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Field Performance Study and Analysis of Semiconductor & Solar Grade Silicon Based Photovoltaic (PV) Modules/Arrays

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Abstract **- This paper details the short term outdoor performance evaluation of Solar Grade Silicon (Elkem Solar Silicon ESS^{TM}) and Semiconductor Grade Poly Crystalline Silicon (Poly-Si), Photovoltaic (PV) cells/modules. The long term testing/evaluation is being carried out at BVRIT, an engineering college at Narsapur, affiliated to Jawaharlal Nehru Technological University (JNTU), near Hyderabad, India. 28 PV modules (14 of SoG Si & 14 of Poly Si) are configured in four parallel strings, each string containing 7 series-connected PV modules of the same technology (either SoG-Si or Poly-Si). The strings/arrays are south facing with a fixed tilt of 17 degrees and are connected to two grid-connected single phase inverters, which have maximum power point tracking (MPPT). The instruments used include Met One anemometer, Kipp & Zonen CMP11 pyranometer (POA & Horizontal), Met One 10409 Linear Immersion thermistor type sensors, CR3000 data logger (to record ambient & module temperatures, wind velocity& direction and irradiance), Daystar I-V curve tracer & Testo Thermal imager, energy meters AC & DC (Elmeasure make). Special software has been developed to log all the relevant data at 5-min intervals. It is observed that in the period of evaluation, April-September, 2012, the ESS^{TM} modules/arrays have demonstrated better performance than the Poly-Si modules/arrays. This project has been funded by the Research Council of Norway, with Elkem Solar as the research partner, Titan Energy Systems Ltd, Hyderabad as the Industry partner & BVRIT as the Academic Partner.**

Index Terms—Photovoltaic (PV), Solar Grade Silicon, Elkem Solar Silicon (ESS^{TM}), maximum power point tracking (MPPT), grid-connected. Plane of Array (POA)

I. INTRODUCTION

Alternative sources of energy have assumed considerable significance in the context of the fast depleting conventional sources such as coal, oil, gas and so on. The latter sources also emit harmful GHG apart from being increasingly cost prohibitive. Photovoltaic's (PV), which is the conversion of light energy into electric energy, is expected to occupy a progressively increasing proportion of the energy portfolio of the country. PV provides clean energy. But costs of PV cells / modules still rule high accentuating the need for cost reduction through better or cheaper technology that would increase the benefit / cost ratio. It is against this backdrop that various manufacturers have developed solar grade silicon as a cheaper option vis-a-vis semi-conductor grade silicon. While solar grade silicon cells / modules have been evaluated for their performance under European conditions, they have not so far been tested / studied under Indian conditions of high irradiance and temperature.

PV modules can be designed for a variety of applications and operational requirements. A reliable PV module is expected to perform satisfactorily for 20 to 30 years, under the operating conditions encountered. But the PV module output performance varies over extended periods under varying atmospheric conditions and will differ, as dictated by the site conditions, from the output rating quoted by the manufacturer, at Standard Test Conditions (STC, i.e. the solar spectrum AM1.5, 1000 W/m2 solar radiation intensity, 25°C module temperature) [Malik AQ et al., 2003]. Long term testing/evaluation of PV modules of different photovoltaic technologies are necessary to establish their performance & reliability under different conditions (tropical in this case).

Field experiments are performed by many to ascertain and analyze the changes in the PV performance after a certain time interval of outdoor light exposure [Malik AQ et al., 2003, Mitchell KW et al., 1986]. However, the test results are site-dependent and would also be governed by the period of investigation.

Since sunlight is an intermittent energy source, PV modules have to operate under conditions that vary a lot. This places certain restrictions on their use, because they cannot produce energy at a constant rate and the power delivered at a certain instant is still very much a function of the weather conditions at hand. Two critical parameters are the solar irradiance and the temperature of the module. The other parameters that also affect the performance are wind speed, module degradation and module aging [Green et al., 1982, Gxasheka et al., 2005].This paper presents the results of outdoor evaluation of two relevant cell technologies under identical meteorological conditions of a DC-AC grid connected system.

