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A FIRST-TIME STUDY ON LONG-TERM PERFORMANCE ANALYSIS OF PHOTOVOLTAIC (PV) PLANTS AT BHIMAVARAM (LATITUDE- 16.54^0 N, LONGITUDE- 81.52^0 E, MSL 7 M), INDIA

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A B S T R A C T

This study evaluates the daily, monthly, and annual performance of roof-top 200 KWp grid-interactive solar PV power plants installed atop Sri Vishnu Educational Society buildings in India. This plant generated ~ 300,000 units/ year, with a maximum yielding of ~800 KWh/ day during summer (March-June) and a minimum during the rainy season (July-September, ~ 600 KWh/ day). 1237 ton of CO_2 *emissions were avoided and $2,10,000 was made. As a result, the payback took 7-8 years to complete. The statistical study revealed a minimum (1%-15%) drop in power yielding, which indicates this plant used high-standard solar cells (polycrystalline), sophisticated inverters, top-quality molded case circuit breakers, and others. The optimal level of power output generation, V-I characteristics and power and economic graphs were predicted using a simulation study. Inter-institutional comparisons made with new 302.4 KWp power plants show an identical daily pattern, albeit 302.54 KWp power plant yieldings oftentimes show marginal magnitudes.*

1. INTRODUCTION

Abundantly available solar energy, long-lasting and clean energy is a most effective alternative to non-renewable sources such as coal, oil, and natural gas. Photovoltaic (PV) cells will be made of semiconductor materials that let solar energy (in the visible spectrum and partially in the ultraviolet and infrared spectrum) be converted into electricity. Ever since the development of PV technology took place in Bell labs of USA in the year 1954, various technological advancements and highly encouraging government policies over the years have brought the prices of PV modules to affordable rates, and, hence, the production and utilization of solar energy have increased tremendously many folds even in under developing countries such as Kenya and Morocco (Abdullahi et al., 2017). On the flip side, solar power

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still only accounts for a mere 5% of capacity and 2.2% of electricity generation globally (Global Market Outlook for Solar Power, 2019-2023), which implies that still a lot of subsidiaries may be provided to encourage the effective usage of solar energy, and other appropriate measures need to be adopted. Secondly, proper quantification of output power generated from a PV power plant shall be done adequately to enhance the belief of the end-users in this ever- increasing market, so that an adequate rise in investments would be possible.

The performance and energy produced by PV systems installed at any location are dictated by the prevailing environmental conditions and their technology (Makrides et al. 2009). Several research studies have been conducted on the power that is going to decline over time (degradation rate) cable losses, and others. It is estimated that only 76.2 % of solar power can be yielded at the output (at the electricity grid) even under extremely amicable conditions. Various losses contribute to the degradation rate including, shading losses (7 %), dust and dirt (2%), reflection (2.5%), spectral losses (1%), irradiation (1.5%), thermal losses (4.6%), array mismatch (0.7%), DC cable losses (1%), inverter (3%) and AC cable losses (0.5%), according to a study conducted by Ekici and Kopru (2017). Several studies have appeared in the literature that used high-end software to present simulation studies that enabled end-users to optimize the existing PV power plants (Kim et al., 2009; Maghami et al., 2016; Tremblay et al. 2007; Arribas et al., 2010; Natsheh & Albarber, 2012).

The majority of PV cell manufacturers claim that their panels will produce 90% of the maximum power after 10 years, and 80% of the maximum power after 25 years. However, the ground reality is completely different in that most power plants, often, are unable to reach the expected levels, possibly due to various inherent and unexpected losses, wrong installations, and lack of proper cleaning methods, etc. In this context, proper knowledge of the performance of solar power plants will result in correct investment decisions, a better regulatory framework, and favorable government policies. Also, it is very much essential to monitor and evaluate the performance of a power plant that would improve the overall operation and reliability. It is known that solar PV plant generation depends on the availability of input solar radiation and ambient temperature (Dondariya et al., 2018).

