PERFORMANCE ASSESSMENT OF THE GRID CONNECTED PHOTOVOLTAIC POWER PLANT: A CASE OF AN INDIAN UNIVERSITY

Ibrahim Joseph Mwasubila[1], Dr. M .L. S. Deva Kumar[2]
[1]M.Tech student department of mechanical engineering ,Jawaharlal Nehru Technological University Anantapur, Andra Pradesh , India
[2]Professor department of mechanical engineering, Jawaharlal Nehru Technological University Anantapur, Andra Pradesh , India
Department of Mechanical Engineering, College of Engineering Anantapur, Jawaharlal Nehru Technological University, India

ABSTRACT: The main objective of this project is to conduct the Performance assessment of the existing photovoltaic power plant at Jawaharlal Nehru Technological University Anantapur (JNTUA). Assessment of the grid-connected plants could help to improve the existing system and help to improve the future design installations and maintenance of the solar power plants. JNTUA installed the photovoltaic power plant which is connected to the grid by the use of net metering; this helps the university to address the problem of power. In this study the annual performance of the power plant, performance ratio, capacity of utilisation (CUF) and energy yield were analyzed along with power plant design aspects. Various types of power losses were identified. The collected data were evaluated by using Microsoft® Excel, computation equations and validated by experiment then benchmarked. Based on the analysis the power plant has a low capacity of utilisation and low-performance ratio in one subsection. In order to improve the performance and solve the existing problem various ways of improving the performance were provided. Measures suggested could help improve the performance of the existing solar power plant and future designs.

Keywords: *performance, photovoltaic, power plant, grid solar power plant, India.*

1.0 INTRODUCTION.

India is one of the countries with high population in the world, the population is about 1.366 billion according to (World Population Review, 2019),but over 300 million people still have no access to electricity due to various reasons, some of these reasons are remoteness of areas, low production compared to demand, poor infrastructure and others. Solar energy is one of the viable long-term sources of energy; it is a renewable source and is considered as a clean resource with zero emission. Solar is a tremendous potential for energy and can be harnessed by using different methods and forms(MNRE, 2019).

1.1 Energy policy and Demand

The primary energy demand in India keeps on increasing from 450 million ton of oil equivalent in 2000 to 7700 million tons of equivalent oil (toe) in 2012 and the projected demand by IEA is estimated to increase to 1250 toe in 2030 while the report of integrated energy policy the primary requirement will reach 1500 toe in 2030. This increase in demand for primary energy is due to various reasons such as technological advancement, improvement of living standard, population increase and economic growth. The rapid growth in energy demand which is driven by economic growth and incomes. This leads to a high demand for energy services such as heating, Ventilating, and Air Conditioning (HVAC), lighting, transportation, cooking, mobility and industrial activities.

1.2 Energy Scenario and Emission

The energy scenario in India poses a great challenge to future policies due to increase in demand. The energy supplied in 2011 was about 750 million toe (tonnes of oil equivalent) and was estimated to increase up to the range of 1200-1700 million toe by 2030. As per the ministry of environment and forests report National Telecommunications Commission (NATCOM), India emitted an equivalent of 1,728 million tonnes of CO_2 as a greenhouse gas. The electricity demand will rise due to the increase in the urban population at which it is estimated to increase by 600 million plus by 2030. The Bureau of energy efficiency mandates formulates schemes so as to improve the energy efficiency and saving energy by promoting the use of efficient energy lights, heating, ventilation, air-conditioning (HVAC) and domestic and commercial energy efficient motor establishments across the country (NATCOM, 2017).

1.3 Problem Statement

Jawaharlal Nehru Technological University Anantapur (JNTUA) is one of the universities which produces electrical power from the solar power plant. This power plant is suffering from various problems such as frequent disconnection from grid, poor maintenance of the plant and low production in some months. The power plant has a low-performance ratio and capacity of the utilisation of the power plant due to various factors like temperature, power plant maintenance, inverter errors and other related problems. Therefore, due to the stated problems, the power plant was failing to attain its production. Because of this, this research aims to perform the assessment and establish ways to improve the performance of the power plant which would help the college to improve power production.

1.4 OBJECTIVES

1.4.1 Main objective

To assess the performance of the grid-connected solar power plant at jawaharlal nehru technological university anantapur (JNTUA).