II. PV SYSTEM DESCRIPTION

Fig1. shows the photograph of the installation of PV system on the rooftop of one of the buildings at BVRIT near Hyderabad, in the Southern part of India, on stainless steel support structure facing south (Latitude: 17.37°, Longitude: -78.47°, Altitude: 489 m) at 17 degree tilt angle chosen to maximize yearly energy production. The utility power available at the site is 230 Vac, single phases, 50 Hz. Total Installed capacity of the plant is 6.72KW, grid connected. The plant consists of a total 28 PV modules [14-solar grade silicon (Elkem Solar Silicon, ESS^{TM}) and 14-poly crystalline silicon]. Each PV module contains 60cells with individual cell area 243.36cm$^{2.}$ The PV system is arranged in 4 arrays/strings, with 7 series-connected modules in each, and connected to two String Inverters (fig.5) POWERONE-Aurora-PVI-6000-OUTD. Real-time data in-terms of energy fed to the grid by each string, and environment parameters measured continuously are monitored and stored at 5-min intervals with the help of special software developed in-house. This would lend itself to analysis of the PV modules/arrays during- and post-operation.

Fig.1 Test bed System (6.74kW PV plant)

The modules are categorized according to batches.
ESS Bottom (EB): bottom part of 100% Elkem Solar Silicon (ESS^{TM}) ingot – Array.1
ESS Top (ET): top part of 100% (ESS^{TM}) ingot – Array.2
Poly Bottom (PB): bottom part of 100% poly silicon ingot – Array.3
Poly Top (PT): top part of 100% poly silicon ingot- Array.4

Array type	Installed Capacity (kWp) at STC
ESS Bottom(EB)	1.69
ESS Top(ET)	1.67
Poly Bottom(PB)	1.71
Poly Top(PT)	1.67
Total (at STC)	6.74 (kWp)

The information relating to one of the PV modules is given below (Table.1), i.e., the manufacturer serial number, cell technology, peak power at standard test conditions (STC: irradiance 1000W/m^2, cell temperature 25^{0}C, Air Mass 1.5) and the module efficiency etc.

PV Module	Specification
Type	TITAN-M6-60 (ELKEM SOLAR)
Number of cells	60 connected in series
Weight	19kg
Nominal power(Pmp)	240 Watts
Maximum dc system voltage	1000Volts
Maximum output power voltage(V_{peak})	30.23Volts
Maximum output power current(I_{peak})	7.94Amps
Open circuit voltage(Voc)	37.56Volts
Short circuit current(Isc)	8.44Amps
Power tolerance	±2.5%
Electrical parameters tolerance	±5%
NOCT at STC	45±10
Maximum over current protection rating	15Amps
Efficiency	14.67%
Diode ratings	Vrrm,= 40V, If=15Amps
Module dimensions(length, width, hight)	1657mm, 987mm, 42mm

Table1. Data sheet of the solar PV modules

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III. DATA ACQUISITION SYSTEM

Weather Station: The weather station (fig.2) collects the information on (a) Global radiation using Kipp & Zonen CMP11 Pyranometer (Plain of array & Horizontal), (b) Wind speed & wind direction using Met One 034B Wind Set, (c) Ambient temperature using Met One T-200A pt100 air temp sensor, and (d) Cell/Module temperature using Met One 10409 (Linear Immersion thermistor type) sensors which are connected to each string. All the weather station sensors are connected to CR3000 Micro Data Logger (fig.3) Campbell Scientific make. Every parameter is logged for at 5min intervals and stored in the logger. Using PC400 software this data can download into PC for analysis purpose.

Fig.2 Whether Station

Fig.3 Campbell Scientific CR3000 Data logger

Analyzing the PV module performance would also require DC/AC Energy Meters (El Measure) connected to each string i.e., voltage (Volts), current (Amps), Instantaneous Power (Watts), Energy output (KWh), power factor (p.f), frequency (Hz) etc. All the meters are interfaced to a personnel computer through RS 485 – RS232 SMART INTERFACE CONVERTER (ElMeasure). All electric parameters stored in the computer are at 5-min intervals and have the same time stamp.