In this research, we carry out a statistical analysis of power yielded out of three solar plants (total capacity is 200.0 KWp) established in December 2013 atop different academic buildings of the Shri Vishnu Educational Society (SVES) campus, Bhimavaram, Andhra Pradesh state, India. This study, therefore, presents and evaluates these three power plants' performance over the last five and a half years. Particularly, as the 200 KWp power plants were commissioned in December 2013, this present study could be the first attempt to present such long-term yielding data from the Indian region to the best of the authors' knowledge. The performance of the present power plants will be analyzed based on daily, monthly, and yearly databases and a comparison will be made with inter-institutional plants (of 302.4 KWp) to understand the yielding capacity of the 200 KWp power plants over the five and a half year period.

2. SOLAR POWER PLANTS IN SVES CAMPUSES, INDIA

Under the auspicious of SVES, several academic institutions were established in Bhimavaram, India over the years including, Shri Vishnu Engineering College for Women (SVECW), Vishnu Institute of Technology (VIT), Vishnu Dental College (VDC), Shri Vishnu College of Pharmacy (SVCP), Vishnu School, Smt. Seetha Polytechnic College (SBSP), and B V Raju Institute of Computer Education (BVRICE). Initially, solar panels were installed atop VIT (100 KWp), VDC (50 KWp), and BVRICE (50 KWp) blocks in December 2013. Figure 1 depicts the 100 KWp solar power plant located atop VIT, Bhimavaram, India.

Figure 1. Picture depicts 100 KWp power plant established atop VIT Block, Bhimavaram, India

To produce 10% of the SVES campus's power requirement, 200 KWp (kilowatt peak) grid-interactive solar power plants were established with a cost of USD ~ 4, 00, 000. Out of this, a 30% grant released by the Ministry of New and Renewable Energy (MNRE), Government of India as a capital subsidy and the remaining fund is met by SVES, India. This power project has been designed, supplied, installed, and commissioned by M/s. Varshini Power Projects India (Private) Limited, Hyderabad, India. 304.5 KWp power plants were commissioned in SVES campuses atop VIT (100.8 KWp), SVECW (50.4 KWp), SBSP (100.8 KWp), and SVCP (100.8 KWp) in December 2017. Nevertheless, we only present statistics of the 200 KWp power plants in this research. The total number of solar modules in different academic institutions is 800, each module rating is 250 Wp, the total number of inverters is 12, and each inverter rating is 15 KWp other salient features of these solar power plants are presented in Table 1.

Table 1. Salient features of solar power plant atop VIT, VDC, and BVRICE

Location /Parameters	Plant capacity (KWp)	Solar modules numbers	Solar inverters numbers	Roof area	Performance ratio (%)	Capacity utilization factor (%)
VIT	100	400	6	1256 m^2	75.3	16.07
VDC	50	200	3	628 m^2	75.3	16.07
BVRICE	50	200	3	628 m^2	75.3	16.07

3.0 DATA ANALYSIS METHODOLOGY AND RESULTS

3.1 Local climatic conditions

As local climatic conditions would also affect the yielding capacity of solar power plants (Khatib et al., 2013), we present here the climatic conditions of Bhimavaram, a big municipality in the state of Andhra Pradesh, which is located in the southern part of India. The climate of the present station is hot and humid as it is near the sea coast (the Bay of Bengal, just 25 km away). Being a tropical and nearby sea coast station, the present location also experiences sea and land breezes frequently (Brahmanandam et al., 2023). The annual temperature is approximately 27.9 °C and the average rainfall is approximately 1072 mm, and the elevation (mean sea level, MSL) of this station is 7 m. The geographical coordinates of this place are: Geographical Latitude 16.54 ^{0} N and Geographical Longitude 81.52 ^{0} E, and, hence, the tilting angle of the arrays is equal to 16.54^0 (Junaidh et al., 2017). To provide more clarity, we present annual temperature and rainfall variations in Figures 2 and 3. It is evident from Figure 2 that with an average of 32.6 °C May is the warmest month. In January, the average temperature is 23.5 °C, and it is the lowest average temperature of the whole year. It is also obvious from Figure 4 that the driest month is January and most precipitation falls in July, with an average of 240 mm.

