Long Term Field Performance Evaluation of Grid Connected PV System Considering ESS & PSS PV Modules

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ABSTRACT:

The utilization of solar energy address the world's most critical issues such as reduces greenhouse gas emissions, and mitigates the effects of global warming. The crucial component of harnessing solar energy is PV modules. These are the key technologies that convert sunlight into electrical energy. Despite the widespread use of photovoltaics, there are still many challenges that need to be resolved. PV modules are prone to operating in non-ideal environments, such as partial shade and varying levels of irradiance. These conditions can affect their efficiency and performance. Hence in this work long term performance evaluation of Elkem solar PV system (ESS) in comparison with standard polysilicon PV system (PSS) under various climatic and solar irradiance conditions is proposed. The proposed system is installed in the sunbelt region at Narsapur, India. It consists of 14 ESS and 14 PSS modules with a total of 28 modules having at total capacity of 6.756 kWp connected to single phase grid of 230 V 50 Hz. The results revealed that the proposed ESS modules exhibited the improved performance than the standard PSS modules. The ESS modules generates higher energy yield than the PSS modules.

Keywords: Photovoltaic, Module, Polysilicon, Multicrystalline.

1. Introduction

The surge in solar energy demand over the past few years can be attributed to various factors. These include technological advancements, the increasing number of people who are concerned about the environment, and the economic advantages of solar power. As people look to cut down on their reliance on fossil fuels and address the effects of climate change, solar energy is an ideal choice. Furthermore, The cost of solar panels has also decreased, which has made it more accessible to households and businesses. This growing demand contributes to the growth of the renewable energy industry and creates jobs. As the world moves toward a more sustainable energy system, the demand for solar power

surges. This represents a pivotal shift in the energy paradigm [1].

Global PV market in 2022, the Chinese market continued to grow at a remarkable rate, and it was estimated that it had installed over 106 gigawatts. The European Union was next with 38.9 gigawatts, followed by the US with 18.6 gigawatts. These two countries were hit by various issues such as grid connection backlogs and trade disputes. India, on the other hand, experienced an increase of 18.1 gigawatts. In order to reach the top 10 for new solar power capacity in 2022, countries had to install at least 3 gigawatts of PV systems. Unfortunately, France and Korea were unable to maintain their positions in the top 10. Despite their relatively high performance, the Netherlands and Poland were able to overtake them. The gap between the top 10 countries and the next five is significant. For instance, Italy, Spain, Australia, and Brazil have cumulative capacities of around 20 gigawatts to 30 gigawatts while Germany has capacities of less than half that [2].

In the last few years, the rapid emergence and growth of solar energy has greatly impacted the energy scenario in India. Through distributed and decentralized solar energy systems, people in the country have been able to meet their energy needs. Through the distribution of solar energy systems, women and girls in rural areas have been able to reduce their labor and improve their standard of living. This has also resulted in a reduction in the risks of contracting eye and lung ailments. The country has the potential to generate over 748 gigawatts of solar energy by 2022, assuming that 3% of the waste land area in the country is covered by photovoltaic modules. This is a central component of India's Climate Action Plan. The NSM is also one of the key missions that the country has undertaken to address climate change. The objective of the NSM is to establish a framework for the rapid development of solar energy in the country. This will help India achieve its goal of becoming a global leader in this field by 2030. It is also aligned with the country's NDCs to reduce its greenhouse gas emissions by 45 percent by 2030 [3].