To summarize the monitoring system measures the following parameters in order to study/analyze the performance of PV Systems (short-term and long-term):
Electrical measurement parameters : -DC and AC voltages, currents, Energy (kWh), Output Power (Kw)
Meteorological measurement parameters : -Irradiance on horizontal plane & plane of PV array
- PV module back surface temperature & ambient temperature (RTD air)
-Wind speed & Wind direction

IV. SYSTEM PERFORMANCE & RESULTS

The 6.74kWp grid connected PV system installed in Hyderabad, India, is currently undergoing long term outdoor evaluation. This paper presents the analysis of parameters monitored between April 2012 to September 2012 on daily, and monthly basis, as shown in table 2.

Solar irradiation & Ambient Temperature: The solar irradiance measured during the analysis period and calculated daily, monthly average and minimum, maximum values are also obtained. The average daily maximum value occurred on 13th April, 2012 (629.59W/m^2), while the average daily minimum value was observed on 20th July, 2012 (119.57kW/m^2). Variation of irradiance on some selected days i.e. 27th April, 17th May, 7th July is shown in fig.5. During this period the ambient temperature also studied, the average maximum temperature/day observed on 2nd June, 2012 (38.13^0 Celsius), while the average minimum temperature/day observed on 20th July, 2012 (23.79^0 Celsius),

Generated Energy by Each Array: The average generated DC power output (kW) per/day/hour during the analysis period from 1st April -- 30th September, 2012 was found to be 0.546*kW (ESS Bottom), 0.568kW (ESS Top and 0.549kW (POLY Bottom), 0.543kW (POLY Top)*. During this period the total grid-connected time is 1831.58hrs and average POA isolation per day was 400.58W/m^2 and average ambient temperature/day was found to be 29.25^0 Celsius.

For the purpose of analysis the estimated energy yield was calculated with respect to STC values, considering all the meteorological parameters and grid-availability etc. The formulae used to compute estimated energy- yield & cell temperatures- are given below:

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$$E_{exp} = \left[P_{STC} \times \frac{G_{POA}}{G_{STC}} \times (1 - k(T_{MOD} - T_{STC}))\right] * h \qquad \text{.................... (1)}$$

Where:

E_{exp} = Estimated Energy Output as per site conditions/day (kWh)
G_{POA} = Average plane of array irradiance/day (W/m^2)
G_{STC} = Irradiance at STC (1000 W/m^2)
k = Temperature coefficient of power (0.45)
T_{MOD} = Module or Cell Temperature
T_{STC} = Module or Cell Temperature at STC (25^0 C)
h = grid-availability time (hrs)

$$PR = \frac{E_{exp}}{E_{actual}} \qquad \text{........................ (2)}$$

Where:

PR =Performance Ratio
E_{exp} = Estimated Energy Output as per site conditions/day (kWh)
E_{actual}= Actual Energy Output/day generated by each array (kWh)

Month	EB		ET		PB		PT	
	Estimated (kWh)	Actual (kWh)	Estimated (kWh)	Actual (kWh)	Estimated (kWh)	Actual (kWh)	Estimated (kWh)	Actual (kWh)
Apr,12	229.53	200.48	228.37	206.47	233.45	207.40	227.03	193.96
May,12	231.08	200.68	227.96	209.60	233.15	194.02	228.28	195.78
June,12	211.70	176.90	208.70	185.55	213.74	177.95	208.98	179.38
July,12	167.73	162.22	165.18	168.43	169.12	165.11	165.55	164.66
Aug,12	162.52	132.02	159.48	137.08	163.28	133.33	159.94	133.07
Sep,12	151.89	127.08	149.29	132.47	152.86	127.43	149.71	127.35