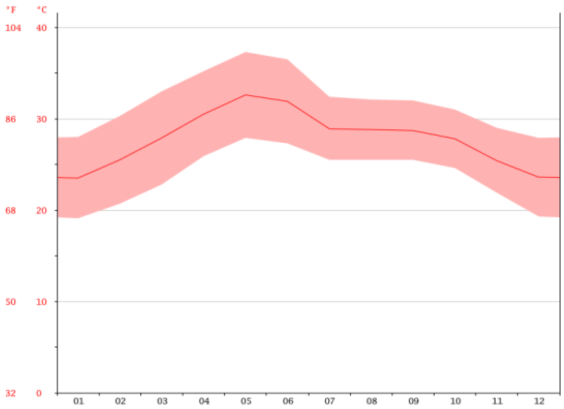

Figure 2. Monthly variations of temperature (in both Fahrenheit and Celsius) against months.

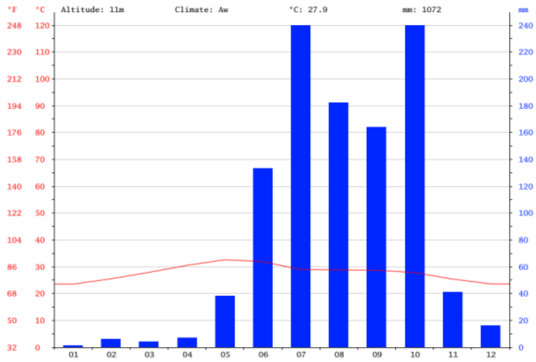

Figure 3. Monthly variations of rainfall against months, along with temperatures in both Fahrenheit and Celsius

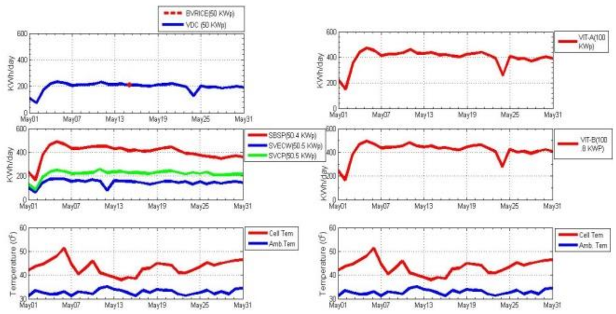

Figure 4. Day-wise power yieldings (KWh/day) in May 2019 generated from power plants (07 in numbers) established in December 2013 (VIT-A, BVRICE, and VDC) and January 2018 (VIT-B, SBSP, SVECW, and SVCP) atop SVES, India. Also shown are cell and the ambient temperatures (in ^{0}C) in the bottom panels.

3.2 Daily, Monthly, and Annual Variations

To analyze the performance of 200 KWp power plants, we have collected energy production data for five continuous years (2014-2018) located in the SVES campus, India. The assembled data from these five years were organized, analyzed, and filtered to avoid possible deviations from normal behavior. All these steps allowed us to have the exact look of the graph showing daily, monthly, and annual average production.

Daily variations of power yieldings of the 200 KWp power plants (established in December 2013 atop VIT-A, BVRICE, and VDC blocks) during May 2019 are compared with the power yieldings generated out of 302.4 KWp power plants (established in January 2018 atop VIT-A, SVECW, SBSP, and SVCP) to verify relative performance of the 200 KWp power plants, even after a five and a half year tenure. Figure 4 shows day-wise (KWh/day) variations of different power plants' yieldings in May 2019, along with cell and ambient temperatures in Celsius (c). Almost similar variations in power yieldings of both 200 KWp and 302.4 kWp can be noticed, though a moderate difference in magnitudes exists between them, and such differences are more evident in SBSP (50.4 KWP) and VIT-B (100.8 KWp) trends.

Interestingly, both BVRICE (50 KWp) and VDC (50 KWp) variations show near similitude or even better performance compared to SVECW (50.5 KWp) and SVCP (50.5 KWp) variations, though they have completed more than a five and a half year tenure. As far as the relation between cell temperature and power output is concerned, a negative relation does exist between them and such a similar relation can also be witnessed from these figures. These results are also following earlier studies (Labed & Lorenzo, 2004).