Despite the widespread use of photovoltaics, there are still many challenges that need to be resolved in order to ensure that they can provide a reliable and clean energy source. One of these is the intermittence of sunlight, which can affect the generation and transmission of electricity. In addition, photovoltaics modules are prone to operating in non-ideal environments, such as partial shade and varying levels of irradiance. These conditions can affect their efficiency and performance. The initial cost of PV systems is also a major factor that prevents widespread adoption. Hence in this work long term performance evaluation of Elkem solar PV system (ESS) in comparison with standard polysilicon PV system (PSS) under various climatic and solar irradiance conditions is proposed. The proposed system is installed in the sunbelt region at B V Raju Institute of Technology (BVRIT), Narsapur, India. It consists of 14 ESS and 14 PSS modules with a total of 28 modules having at total capacity of 6.756 kWp connected to single phase grid of 230 V 50 Hz. The results revealed that the proposed ESS modules exhibited the improved performance than the standard PSS modules. The ESS modules generates higher kWp than the PSS modules.

Literature Review

In [4] evaluates the utility-scale efficiency of a PV system that powers an academic institution. The research explores the advantages of a grid-tied silicon-poly photovoltaic system with a peak output of 20.0 kW and a voltage of 17v. In [5], a series of SC bank supercapacitors has been utilized as the load-to-PV generators for this study. The results of the investigation revealed that the system's efficiency was consistent across West Bengal's varying ambient temperatures and insolation levels. The results of the regression analysis revealed that the values of poly-Si photovoltaic modules, which are the most critical building blocks of PV arrays in India, are above 0.997. This is a significant step toward the availability of easy-to-use and portable I-V plotters for the country's PV industry. According to [6], the power output reduction of a PV module can be affected by its type. For instance,

the modules made of amorphous silicon are more prone to experiencing dust soiling than those made of polycrystalline silicon. In addition, the latter's spectrum response allows it to produce full energy.

In [7] presented an AI-based method that can predict the PV module's temperature based on the weather conditions in the region where it's located. It can also take into account other factors such as indoor comfort parameters. In [8] presented an experimental dataset of 28296 poly-Silicon PV modules with various environmental parameters taken as their inputs and outputs. The training algorithm for this project is based on the Levenberg-Marquardt algorithm. The proposed ANN has a layer size of 15 and is designed to accurately predict the power of the modules. In [9] evaluated the performance of mono-crystalline silicon and poly-crystalline silicon photovoltaic modules was evaluated in Ghana using the I-V Tracer. The maximum output power of these modules was 87.9 W and 136.7 w, respectively, at high irradiance conditions. In [10] reviewed the various issues that can be encountered with mono-crystalline and polycrystalline silicon photovoltaic modules when operating in Saharan medium fields. This study aims to identify and evaluate the defects in these modules that are commonly found in older and recent installations. In [11] presented an experimental analysis of the PV parameters that are affected by temperature levels and irradiance variations in a polycrystalline silicon photovoltaic cell. The study used 130 characteristic curves to analyze the data. Temperature levels ranging from 19 to 68 degrees Celsius and irradiance values from 29–1023 W/m2 were considered.

In [12] presented a comprehensive evaluation of the various advantages and challenges of thin Si photovoltaic modules. Through a combination of simulation and cost modelling, the paper aims to provide a viable and sustainable solution for future and current PV modules. The paper indicates that the comparable efficiency of both 50 m and 160 m wafers can be achieved with the use of an advanced technology. In [13] presented the best cleaning material for PV panels based on their performance. In order to achieve this, the effects of different easy-to-clean materials on the efficiency of polycrystalline silicon PV modules were studied. In [14] used a variety of PV modules to analyse their thermal performance under different environmental conditions. Some of these include copper indium diselenite, monocrystalline silicon, amorphous silicon, and micro crystalline silicon.

