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Temperature Effect on the Performance Metrics of Gridtied SPV Plant

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Abstract

This article methodologically investigates the temperature effect on the performance metrics of Grid-tied Solar Photo-voltaic plants and importance of these metrics. Performance Ratio (PR), System Efficiency (SE) are two critical performance metrics that are very sensitive to temperature changes. The effect of variation of the temperature on these metrics are evaluated and analyzed for 120kWp SPV plant on rooftop of EEE Block in CVR College of Engineering for the year 2017. Above performance metrics are calculated manually from the data extracted from web-interface. The investigation reveals that PR of SPV plant reduces significantly during the months March to June, as the average ambient temperature is more than 29^0C in this period. During these four months, PR and SE of the 120kWp plant is dropped around 2.5% from the average values though plant output energy is more. From the real time data, surprisingly one more interesting observation identified is that the Inverter efficiency also varying with ambient temperature. After analyzing performance metrics, the overall performance of the plant is as good as a MW scale commercial Solar PV Plant.

Keywords: Grid-tied SPV Plant, Inverter Efficiency Performance Metrics, Performance Ratio (PR), System Efficiency (SE), Temperature Corrected Performance Ratio (TCPR).

I. INTRODUCTION

India has abundant amount of solar energy almost in every part, with an average of 300 sunny days in an year. This clean, non polluting, green and renewable solar energy is the greatest alternative to the energy needs in the country.

The most excellent way to generate electrical energy from the solar power is by Photo-Voltaic effect. In this process photon energy of the solar radiation is directly transformed in to DC electrical energy using the Solar Cell. One solar cell can generate only small quantity of electrical power. Hence, to generate reasonable power more number of solar cells are connected either in series or parallel to form a Solar array to get the required power.

Grid-tied PV systems are widely being used because of many advantages. Power production from such grid-tied SPV plants have to be monitored properly for better utilization of plant and available resources [1-4]. Performance of SPV plants can't be judged easily by considering the magnitude of energy generated from the plant every day. The output of solar plant depends upon the quantum of solar irradiation that falls on effective surface area of PV array. This solar radiation will not be same right through the year and in all locations. It is best in summer, more in winter and moderate in monsoon season. Hence, justifying the performance of the plant depending on the quantum of electrical energy produced by the plant is not hypothetical. Therefore, to analyze the performance of SPV plants, few metrics are essential. The best metrics that are adopted by the SPV industry experts to analyze the performance of SPV plant are, Performance Ratio (PR), System Efficiency (SE) [816].

Climatic conditions like high temperature and high humidity have negative influence on performance and consistency of PV modules. Besides the module performance, efficiency of the inverter is also a significant factor which seriously impacts the overall system performance and behavior. Effect of the temperature on the performance of inverter is also worth investigating as the effectiveness and performance of this power electronic device also influenced by operating temperatures.

Besides temperature, various factors that influence the plant performance are Solar insolation , shading effect, Effect of climate, Wind speed, Electrical load matching , Dust on panels, Accuracy of MPPT operation. Different losses that are occurring in the system are Array capture losses, Soil losses, Inverter losses, etc. The industry experts need to understand the each and every influencing parameter and its effect on performance of this plant. This research mainly concentrates on the temperature effect on plant's performance [5-6].

The organization of this paper is: Chapter II describes the climatic conditions and solar insolation values at the site and configuration of the grid-tied plant under analysis. Chapter III clearly discusses the various plant’s Performance Metrics viz. Performance Ratio, Temperature Corrected PR & System Efficiency in detail. Chapter IV analyzes the results in a organized manner and discussion of Plant performance using these metrics followed by conclusions and references.

II. SPECIFICATIONS OF GRID TIED PV PLANT

Design of every grid –tied SPV plant depends upon so many factors like weather , solar insolation data and it's geographical coordinates. The geographical location determine the tilt of the PV modules.

