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The Defining Positive Role of High Cell Temperature on the Efficiency of a Multicrystalline Solar Photovoltaic Array

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ABSTRACT
The progress in solar photovoltaic cell technology has led to development of several different types of cell varying widely in efficiency, performance and cost but still multicrystalline cell is the most widely used commercial cell. The maximum laboratory efficiency of multicrystalline cell is about 22% which is hardly attainable in field due to entirely different and variable climatic conditions. Increasing the efficiency in real field conditions is one of the greatest challenges of solar photovoltaics. Evaluating effect of major climatic parameters on the efficiency in the real field conditions can pave the way for increasing the efficiency of solar photovoltaic power plants. This paper evaluates the relative effect and role of irradiance and cell temperature acting simultaneously on solar cell conversion efficiency and DC power efficiency of a multicrystalline photovoltaic array for the climatic conditions of Western Rajasthan. It brings forward for the first time ever the defining positive role of cell temperature on the solar cell conversion efficiency and DC power efficiency of a multicrystalline photovoltaic array in contrast to literature and research papers all which show efficiency decreases with increase in temperature.

General Terms
Solar Irradiance; Efficiency; Real Field Climatic Conditions; Grid Connected PV Power Plant; Western Rajasthan.

Keywords
Solar Cell Conversion Efficiency; DC Power Efficiency; Energy Yield; Multicrystalline PV Array; Cell Temperature; Plane Of Array Irradiance (POA).

1. INTRODUCTION
The solar cell conversion efficiency and the power output of PV plant are specified at STC conditions which are far different from actual values. The reason for the vast difference is that the STC conditions rarely exists, the performance of technological parameters viz solar cell conversion efficiency and DC power efficiency are evaluated in laboratory conditions which are entirely different from real field conditions. Further evaluation is based on models developed on theoretical basis and in few papers simultaneous effect of irradiance and cell temperature has not been considered although they go hand in hand.

Literature and several research papers show that both power output and efficiency decrease with increase in temperature [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Elminir et al. showed that temperature coefficient for current, power and efficiency were about + 40 μA/^{o}C, -0.4mW/^{o}C and -0.4%/^{o}C respectively [2]. Radziemska reported -0.65%/^{o}K and -0.08%/ ^{o} K as the temperature coefficient for power output and solar cell conversion efficiency respectively [3]. Skoplaki et al. concluded that power output and efficiency decrease linearly with increase in cell temperature [4]. Milosavljevic et al. investigated efficiency of monocrystalline solar photovoltaic (SPV) power plant and found that increase in solar radiation increases cell temperature which in turn decreases open circuit voltage reducing efficiency [5]. Power temperature coefficient of -0.5%/^{o}C for polycrystalline silicon and -0.25%/^{o}C for amorphous silicon was reported by King et al. while -0.4%/ ^{o}C for crystalline silicon was reported by Sick and Erge [6]. Cotfas et al. found that power coefficient for different types of cell varied between -0.14%^{o}C to -0.47%/^{o}C [7]. Kamuyu et al. showed that efficiency decreases with increase in temperature and that Floating PV system produce 10% more energy as compared to land-based system due to cooling effect of water [8].

Few researchers have shown that energy yield in summers that is at higher temperature is higher due to dominating effect of irradiance despite decrease in efficiency with increase in temperature [9, 10]. Touati et al. investigated that decrease in efficiency was about 0.15%/^{o}C and 0.43%/^{o}C for monocrystalline and amorphous PV respectively although maximum power was generated during peak hours at high temperature [11]. Mazzeo et al. mentioned that concentrating photovoltaic system have greater conversion efficiency and consequently higher electricity production compared to conventional system. It also showed that production in summers was far greater than in winters [12].

Positive effect of temperature on efficiency has been reported by few researchers [11, 13]. Garg JB showed defining positive role of cell temperature on DC power and energy yield but effect on the solar cell conversion efficiency was not considered [14]. This paper presents visual representation of relative contribution of irradiance and cell temperature acting simultaneously on solar cell energy conversion efficiency (E_1) and DC power efficiency (E_2) and evaluates relative contribution and role of irradiance and cell temperature on E_1 and E_2. The evaluation is based on the data of a multicrystalline PV array installed in Western Rajasthan. It brings forward for the first time ever the defining positive role of cell temperature on the efficiency in contrast to negative effect of high cell temperature.

A solar cell's energy conversion efficiency (η, "eta"), is the percentage of power converted from absorbed light to electrical energy when connected to an electrical circuit that is ratio of output power to input power and is given by equation 1. It is measured at STC [9, 15, 16].

1. $\eta = P_m/(E*A_c)$ ………………………. (1)

Where

P_m = maximum power in kW,

E = Input light irradiance at STC that is $1kW/m^2$,

A_c = surface area of the solar cell in m^2.

Power output efficiency (η_p) in % as mentioned by N. Amin, et al. and Ghazali et al. is given by equation 2 [17,18].

2. η_p = Power output efficiency (%)

$\eta_p = (P_{mea} / P_{max}) * 100\%$ ……………. ……………. (2)

Where

P_{mea} = Average power output (W) measured on site in the given period,

P_{max} = Maximum power output of panel.

The solar cell conversion efficiency (E_1) at time t and power output efficiency(E_2) at time t in % are defined as follows

3. $E_1 = \{P_t/(E*A_c)\} * 100$ …………………. (3)

Where

P_t = Power output at time t;

E = Input light irradiance at STC that is $1kW/m^2$,

A_c = surface area of the solar cell in m^2.

4. $E_2 = (P_t/ P_{max}) * 100\%$ …………………. (4)

Where

P_t = Power output at time t;

P_{max} = Maximum power output of panel at STC that is maximum rated value of the array.

As per the Photovoltaics Report, prepared by Fraunhofer institute for Solar Energy Systems, the record lab efficiency for monocrystalline and multicrystalline silicon cell are 26.7% and 22.3% respectively. For the modules with concentrator technology efficiency up to 38.9% has been achieved [19]. The solar cell conversion efficiency for the module investigated as specified by the manufacturer at STC is 16.936%.

2. METHODOLOGY

The module used for analysis is a multicrystalline module having specifications as shown in table 1.

Table 1. The module specifications at STC (Standard Test Conditions), for the 5 MW grid connected multicrystalline PV power plant located at Ramgarh.

S. No.	Electrical Characteristics	Values
1.	Maximum power P_{mpp}/ P_{max}	247.39W
2.	Voltage at P_{max}, V_{mpp}	30.64V
3.	Current at P_{max}, I_{mpp}	8.07 A
4.	Open circuit voltage V_{oc}	37.67 V
5.	Short circuit current I_{sc}	8.26 A
6.	Temperature coefficient of P_{max}	-0.447 %/ ^oK
7.	Temperature coefficient of V_{oc}	-0.353 %/ ^oK
8.	Temperature coefficient of I_{sc}	0.104 %/ ^oK
9.	Power Tolerance	-0 / + 5 W
10.	Fuse rating	15 A
11.	Maximum System Voltage	1000 V

2.1 The analysis is based on the average reading of five array with maximum rated DC voltage, maximum rated DC current and maximum rated DC power being equal to 735.36V (24*30.64), 161.4A (20*8.07) and 118.687kW (735.36*161.4) respectively.

2.2 The solar conversion efficiency (E_1) and DC power efficiency(E_2) at time t are evaluated and are plotted with respect to time along with variation in POA and cell temperature with respect to time to observe simultaneous effect of irradiance and cell temperature for different days of the year chosen randomly. The evaluated data extends from September 2015 to July 2016.

2.3 The solar cell conversion efficiency, DC power efficiency, DC voltage, DC current and cell temperature are represented by E_1, E_2, V_{dc}, I_{dc} and T_c respectively. The corresponding units for E_1, E_2, V_{dc}, I_{dc} POA and T_c are %, %, V, A, W/m^2 and ^oC.

2.4 The irradiance used is plane of array irradiance and is represented by POA. The variations in graphs are followed by respective dates for example E1-18-10-15 represents variations of E_1 for 18th October 2015 and E2-22-2-16 represents variations of E_2 for 22nd February 2016.

2.5 The monitored period is divided into four seasons namely Post monsoon, Winter, Spring and Summer.

2.6 The average value of E_1, E_2, cell temperature and POA is also evaluated and is represented by E_{1av}, E_{2av}, T_{cav} and POA_{av} respectively. The energy yield of the day is also evaluated.

2.7 The effect of dust, wind, humidity and other environmental parameters has not been considered.

3. EXPERIMENTAL DATA ANALYSIS

Relative contribution and role of cell temperature and irradiance acting simultaneously on efficiency is observed and evaluated for various seasons by plotting variations of solar cell conversion efficiency, DC power efficiency, POA and cell temperature with respect to time. To elaborate the significance of voltage variations in comparison to current, variations in the technical parameters viz E_1, V_{dc} and I_{dc} with respect to POA are also plotted.

3.1 Variation of Solar Cell Conversion Efficiency(E_1), DC Power Efficiency(E_2), Cell Temperature and POA with Time for Post Monsoon Season

The post monsoon season extends from September to October. The two dates 11th September and 18th October of the post monsoon season have been chosen randomly. Variation of E_1, V_{dc} and POA with time for 11th September and 18th October are shown in figure 1 and 3 respectively. Figure 2 and 4 shows variation of E_1, E_2 and cell temperature with time for 11th

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September and 18th October respectively. Variations in E_1 and V_{dc}, variations in E_1 and I_{dc} with respect to POA for 18th October are plotted in figure 5 and 6 respectively.

