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Combined Effect of Deterministic and Stochastic Variables on Comparative Performance Analysis of 110 kW A-Si PV and C-Si PV based Rooftop Grid Tied Solar Photovoltaic Systems in Jodhpur

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The main objective of this paper is to review the state of the art of IIT Jodhpur Rooftop installed 110 kW PV systems. This is done analyzing the operational data of 110 kW PV systems (43.30 kW located in Block 1 and 58.08 kW in Block 2). Performance analysis depends on three basic term of solar PV. How much energy do they produce? What level of performance is associated to their production? Which are the key parameters that most influence their quality? During the year 2011, the PV systems in Jodhpur, India have produced a mean annual energy of 1290.64 kWh/kWp in block-1 and 1290.64 kWh/kWp in Block-2. As a whole, the location of Solar PV system is the main reason of energy variability and system output. The overall mean Performance Ratio is 75% in both Blocks. Solar power variability depends on the two variables, deterministic and stochastic variable. In last few years researcher work on finding deterministic variable such as system losses (module efficiency, DC cable losses, inverter losses and AC cable losses) but these deterministic variables are not enough to give accurate forecasting so with the help of combined effect of these both variable give accurate plant performance and reliable solar power forecasting for solar power scheduling and dispatchability.

Keywords: *PV System description, Roof of academic blocks, Performance analysis of solar PV, Performance ratio, Deterministic variables and Stochastic variables.*

1.0 INTRODUCTION

In 21st century the energy management and environmental Security are the biggest challenges for us. In this era the current issue is global energy problem can be attributed to insufficient fossil fuel supplies and excessive greenhouse gas emissions resulting from increasing fossil fuel consumption. Which we can see in the form of global warming. Energy demand and supply has become one of the most important problems facing humanity [1]. The day by day increasing demand for energy is show fossil fuel supplies [2] and record-high oil and gas prices due to global population growth. So the energy shortage has played an important role in the future for our society. Because of increasing fossil fuel consumption we all are facing problem of Global warming and energy crisis [3–5]. At this large scale, solar energy seems to be the most viable choice to meet our clean energy demand. The sun continuously delivers to the earth 120,000 TW of energy, which dramatically exceeds our current rate of energy needs (13 TW) [6]. This implies that covering only 0.1% of the earth's surface with solar cells of 10% efficiency would satisfy our current energy needs [7]; however, the energy currently produced from sun light remains less than 0.1% of the global energy demand [8, 9]. The solar energy can be broadly used in two areas: (a) PV systems which convert solar energy directly into electrical energy and; (b) thermal systems that convert solar energy

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into thermal energy. The solar energy is used in various application such as solar heating and cooling, Building integrated Photovoltaic (BiPV) systems and products, grid connected Renewable Energy (RE) systems Including biomass and PV systems, day lighting, solar thermal electricity generation, and solar refrigeration. Gartner has predicted an increase in PV industry revenue to increases within the next five year [10].

Generally PV system can be classified into three types:

(a) Stand-alone system

(b) Hybrid system and

(c) Grid-connected system.

A grid-connected system comprises of the modules and an inverter. The inverter converts the direct current (DC) electricity generated by the PV array into alternating current (AC) electricity that is synchronized with the mains electricity .The electric power produced by PV system then can be consumed by the connected load and no power is taken from the main grid unless load connected to the system is less than capacity of PV systems [11]. Roof and facades of existing buildings represents a huge potential area for PV system installation, allowing the possibility to combine energy production with other functions of the building or non-building structure. BiPV systems seem to offer the most cost and energy effective application of grid connected PV systems [11–14]. 43 kW grid-connected Amorphous PV system and 58kW grid-connected Crystalline PV system are recently installed at academic block-I and II building Indian Institute of Technology Jodhpur, Jodhpur. Jodhpur city which is called as SUN CITY has 320 days of sun availability in a year i.e. there is huge potential in the field of solar systems which can be harnessed to solve numerous local problems such urban and rural electricity, cooling and water related problems. In this point of view IIT Jodhpur has strong vision to explore the different R&D and tapping the solar resource for different applications at its permanent campus. The above installed grid-connected PV system is going serve as test bed to the future proliferation of solar systems. So, it becomes almost necessary that, data regarding their performance must be studied in local climate conditions and a comparative conclusion may be drawn, because the energy produced by a grid connected PV system depends on local climate factors such as; incident solar radiation and module working temperature; inverter characteristics such as; yield, working point and operation threshold; and the coupling system to the grid, which depends on the characteristics of the energy produced by the inverter on grid stability and availability. In this installation, the measured data were the ambient temperature, module temperature, DC voltage, DC current, inverter output energy and solar irradiance. From these data, the performance indicates were obtained with regards to DC power, energy produced by the PV modules, solar irradiance, module conversion, inverter efficiency. In this project we have estimated the performance of PV array and power conditioning unit (PCU) and also analyzed energy outcome which is dependent on solar irradiance, ambient temperature and module temperature by multiple linear regression analysis.