II.I LOCATION OF THE SPV PLANT

The grid –tied SPV plant for the investigation of different performance metrics is located on the roof top of the CVR College of Engineering, Ibrahimpatnam mandal, Hyderabad, Telangana state. The global coordinates of the site are Latitude: 17.20^0 N, Longitude: 78.60^0 E. This project location is at an altitude of 545.m above the sea level. Table.1 shows the measured monthly Solar Irradiation per day in kWh/m^2/day, ambient temperature (^{0}C) and Module temperature (^{0}C) for the year 2017.

Table 1. Month-Wise Average Solar Radiation, Average Ambient Temperature and Average Module of SPV Plant

Month & Year	**Avg. Solar Radiation**	**Avg. Module Temperature in Centigrade**	**Avg. Ambient Temperature in Centigrade**
January'17	5.66	27.2	23.2
February'17	5.94	29.3	25.7
March'17	6.26	36.6	29.1
April'17	6.45	44.5	31.4
May'17	6.72	46.4	32.6
June'17	5.91	37.3	29.2
July'17	5.38	34.1	26.8
August'17	5.15	31.3	25.7
September'17	4.09	25.8	20.1
October'17	5.18	30.7	25.5
November'17	5.32	29.2	23.9
December'17	5.52	26.4	22.1
Yearly Average	5.66	33.2	26.3

II.II CAPACITIES OF PHOTO VOLTAIC PLANT

The maximum capacities of various grid –tied SPV sub plants on the rooftops of different independent buildings in CVRCE are given in Table 2. including the commercial dates of operation of each sub plant to their full name plate ratings. The essential electrical equipment that are required for grid interactive SPV plants are: SPV Modules (Array) , DC Solar Cables, Grid tied String Inverters, AC Cables, Junction Boxes, Switchgear Equipment, Net- Metering facility (Bi-directional energy meter), Lighting Arrestors and electrical earthings at appropriate locations. The entire apparatus, components and devices used in this SPV sub-plants are according to the IEC 61724 standards as per the guidelines given by MNRE[7].

Table 2. Details of sub plants , their capacities and date of commencement of plant

Name of the Sub Plant	Location of the Plant	Installed Power	Date of Commencement of Plant
CVR PG Block	EEE Block	120 kW_p	03-03-2014
Single Axis Tracking	Main Block	40 kW_p	18-01-2015
Library	Library Block	20 kW_p	23-02-2015
Single Axis Polar Tracking	Main Block	40 kW_p	11-03-2015
CVR CS Block	CSE Block	60 kW_p	22-10-2015
CVR New	First Year Block	80 kW_p	03-03-2016
Overall Plant Capacity		360 kW_p	----

Table 3. Details Of Grid Integrated Refusol 020k Solar String Inverter

	REFUsol 020K
DC DATA	
Recommended Max. PV Power, kWp	21.6
MPPT Range	480 V-850 V
DC Start Voltage	350 V
Max. DC Voltage	1000 V
Max. DC Current	41 A
MPP Trackers	1
AC DATA	
Rated AC Power	19.2 kVA
Max. AC Active Power	19.2 kW
Rated Power factor	1
Max. AC current	3 X 29
Distortion factor THD	<1.8 %
Max. efficiency	98.20%
European efficiency	97.80%

The solar PV array is the interconnection of different solar modules either in series/ parallel depending upon system design, rating and configuration. The modules commissioned for this rooftop SPV plant are supplied by Kohima Energy Pvt. Ltd. The module manufacturing number is KE-60-M250, with peak DC electrical power rating of 250W_p at STC conditions (25^{0}C ambient temperature, 1000 W/m^2 Insolation, Air mass ratio is 1.5). The other Specifications of Solar Module -KE-60M250 are given in

Table III [8]. As per the design, there are 80 no's of above KE-60M250 solar modules. These 80 modules are further connected in 4 parallel strings each string consists of 20 modules in series. Fig.1 shows the 20kW grid tied REFUsol 008K-020K string inverter. Its maximum efficiency is 98.2% at STC conditions. For every 20kW array one independent string inverter is commissioned. Consequently whole 120kW SPV plant has Six (6) individual string inverters. However, for superior understanding, all these 6- inverters are assumed as single central inverter.

Table 4. Specifications of solar module kohima energy pvt. Ltd.