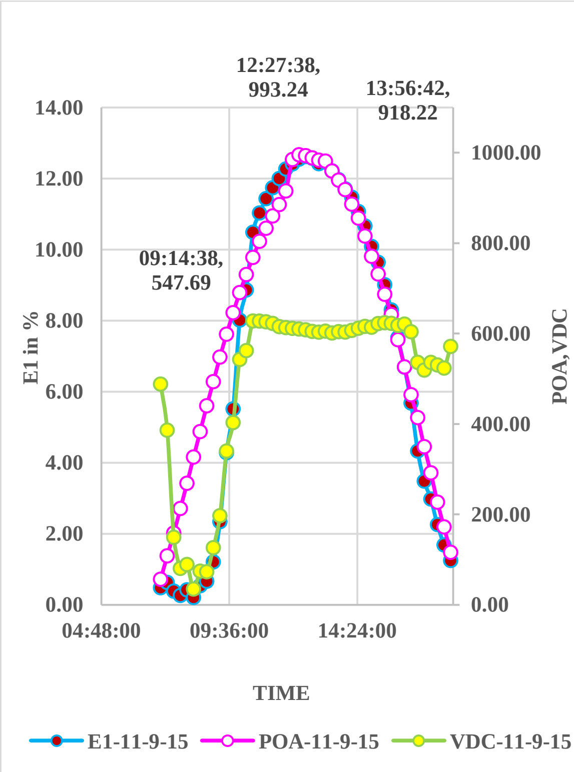

Figure 1: Variation of E1 and POA for 11th September 2015.

For 11th September the points corresponding to POA are marked in figure 1 and points corresponding to E_1, E_2 and T_c are marked in figure 2. Following conclusions can be drawn from figure 1 and 2.

- With increasing POA as POA increases from 547.69W/m^2 to 993.24W/m^2 shown vide figure 1, T_c increases from 41.71°C to 54.46°C, E_1 increases from 2.34% to 12.62%, E_2 increases from 13.79% to 74.49% as shown vide figure 2, depicts a significant increase in E_1 and E_2 with increase in POA and cell temperature.
- With decreasing POA as POA decreases from 993.24 W/m^2 to 918.22 W/m^2 shown vide figure1, T_c continues to increase from 54.46°C to 56.41°C with slight decrease in E_1 and E_2 but still E_1 and E_2 as high as 11.71% and 69.12% respectively are obtained at 56.41°C. Thereafter cell temperature, E_1 and E_2 all decrease with decreasing POA. The slight decrease in E_1 and E_2 with decreasing POA and increasing cell temperature is insignificant compared to its value at low temperature.

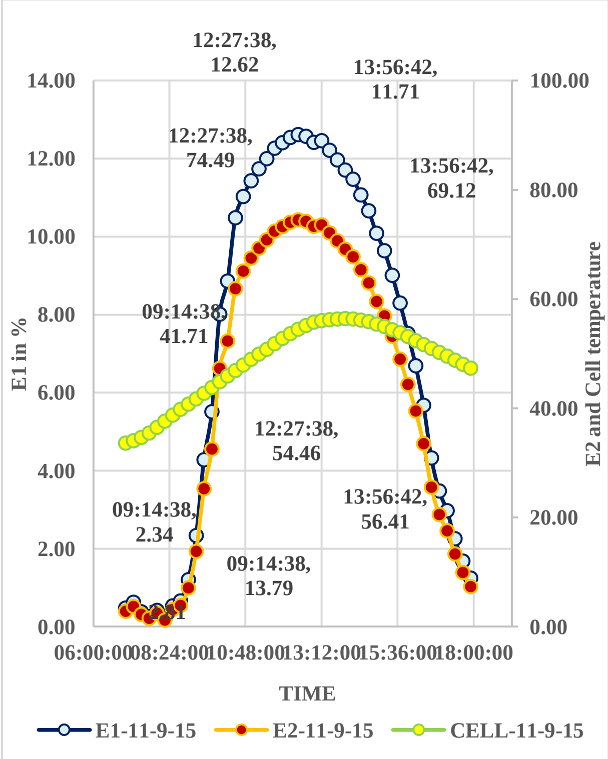

Figure 2: Variation of E_1, E_2 and cell temperature for 11th September 2015.

Similar results are obtained for 18th October and the points corresponding to POA are marked in figure 3 and corresponding to E_1, E_2 and T_c are marked in figure 4. It is observed that both DC power conversion efficiency(E_2) and solar cell conversion efficiency(E_1) varies in direct proportion to irradiance and cell temperature with E_1 and E_2 as high as 13.39% and 79.07% respectively at cell temperature 57.47°C for 18th October as shown vide figure 4. For 18th October E_1 decreases from 13.39% to 13.17%, E_2 decreases from 79.07% to 77.74% as cell temperature increases from 57.47°C to 58.11°C and that too due to decrease in POA from 966.90 W/m^2 to 948.16 W/m^2. The slight decrease in E_1 and E_2 with decreasing POA and increasing cell temperature is insignificant. Figure 1 and 3 show variations in E_1 follow variations in POA only after V_{dc} attains saturation maintaining high and nearly constant value. As I_{dc} varies in direct proportion to POA it can be said that E_1 varies in accordance to I_{dc} for nearly constant V_{dc}. The fact is further elaborated by plotting variation of E_1 and V_{dc}; variation of E_1 and I_{dc} with respect to POA in figure 5 and 6 respectively for 18th October.

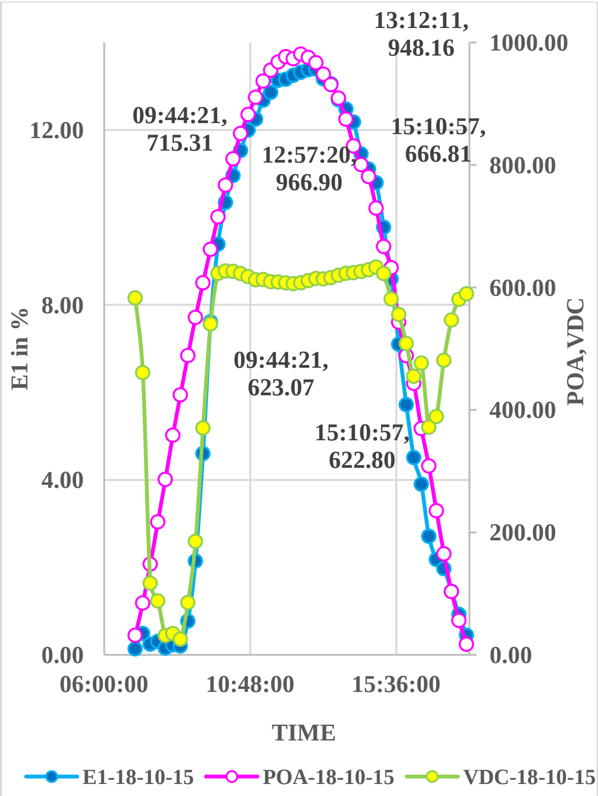

Figure 3: Variation of E_1 and POA cell temperature for 18th October 2015.

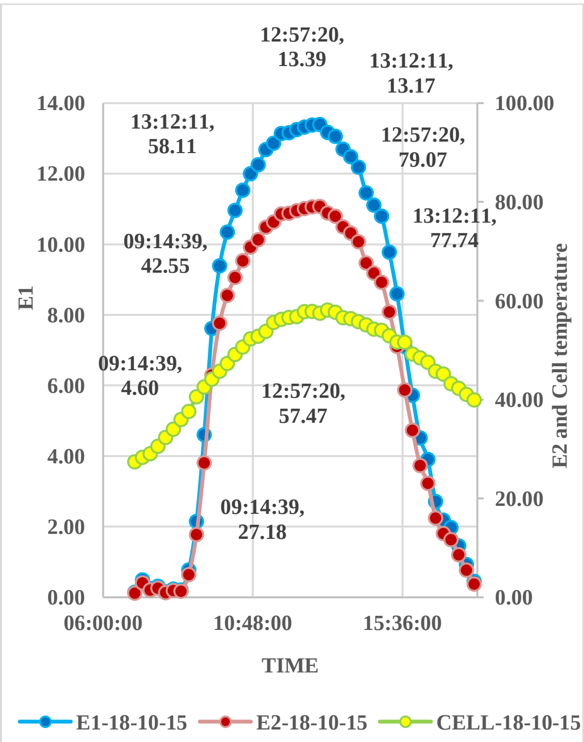

Figure 4: Variation of E_1, E_2 and cell temperature for 18th October 2015.

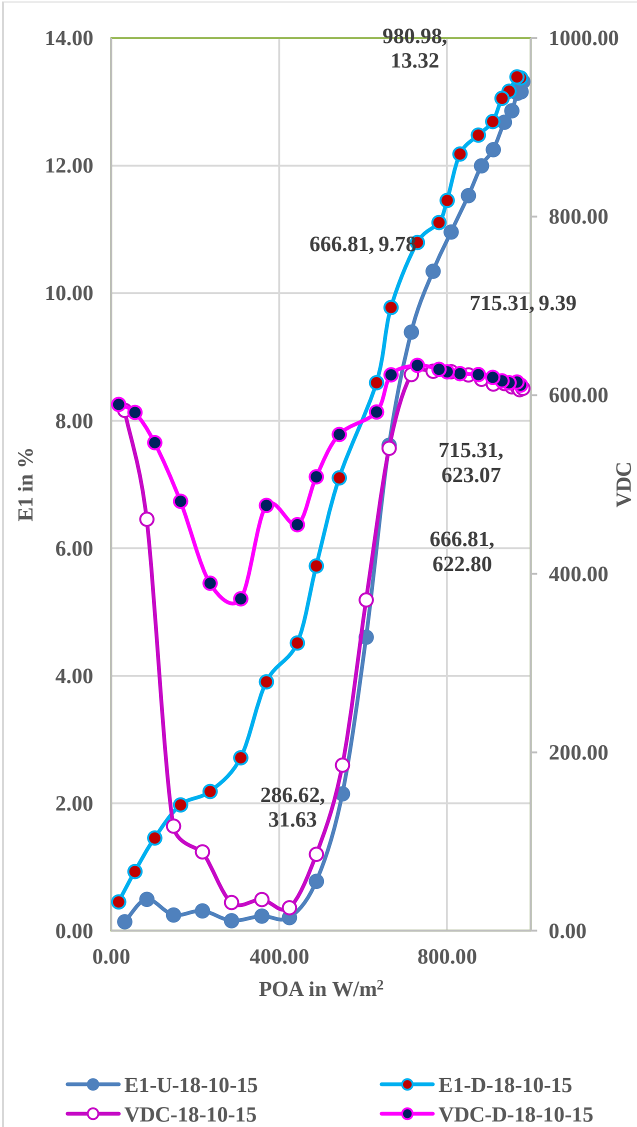

Figure 5: Variation of E_1 and V_{dc} with respect to POA.