1.4.2 Specific objectives

i. To determine the actual power production of the solar power plant.
ii. To determine the power inputs and outputs of the system.
iii. To identify key performance indicators, factors which affect the performance and computation of performance of the power plant.
iv. To conduct experiments and validate the data collected.
v. To suggest the measures to be taken.

2.0. LITERATURE REVIEW

2.1 Introduction to PV technology

The solar cell construction is shown in Figure 1. The solar cell is made by n and p layer of the semiconductor material. The combination of these two materials tends to form a junction at which charge carriers or electrons in the n-type material flow through a band gap to the p-type and holes flow to the n-type. More electrons and holes are created when photons are absorbed by the PV cell. The charge which flows to the external circuit and it is termed as current (Schenck, 2010).

To improve the efficiency of the solar cell, most of the incident solar radiation falling on the panel should be able to be converted to electric charges by absorbing radiations falling on it. where the most energy is available from the sunlight. The spectrum range of infrared and ultraviolet (UV) ranges from 0.5 electronvolts (eV) to 2.9 eV. The effective Photovoltaic semiconductors have energy gap ranging from 1.0 to 1.6 eV, and band gaps in semiconductors are in the 1 to 3 eV range. The minimum energy required by the silicon for its charge carrier to move from the valence band to conduction band is 1.1 eV (Abbas Ghasemi, 2011).

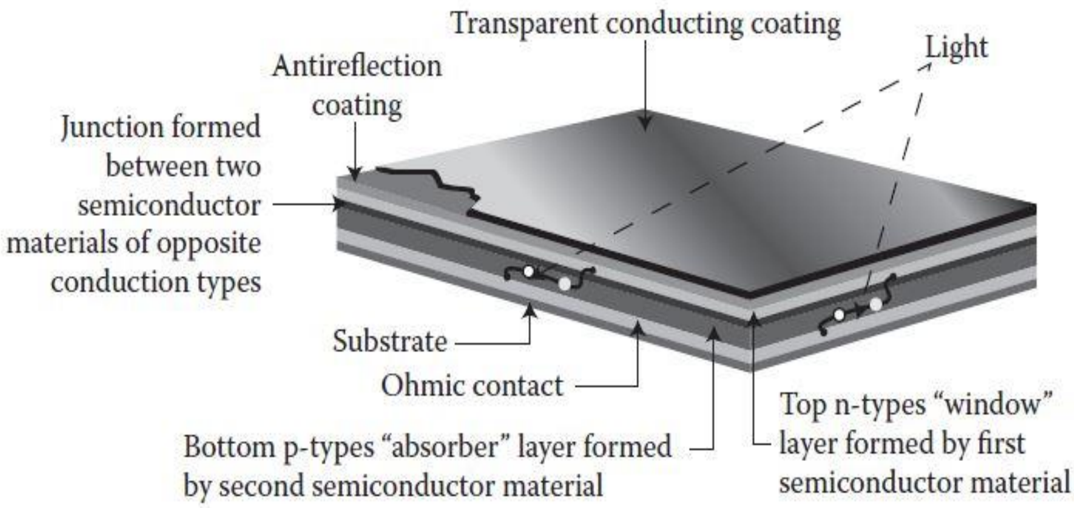

Figure 1. Photovoltaic cell structure (Abbas Ghasemi, 2011)..

2.2 Photovoltaic Systems

Photovoltaic systems can be broadly classified as grid-connected systems, stand-alone system and hybrid system. When the power produced and supplied directly to the grid, this kind of system is known as grid-connected systems, and sometimes they are called utility connected, grid interconnected. The grid-connected systems can be categorised based on the storage of power which is Grid connected system with no battery or backs up and grid connected system with battery backup. The system without battery backup is the least expensive among all systems and reliable; this system tends to shut down when there is no solar radiation falling on panels. For a battery backup system tends to store the excess energy and it does not stop to supply power when there is no solar radiation; hence it utilises the power stored during production.

A hybrid system operates with the help of other sources of energy such as generator back-up if the facility cannot tolerate power outages. The word hybrid in energy systems is used to describe a system which combines more than one source of power such as wind and solar, solar and generator, solar wind and generator. For a standalone system are commonly used in small scale application like domestic, irrigation and others, these systems are not connected to the grid (D.Yogi Goswami, 2015).