STC–Irradiance of 1000 W/Sq. m at 25°C	KE-60-M250
Maximum Power (P_{max})	250 W
Maximum Power Voltage(V_{mp})	31.44 V
Maximum Power Current(I_{mp})	7.95 A
Open circuit Voltage(V_{oc})	37.86 V
Short Circuit Current(I_{sc})	8.69 A
Fill Factor	75.98%
Module Efficiency(η)	15.40%
Nominal Operating Cell Temperature (NOCT)	45+2
Temperature Coefficient of Isc (α)	0.04 /0C
Temperature Coefficient of Voc (β)	-0.32 /0C
Temperature Coefficient of Pmax (ϒ)	-0.45 /0C
Cells per module	60
Cell type	Multi crystalline Silicon
Cell Dimensions	156 m.m X 156 m.m

Fig.2 shows the on-site photograph of the 120 kW_p Solar PV plant on the rooftop of EEE Block. Fig.3 shows the electrical layout of the 120kWp -PV Plant. All these modules are tilted about 17^0 with reference to horizontal, facing true south.

Fig.1 String Inverter used in SPV plant on rooftop of EEE Block

Fig. 2 120kW$_p$ Solar PV Plant on EEE Block of CVR College of Engineering

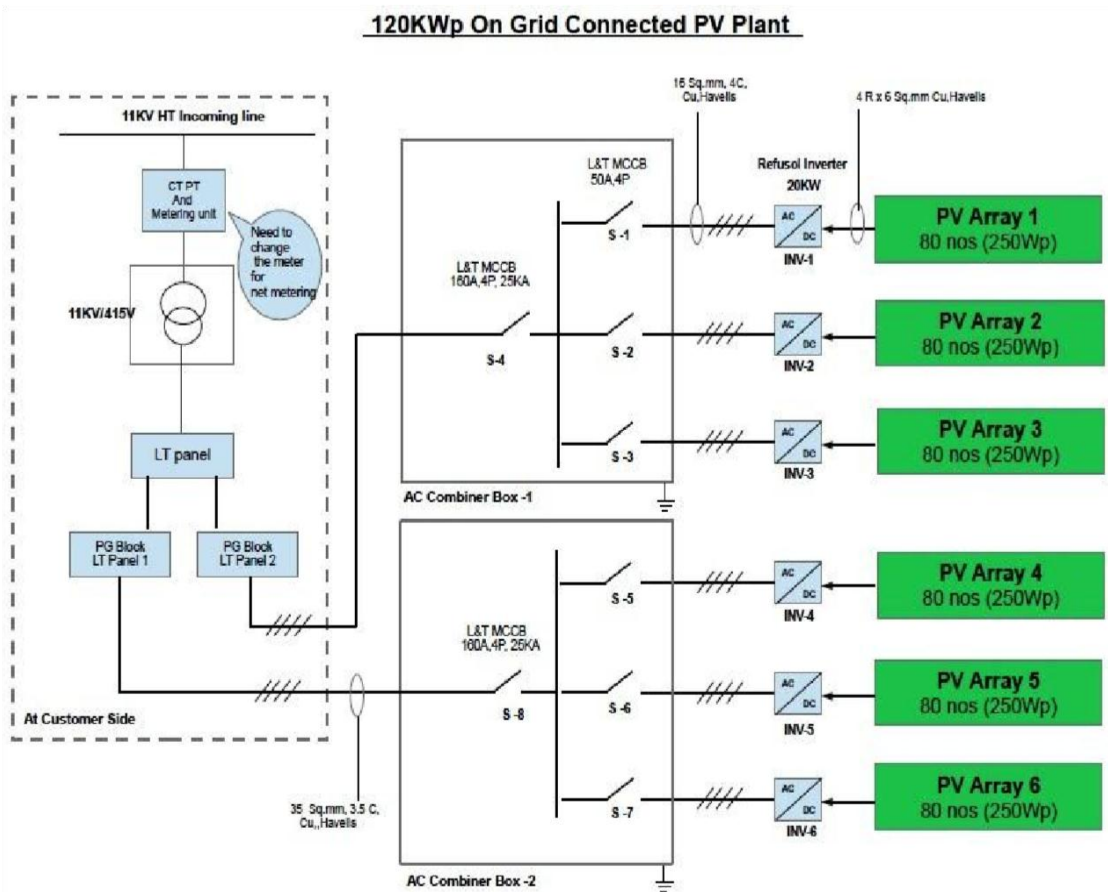

Fig.3 Electrical Layout of Solar PV Plant on Library Block of CVR College of Engineering