V_{dc} attains nearly constant value in the time interval 9:44:21 to 15:10:57 with corresponding V_{dc} and POA equal to 623.07V, 715.31 W/m^2 and 622.80V, 666.81 W/m^2 respectively, shown vide figure 3. As POA increases from 286.62 W/m^2 to 715.31 W/m^2 variation in E_1 follow variations in V_{dc} shown vide figure 3 and 5. With further increase in POA from 715.31 W/m^2 to 980.98 W/m^2, reducing back to 666.81 W/m^2 with descending sun E_1 varies linearly with I_{dc} as shown vide figure 5 and 6. With increasing POA both I_{dc} and E_1 vary linearly with POA, with decreasing POA there is slight change in gradient of I_{dc} at short interval which is correspondingly reflected in E_1 curve also. Outside this interval, voltage variations are reflected in E_1 although I_{dc} varies in perfect linear manner.

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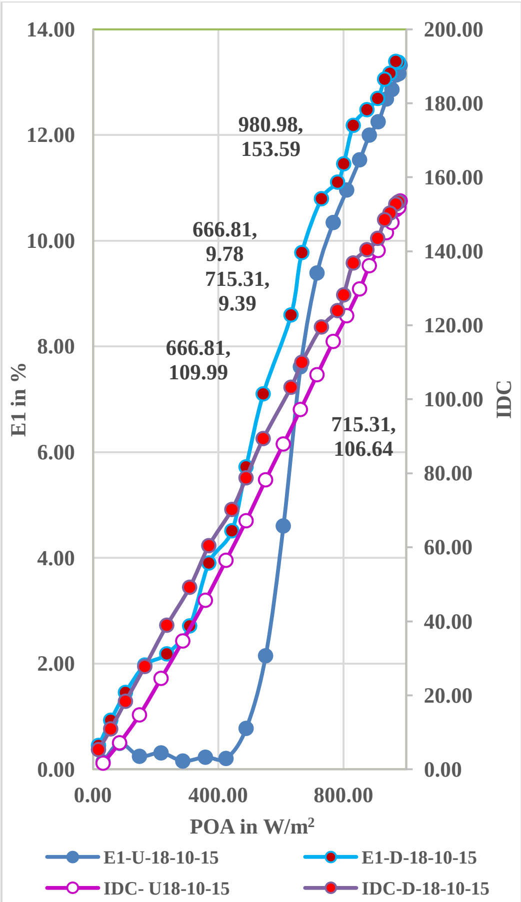

Figure 6: Variation of E_1 and I_{dc} with respect to POA.

3.2 Variation of Solar Cell Conversion Efficiency(E_1), DC Power Efficiency(E_2), Cell Temperature and POA with Time for Winter Season

The winter season extends from November to January with high POA for very short duration and low cell temperature. Variation of E_1, V_{dc} and POA with time for 13th November, 22nd December 2015 and 8th January 2016 are shown in figure 7, 9 and 12 respectively. Variation of E_1, E_2 and cell temperature with time for 13th November, 22nd December 2015 and 8th January 2016 are shown in figure 8, 10 and 13 respectively. Variation of E_1 and V_{dc} with respect to POA for 22nd December 2015 are plotted in figure 11.

It can be observed that at lower cell temperature higher POA is required to attain high efficiency. On 13th November E_1, and E_2 are only 1.75% and 10.31% respectively at T_c equal to 39.36^{o}C and POA equal to 632.90 W/m^2 attaining maximum value of 10.53% and 62.15% respectively for POA equal to 799.32 W/m^2 and T_c equal to 47.80^{o}C as shown vide figure 7 and 8. V_{dc} varies in accordance to POA for very short duration when V_{dc} is nearly constant as shown vide figure 7. Similar results are obtained for 22nd December and 8th January as shown vide figure 9-10 and 12-13 respectively showing very low efficiency at low temperature even at much higher POA. At low temperature V_{dc} does not attain constant value and E_1 curve follows V_{dc} curve for the entire duration as shown vide figure 9 and 12 for 22nd December and 8th January respectively. This is further verified vide figure 11 for 22nd December which shows E_1 varies in accordance to V_{dc} for the entire duration.

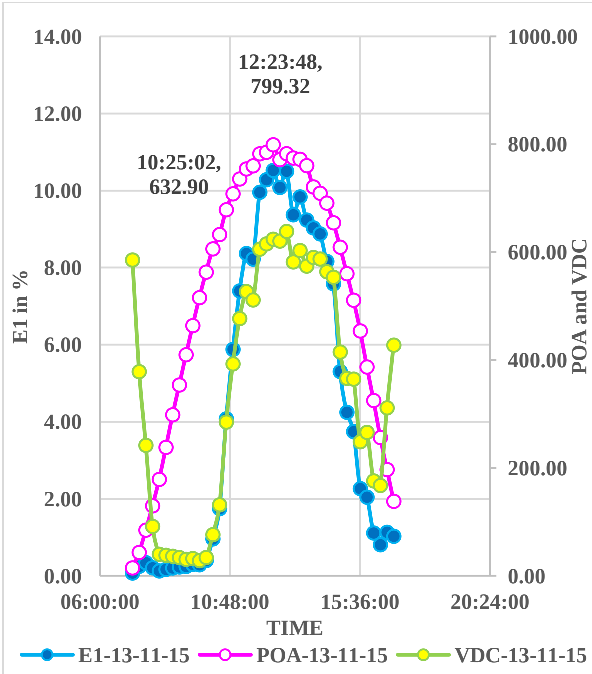

Figure 7: Variation of E_1, V_{dc} and POA for 13th November 2015.

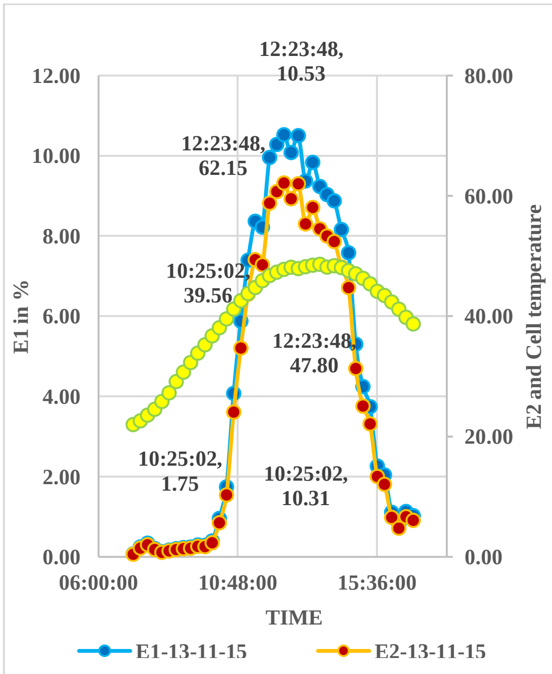

Figure 8: Variation of E_1, E_2 and cell temperature for 13th November 2015.

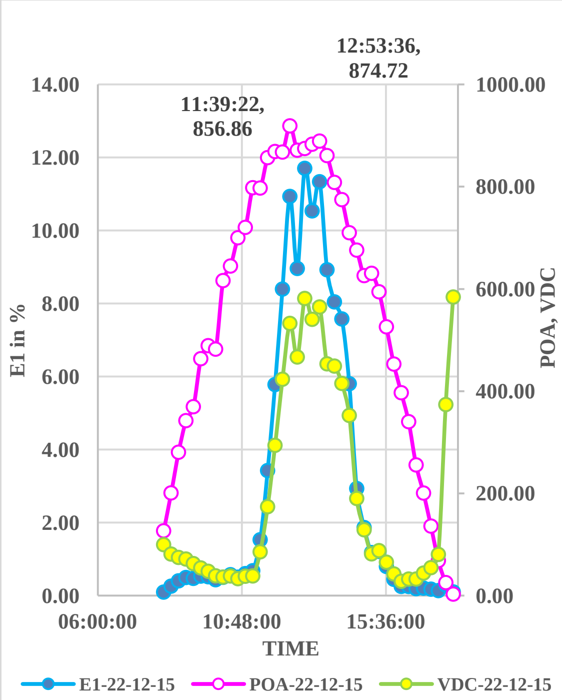

Figure 9: Variation of E_1, V_{dc} and POA for 22nd December 2015.