In [15] focused on the faults and defects of multicrystalline silicon photovoltaic modules that were installed outdoors from 2000 to 2011. It was carried out through a variety of methods such as visual inspection, temperature profiling, and infrared thermal imaging. The effects of partial shading on the efficiency of multicrystalline silicon PV modules are analysed in [16]. In [17] analysed how soiling on PV panels affected the performance of a stadium in Brazil's Minas Gerais state. It also studied the chemical and physical properties of the dust. Luminescent based layer for MC Si – PV modules are presented in [18]. In [19] conducted accelerated lifetime tests on multicrystalline silicon PV panels at 85 degrees Celsius and 85% RH in 45 degrees Celsius and 30 RH. The active layer was placed in either negative or positive 600 V bias. In [20] to analysed the potentials of the installation of PV systems in different economic and environmental viewpoints. It has been conducted in France and Morocco. Two large-scale PV systems, which are capable of producing up to 1 gigawatt of electricity, are simulated. In [21] revealed that the presence of other ions in the PV modules could cause PID. This finding indicates that the chemical composition of these ions does not correspond to the specific characteristics of PID. In [22] presented a comprehensive analysis of the life cycle of electricity generation from various photovoltaic technologies in Singapore. It takes into account the various factors that affect the value chain of PV, such as the mining of silica sand, the installation of PV systems, and the electricity generated by these technologies. In [23] presented an extended method that can be used to calculate losses in a single module when the short-circuit conditions are present. The method also introduces the concept of effective area coverage. In [24] compares and evaluates the

various mountings and sensor types for long-term monitoring of photovoltaic modules. It also presents a standard method for determining the cell's ambient temperature. The study conducted in Brazil [25] explores the possibility of induced degradation in multicrystalline silicon photovoltaic modules. It was established in a test site situated in the southern part of the country. In [26] analysed the various implicit and explicit correlations in three different PV modules. These were multicrystalline silicon, amorphous silicon, and hetero-junction thin layer. The results of the investigation revealed that the Faiman correlation was most effective for all three technologies when the temperature range was at its highest.

2. Performance Metrics and Mathematical Framework

The comparative field performance of the two types of PV modules is evaluated using the key metrics proposed by the International Electrotechnical Commission (IEC 61724) and the International Energy Agency (IEA). These metrics adjust raw energy values based on the system size and available sunlight so that they represent unaffected measures of system performance and losses. The definitions and explanations of the main quantities are presented throughout this paper.

A. Total Energy Output (E_{DC}, E_{AC})

The total energy collected at the inverter input (DC side) and transferred to the grid (AC side) over a specified period T.

These are calculated by time-integrating the instantaneous power measurements:

$$E_{\mathrm{DC}} = \int_{t_0}^{t_0+T} P_{\mathrm{DC}}(t)\,\mathrm{d}t \quad , \quad E_{\mathrm{AC}} = \int_{t_0}^{t_0+T} P_{\mathrm{AC}}(t)\,\mathrm{d}t$$

……..(1)

Where

- $P_{\mathrm{DC}}(t)$ is the summed DC power from all strings
- $P_{\mathrm{AC}}(t)$ is the AC power output of the inverter.

In practice, these integrals are assumed by discrete sums over the 1-min sampling interval Δt:

$$E_{\mathrm{DC}} \approx \sum_{k=1}^{N} P_{\mathrm{DC},k}\ \Delta t \quad , \quad E_{\mathrm{AC}} \approx \sum_{k=1}^{N} P_{\mathrm{AC},k}\ \Delta t$$

……(2)

Where

- $N = T/\Delta t$

B. Array Yield (Final Yield), Y_F

The array yield (often called the final yield) normalizes the DC energy to the rated DC capacity P_{rated} under Standard Test Conditions (STC, 1 kW/m², 25 °C cell temperature):

$$Y_F = \frac{E_{\mathrm{DC}}}{P_{\mathrm{rated}}} \quad [\mathrm{h}]$$

……..(3)

C. Reference Yield, Y_R

The reference yield converts the in-plane irradiance $G(t)$ into an equivalent duration of peak sunlight:

$$Y_R = \frac{1}{G_{\mathrm{STC}}} \int_{t_0}^{t_0+T} G(t)\,\mathrm{d}t \quad [\mathrm{h}]$$

…….(4)

where $G_{\mathrm{STC}} = 1\ \mathrm{kW/m^2}$. Discretely,

$$Y_R \approx \frac{1}{1{,}000} \sum_{k=1}^{N} G_k\ \Delta t$$

……..(5)