III. PERFORMANCE METRICS (PR, SE)

III.I PERFORMANCE RATIO (PR)

PR is the most significant metric that is evaluated for grid –tied SPV plants. The empirical formula to evaluate the PR is as follows.

PR= Actual AC Energy Produced by plant / Nominal Energy

Where Nominal Energy =

GHI (in kWh/m^2) X Rated Module efficiency X Total Active PV area (in m^2) - (1)

PR is usually evaluated for a year to get complete idea about the plant. PR also can be evaluated on daily, weekly, or monthly basis. In above empirical formula, the denominator expression consists of GHI, Module efficiency and Active PV area. Module efficiency value is picked from nameplate ratings given by the panel manufacturer. Active area is basically area covered by PV cells alone in entire solar array. Whereas GHI of site or plant location depends upon several factors like ambient temperature, Cell temperature, soil and dust losses, partial shading, weather conditions, etc. Hence calculation of PR includes all the factors into account. Consequently, the effect of above factors will be reflected in Performance Ratio evaluation. If the evaluated PR value is near to the 100 %, it reflects that PV plant is in excellent operating condition.

The manual procedure to compute PR of the plant is as follows:

- Determine the time period of analysis (Optimum period is one calendar year).
- Active PV area of solar array is computed by number of modules connected in PV array.
- Collect the Solar module efficiency from the datasheets.
- AC energy production of the Plant from the data logger.
- Collect the real time values of measured solar insolation using Pyranometer.

PR is the appropriate performance metric to compare various SPV plants located at different geographical locations and climate conditions. Deviations from the expected PR indicate either a fault or some difficulty/problem with in the PV plant to generate expected energy.

The most accepted global standard to measure the performance of a SPV plant is PR. Most of the stakeholders & Independent Power Producers (IPP) are very keen to evaluate and compare the PR's of the dissimilar rated solar plants across the globe, which located at different geographical locations [9-13].

III.II TEMPERATURE CORRECTED PERFORMANCE RATIO (TCPR)

According to the IEC 61724 standards, the key parameter to be calculated for the investigation of the performance of the SPV plant is Performance Ratio. Conventionally, PR of the plant is evaluated using equation (1). However this equation doesn't include all weather dependent factors other than irradiance. Yet it is extremely important to include the effect of temperature on PV module efficiency. PV module output power changes with variation in temperature. Temperature coefficient of the power (ϒ) is the parameter which include the effect of temperature on module output power . The module rated output power is simply the value of DC electrical power output, when 1000 W/m^2 solar insolation incident on entire solar PV module active area at 25^oC, with Air mass ratio of 1.5. The modules used in existing plant have Maximum power of 250Wp, with temperature coefficient of the power (ϒ) is - 0.45 % /^oC (negative). Complete module parameters along with other details are mentioned in Table 4.

It is known fact that modules in solar array are always exposed to ambient weather conditions, it is impossible for PV module to generate it's maximum DC electrical output power. Because, throughout the operation of the plant the solar insolation values & ambient temperature change invariably for every second. Hence the calculation of PR by considering the rated maximum power at 25^oC may not give feasible, exact and reliable results. To include the influence/effect of temperature in PR, another metric called temperature corrected PR (TCPR) is introduced by industry experts. This TCPR is also approved and included in updated latest IEC 61724 standards.

The mathematical expression to evaluate the TCPR is given by the equation 2

Temperature Corrected PR = Calculated Nominal PR at STC / [1- Υ*(T_{amb}- 25)] -- (2)

where Υ- is temperature coefficient of the power and T_{amb} is ambient temperature averaged (in centigrade).