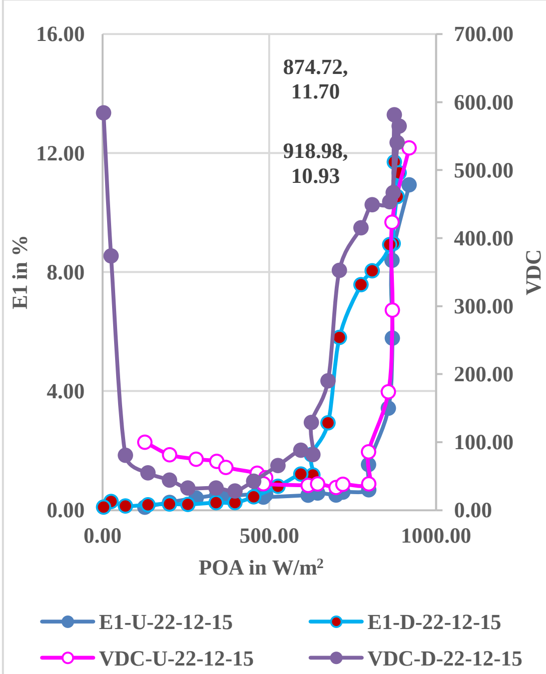

Figure 11: Variation of E_1 and V_{dc} with respect to POA for 22nd December 2015.

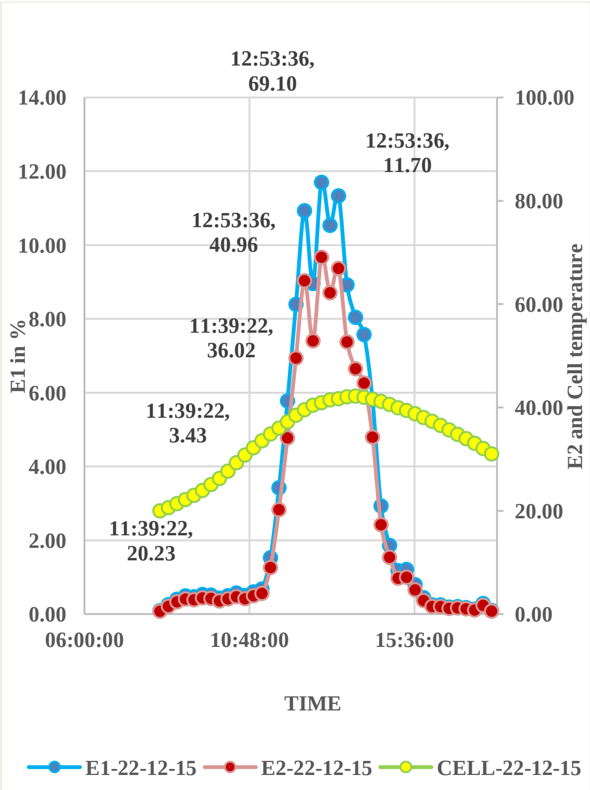

Figure 10: Variation of E_1, E_2 and cell temperature for 22nd December 2015.

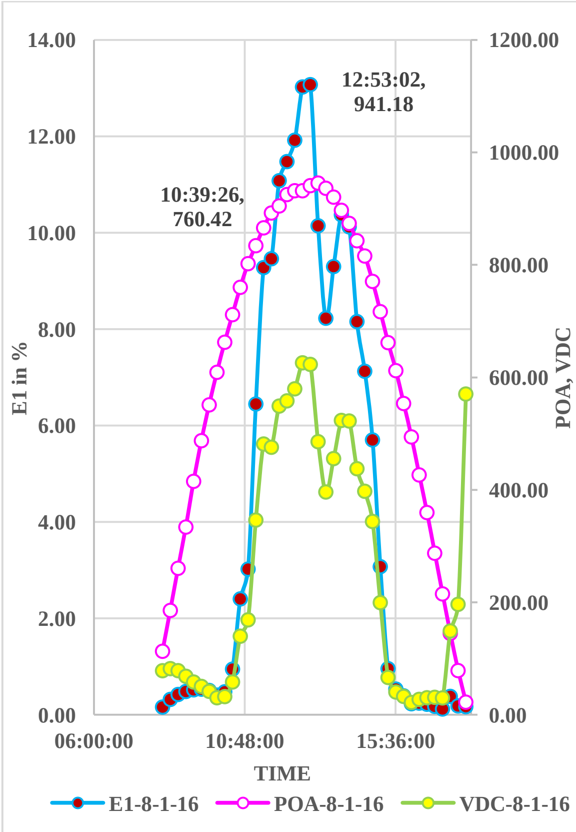

Figure 12: Variation of E_1, V_{dc} and POA for 8th January 2016.

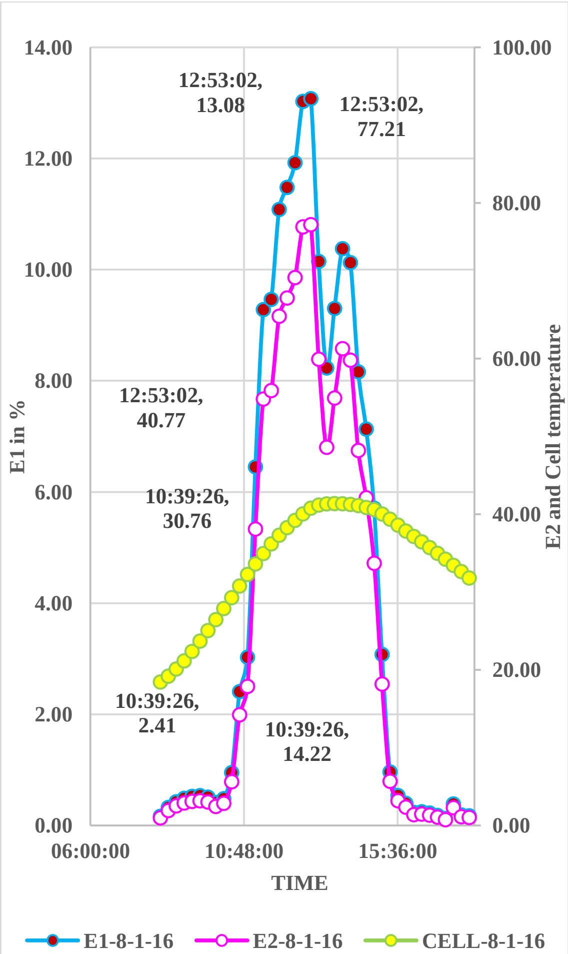

Figure 13: Variation of E_1, E_2 and cell temperature for 8th January 2016.

3.3 Variation of Solar Cell Conversion Efficiency (E1), DC Power Efficiency (E2), Cell Temperature and POA with Time for Spring Season

The spring season with moderate cell temperature in 40-53^{o}C range and high POA for reasonable duration extends from February to March. Variation of E_1, V_{dc} and POA with time for 22nd February and 8th March are shown in figure 14 and 20 respectively. Variation of E_1, E_2 and cell temperature with time for 22nd February and 8th March are shown in figure 15 and 21 respectively. Variation of E_1, I_{dc} and cell temperature with respect to time is shown in figure 16. Variation of E_1 and V_{dc}, variation of E_1 and I_{dc}; variation of I_{dc} and cell temperature with respect to POA for 22nd February are shown in figure 17, 18 and 19 respectively.

High efficiency with E_1 and E_2 as high as 15.16% and 89.54% respectively are obtained on 22nd February at T_c equal to 46.77^{o}C and POA 991.34W/m^2 while lower E_1 and E_2 equal to 13.63% and 80.46% are obtained at higher POA and lower T_c that is 994.09 W/m^2 and 42.98^{o}C respectively as shown vide figure 14 and 15 showing positive effect of cell temperature on efficiency, increasing with increasing cell temperature even though POA decreases. E_1, E_2 equal to 14.36 % and 84.81 % respectively are obtained on 8th March at T_c equal to 48.42^{o}C, POA equal to 984.92W/m^2 with comparatively lower E_1 that is 13.86% at higher POA that is 989.64W/m^2 and lower T_c that is 44.13 ^{o}C shown vide figure 20 and 21, due to positive effect of cell temperature for nearly constant POA. The positive effect of cell temperature is normally not visible as variations in POA are more significant compared to variations in cell temperature but for nearly constant POA for example on 22nd February variations in cell temperature are far more significant compared to POA, the result is increase in I_{dc} from 155.52A to 168.34A with corresponding increase in E_1 from 13.63% to 15.16% as cell temperature increases from 42.98^{o}C to 46.77 ^{o}C as shown vide figure 16 although POA decreases from 994.09 W/m^2 to 991.34W/m^2 as shown vide figure 14 and 17, depicting positive effect of cell temperature on both I_{dc} and E_1.

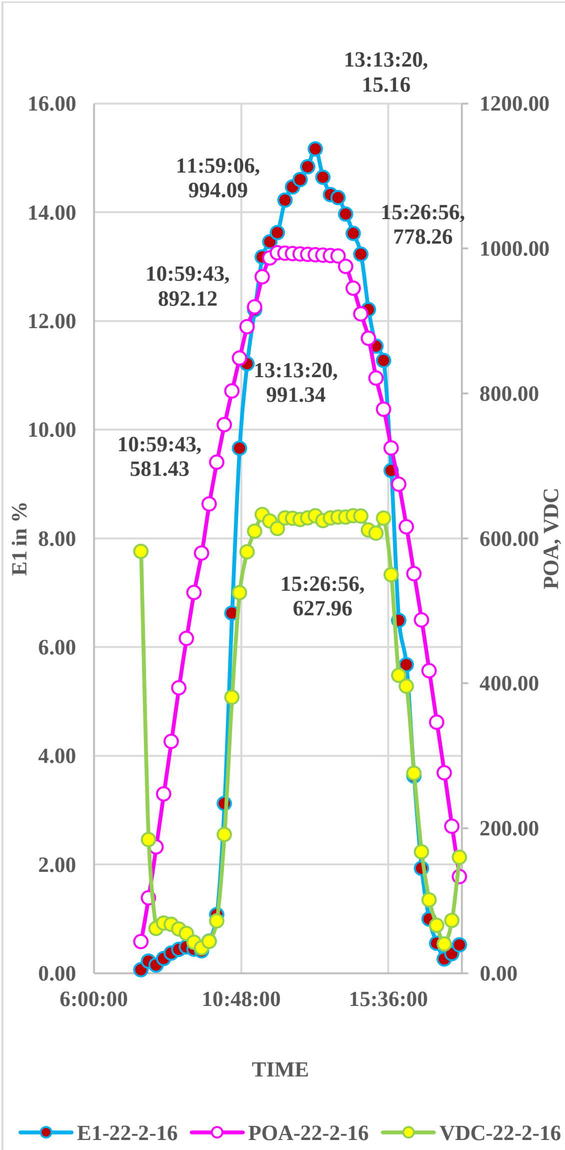

Figure 14: Variation of E_1, V_{dc} and POA for 22nd February 2016.