D. Performance Ratio, PR

The performance ratio is the ratio of the energy actually delivered (normalized by DC capacity) to the energy that would have been delivered under ideal conditions (normalized by solar resource):

$$PR = \frac{Y_F}{Y_R}$$

……(6)

Expressed as a percentage,

$$PR(\%) = 100 \times \frac{Y_F}{Y_R} \quad \ldots\ldots(7)$$

E. Capacity Utilization Factor, CUF

Although closely related to PR, the Capacity Utilization Factor (CUF) offers a high-level view of how much energy the plant delivers relative to its theoretical maximum over Time (T):

$$CUF = \frac{E_{\text{AC}}}{P_{\text{rated}}\, T} \quad \ldots\ldots(8)$$

F. Specific Yield

It is defined as the ratio of AC energy generated to installed PV capacity

$$Y_{sp} = \frac{E_{AC}}{P_{rated}} \quad \ldots\ldots(9)$$

Where

E_{AC} = AC energy generated (kWh)

P_{rated} = installed PV capacity (kWp)

G. Capacity Factor

It is a performance metric which give the how the plant is operating efficiently

$$CF = \frac{E_{AC}}{P_{rated} \times 8760} \quad \ldots\ldots(10)$$

H. Degradation Rate

It is defined as the periodic rate of gradual reduction in power

$$DR = \frac{P_{initial} - P_{year}}{P_{initial} \times N} \quad \ldots.(11)$$

3. Proposed ESS and PSS Module Test Case

In this work long term performance evaluation of Elkem solar PV system (ESS) in comparison with standard polysilicon PV system (PSS) under various climatic and solar irradiance conditions is proposed as shown in Fig. 1.

Fig. 1 Proposed PV system at BVRIT

Figure 1 shows PV system mounted on the roof of a building at BVRIT in India. It was mounted on a steel support structure. The entire project consists of 28 solar modules, and each of them has its own dedicated voltage regulator. The plant has a total installed capacity of 6.756 kWp. The main difference between the ESS and PSS modules is that the initial feedstock is the ingot

material. This process is done in the same cell line, and the modules are made by the same company. Each module has a capacity of 240Wp and has a single cell area of 243.36 cm². The system consists of 4 arrays/strings, connected to 2 string inverters, each array/string consist of 7 series connected modules. These devices provide real-time data on the energy fed to the grid, as well as current and CO^2 emissions data. The data is collected and stored at 1 minute intervals from 2016 to 2017. Array 1 & 2 are ESS arrays, Array 3 & 4 are Poly arrays. The PV module specifications are presented in Table 1, the experimental setup parameters are presented in Table 2

Table 1 Complete Specifications

Category	Parameter	ESS Module	PSS Module
PV Module Specifications	Technology	Elkem Solar Silicon (ESS)	Polycrystalline Silicon (PSS)
	Rated Power (Pmp)	240 Wp	240 Wp
	Number of Cells	60	60
	Maximum Power Voltage (Vmp)	30.23 V	30.1 V
	Maximum Power Current (Imp)	7.94 A	7.90 A
	Open Circuit Voltage (Voc)	37.56 V	37.20 V
	Short Circuit Current (Isc)	8.44 A	8.38 A
	Cell Area	243.36 cm²	243.36 cm²
Temperature Coefficients	Power Coefficient (γPmax)	−0.41 %/°C	−0.45 %/°C
	Voltage Coefficient (βVoc)	−0.32 %/°C	−0.34 %/°C
	Current Coefficient (αIsc)	+0.05 %/°C	+0.04 %/°C
Degradation Rates	First Year Degradation	1.5 %	2.0 %
	Annual Degradation Rate	0.65 %/year	0.82 %/year
Mounting Configuration	Installation Location	BVRIT Narsapur, India	Same
	Mounting Type	Fixed tilt rooftop	Fixed tilt rooftop
	Tilt Angle	~17°	~17°
	Orientation	South facing	South facing
Inverter Characteristics	Inverter Type	Grid-connected string inverter	Same
	Rated AC Power	6 kW	6 kW