III.III SYSTEM EFFICIENCY (SE)

System Efficiency is another performance metric which illustrates the on-site Plant performance. System Efficiency gives idea about how much percentage of incident solar irradiation on modules is converted into AC electrical energy. Consequently it reflects the overall plant efficiency. Thus it takes the performance of entire SPV system into consideration.

The empirical formula to calculate the System Efficiency is given by the equation 3.

System efficiency =

Temperature corrected SPV array Efficiency X Efficiency of inverter - (3)

If the purpose is to calculate monthly system efficiency, then substitute the annual parameters with monthly parameters.

IV. RESULTS & DISCUSSIONS

A Radiation sensor (Pyranometer) is positioned on the mounting frames of the 120kWp SPV modules with a tilt of 17^0 and facing true south. This allows to sense and measure the exact value of solar insolation in W/m^2.Two temperature sensors are also placed at in the plant location. One is to sense and measure the ambient temperature and the other is to measure the reference module temperature. The table 5 demonstrates the month wise average solar insolation, average ambient temperature & average module temperature.

During the summer i.e from March to May, the solar radiation is high and also the ambient temperatures. The highest average temperature is observed in the month of May'17 and lowest is in the month of September '17 due to high monsoons.

IV.I CALCULATION OF NOMINAL PERFORMANCE RATIOS (AT STC)

Table 5. shows the calculated monthly nominal Performance Ratio's of the $120kW_p$ SPV plant at STC conditions. As per the discussions earlier in the chapter III , the temperatures of the modules will vary continuously due to change in solar insolation and weather conditions. The output power labeled on the nameplate of solar module are obtained at laboratory conditions(STC conditions are 25^o C of ambient temperature , solar radiation of 1000 W/m^2 & Air-mass ratio of 1.5). Hence the values calculated for PR at STC conditions won't give exact picture about plant performance, as plant always operates at different weather conditions and temperatures all over the year.

Table 5. Month-wise average actual ac energy generated, average theoretical DC energy could generated at 25^oC and nominal PR of 120kw SPV plant

Month & Year	Actual AC Energy Produced	Theoretical DC Energy at 25 ° C	Nominal PR
January'17	14639.70	18938.10	77.30
February'17	15168.90	17951.58	84.50
March'17	15951.40	20945.67	76.16
April'17	15780.40	20885.23	75.56
May'17	16287.10	22484.81	72.44
June'17	15395.60	19136.69	80.45
July'17	14362.10	18001.23	79.78
August'17	13876.50	17231.66	80.53
September'17	10122.20	13243.50	76.43
October'17	14486.50	17332.04	83.58
November'17	14378.70	17226.26	83.47
December'17	14456.90	18469.66	78.27
Yearly Average	14592.20	18487.20	79.04

From the previous discussions, we can understand that effect of temperature on the performance of PV generator is very high about 15% . If the effect of this temperature is incorporated in the calculation of the PR, then one can understand the exact plant performance as close to the real time performance. The procedure to evaluate the TC PR is explained in the chapter 3. Table. 6 shows the comparison of month-wise nominal PR of the plant with TC PR's.

IV.II CALCULATION OF TEMPERATURE CORRECTED PERFORMANCE RATIO (TCPR)

The mathematical expression to calculate temperature corrected PR is given by the equation no (2). The rated module output power is $250W_p$ at STC conditions for the Kohima modules used in this plant . The temperature coefficient of the power (ϒ) is -0.45 % /^{o}C (negative) as mentioned by the manufacturer for these multi-crystalline silicon modules.

