, 280, 400 and 515 W/m^2 are tabulated in Table 2–3.

The relative change in the maximum output power with temperature was calculated using relation concerned.

$$\frac{1}{P_{\max}}\frac{dP_{\max}}{dT} \approx -0.002 \text{ per °C}. \tag{7}$$

The efficiency of solar cell is given (Singh and Ravindra, 2012).

$$\eta = \frac{P_{\max}}{P_{in}} = \frac{V_{\max} \times I_{\max}}{I\,(t) \times A} = \frac{FF \times V_{oc} \times I_{sc}}{I\,(t) \times A}. \tag{8}$$

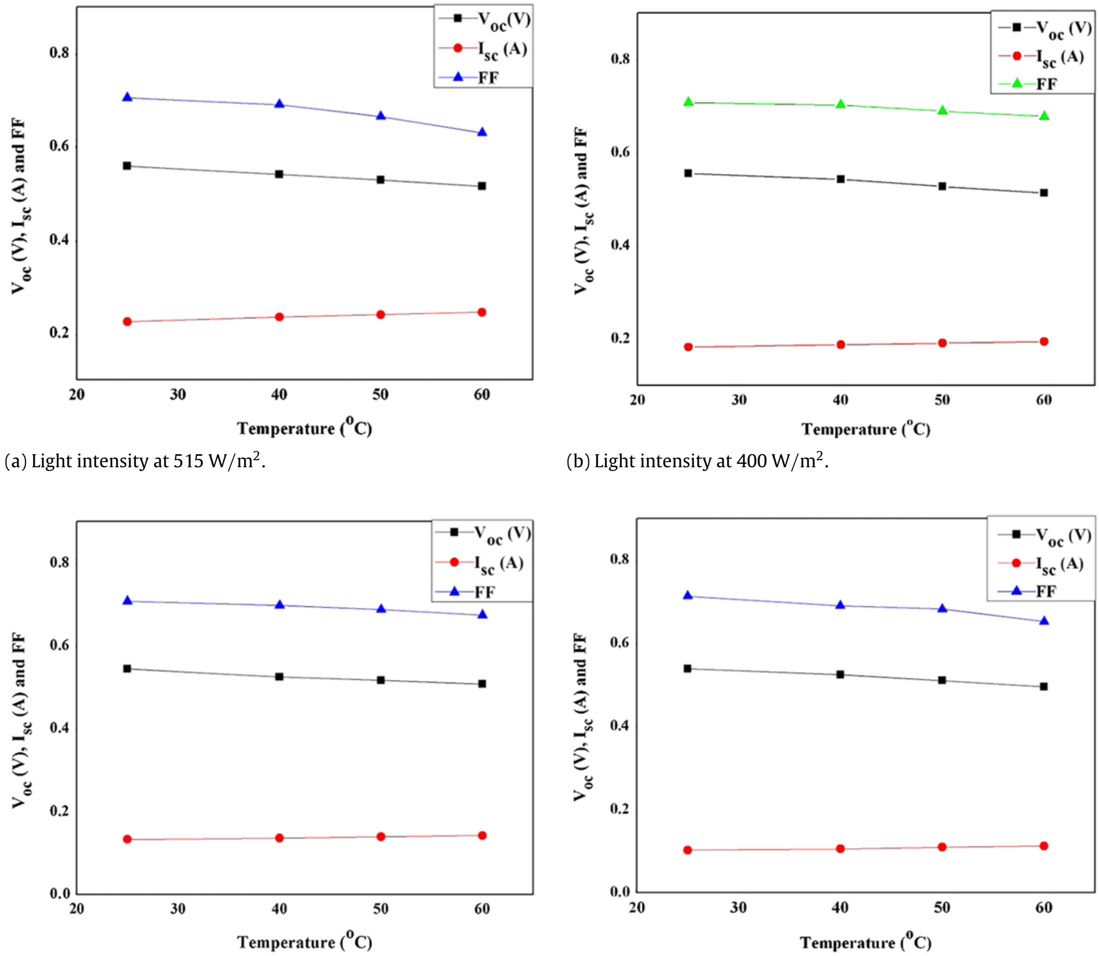
Here, P_{in} is the input power, $I(t)$ is the light intensity which may be defined as irradiance (E), i.e. the power of electromagnetic radiation per unit area incident on a surface and A is the surface area of silicon solar cell. The maximum output power is observed to be decreased with cell temperature at all constant light intensities as illustrated in Table 2 which revealed a decrement in the voltage with cell temperature. It is clearly visible in Table 3 that the efficiency is found to be decreased with cell temperature at all constant light intensities due to decrease in corresponding open circuit voltage and fill factor. The cell temperature dependent efficiency is given (Dubey et al., 2013) as:

$$\eta_c = \eta_{\text{Tref}}[1 - \beta_0\,(T_c - T_{\text{ref}})]. \tag{9}$$

Here, η_c and η_{Tref} are efficiencies of solar cell at cell temperature and room temperature respectively, β_0 is the efficiency temperature coefficient (0.004 K^{-1}), T_c and T_{ref} are the cell temperature and reference temperature of solar cell respectively. The quantity ($T_c - T_{\text{ref}}$) increases with cell temperature and consequently efficiency decreases. The calculated efficiency is similar to the earlier reported work (Radziemska, 2003; Dubey et al., 2013).

4. Conclusion

In this paper, the effect of cell temperature on the photovoltaic parameters of mc-Si solar cell is reported. The experiment was carried out employing solar cell simulator with cell temperature in the range 25–60 °C at constant light intensities 215, 280, 400 and 515 W/m^2. The results show that the cell temperature has a significant impact on photovoltaic parameters and it controls the quality and performance of mc-Si solar cell. The open circuit voltage (V_{oc}), maximum power point ($P_{\max}$), fill factor (FF) and cell efficiency (η) are found to be decreased with cell temperature while the short circuit current is observed to be increased slightly owing to the increasing rate of generation of charge carriers with



(a) Light intensity at 515 W/m^2.

(b) Light intensity at 400 W/m^2.

(c) Light intensity at 280 W/m^2.

(d) Light intensity at 215 W/m^2.

Fig. 2. The variation of open circuit voltage (V_{oc}), short circuit current (I_{sc}) and fill factor (FF) of mc-Si solar cell with cell temperature in the range 25–60 °C at constant light intensities (a) 515 W/m^2, (b) 400 W/m^2, (c) 280 W/m^2 and (d) 215 W/m^2.

Table 2
The maximum output power (P_{max}) of mc-Si solar cell with cell temperature at different constant light intensity.

Temperature (°C)	Maximum output power P_{max} (mW)			
	At 515 W/m^2	At 400 W/m^2	At 280 W/m^2	At 215 W/m^2
25	88.43	71.455	51.15	39.15
40	87.56	71.149	50.344	37.944
50	84.192	69.36	49.288	37.904
60	79.40	67.375	48.5	36.127

Table 3
The efficiency (η) of mc-Si solar cell with cell temperature at different constant light intensity.

Temperature (°C)	Efficiency (η%)			
	At 515 W/m^2	At 400 W/m^2	At 280 W/m^2	At 215 W/m^2
25	10.049	11.165	11.417	11.381
40	9.95	11.117	11.238	11.03
50	9.856	10.837	11.002	11.019
60	9.023	10.527	10.826	10.502

cell temperature. The temperature coefficient of the open-circuit voltage, fill factor and maximum output is found to be negative while positive for the short circuit current. The relative change in photovoltaic parameters with temperature is also calculated and found from −0.0022/°C to −0.0025/°C, 0.002/°C, −0.0013/°C and −0.002/°C for open circuit voltage, short circuit current, fill factor and maximum output power respectively. The results are in good agreement with the available literature.

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