2.3 Performance analysis

This section aims to describe the performance of photovoltaic power plants. These performance measures are used for analytical assessment of performance analysis of the photovoltaic power plants, identification of the grid system problems and reliable electric power services(Kymakis, Kalykakis, & Papazoglou, 2009)

International Energy agencies developed the performance indices for solar power plants. The description of IEA indices was described in International Electro-technical Commission IEC 61724 standards for PV monitoring systems(Internation Standards, 2017). The performance parameters are presented in Table 1.

Table 1.Performance parameters

S.No	Parameters	Notation
1.	Plant energy out	Eac
2.	Array yield	Ya

3	Final yield	Y_f
4	Performance ratio	PR
5	Capacity utilization Factor	CUF

2.3.1 Plant energy output

The AC energy measured from the photovoltaic power plant is represented by a notation $E_{ac,d}$ for daily power generation and $E_{ac,m}$ for monthly energy output from the photovoltaic power plant and its computation is shown in equations 1 and 2.

$$E_{ac,d} = \sum_{dt=1=1}^{t=24} E_{ac,d} \quad (1)$$

$$E_{ac,m} = \sum_{d=1}^{N} E_{ac,d} \quad (2)$$

2.3.2 Array yield

The daily array yield $Y_{a,d}$ is the ratio of array-based DC energy output to the rated DC power of solar power plant, and it can be calculated as shown in equations 3 and 4. Daily yield is shown in equation 3 and monthly yield as shown in equation 4.

$$Y_{a,d} = {E_{ac,d}}/{Ppv\ rated}$$
(3)

Moreover, the monthly array yield

$$Y_{a,m} = \frac{1}{N}\sum_{d=1}^{N} Y_{a,d} \quad (4)$$

2.3.3 Reference yield

The reference yield (Yr) is the ratio of the total in-plane irradiance to reference irradiance at PV module level. It can be described as generated energy under standard test conditions (STC) and for a day (IEA-PVPS, 2007).

2.3.4 Performance ratio (PR)

The performance ratio is one of the performance measures which shows the relationship between the actual power outputs from the PV power plant to the theoretical power output of the power plant.(IEA, 2007) explains well about peromance and reliability of the system, The performance ratio of the power plant shows the effect of losses on the system's nominal power output. According to (IEA-PVPS, 2007), PR equation 5 shows how to compute the PR of the power plant.

$$PR = 100\ \% \times \frac{Energy\ measured\ (KWh)}{Energy\ output\ \ (KWh)} \quad (5)$$

2.3.5 Capacity of utilisation factor (CUF).

The Capacity utilisation of the solar power plant is defined as a ratio of the actual amount of power produced in kWh from a solar plant to the maximum installed capacity of the plant. If there are no other external factors which affect the performance, the power plant will produce the installed power which means that the CUF will be 1, practically it is difficult to have 100% efficiency in systems. The capacity utilisation factor for a grid-tied photovoltaic plant can be computed as shown in equations 6 and 7 (Decker & Jahn, 2012).

$$CUF = \frac{Energy\ measured\ (KWh)}{Installed\ capacity\ \times 8760\ hours} \quad (6)$$

$$CUF = \frac{Eac}{PPV\ rated\ \times 8760} \quad (6)$$

2.4 Factors affecting PV efficiency.

The efficiency of the solar power plant can be affected by so many factors; some of the factors are:

2.4.1 Battery Efficiency

When energy saving or backup is required batteries are needed for charge storage. There are different storage batteries, but the commonly used one is lead acid. All batteries discharge less charge or energy than what goes into them. There some factors which affect the efficiency of the battery such as design and quality of construction, some are certainly more efficient than others.

Equations 8 and 9 shows the energy which is used to charge and discharge the battery respectively, while equation 10 shows the efficiency of the battery computation.

$$E_{in} = I_C \times V_C \times \Delta T_C \quad (7)$$

Where IC is the current during the charging process, charging voltage (V_C), ΔTC is the charging time per time taken to charge the battery and E_{in} is the energy stored. The energy discharged from the battery at a constant current I_D, at a voltage V_D and at time ΔT_D is given by the equation 9.

$$E_{OUT} = I_D \times V_D \times \Delta T_D \quad (8)$$

Hence the battery efficiency can be calculated by equation 10 and 11.

$$Efficiency = \frac{Eout}{Ein} \quad (9)$$

2.4.2 Inverter Efficiency

Solar PV power plants generate DC power; hence due to the needs of the AC loads an inverter is needed. Although inverters come with wide range efficiencies but typically affordable solar inverters are ranges from 80% to 90% efficient (Tyler J. Formica, 2017).