2.0 THE PV SYSTEM DESCRIPTION

The PV solar power plant describe in this project has been installed on the roof of academic block I and block II, 43 kW grid-connected Amorphous PV system installed at block I and 58 kW grid-connected Crystalline PV installed at block II in Indian Institute of Technology Jodhpur, Rajasthan, located at Jodhpur, the second largest city in the Indian state of Rajasthan at coordinates 26°17’N 73°01’E which is 335 km west from the state capital, Jaipur and 200 km from the city of Ajmer is shown in Figure 1.

FIG. 1 ACADEMIC BLOCK II BUILDING, LOCATED AT ‘IIT JODHPUR’ JODHPUR.

2.1 58 kW C-Si based Solar PV System Description

The PV system has a nominal peak power of 58kWp and installed on the roofs of the academic block II building. The overall surface area is 724.16 m^2. It consist of 270 modules for a total of 18 array each array consist of 15 module, which is connected to the inverter, each inverter have three array in which modules are connected in series and arrays are connected in parallel. Total numbers of inverters are 6 is shown in Figure 2.

FIG. 2 C-Si BASED 58 kW ROOFTOP GRID TIED SOLAR PHOTO VOLTAIC SYSTEM.

Figure 3 is shows the schematic diagram of the grid connected PV system with data acquisition system and data logger.

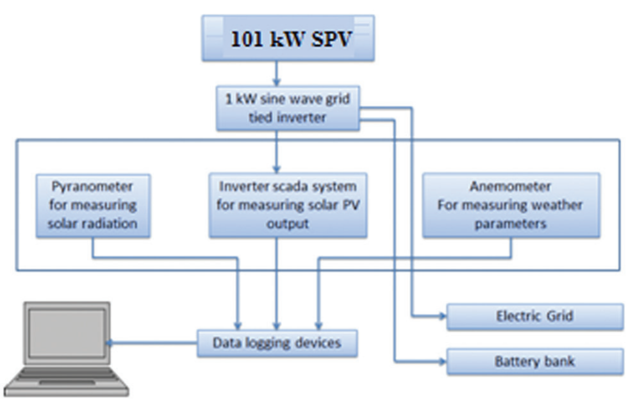

FIG. 3 THE PV ROOF AND SCHEMATIC DIAGRAM OF THE GRID CONNECTED PV SYSTEM.

2.2 System Specification

The main features of the PV system and module specifications are summarized in Tables 1 and 2.

TABLE 1

58 kW C-Si BASED SOLAR PV SYSTEM

1	Total no. of modules	270
2	No. of inverter	6
3	Inverter rating	1000 W
4	No of modules/ string	15
5	No. of strings/ Inverter	3
6	DC voltage(DC) / inverter	546 V
7	DC Voltage (at P_{max})/ Inverter	438.5 V
8	DC Current (I_{sc})/ Inverter	24.51 A
9	DC Current (at P_{max})/ Inverter	22.23 A
10	Inverter AC Voltage	230 V

TABLE 2

C-Si MODULE SPECIFICATION

1	Product	MBPV CAAP
2	Type	Max series
3	Maximum power (P_{mpp})	216.53 W
4	Voltage at maximum power (V_{mp})	29.23 V
5	Current at maximum Power (I_{mp})	7.41 A
6	Open circuit voltage (V_{oc})	36.40 V
7	Short circuit current (I_{sc})	8.17 A
8	Fuse rating	10.00 A
9	Weight	19.5 kg
10	Dimension	1661 × 991 × 40 (mm)
11	NOCT	47 + –2
12	Operating temp	–40 to +85
13	Cell type	Multi-crystalline
14	Cell dimension	156 × 156 (mm)
15	No of cells	60
16	Temperature coeff. of P_{max} (%/k)	–0.43
17	Temperature coeff. of V_{oc}(%/k)	–0.344
18	Temperature coeff. of I_{sc}(%/k)	0.11

2.3 43 kW A-Si based Solar PV System Description

The PV system has a nominal peak power of 43 kWp and installed on the roofs of the academic block I building (Figures 4–6). The overall surface area is 652.34 m^2. It consist of 114 modules for a total of 38 array each array consist of 03 module, which is connected to the inverter, each inverter have six array in which modules are connected in series and arrays are connected in parallel. Total numbers of inverters are six.