	MPPT Voltage Range	150 – 450 V	150 – 450 V
	Maximum Efficiency	96–97 %	96–97 %
	Grid Connection	230 V, 50 Hz	Same
System Losses	Temperature Loss	5–8 %	6–9 %
	Inverter Loss	2–3 %	2–3 %
	Mismatch Loss	~2 %	~2 %

Table 2 Experimental Setup

S. No.	Component/Parameter	Description
1	Location	Rooftop of a building at B V Raju Institute of Technology (BVRIT), India
2	Mounting Structure	Steel support structure
3	Total Number of Modules	28 modules
4	Module Capacity	240 Wp per module
5	Total Installed Capacity	6.756 kWp
6	Module Type	ESS® (Elkem Solar Silicon) and PSS (Conventional Polycrystalline Silicon)
7	Module Cell Area	243.36 cm^2
8	Number of Arrays/Strings	4 (Array 1 & 2: ESS; Array 3 & 4: PSS)
9	Modules per Array	7 modules in series per array
10	Inverter Configuration	2 String Inverters (Each connected to 2 arrays)
11	Voltage Regulation	Each module equipped with a dedicated voltage regulator
12	Data Acquisition Interval	1 minutes

4. Results and Discussions:

The results are presented in outdoor reports and are filtered before they are analysed. The calculation shows the maximum deviation between the two PV materials. The accumulated output energy ratio is presented in Fig. 2. The maximum is recorded at 12:00 hrs.

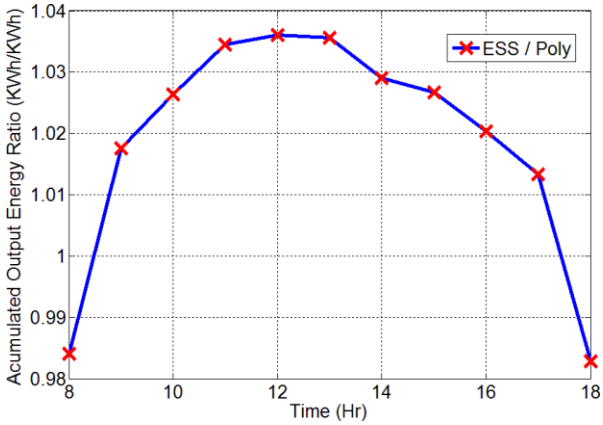

Fig. 2. ESS Vs Poly Output Energy Ratio

The average output energy is presented in Fig. 3. The output energy of the ESS modules is higher over most of the day, but lower in the early hours of sunrise and sunset when compared to the PSS modules.

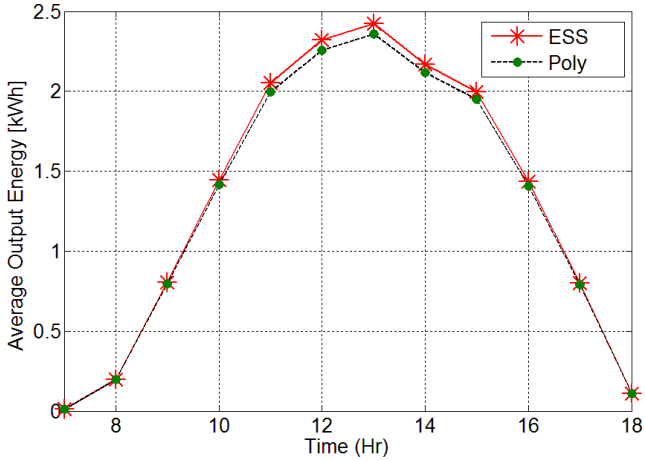

Fig. 3. Average Output Energy

The hourly based total energy harnesses by the each module is presented in Fig. 4. At the 7th, 8th and 18th hours the ESS and PSS total energy is almost the same in the remaining hours the ESS modules produces more energy than the PSS modules.