2.4.3 Cable Thickness

Most of solar panels are designed to produce 12, 24 and 24 VDC and most of the appliances use 220 Volts which is higher compared to what is produced by a solar panel. To reach the appliance requirement panels are arranged in parallel and series to obtain the desired current and voltage. The power produced is transmitted through cables which contain resistance; the power loss in cables can be reduced by selecting the required size and length. Doubling the system voltage can be used to reduce the voltage drop by 0.25. The Ministry of New and Renewable Energy (MNRE) India provides the guidelines which and the cable specification must adhere to international cable specifications and standards as described in IEC 60227 / IS 694 or IEC 60502 / IS 1554 (Part I & II) standards (IEC60502, 2004)

2.4.4 Shading

Solar panels should be installed at a place where there are no shadows since the photovoltaic module comprises several cells which are connected in a series circuit. Because of this, a small shade on a solar panel can have a surprisingly high effect on the power output of solar power plant. There is a common misconception in understanding the performance of the solar panels and effects of shading; most people think that a partial shading does not affect the power from the system. Hence shading should be avoided during the planning phase and if it is difficult to avoid at 100% the concepts of bypass and to use micro inverters should be used. Shading can cause a lot of problems in the solar module such as overheating and cell distortion. Figure 2 shows the defect of shading on the solar panel, as shading increases the power plant output decreases as shown in Figure 2 (Sulaiman, Singh, Mokhtar, & Bou-Rabee, 2014).

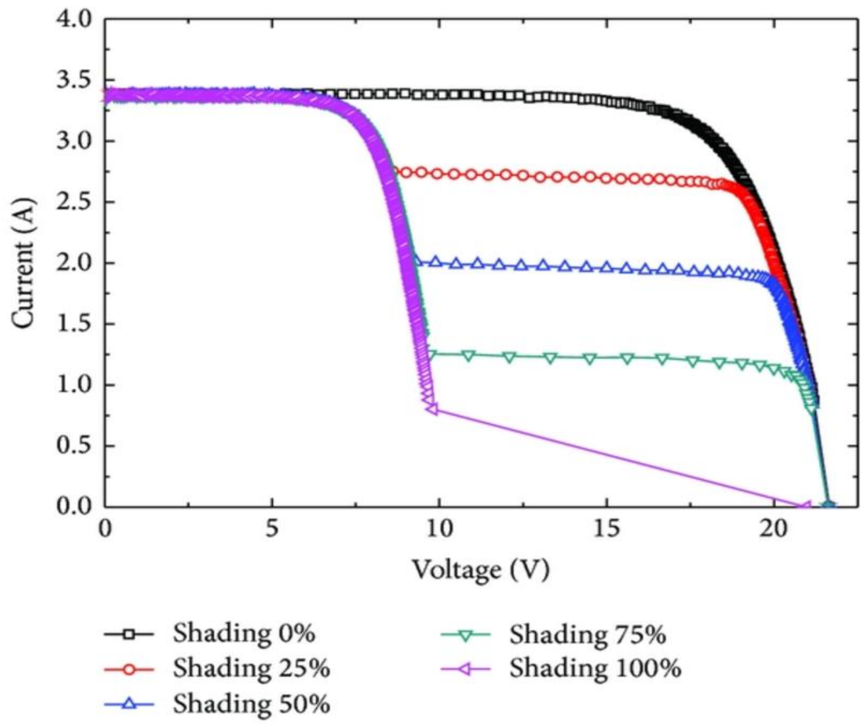

Figure 2. Effects of shading on the solar panel power output.

2.4.5 Temperature

The solar performance can be affected by the temperature of surrounding, Solar cells perform better in the cold rather than in hot climate and as things stand. Rating of solar panels is conducted under a controlled room with artificial light which mimics as solar radiation when the solar rating is conducted the temperature should be 25˚C and 1000w/m^2 irradiance, these parameters are known standard test condition(STC), the STC is different from the real operating environment. The effect of temperature can be expressed as each degree rise in temperature above 25˚C (STC) lowers the power output by 0.25 (amorphous solar cell), 0.43% for crystalline solar cell. Figure 3 shows the effect of temperature on power output current-voltage curve. From Figure 3 as the temperature increases the power produced reduces and this affects negatively the performance of the power plant (PVeducation, 2019).