FIG. 4 ACADEMIC BLOCK I BUILDING, LOCATED AT “IIT JODHPUR” JODHPUR.

FIG. 5 A-Si BASED 43 kW ROOFTOP GRID TIED SOLAR PHOTO VOLTAIC SYSTEM

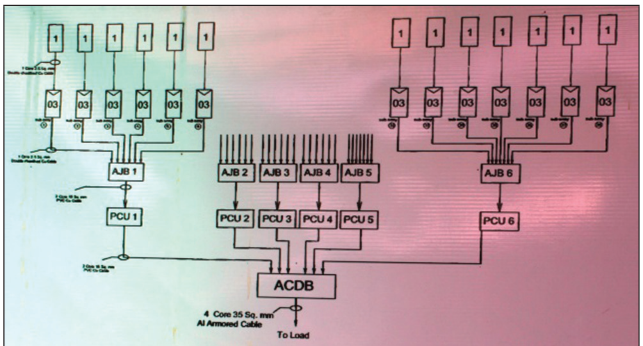

FIG. 6 LINE DIAGRAM OF 43 kW A-Si BASED ROOFTOP GRID TIED SOLAR PHOTO-VOLTAIC SYSTEM.

2.4 System Specification

The main features of the PV system are summarized in Tables 3 and 4.

TABLE 3		
43 kW A-Si BASED SOLAR PV SYSTEMS		
1	Total no. of modules	114
2	No. of inverter	6
3	Inverter rating	7000 W
4	No. of modules / string	38
5	No. of strings / inverter	7
6	DC voltage(DC) / inverter	560 V
7	DC voltage (at P_{max}) / inverter	340 V
8	DC current (I_{sc}) / inverter	23 A
9	DC current (at P_{max}) / inverter	22 A
10	Inverter AC voltage	230 V

TABLE 4		
A-Si BASED MODULE SPECIFICATION		
1	Product	MBPV CAAP
2	Type	Max series
3	Maximum power (P_{mpp})	380 W
4	Voltage at maximum power (V_{mp})	143.4 V
5	Current at maximum power (I_{mp})	2.65 A
6	Open circuit voltage (V_{oc})	187.8 V
7	Short circuit current (I_{sc})	3.27 A
8	Fuse rating	10.00 A
9	Maximum system voltage	1000 V
10	Weight	19.5 kg
11	Dimension	2.5 m × 2.2 m
12	NOCT	47+-2
13	Operating temp	-40 to+85
14	Cell type	Amorphous Silicon
15	Cell dimension	156 × 156 (mm)
16	No of cells	60
17	Temperature coeff. of P_{max} (%/k)	–0.41

18	Temperature coeff. of V_{oc} (%/k)	–0.334
19	Temperature coeff. of I_{sc} (%/k)	0.9

3.0 DATA ACQUISITION SYSTEM WITH ONLINE MONITORING

The system output monitored at the PV inverters by a data acquisition system controlled by a measurement and analysis Program (Sunny sensor web box). Data is measured and recorded after every 15 min. The measured data are:

- Electrical power output of each PCU
- Solar irradiance
- Module temperature
- Ambient temperature
- Energy generated

The data acquisition system consisted of a sunny boy 1000 inverter, sunny web box and sensor box. The Sunny Sensor Box was measure solar irradiance at horizontal surface and sunny web box sensor for measuring important weather parameter such as ambient temperature, wind velocity, module temperature and this whole system is connected via RS485 link with computer. Data recorded on 15 minute interval in the Web Box and data can be retrieve via USB and storage device and read directly in to a system and this whole data is saved in .CSV file.

4.0 DATA OBSERVATION

Figure 7 shows hourly solar insolation on the photovoltaic modules captured on 02/08/11 for 24 hours.