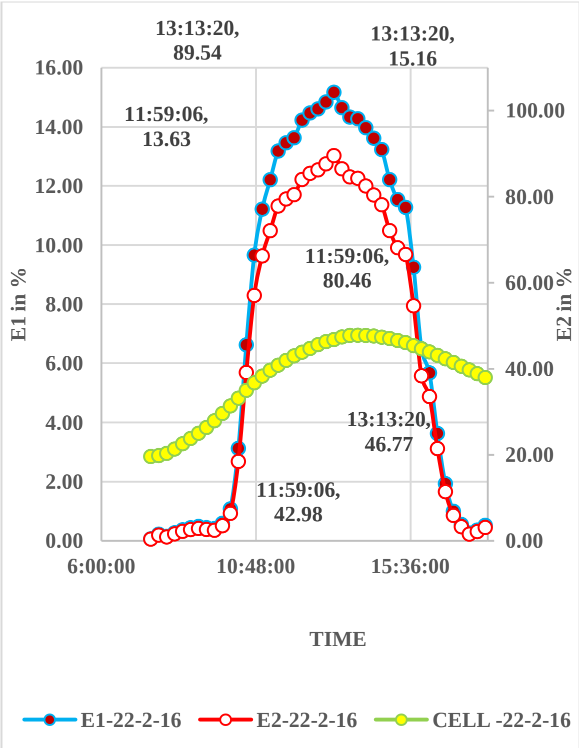

Figure 15: Variation of E_1, E_2 and cell temperature for 22nd February 2015.

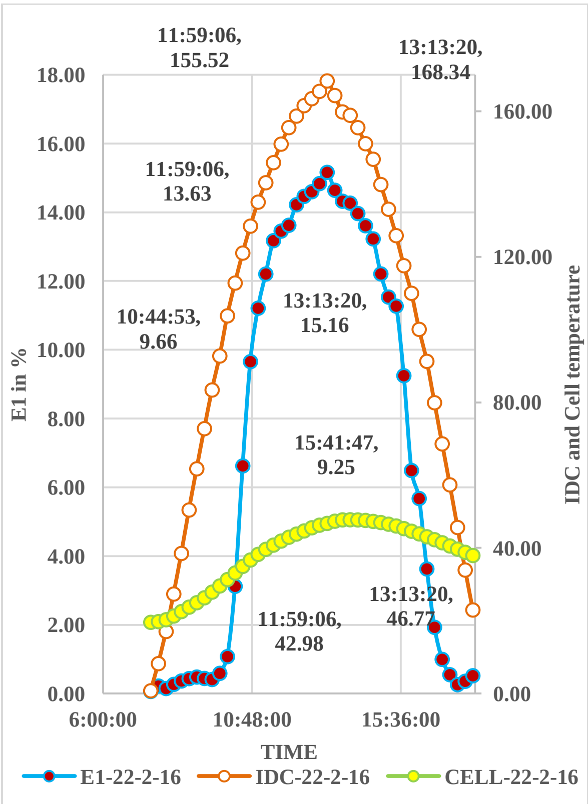

Figure 16: Variation of E_1, I_{dc} and T_c with respect to time for 22nd February 2016.

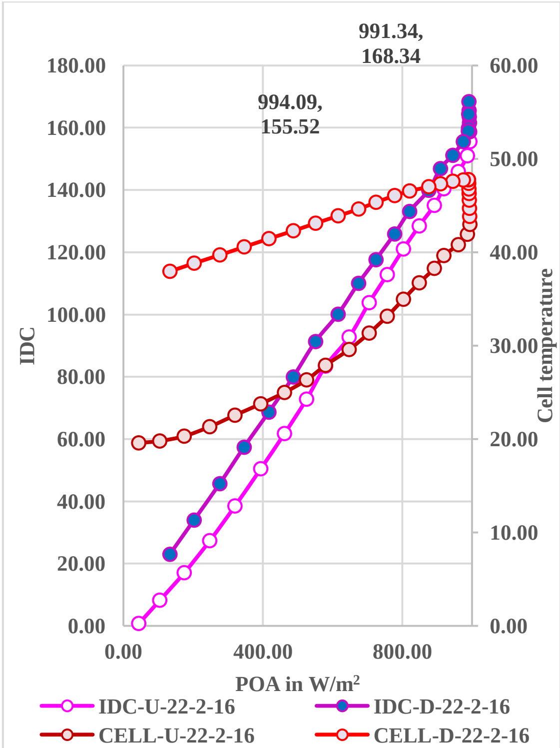

Figure 17: Variation of I_{dc} and T_c with respect to POA for 22nd February 2016.

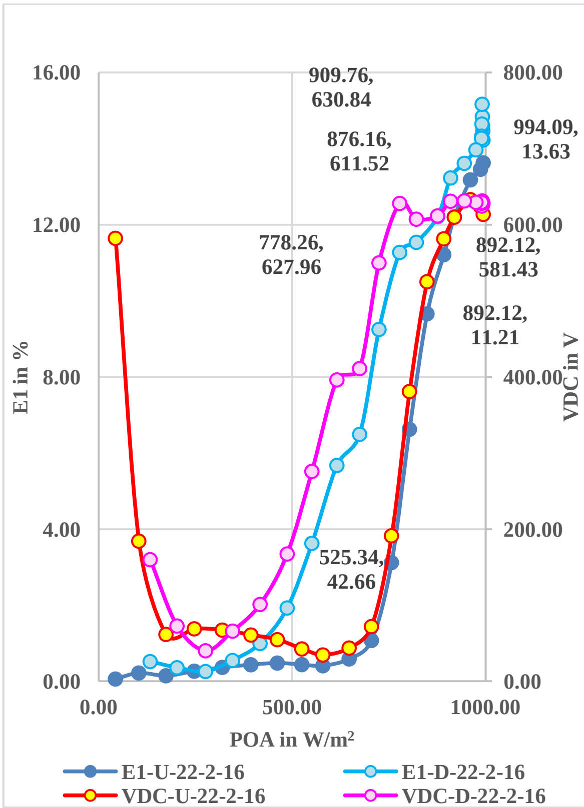

Figure 18: Variation of E_1, and V_{dc} with respect to POA for 22nd February 2016.

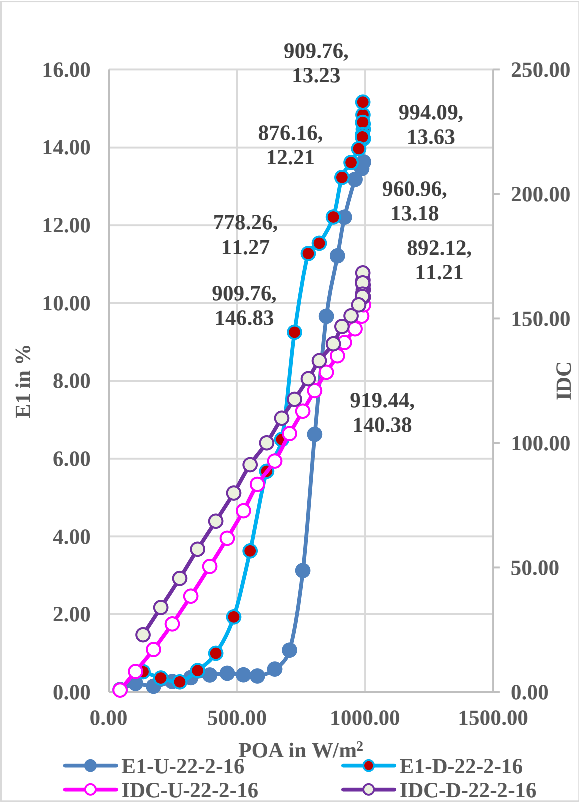

Figure 19: Variation of E_1, and I_{dc} with respect to POA for 22nd February 2016.

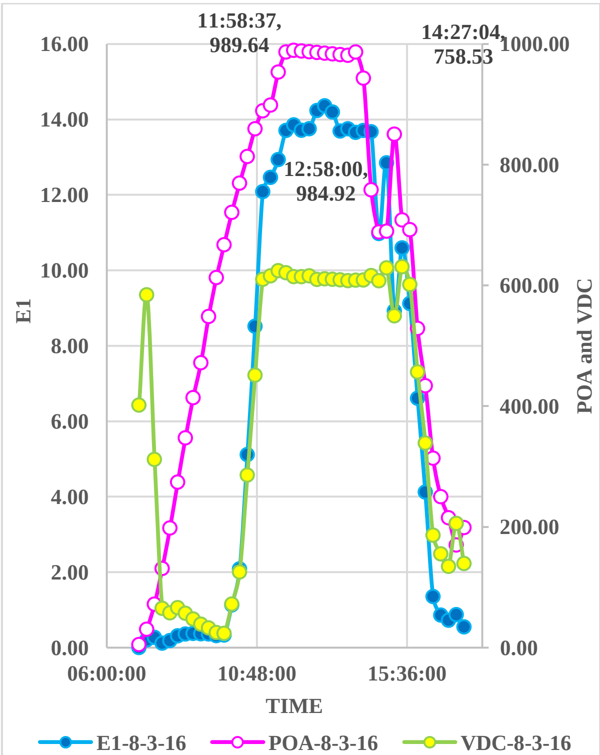

Figure 20: Variation of E_1, V_{dc} and POA for 8th March 2016.