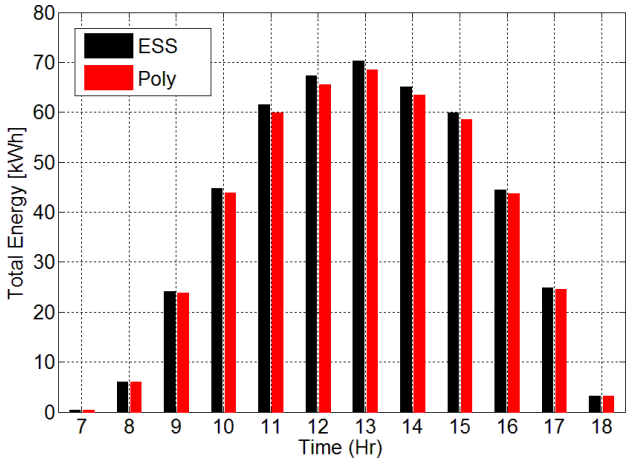

Fig. 4. Hourly based Total Energy

The output power day profile for ESS and PSS modules are presented in Fig. 5 and Fig. 6 respectively. It shows that the power and current from sunrise to sunset can be used as a function

of in-plan irradiance. By considering the different irradiance intervals, it has been observed that the output of ESS modules is higher than PSS modules.

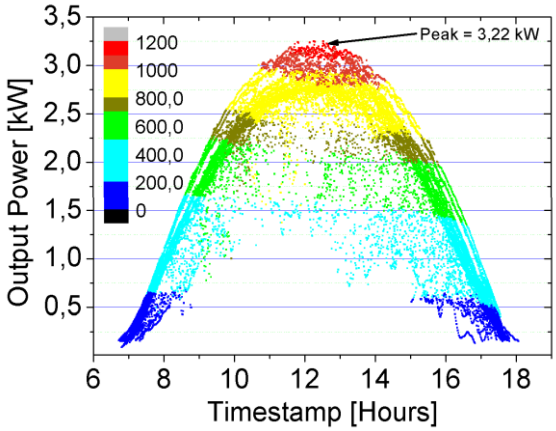

Fig. 5. Output power Day profile for ESS module

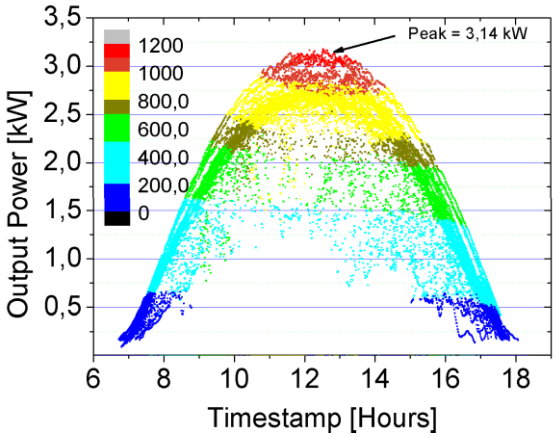

Fig. 6. Output power Day profile for Poly module

The output power ratio between ESS and PSS modules is presented in Fig. 7. The output power ratio for ESS modules is higher than the PSS modules after 200 W/m². An average of 2.27% of more power is recorded with ESS modules.