The maximum solar insolation was found to be 771.2 W/m^2 and it is founded that because for weather there is variability in solar radiation is a unpredictable factor for solar power forecasting because deterministic variable can be predict well in the case for solar power forecasting and stochastic variable much unpredictable because of nature. Figure 8 shows the hourly temperature on the basis of 15 minutes interval.

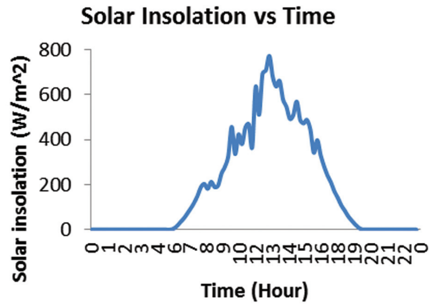

FIG. 7 HOURLY SOLAR INSOLATION OVER THE DAY.

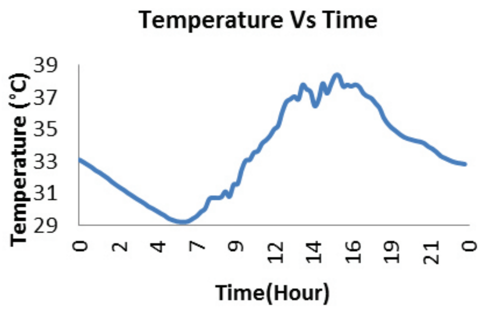

FIG. 8 HOURLY TEMPERATURE OVER THE DAY.

Figures 9 and 10 shows the module temperature with ambient temperature which is play a deterministic role in performance analysis and solar power forecasting. And Figure 11 shows the variation in module temperature with respect to ambient temperature.

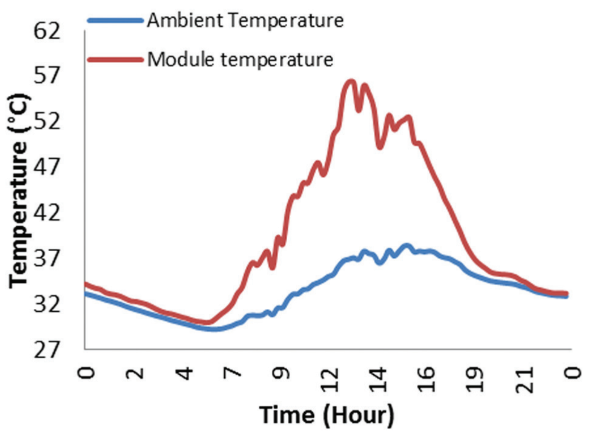

FIG. 9 HOURLY AMBIENT TEMP WITH MODULE TEMPERATURE FOR C-Si MODULE.

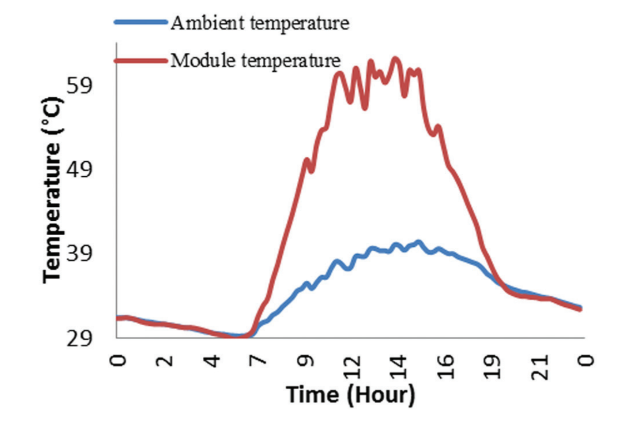

FIG. 10 HOURLY AMBIENT TEMP WITH MODULE TEMPERATURE FOR A-Si MODULE.

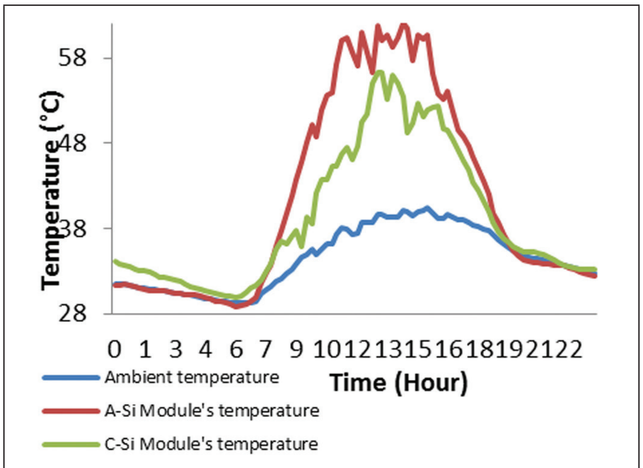

FIG. 11 COMPARATIVE ANALYSIS OF AMBIENT TEMPERATURE AND MODULE TEMPERATURE WITH RESPECT OF TIME.