Table 6. Month wise nominal Performance Ratios vs Temperature Corrected PR of 120kw SPV plant

Month & Year	Ambient Temperature	Nominal PR at STC	Temperature Corrected PR
January'17	23.2	77.30	78.08
February'17	25.7	84.50	86.17
March'17	29.1	76.16	80.35
April'17	31.4	75.56	82.83
May'17	32.6	72.44	80.15
June'17	29.2	80.45	85.16
July'17	26.8	79.78	83.19
August'17	25.7	80.53	82.88
September'17	20.1	76.43	76.71
October'17	25.5	83.58	85.78
November'17	23.9	83.47	85.08
December'17	22.1	78.27	78.77
Monthly Avg.		79.04	82.10

Using the equation no 2, the temperature corrected PR of the SPV plant is evaluated for every month for the year 2017 and tabulated in Table No 6. Fig.4 shows the comparison of Nominal PR with TCPR in graphical form. During the summer, i.e March'17 to June'17, average ambient temperatures are relatively higher than the other months. Hence the variation of TCPR with respect to PR is little higher in these months. Fig.5

shows the graphical representation of temperature Vs temperature corrected PV system efficiency.

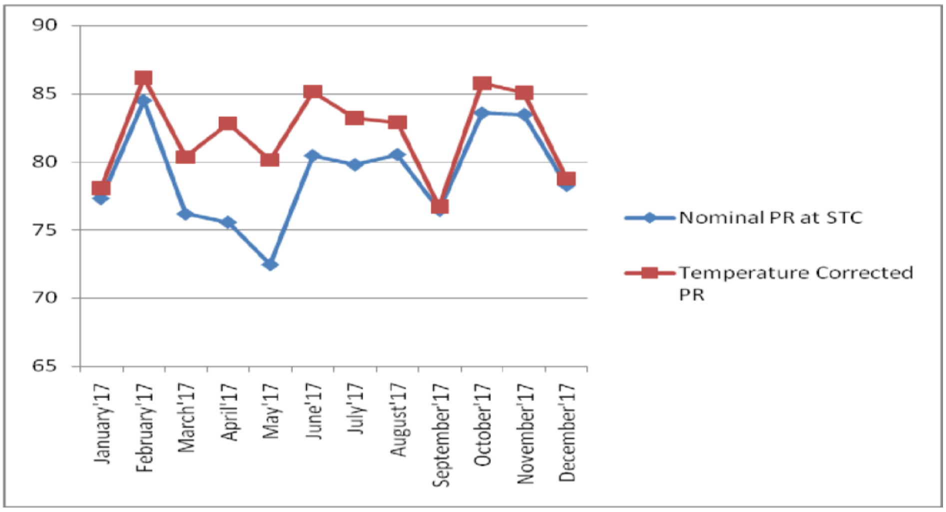

Fig.4 Monthly Nominal Performance Ratios Vs Temperature corrected PR of 120kWp SPV plant on rooftop of EEE Block

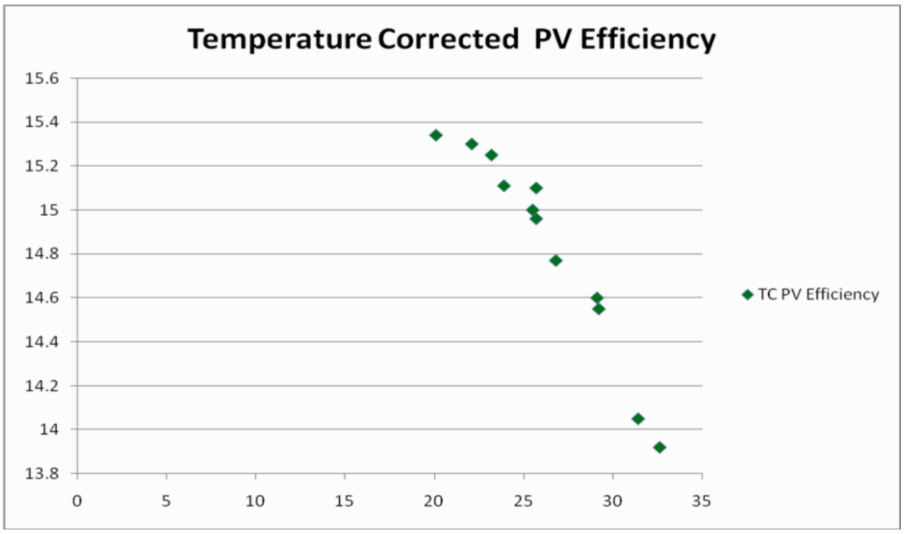

Fig.5 Temperature Vs temperature corrected PV system efficiency of SPV plant on rooftop of EEE Block