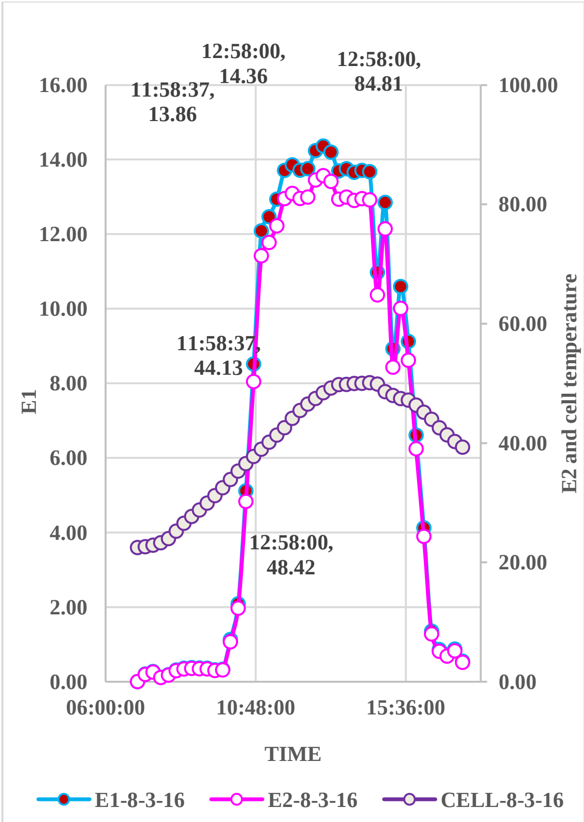

Figure 21: Variation of E_1, E_2 and cell temperature for 8th March 2016.

E_1 and E_2 vary in accordance to V_{dc} until V_{dc} attains nearly constant value, thereafter it varies in accordance to I_{dc} until V_{dc} is nearly constant as shown vide figure 14 and 20 for 22nd February and 8th March respectively. This is further verified vide figure 18 and 19 for 22nd February. V_{dc} remains nearly constant in the time interval 10:59:43 to 15:26:56 with corresponding V_{dc} value equal to 581.43V and 627.96V respectively and corresponding POA equal to 892.12 W/m^2 and 778.26 W/m^2 respectively as shown vide figure 14. As POA increases right from very low value to 892.12 W/m^2, E_1 varies according to V_{dc} as shown vide figure 14 and 18. With further increase in POA from 892.12 W/m^2 to 994.09 W/m^2 and then reducing back to 909.76 with descending sun, the E_1 curve follows I_{dc} as shown vide figure 19 thereafter although high V_{dc} is maintained V_{dc} reduces by about 1 % of its maximum rated value that is from 630.84 V to 611.52V as POA reduces from 909.76 to 876.16W/m^2, the result is that although I_{dc} decreases linearly, E_1 shows variation in gradient reflecting effect of voltage variations. Thus, for any two consecutive points if voltage variation is less than 1% of its rated value E_1 follows I_{dc} curve in perfect linear manner but voltage variation greater than 1% are reflected in E_1 and correspondingly E_2 curve showing significant effect of voltage variations in comparision to current variations.

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3.4 Variation of Solar Cell Conversion Efficiency(E1), DC Power Efficiency(E2), Cell Temperature and POA with Time for Summer Season

The rainy season may extend from June to August but the days considered for analysis, 4th June and 11th July represents clear sunny day and so have been considered in summer season. Variation of E_1, V_{dc} and POA with time for 12th April, 13th May, 4th June and 11th July are shown in figure 22, 24, 26 and 30 respectively. Variation of E_1, E_2 and cell temperature with time for 12th April, 13th May, 4th June and 11th July are shown in figure 23, 25, 27 and 31 respectively. Variation of E_1 and V_{dc}, variation of E_1 and I_{dc} with POA for 4th June are shown in figure 28 and 29 respectively.

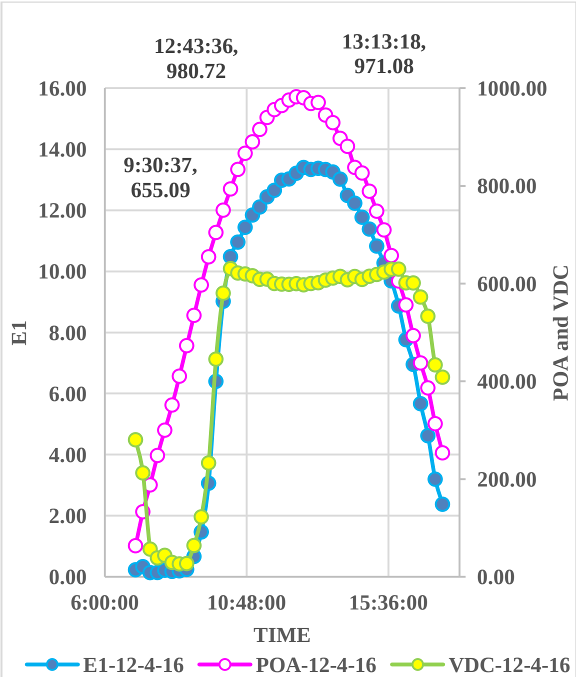

Figure 22: Variation of E_1, V_{dc}, POA and cell temperature for 12th April 2016.

In summers both E_1 and E_2 increase with increase in POA and increase in cell temperature even as cell temperature increases up to 58.92°C. On 12th April E_1 increases from 3.07% to 13.41%, E_2 increases from 18.10% to 79.17% as T_c increases from 39.91°C to 54.90 °C and POA increases from 655.09 W/m^2 to 980.72 W/m^2 shown vide figure 22 and 23. On 13th May maximum E_1 and E_2 with values 12.61% and 72.27% respectively are obtained at cell temperature as high as 58.92°C and POA equal to 914.23W/m^2 shown vide figure 24 and 25. At maximum T_c of 61 °C, E_1 and E_2 reduce slightly to 12.24% and 72.27%. On 4th June maximum E_1 and E_2 with values 13.51% and 79.77% respectively are obtained at cell temperature as high as 58.14°C and POA 989.68 W/m^2 shown vide figure 26 and 27. E_1 and E_2 with values 12.82% and 75.70% respectively are obtained at maximum cell temperature of 61.28°C, that is remarkably high values of E_1 and E_2 at high cell temperature. On 11th July maximum values for E_1 and E_2 are 12.75% and 75.31% respectively at POA 896.15 W/m^2 and T_c 54.25°C depicted vide figure 30 and 31, showing remarkably high efficiency at high cell temperature.

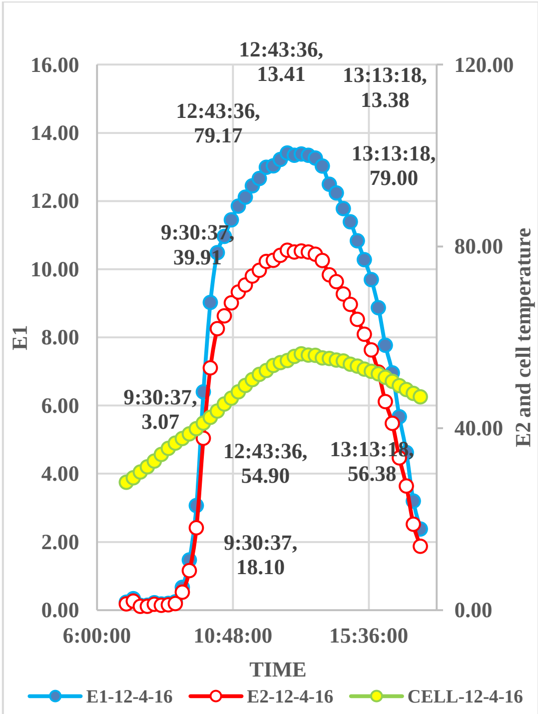

Figure 23: Variation of E_1, E_2 and cell temperature for 12th April 2016.

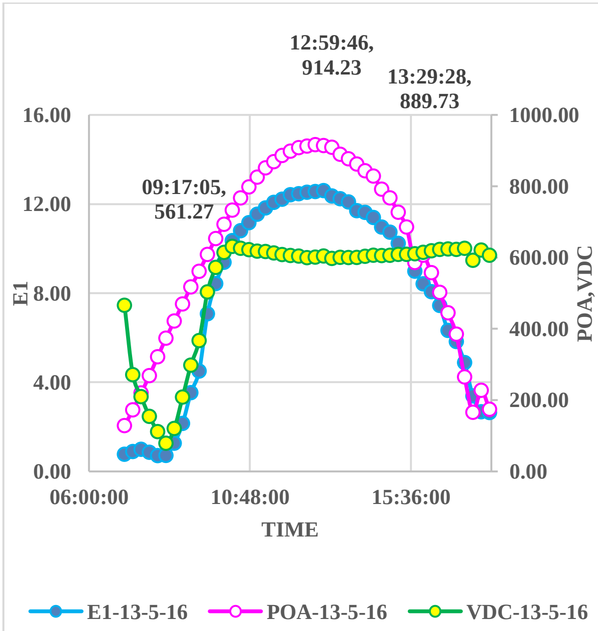

Figure 24: Variation of E_1, V_{dc} and POA cell temperature for 13th May 2016.