5.0 COMPARATIVE STUDY OF ENERGY LOSSES

Solar plant performance analysis needs the study of deterministic variable and stochastic variable. These are the main reason of solar power variability. So, in way of compute the power, energy and yield related performance of electricity grid tied PV system, particular parameter are to be found as factor which are comes under deterministic and stochastic variable. And these parameters are to be calculated using data collected during the running situation of the plant. These variables are known as losses in generated solar power and it can be classified in following category [15]:

- Deterministic losses
  - System losses
  - Wiring losses
  - MPP losses
  - Inverter losses
  - Transformer losses
  - Mis-sized inverter
  - Operation and maintenance losses
- Module losses
  - Conversion losses
  - Thermal losses
- Pre module losses
  - Tolerance of rated power
  - Shadows
  - Dirt
  - Reflection
- Stochastic losses
  - Weather parameter
  - Solar insolation
  - Ambient temperature
  - Cloud shadow
  - Wind velocity
  - Rain fall

Figure 12 show the level of variation in module temperature when ambient temperature varies with solar radiation. And the PV module temperature increases at solar insolation level 300-650 W/m^2 .as per observation at the higher level of solar radiation module temperature goes down.

The ambient air temperature and module temperature are usually increased with solar insolation and after the certain level it again decreases because of ideal temperature of Module is around 25–30° C.

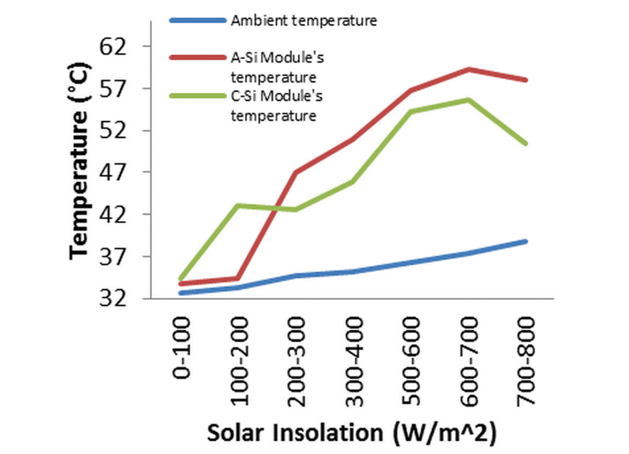

FIG. 12 COMPARATIVE ANALYSIS OF AMBIENT TEMPERATURE AND MODULE TEMPERATURE WITH RESPECT OF LEVEL OF SOLAR INSOLATION.

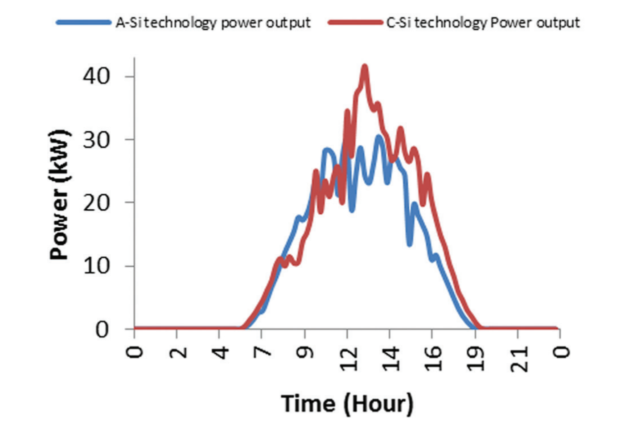

FIG. 13 COMPARATIVE ANALYSIS OF POWER OUTPUT FROM BOTH POWER PLANTS WITH RESPECT TO TIME.