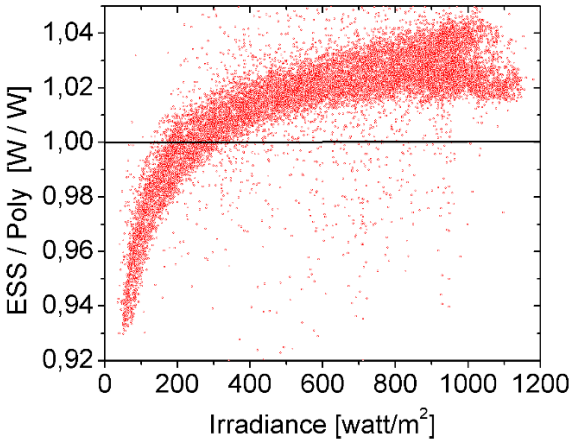

Fig. 7. Ratio of Output power between ESS/Poly

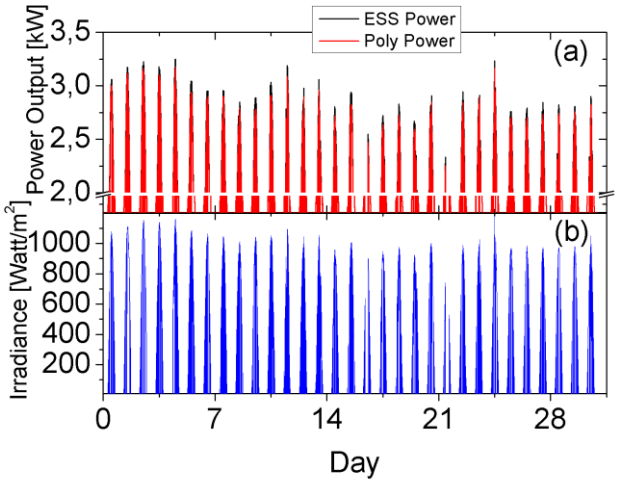

Fig. 8. Monthly Power Production

The monthly power production for ESS and PSS modules are presented in Fig. 8. The proposed ESS modules exhibited the improved performance in the sunny days than the cloudy days. For different irradiance intervals, the performance of the system is evaluated and presented in Fig. 9. The average irradiance distribution is also the same for the two types of arrays.

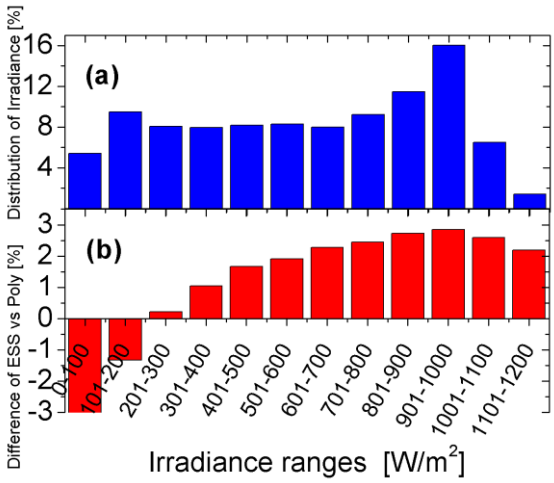

Fig. 9. Distribution of Irradiance

The Reference Yield (Y_R) and Final Yield (Y_F) Comparison between ESS and PSS modules for the months of February, March, April and May are presented in Fig. 10. In all the months ESS modules exhibited the improved performance in comparison with PSS modules. The performance ratio (%) of ESS and PSS modules for the months of February, March, April and May are presented in Fig. 11. In all the months ESS modules exhibited the improved performance in comparison with PSS modules, highest performance ratio of 90.05 % is recorded in the month of May for ESS modules. The total DC energy production of ESS and PSS modules is presented in Fig. 12. . In all the months ESS modules exhibited the improved performance in comparison with PSS modules