IV.III CALCULATION OF SYSTEM EFFICIENCY

System Efficiency gives idea about how much percentage of incident solar irradiation is converted into AC electrical energy. Thus, it reflects the overall plant efficiency[14-17]. Table .7 gives the on-site measured values of DC & AC electrical powers at the inverter input and output terminals respectively. From these values, average monthly inverter efficiencies are evaluated. The average yearly efficiency of Refulog 020K

String inverter is about 93.81%, which is fairly good for non-commercial SPV plants. The inverter efficiency is maximum in December '17 about 95.68% and minimum in May'17 about 90.18%. Fig.6 shows the graphical form of temperature Vs inverter efficiency.

One of the interesting observation made from the above statistics is that, when the ambient temperature is more than 25^{o}C, the efficiency of the inverter too dropped around 1.2% from March'17 to June'17, it is observed that inverter efficiency had reduced considerably and this reduction is quite high in the month of May'17. Month-wise system efficiencies for the plant are calculated using equation no 3 and are tabulated in Table 8. Figure.7 shows the graph between ambient temperature Vs monthly overall system efficiencies for the year 2017.

From graphs, it also found that overall system efficiency is reduced from the average value, when ambient temperature is more than 25^{o}C . The overall system efficiency is maximum in December '17 , when the monthly average ambient temperature of 22.1^{o}C and is low in the month of May'17, when average ambient temperature of 32.6^{o}C .

Table.7 Monthly average ambient temperature vs inverter efficinecy in %of 120kw spv plant for the year 2017

Month & Year	Avg AC Power (kW)	Avg DC Power (kW)	Ambient Temperature	Inverter Efficiency (%)
January'17	1219.98	1287.17	23.2	94.78
February'17	1264.08	1327.67	25.7	95.21
March'17	1329.28	1439.24	29.1	92.36
April'17	1315.03	1443.03	31.4	91.13
May'17	1357.26	1505.05	32.6	90.18
June'17	1282.97	1390.60	29.2	92.26
July'17	1196.84	1274.86	26.8	93.88
August'17	1156.38	1214.17	25.7	95.24
September'17	843.52	0896.21	20.1	94.12
October'17	1207.21	1267.01	25.5	95.28
November'17	1198.23	1254.03	23.9	95.55
December'17	1204.74	1259.14	22.1	95.68
Yearly Average	1214.63	1296.52		93.81