Before the energy yield and performance analysis of the plant a study of total losses in the system is very important and it is play a key role in power variability and because of these losses variation in power generation is very unpredicted in Figure 13 it is clear that fluctuation in power generation is due to stochastic losses such as cloud cover, solar radiation, etc. These stochastic losses is based on impact and frequency of occurrence such as if solar radiation is very less or long hour because of cloud cover then losses will be very high so these losses are probabilistic in nature. It depends on other weather parameter such as ambient temperature is depend on solar radiation or rain fall and rain fall depend on ambient temperature correlation of these parameter are very high. Figures 14–18 shows the different losses in the system.

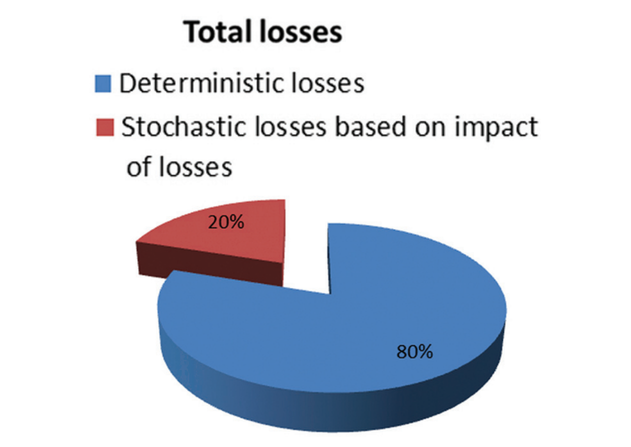

FIG. 14 TOTAL LOSSES IN THE SYSTEM.

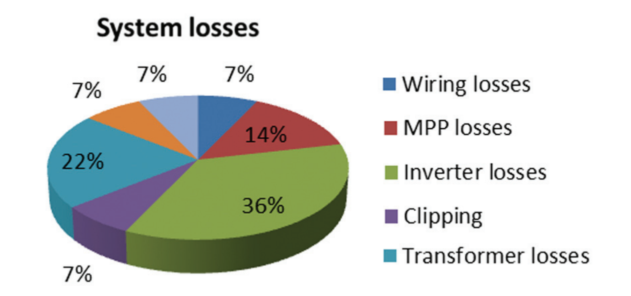

FIG. 15 SYSTEM LOSSES.

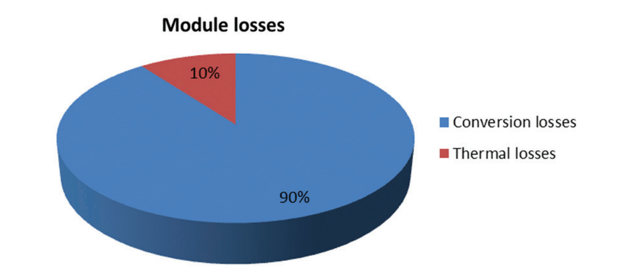

FIG. 16 MODULE LOSSES.

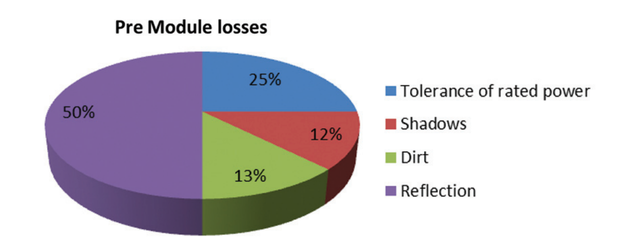

FIG. 17 PRE MODULE LOSSES.

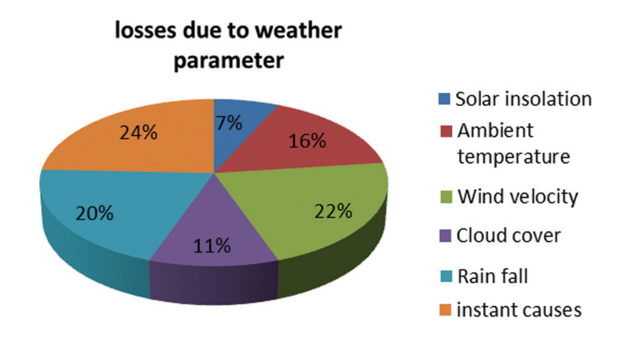

FIG. 18 STOCHASTIC LOSSES IN THE SYSTEM.

6.0 PLANT PERFORMANCE ANALYSIS ON THE BASIS OF ENERGY LOSSES

In grid tied solar PV plant performance analysis some important parameter should compute first [16]. So these all parameter are given below in Table 5.