The monthly average power yieldings (MWh) of various plants atop VIT, VDC, and BVRICE are presented in Figure 5. It is clear from Figure 5 that they show clear seasonal variations, with peak magnitudes during local summer months (February, March, April, and May) and lowest ones during the local rainy season (June, July, August, September, and October), respectively. Both November and December months, in most of the years, also show greater magnitudes even if the temperature does not touch extreme values. The solar insolation and cell temperatures might have played a role in dictating power yieldings (Maghami et al., 2016; Omkar et al., 2015; Chakravarthi et al., 2020). Secondly, with the increase in the PV module's temperature, the power-yielding efficiency shall decrease linearly at standard test conditions and vice versa (Salman et al., 2012).

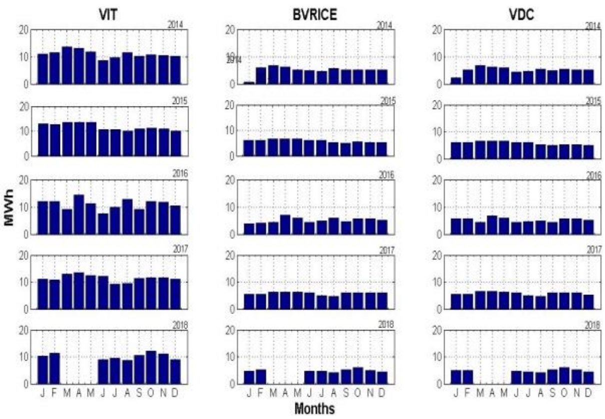

Figure 5. Monthly variations of power yieldings (MWh) of solar power plants atop VIT (100 KWp), BVRICE (50 KWp), and VDC (50 KWp) from 2014 to 2018 (top to bottom)

The relatively higher temperatures over this location, therefore, during the summer season (~30 ^{0}C) could have reduced power yieldings, whereas the moderate temperatures during the winter season (~25 ^{0}C) would have allowed in yielding higher magnitudes. The monthly solar insolation data is shown in Figure 6.

The annual power yieldings generated from the power plants atop VIT, BVRICE, and VDC are shown in Figure 7. Note that VIT is a 100 KWp capacity plant, while both VDC and BVRICE are 50 KWp power plants. A substantial decay in power yieldings can be seen with the progress of years. The decreased power output over time, which is known as the degradation rate, has been carefully calculated. It is estimated that a maximum of ~15% decline in power yielding is noticed, but for a few years (during 2016-2017 for the VDC plant), it is only ~1%. However, the decline for VIT during 2017-2018 is ~ 9%. This huge difference in decline in different years might be due to various technical and weather conditions, which include the ambient temperature of the location, internal network, power electronics, and connected grid (Irfan et al., 2017).