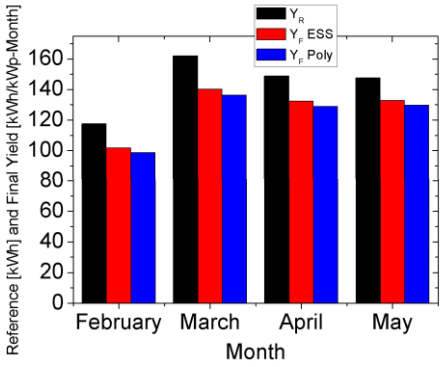

Fig. 10. Reference and Final Yield Comparison

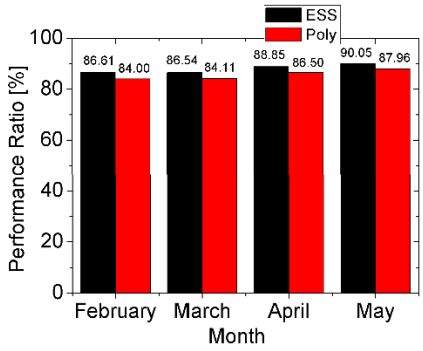

Fig. 11. Performance Ratio

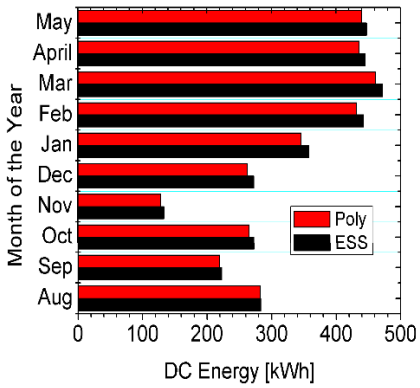

Fig. 12. DC Energy Production

To verify the results, the batches of solar cells that were produced using the same modules have been subjected to IV temperature tests. The temperature coefficient of the cell curve is also determined by the slope of IV parameter vs temperature as shown in Fig. 13 and Fig. 14 respectively.

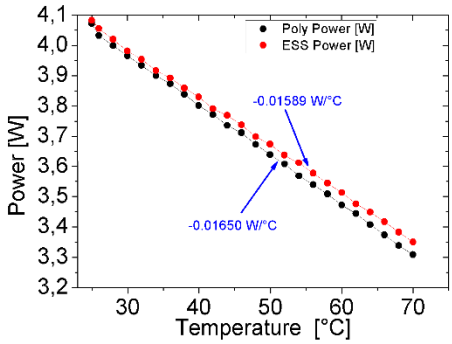

Fig. 13. Feedstock's as a Function of Cell Temperature

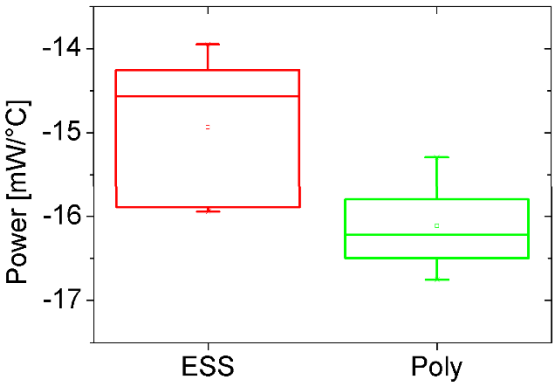

Fig. 14. Boxplot for Temperature Coefficients

Conclusion

In this work long term performance evaluation of Elkem solar PV system (ESS) in comparison with standard polysilicon PV system (PSS) under various climatic and solar irradiance conditions is presented. The proposed system is installed in the sunbelt region at B V Raju Institute of Technology (BVRIT), Narsapur, India. It consists of 14 ESS and 14 PSS modules with a total of 28 modules having at total capacity of 6.756 kWp connected to single phase grid of 230 V 50 Hz. The performance evaluation parameters Output Energy Ratio, Average Output Energy, Hourly based Total Energy, Output power Day profile, Ratio of Output power, Monthly Power Production, Reference and Final Yield, Performance Ratio, DC Energy Production are evaluated. The results revealed that the proposed ESS modules exhibited the improved performance than the standard PSS modules in all the performance parameters. The ESS modules generates higher energy yield than the PSS modules.

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