TABLE 5

PARAMETERS FOR PLANT PERFORMANCE ANALYSIS

Sl. No.	Parameters	Notations
1	Plant energy output	E_{AC}
2	Array yield	Y_a
3	Final yield	Y_f
4	Performance ratio	PR
5	Capacity factor	CF

- PLANT ENERGY OUTPUT

The entire day plant energy output by the photovoltaic system is acquired as [17] in Eqns. (1 and 2):

$$E_{AC,d} = \sum_{t=1}^{t=24} E_{AC}, t \qquad ....(1)$$

$$E_{AC,h} = \sum_{h=1}^{h=24} E_{AC}, h \qquad ....(2)$$

Where h is the number of hour in the day. The instant plant energy generation was obtained by the energy output by the system after the DC/AC inverter on 15 minute interval. And Figure 19 shows the total energy generation output which is 244.46 kWh of 58 kW C-Si based solar photovoltaic system. And Figure 20 shows the total energy output of 43 kW A-Si solar photovoltaic system. And total energy generation is 253.93 kWh which is more than C-Si SPV plant and Figure 21 shows the comparison of energy generation.

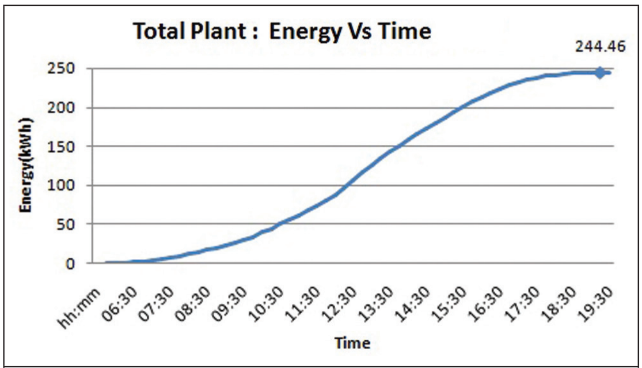

FIG. 19 TOTAL DAILY ENERGY GENERATION BY 58 kW SPV SYSTEMS.

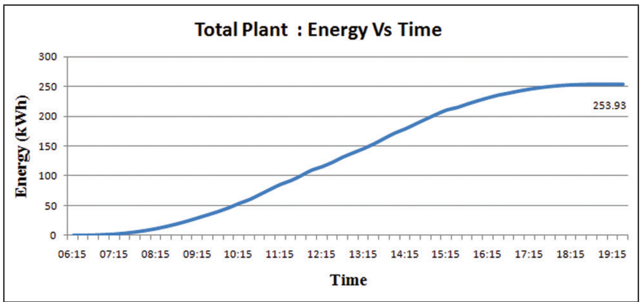

FIG. 20 TOTAL DAILY ENERGY GENERATION BY 43 kW SPV PLANT.

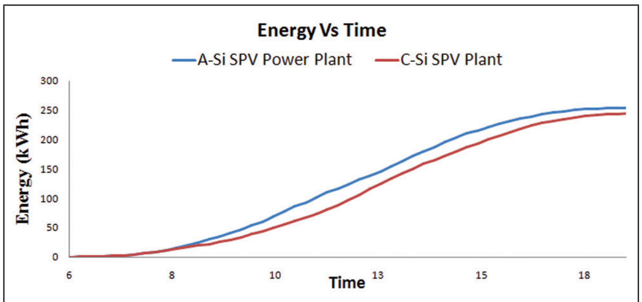

FIG. 21 ENERGY GENERATION OUTPUT OF BOTH SPV PLANT.

- ARRAY YIELD

Array yield (Y_a) is defined as the generated energy output from a photovoltaic array under a certain time (day, month and year) in Eqn. (3) and it obtained by just divided by its rated power.

$$Y_a = \frac{E_{DC}}{P_{pv,\,rated}} \qquad ....(3)$$

Eqn. (4) show the daily array yield and Eqn. (5) daily average hourly array yield ($Y_{a,h}$).

$$Y_{a,d} = \frac{E_{DC,d}}{P_{pv,rated}} \quad \text{....(4)}$$

$$Y_{a,h} = \frac{1}{N}\sum_{h=1}^{h=1h=24} Y_{a,d} \quad \text{....(5)}$$

- FINAL YIELD

The final yield of the plants is defined as the daily, monthly and yearly net AC energy output of the plant divided by the theoretical power of installed photovoltaic array at standard test conditions (STC) [18] in Eqn. (6).

$$Y_{f,a} = \frac{E_{AC,a}}{P_{pv,rated}} \quad \text{....(6)}$$

Figure 22 show the comparison of energy generation in between A-Si and C-Si with time.