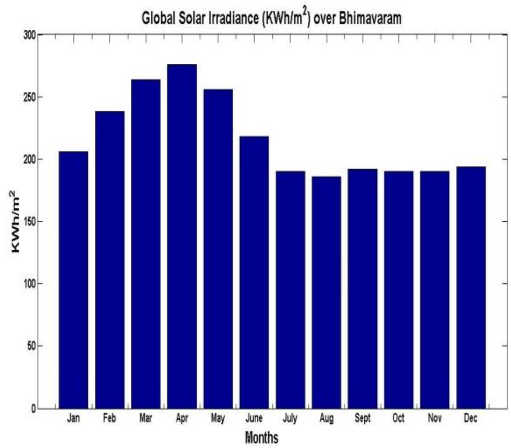

Figure 6. Monthly global solar irradiance over Bhimavaram

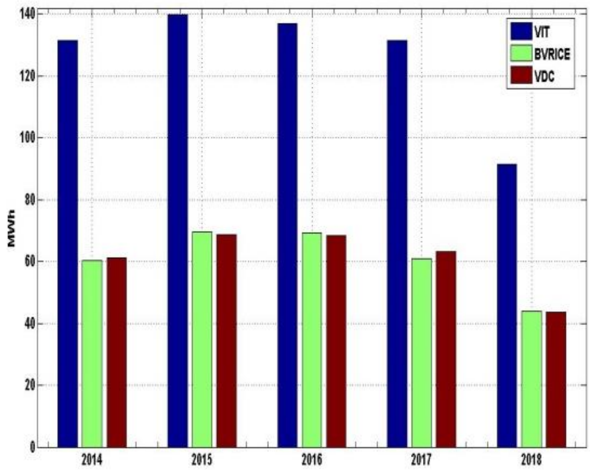

Figure 7. Annual variations of power yieldings (MWh) of solar power plants atop VIT (100 KWp), BVRICE (50 KWp), and VDC (50 KWp) during 2014-2018.

To minimize those losses, proper precautions need to be followed as we have highlighted in the ensuing section of this paper. In general, a 20% decline is considered a failure, albeit there is no consensus on the definition of failure (Jordan et al., 2017). We have also made statistics on the amount of revenue being generated so far and CO_2 emission savings (in tons) per year out of these solar power plants and presented in Table 2. It is estimated that the payback period can be achieved from 7 to 8 years with 10% depreciation and the total CO_2 emission savings are 1237 tons (till May 2019).

Table 2. Statistics of revenue generated and CO_2 emissions savings

S. No.	Year	Revenue generated (Indian rupees)	CO_2 savings (tons)
1	2014	23,29,459.00	219.24
2.	2015	26,48,002.00	244.47
3.	2016	25,59,726.00	229.68
4.	2017	24,38,628.00	250.78
5.	2018	23,28,523.00	201.89
6.	2019 (till May)	22,18,452.00	125.85
	Total	**1,45,22,790.00**	**1236.91**

3.3 Energy losses

An accurate quantification of potential losses of a PV solar system is a difficult task, because of the involvement of several factors and a significant amount of complex interactions among them (Rao et al., 2018). We have made attempts to quantify several losses of an existing 100 KWp atop VIT- B block and 50 KWp atop SVECW in one year and presented them as Sankey diagrams in Figure 9. It is obvious from Figure 8 that the energy losses are as low as -3.5 % (-19.05 KWh) to as high as -7 % (-38.10 KWh) per day. The minimum energy loss was due to inverter losses, whereas the maximum loss was due to temperature losses. It was reported that around 2.2% of losses occurred due to inverted losses and 9.6 % of losses occurred due to temperature losses (Kumar et al., 2019), which significantly reduced the performance of PV systems.

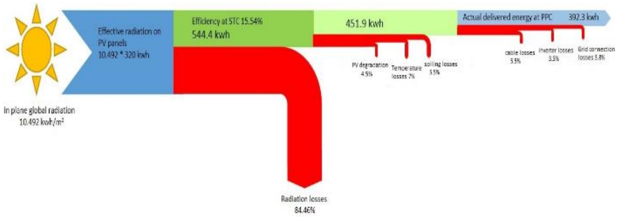

Figure 8. Sanley diagram shows estimated losses of the 50.4 KWp power plant

3.4 Typical comparisons with existing power plants

We have also calculated the performance ratio (PR) and capacity utilization factor (CUF) of our power plants and made attempts to make performance comparisons between our solar plants and other Indian counterparts and a few foreign countries, and such comparisons are presented in Table 3. Note that PR, a dimensionless quantity, is an international measure for describing the level of the utilization of an entire PV system.

Table 3. Performance comparisons of our plants with various power plants located in India and other countries