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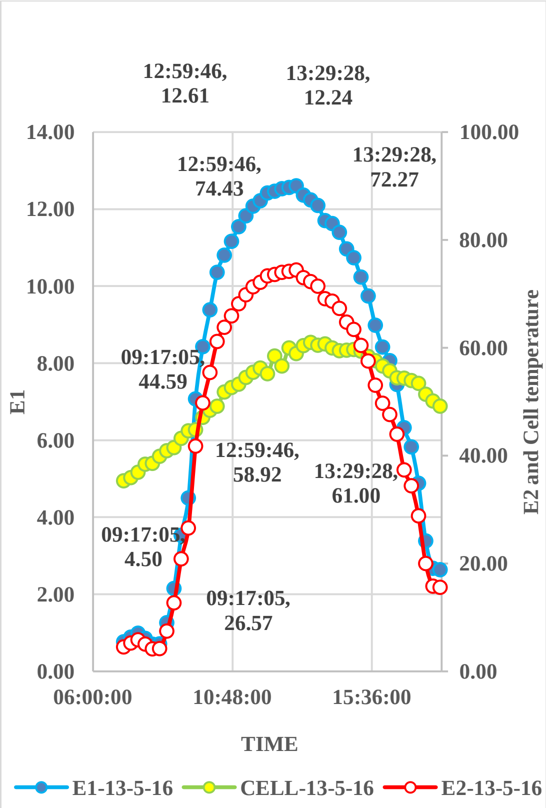

Figure 25: Variation of E_1, E_2 and cell temperature for 13th May 2016.

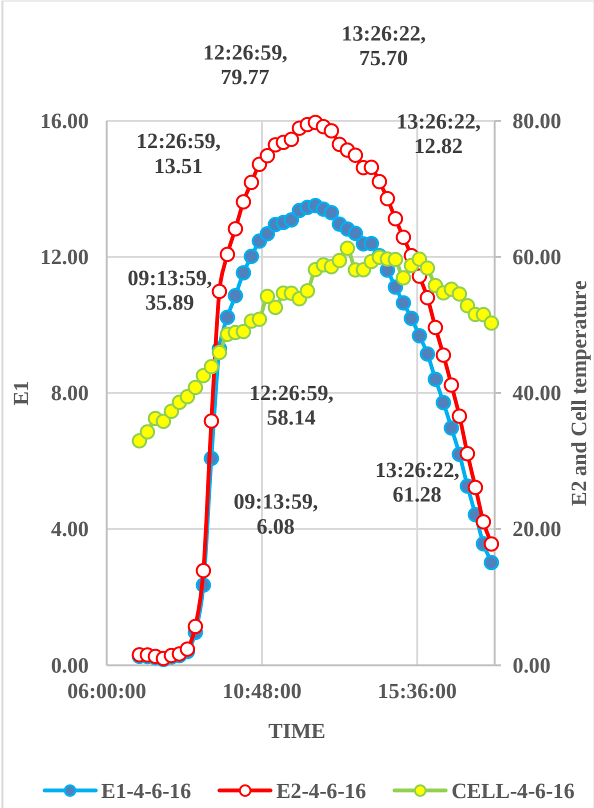

Figure 27: Variation of E_1, E_2 and cell temperature for 4th June 2016.

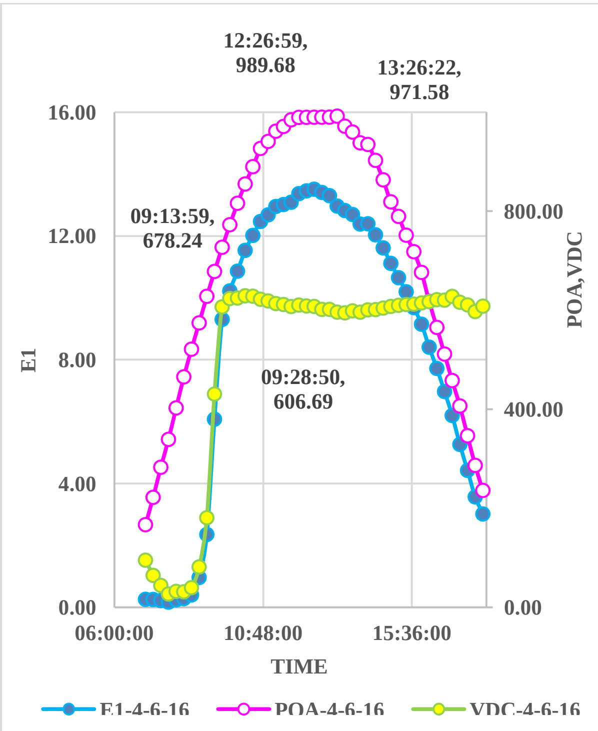

Figure 26: Variation of E_1, V_{dc} and POA cell temperature for 4th June 2016.

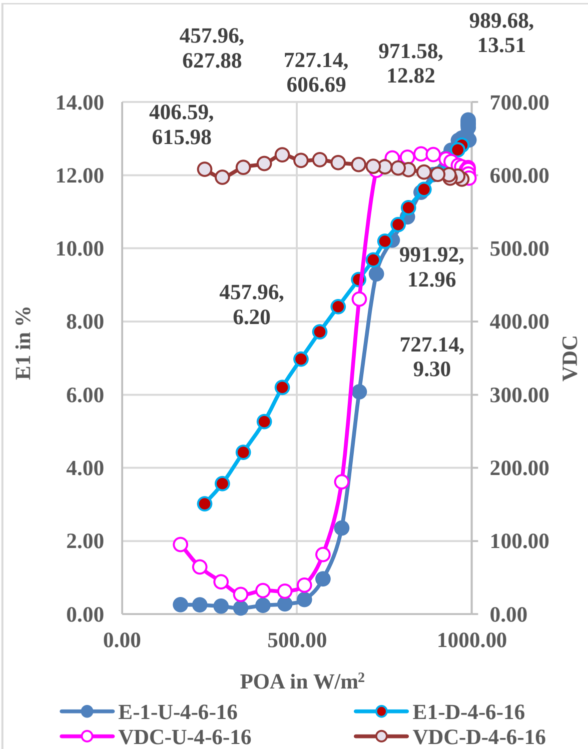

Figure 28: Variation of E_1 and V_{dc} with POA for 4th June 2016.

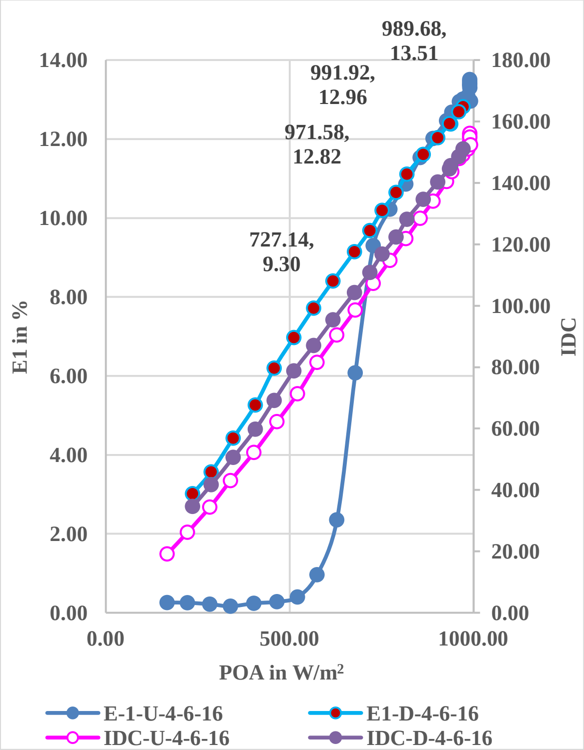

Figure 29: Variation of E_1 and I_{dc} with POA for 4th June 2016.

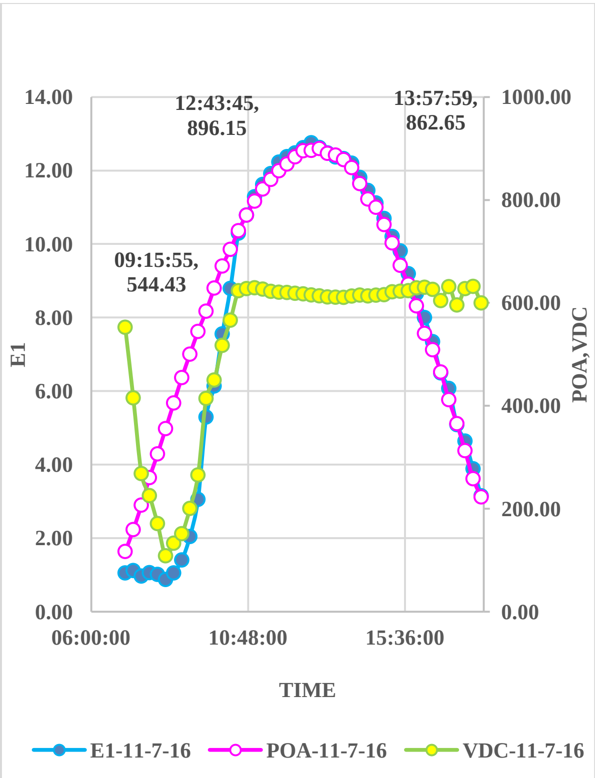

Figure 30: Variation of E_1, V_{dc}, POA and cell temperature for 11th July 2016.