Table.2 Monthly Generated Yield Report

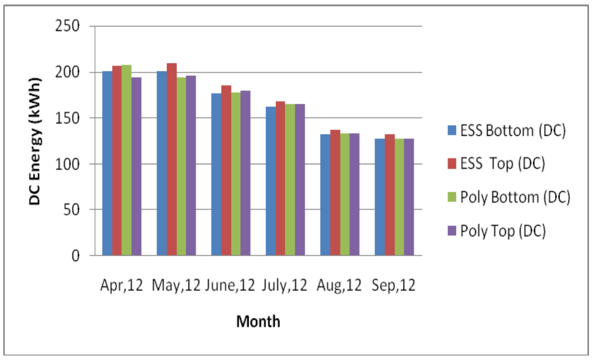

Fig.4 Actual generated kWh

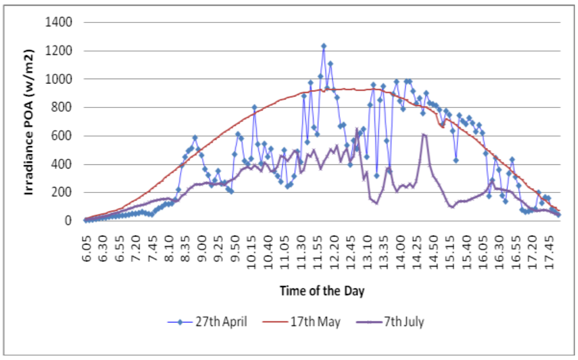

Fig.5 Variation of Irradiance (POA)

Actual generated dc-energy (kWh) by each technology, observed on a monthly basis, during April - September 2012 is shown in fig 4. It is also observed that variation between the technologies is more pronounced in the months of April, July. It is observed from the six-month data that Elkem Top (ET) array generated more energy in comparison with PT, EB, and PB arrays. This was followed by PT performance wise. Power conditioning unit efficiency also calculated during the analysis period and shown in fig.7. DC Power output variation with respect to POA Irradiance and ambient temperature on 17th May also shown in fig.9.

Performance Ratio (PR): Performance ratio has been computed for each technology on daily basis and then averaged on monthly basis shown in fig.6. The PR of different PV technology modules shown high performance in the month of July, followed by June, and also observed that Elkem Top gives higher performance in all the six-month duration in comparison with EB, PT, and PB arrays.

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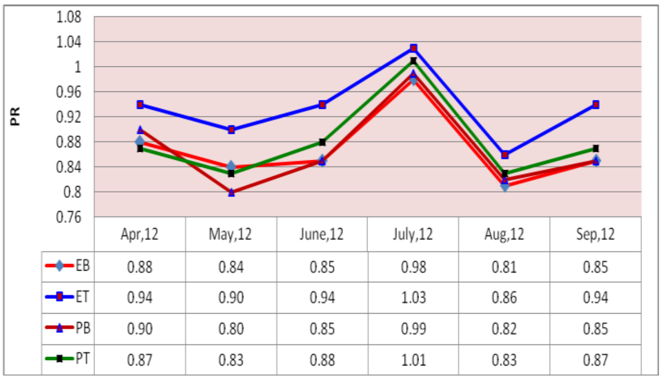

Fig.6 Performance Ratio of different technologies

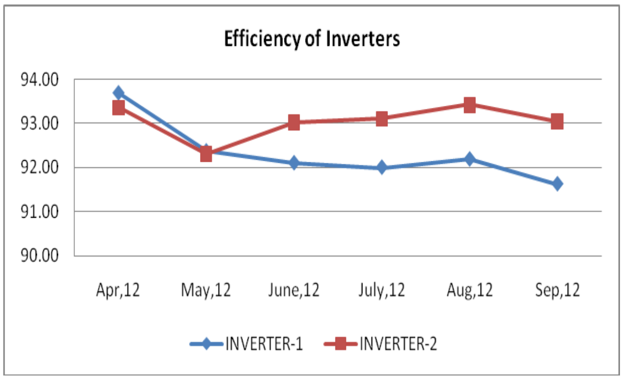

Fig.7 Power Conditioning Unit Efficiency

Month	Irradiance(POA) W/m2			Ambient Temp(Deg C)			Wind Speed(m/s)		
	Max	Min	Avg	Max	Min	Avg	Max	Min	Avg
Apr,12	629.57	298.29	501.42	34.88	28.99	31.04	2.11	0.91	1.64
May,12	548.81	353.27	477.18	36.89	31.53	35.10	3.18	1.45	2.31
June,12	575.64	139.91	382.11	38.13	23.90	29.93	3.65	1.91	2.71
July,12	499.23	119.57	284.54	29.13	23.79	26.55	4.02	1.46	2.57
Aug,12	504.34	216.76	359.54	29.05	24.46	26.32	3.51	0.74	2.42
Sep,12	584.20	148.71	398.70	28.40	24.20	26.56	3.63	0.08	1.73