S. No.	Plant location, country & capacity	Geo. Lat.	Geo. Long.	PR (%)	CUF (%)	Reference
1	DEI, Agra, India- 147.5 KWp	27.17 ^{0}N	78.00 ^{0}E	47.00-91.00	06.00-13.00	Satsangi et al., 2014
2	Ramagundam, India- 10 MW	18.75 ^{0}N	79.46 ^{0}E	73.88-97.50	12.29- 18.80	Shiva Kumar and Sudhakar, 2015
3	Poornima University, Jaipur, India- 100 KWp	26.91^{0}N	75.78 ^{0}E	82.00-88.00	15.00-18.00	Rawat and Rawat, 2017
4	Sarangpur, Chandigarh, India- 200 KWp	30.69 ^{0}N	76.76 ^{0}E	77.27	16.72	Kumar et al., 2019
5	Bhubaneswar, India- 11.2 KWp	20.24 ^{0}N	80.85 ^{o} E	78.00	17.00	Sharma and Goel, 2017
6	Medio San Juan, Colombia- 20 KWp	05.25 ^{0}N	76.8 ^{0}W	63.00-78.00	10.00-15.00	Edison Banguero, 2017
7	Tangier, Morocco- 5 KWp	31.79 ^{0}N	7.09 ^{0}W	58.00-98.00	6.55-21.42	Attari et l., 2016
11	**Vishnu College- 200 KWp**	**16.54 ^{0}N**	**81.52 ^{0}E**	**53.00-89.00**	**02.00-10.70**	**Present Study**

It is clear from Table 3 that the calculated PR of our plants has stood at a moderate level. It has been reported that carefully planned plants achieve annual PR values of between 80 and 90 percent (Wirth, 2019). In general, lower PR might be due to higher operating temperature, varying irradiance conditions, dirt on the solar modules, line resistance, and conversion losses in the inverter. It is also obvious that low CUF (02.00) is noted, which is most probably due to system losses as a result of local weather conditions (Shiva Kumar & Sudhakar, 2015).

3.5 Solar pro simulations

Solar Pro 4.5 (developed by M/s. Laplace Systems Co Ltd., Japan) is robust PV design and energy simulation software that simulates electricity generation precisely with consideration for various elements of a PV system and displays the result comprehensively. We have made several runs of Solar Pro 4.5 software to verify the power yieldings for 200 KWp solar power plants with a similar setup (inclination and shading) and ambient conditions including air temperature, solar irradiance, and PV temperature. Figure 9 depicts one typical simulation, which shows a similar coincidence with the original trend presented in Figure 5.

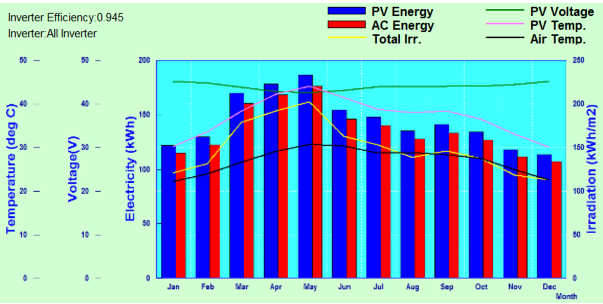

Figure 9. Solar Pro simulation- Power Graph

The power output is showing strong dependence on the ambient temperature, with maximum magnitudes during local summer (March-June) and minimum during the rainy season (July-September). Similarly, we have simulated current-voltage (I-V) characteristics of the 200 KWp power plants and are shown them in Figure 10 along with maximum power point (MPP) (Xiao & Dunford, 2004). Besides, the economic graph of another typical simulation is shown in Figure 11 which shows seasonal variations with maximum (minimum) magnitudes during the summer (winter) season.