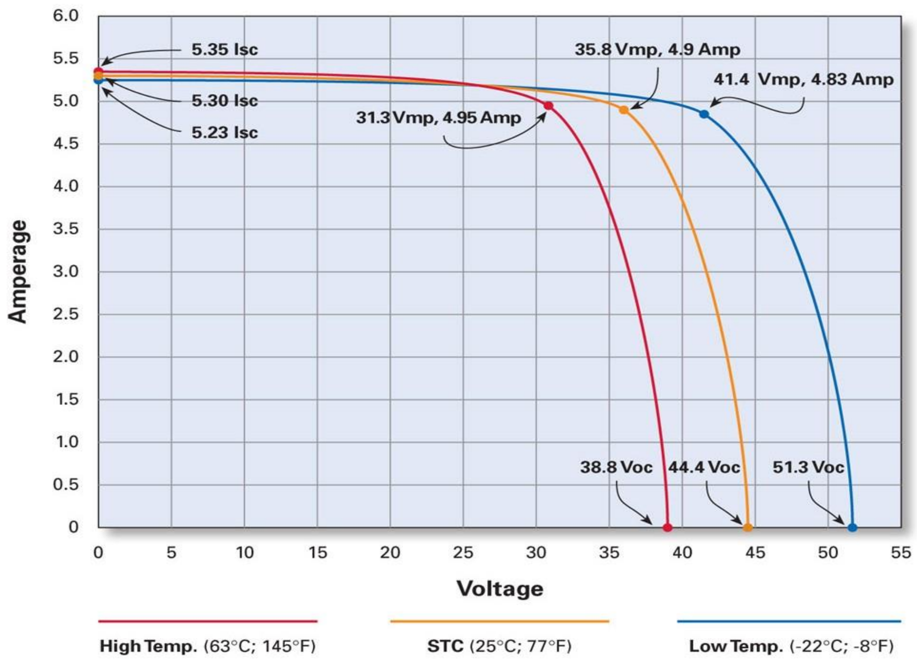

Figure 3. Effect of temperature on the PV output

2.4.6 Maximum Power Point Tracking (MPPT) Losses.

The output from the solar module is not constant throughout the day; it tends to change with the change of the sun's direction. The IV characteristic of a solar module obeys the single maxima characteristic of the curve. Therefore, the maximum peak point will occur at one point in the curve (Northern Arizona Wind & Sun, 2016).

3.0. METHODOLOGY

Data collection methods.

Various techniques and tools were employed to collect various information for the completion of this thesis. Primary and secondary data were collected in this research; secondary data were collected from recorded production while primary data were collected by using different methods such as observation, measurement. Visual observation and measurement were used to collect data from the power plant; the experiment was conducted to collect other data which helps the variation of findings. While Literature review involved studying various researches done by experts in the energy sector, operations and design arrangements, this intended to obtain the knowledge and ideas which have been established by consensus in the same field who worked on the similar case. The aim was to gather useful information to assist in obtaining the well-improved information on solar energy installation and performance.

4.0 RESEARCH FINDINGS AND ANALYSIS

4.1 Analysis of collected data.

The data collected from JNTU power plant were analysed using a Microsoft® Excel and computation methods; the following were observed as presented in Figures and Tables.

Monthly wise data was collected from each inverter at the JNTUA power plant from January to December 2018 (12 months), the whole power plant comprises of five inverters 3@ 50kW one 20kW inverter and 10 kW (kilowatt) inverter, these inverters completes the JNTUA power plant which was installed in 2016. Figure 5 shows the power produced in a 50kW with a maximum capacity of 55kW inverter substation (units in kWh). Figure 6 shows the annual production of the substation of 10kW which is located at the main building (10500 W maximum power inverter).