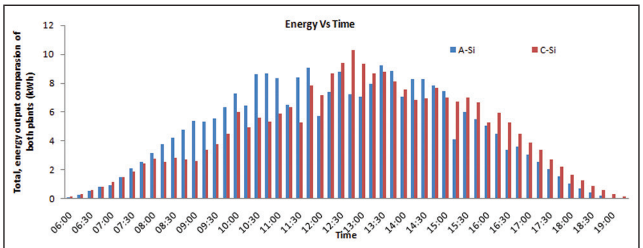

FIG. 22 TOTAL ENERGY GENERATED OVER THE DAY.

And the daily final yield ($Y_{f,d}$) is given below in Eqn. (7):

$$Y_{f,d} = \frac{E_{AC,d}}{P_{pv,rated}} \quad \text{....(7)}$$

- PERFORMANCE RATIO

The performance ratio show the overall effect of losses on photovoltaic array's nominal power output depending on deterministic and stochastic losses and the performance ratio of the photovoltaic system show how accurate it effort in ideal operation conditions [19, 20].

Performance ratio basically represents the total losses in the Photovoltaic system during converting DC to AC and performance ratio is given in Eqn. (8):

$$PR = \frac{E_{real}}{E_{ideal}} = \eta_{\text{deterministic/stochastic losses}} \quad \text{....(8)}$$

- CAPACITY FACTOR

The capacity factor (CF) is basically present the energy produce by the SPV plant. And plant produces the full installed power regularly. Then capacity factor should be unity [20] and it is a ratio of the net yearly energy generated to the net amount of energy the PV plant would generated. The capacity factor for a grid tied Photovoltaic plant is given in Eqns. (9 and 10):

$$CF = \frac{Y_{f,a}}{24 \times 365} \quad \text{....(9)}$$

$$CF = \frac{E_{ac,a}}{P_{pv,rated} \times 8760} \quad \text{....(10)}$$

So on the basis of these factor and losses Figure 23 show the comparative bar chart for annual power generation of both power plant. And Figure 24 shows the annual energy generation.

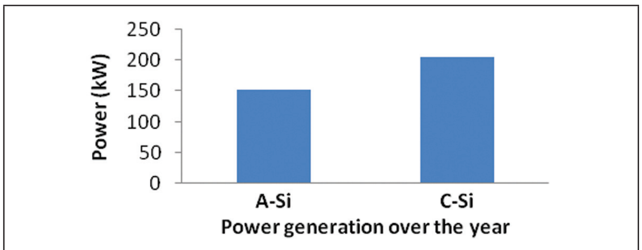

FIG. 23 POWER GENERATION OVER THE YEAR.

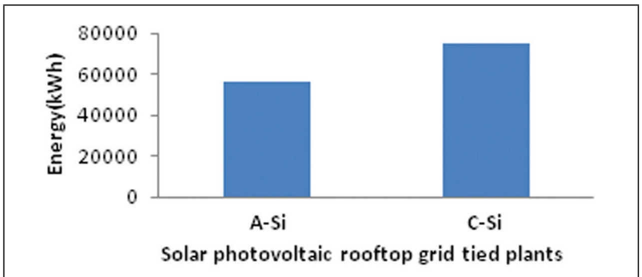

FIG. 24 ENERGY GENERATION OVER THE YEAR.

The compare in commission result from different technology based solar photovoltaic system. The power is watts (W) or kilowatts (kW) and energy in watt-hours (Wh) or kilowatts hour (kWh). And the plant annual net energy yield is given in Eqn. (11):

$$Y_f = \frac{E_{real}}{P_{pv,\,rated}} \qquad \text{....(11)}$$

7.0 CONCLUSION

The 58 kW and 43 kW grid tied power plant installed in Indian Institute and technology Jodhpur, Rajasthan, India was monitored for a single day which is 2nd August 2011 and 24 hour. And plant data during the operating time showed that theoretical solar irradiance, ambient temperature, module temperature, wind velocity, and were 5.2 kWh/m^2/day, 34.4º C, 39.8º C, and 3.9 m/s respectively. From this study it is clear that daily energy yield of 5.2 kWh/kWp/day is extremely dependent on stochastic losses.

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