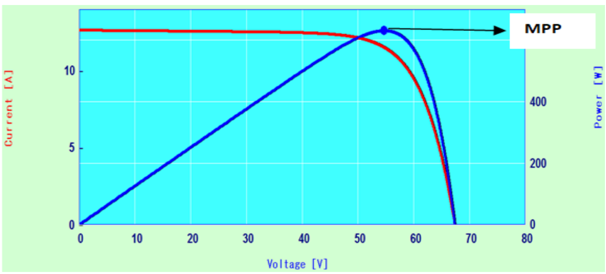

Figure 10. Solar Pro simulation- I/V characteristics

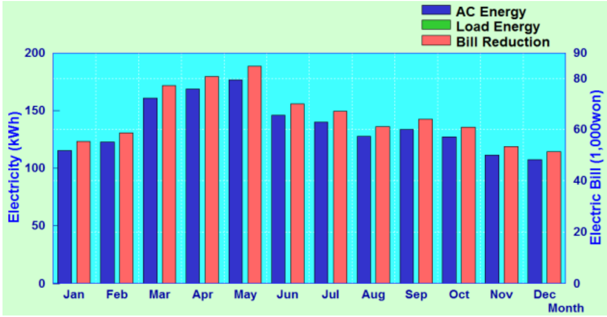

Figure 11. Solar Pro simulation- Economic graphs

4. SUGGESTIONS TO IMPROVE YIELDING CAPACITY OF POWER PLANTS

Since a solar power plant consists of a transparent glass pane on the top which properly traps the solar insolation and reflects into the panel and if the transparent glass gets affected, consequently, the absorption rate reduces which leads to reduced conversion efficiency (Rajput & Sudhakar, 2013; Sulaiman, 2014). It has been estimated that accumulated dust, dirt and snow on transparent glasses roughly contribute more than 2% yielding losses in solar power plants, if the solar panels are not cleaned for weeks together and that losses may further increase as high as 40-50% if they are not cleaned for more than two months (Wable & Ganiger, 201). It is, therefore, imperative that the cleaning of solar modules is very much essential regularly. Several conventional and sophisticated cleaning methods were proposed by several researchers which include, vacuum suction and manual wiping and cleaning and electrostatic precipitator (ESP) (Hudedmani et al., 2017).

The complete purpose, however, will not be served with the conventional cleaning systems, since a proper cleaning is not possible with them due to the typical mounting and mechanisms of solar plants. Besides, these conventional cleaning would require lots of labor and money, which cannot be affordable by several institutes and organizations. As a blessing in disguise, the tilt angle of the PV panel heavily influences the dust deposition density, apart from the geographical latitude of the location and installation design (Mani & Pillai, 2010). As the present power plants were installed with elevation angles around 16.54^0, moderate accumulation of dust, dirt and snow could be anticipated. As we are, currently, adapting manual wiping and cleaning methods only on weekly twice basis, the expected yieldings are not so encouraging, and hence, immediate steps are needed to replace the existing cleaning methods. Fortunately, one of our colleagues is currently on the job of fabrication of a solar panel automated cleaning ecosystem (SPACE), an automatic robotic solar panel cleaning system. Once SPACE fabrication is done, we will seek the usage of SPACE on a regular basis so that optimum power could be harnessed.

Secondly, when solar cells are transferred into a module, series resistance (R_s) arising from the cell interconnection and optical losses caused by the encapsulation may bring additional losses to the module output power, which is evaluated by the cell to module power ratio (CTM). By cutting a fully processed cell into two parts (half-cell), resistance losses can be reduced, providing a power boost of about 5 to 6 W on the module level (Zhang et al., 2018). We are, therefore, planning to install half-cells in the ensuing solar power plants in the future power plants as to harness maximum power from them.

Water bodies could be amicable locations to install solar power plants. The water not only keeps the PV modules cool, which has a positive effect on power yields, while in return, the solar panels protect the surface of drinking water reservoirs from air pollutants or being evaporation. This solar application on water bodies often avoids competition on space usage. Since SVES campus is having a good number of water bodies, installation of solar panels on them shall be a viable option and such efforts will be taken in coming days.

5. CONCLUSION

A part of this important study, we have arrived at the following conclusions, which are listed hereunder:

a) Daily variations of power yieldings (KWh) of 200 KWp power plants in May 2019 show near similitude with 302.4 KWp plants, though moderate differences in magnitudes between them are found.

b) Clear seasonal variations in power yieldings are observed with peak (dip) magnitudes during the local summer (rainy) season, which shows high coherence with temperature variations.

c) The decline of power yielding over five and a half years is between 1% and 15% only.

d) The performance ratio and capacity utilization factor of the 200 KWp power plant are 75.3 % and 16.07 %.

e) The payback period and CO_2 emission savings of the 200 KWp power plants were estimated, which are ~7 to 8 years and ~1237 tons as of May 2019.

f) Software-based simulations are presented.

g) Sankey diagram of estimated losses of a power plant (50 KWp) is drawn.

h) Several critical suggestions are discussed that might help the stakeholders to improve the yielding capacity of existing and ensuing power plants.

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