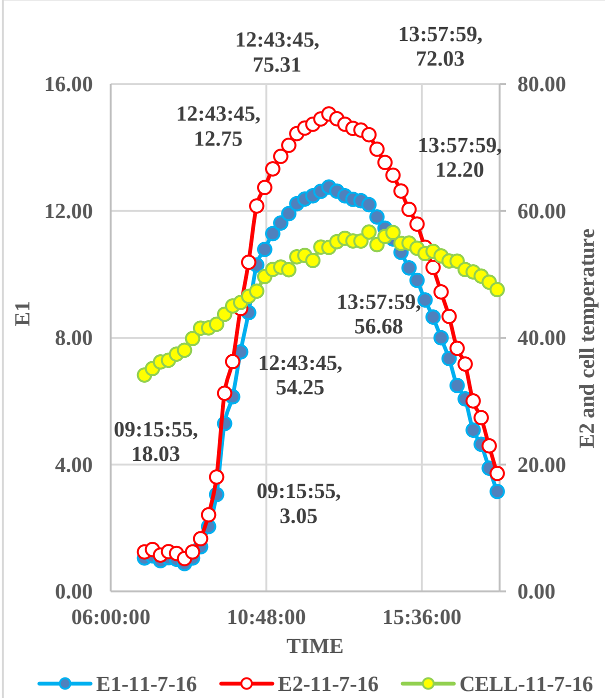

Figure 31: Variation of E_1, E_2 and cell temperature for 11th July 2016.

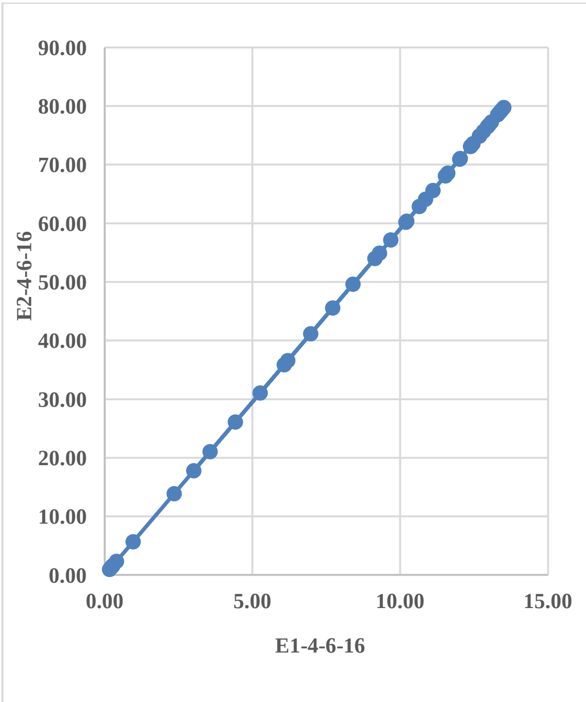

Figure 32: Variation of E_2 with respect to E_1 for 4th June.

High V_{dc} is obtained only at high cell temperature as mentioned by Garg and JB [14] and is also visible from figures 1, 3, 5, 7, 9, 12,14, 18, 20, 22, 24, 26, 28 and 30 but has not been elaborated in this paper. Until V_{dc} attains nearly constant value both E_1 and E_2 vary in accordance to voltage as shown vide figure 22, 24, 26 and 30 for 12th April, 13th May, 4th June and 11th July respectively for E_1 only but holds true for E_2 also as there is perfect linear relationship between E_1 and E_2 shown only for 4th June vide figure 32 but is true for all dates. At high cell temperature V_{dc} becomes independent of POA and remains constant for entire duration as shown vide figure 24, 26 and 30 for 13th May, 4th June and 11th July respectively.

Once V_{dc} attains constant value E_1 and E_2 vary in accordance to POA and I_{dc}. The fact can be further explained for 4th June vide figure 28 and 29. V_{dc} attains 606.69V at 9:28:50 and POA equal to 727.14W/m^2, thereafter it continues to maintain nearly constant value irrespective of POA as shown vide figure 28 and 29. As POA increases from 727.14 W/m^2 to 991.92 W/m^2, reducing back to 457.96 W/m^2 with descending sun, E_1 and correspondingly E_2 varies linearly with I_{dc}. For voltage variation greater than 1% between two consecutive points slight change in gradient of E_1 is observed as can be seen when V_{dc} reduces from 627.88V to 615.98V showing that for E_1 and E_2 even 1% of voltage variations are more prominent compared to current variations.

To evaluate relative effect of POA and T_c over the day average efficiency (E_1 and E_2), average cell temperature, average POA represented by E_{1av}, E_{2av}, T_{cav} and POA_{av} respectively are evaluated in table 2. The maximum value of E_1 and E_2 and energy yield of the day are also recorded in table 2.

Table 2 shows that maximum average E_1 and E_2 are obtained when both average POA and average cell temperature are maximum, the corresponding energy yield is also maximum. On 22nd February highest value of E_1 equal to 15.16% is obtained, average POA is also second highest but as average cell temperature is only 38.28 ^{o}C, the average E_1 and E_2 and energy yield of the day are less compared to March, April, May, July although average POA is higher showing that high cell temperature is must for high average E_1, E_2 and energy yield. Comparing results of 12th April and 13th May although average POA is significantly higher on 12th April but due to low cell temperature average E_1 and E_2 are nearly same with higher energy yield on 13th May.

Table 2 Average Efficiency, Energy Yield and Maximum Efficiency of the Day

Day	E_{1max} in %	E_{1av} in %	E_{2max} in %	E_{2av} in %	T_{cav} in ^{o}C	POA_{av} in W/m^2	P_{dcav} in kW	P_{dc} in kWh/day
11-09-15	12.62	7.10	74.49	41.94	48.49	622.20	49.78	2240.11
18-10-15	13.32	7.44	79.07	43.93	47.53	608.22	52.14	2346.28
13-11-15	10.53	4.37	62.15	25.78	40.10	515.49	30.60	1224.02
22-12-15	**11.70**	**2.98**	**69.10**	**17.58**	**34.20**	**553.77**	**20.87**	**834.78**
08-01-16	13.08	4.30	77.21	25.38	33.95	617.62	30.12	1204.86
22-02-16	**15.16**	**7.20**	**89.54**	**42.52**	**38.28**	**675.23**	**50.46**	**2169.86**
08-03-16	**14.55**	**7.40**	**85.92**	**43.71**	**42.62**	**627.45**	**51.88**	**2334.64**
12-04-16	13.41	7.94	79.17	46.88	46.84	668.08	55.64	2420.26
13-05-16	**12.61**	**7.90**	**74.43**	**46.66**	**51.85**	**617.50**	**55.37**	**2491.84**
04-06-16	**13.51**	**8.44**	**79.77**	**49.81**	**51.38**	**707.07**	**59.12**	**2660.44**
11-07-16	12.75	7.76	75.31	45.84	48.89	612.55	54.41	2448.53

4. RESULTS

- Maximum solar cell conversion efficiency of 15.16% is obtained at moderate cell temperature and very high POA in February but due to comparatively lower temperature average efficiency over the day is only 7.20% while in June although maximum E_1 is only 13.51% but as average POA and average temperature are maximum and correspondingly the average efficiency and energy yield are also maximum with values 8.44% and 2660.44 kWh/day respectively.

- At high cell temperature in the month of May and June when the temperature is as high as 62^{o}C and the average temperature is around 51-52 ^{o}C, V_{dc} becomes independent of POA and nearly constant and high V_{dc} is obtained for longer duration leading to higher energy yield.

- The average efficiencies in winters are extremely low with average value of E_1 varying between 3 to 4.4% and average value of E_2 varying between 17 to 26%. In the month of December when average POA and cell temperature are minimum, the average E_1 and E_2 are minimum with corresponding values 2.98% and 17.58% respectively. The energy yield is also minimum in December.

- For spring season, the average cell temperature varies between 39-43^{o}C with average E_1 and E_2 varying between 7.20 to 7.40% and 42.52% to 43.71% respectively.

- The average E_1 in post monsoon season varies between 7.10 to 7.44% and E_2 varies between 41.94 to 43.93%. the energy yield is more compared to spring season due to slightly higher temperature.

The above analysis shows that both E_1 and E_2 increase with increase in POA and increase in cell temperature even as cell temperature increases up to 58.92^{o}C. The slight decrease in efficiency with decreasing POA and increasing temperature for short duration is insignificant. Higher efficiency is obtained at higher POA but much higher POA is required to attain same efficiency for cell temperature less than about 49^{o}C.

Variations in E_1 and correspondingly E_2 shown only for E_1 in figure 1, 3, 5, 7, 9, 11, 12, 14, 18, 19 20, 22, 24, 26,28,29 and 30 follow variations in V_{dc} until V_{dc} attains nearly constant high value thereafter it follows POA curve and consequently I_{dc} as I_{dc} varies linearly with POA clearly illustrating variations in V_{dc} are more significant compared to variations in current. This is in accordance to the theoretical fact as DC power is product of DC voltage and DC current and as the maximum DC voltage of the array is 735.36V while maximum DC current of the array is only 161.4A, consequently weightage of V_{dc} is much more compared to weightage of current. As voltage variations are governed by cell temperature and current variations are governed by irradiance, it is the cell temperature that governs the efficiency and corresponding energy yield, signifying the defining positive role of high cell temperature.

5. CONCLUSION

In contrast to literature and research papers [1,2,3,4,5,6,7,8,9,10] all which shows DC power efficiency and solar cell conversion efficiency decrease with increase in cell temperature above 25^{o}C, this paper brings forward for the first time ever the defining positive role of high cell temperature on DC power efficiency and solar cell conversion efficiency. High efficiency is obtained only at high temperature, further efficiency variations are governed by voltage variations and as voltage variations are governed by cell temperature it is the cell temperature that plays the defining positive role on both E_1 and E_2. As further work simultaneous effect of cell temperature and irradiance on efficiency and energy yield for several days, for different types of solar PV module and for various locations of the world need to be done.

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