Table3. Environmental Data

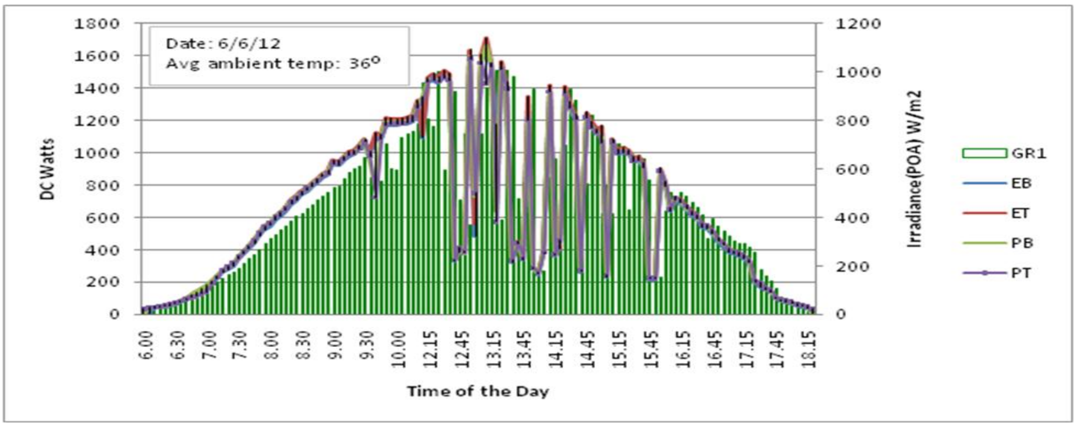

Fig.8 Variation of DC Power Output w.r.t Irradiance (POA)

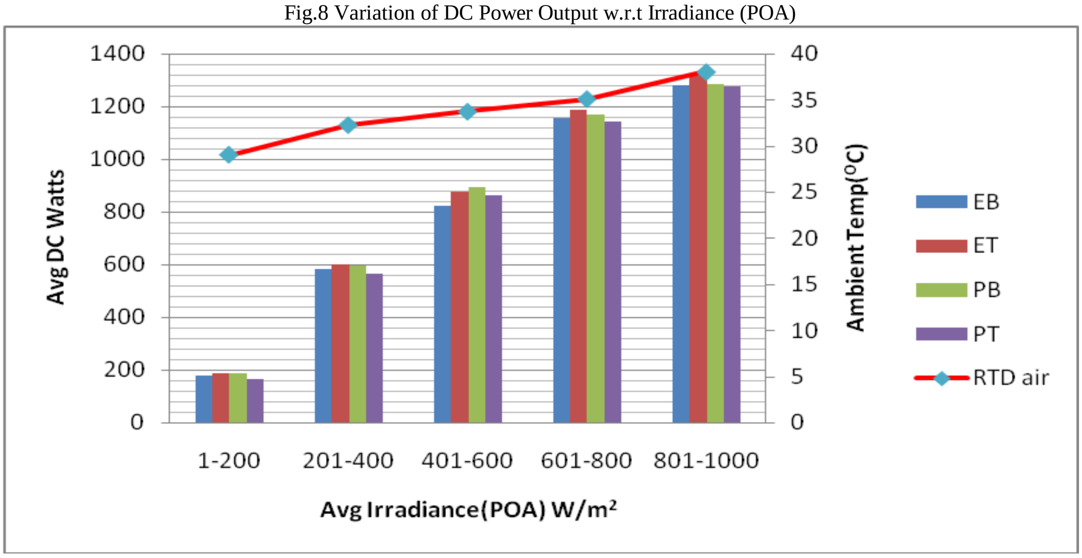

Fig.9 Variation of DC Power Output w.r.t Irradiance (POA) on 17th May, 2012

V. CONCLUSIONS

In this paper, we discussed and analyzed the field performance of 6.74kw grid-tied PV system installed in the Southern part of India, comprising semiconductor and solar grade silicon based photovoltaic modules/arrays. It is observed that across the six-month- period of evaluation Elkem Solar top (ET) string is the best performer followed by Poly top (PT). It is also observed that during the analysis period, variations in performance ratio (PR) of different strings are EB (0.81-0.98), ET (0.86-1.03), PB (0.82-0.99) and PT (0.83-1.01). This evaluation will continue for a protracted period of time. More SOG Si PV modules and Monocrystalline Silicon PV modules are also expected to be evaluated.

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