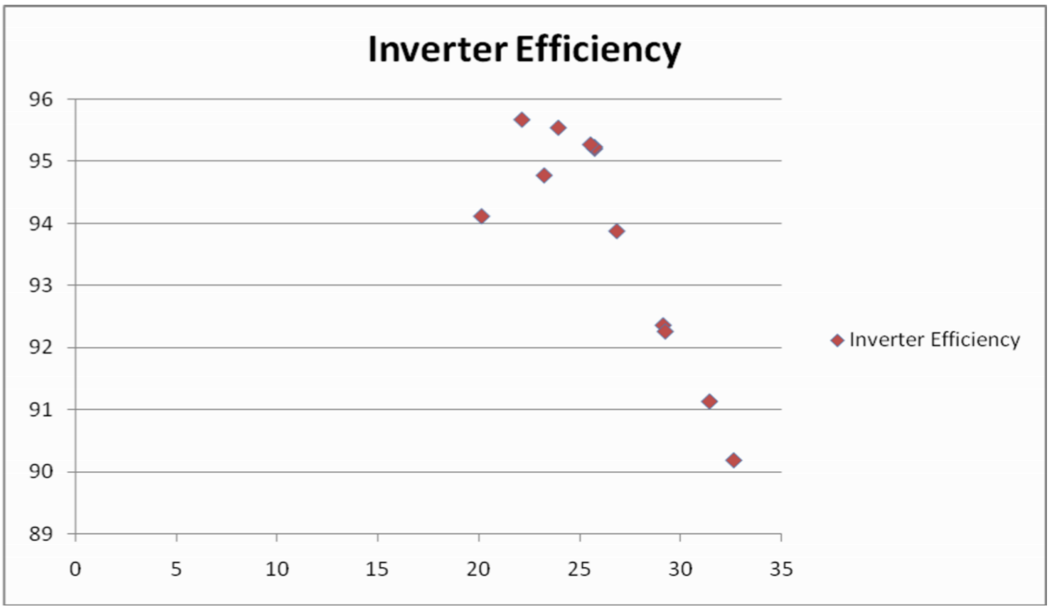

Fig.6 Inverter efficiency Vs Temperature of 120kWp SPV plant on rooftop of EEE Block

Table 8. Monthly average ambient temperature vs overall system efficiency in % of 120kw spv plant for the year 2017

Month & Year	Ambient Temperature	TC PV Efficiency	Inverter Efficiency	Overall System Efficiency
January'17	23.2	15.25	94.78	14.45
February'17	25.7	15.10	95.21	14.38
March'17	29.1	14.60	92.36	13.48
April'17	31.4	14.05	91.13	12.80
May'17	32.6	13.92	90.18	12.55
June'17	29.2	14.55	92.26	13.42
July'17	26.8	14.77	93.88	13.87
August'17	25.7	14.96	95.24	14.25
September'17	20.1	15.34	94.12	14.44
October'17	25.5	15.00	95.28	14.30
November'17	23.9	15.11	95.55	14.44
December'17	22.1	15.30	95.68	14.64

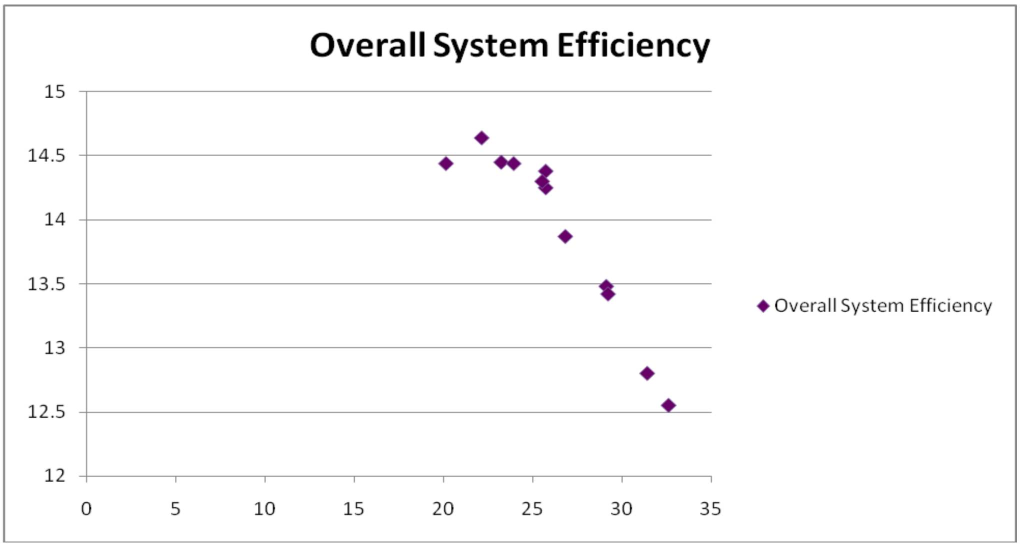

Fig.7 Temperature Vs Overall efficiency of 120kWp SPV plant on rooftop of EEE Block

V. CONCLUSIONS

In this paper, the effect of temperature on Performance Ratio & System Efficiencies are computed manually for 120kWp grid connected SPV plant on rooftop of EEE block. Performance Ratio and System Efficiency are observed to be more sensitive for the variations in the ambient temperature. During the summer i.e March'17 to to June'17 , the variations in above two metrics are significantly more with variation in temperature as the average ambient temperatures are more than 29^{o}C. The calculated performance metrics, of this 120kWp SPV plant are as good as commercial PV plants. It is also observed that inverter efficiency also highly influenced by temperature, when ambient temperature is greater than 29^{0}C.

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