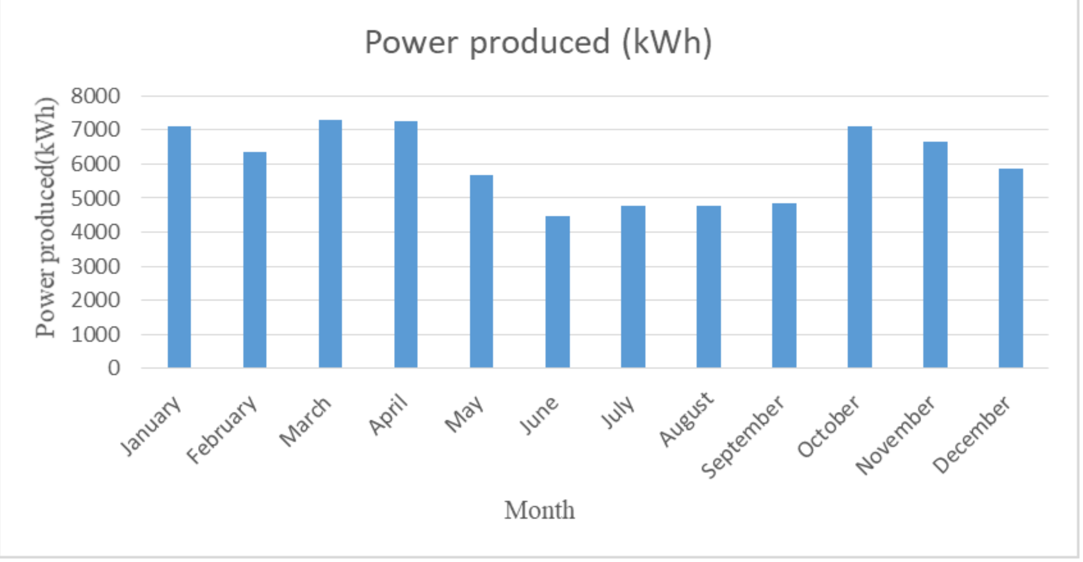

Figure 4 . Annual power produced by a 50kW substation

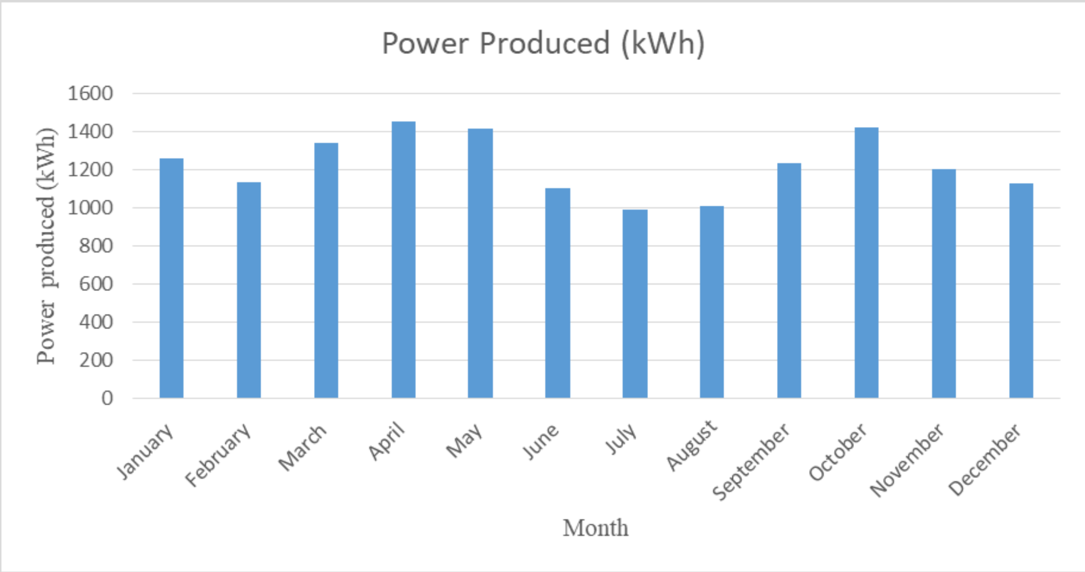

Figure 5. Annual power produced by a 10kW substation at the main building.

The other substation is located at the top of the hostel building at which two 55 kW inverters and 22000 kW were installed. Hence the same measurement and data were taken from inverters. Figure 7 shows the power produced at the inverter A and a Figure 8 shows the power produced at 50kW inverter, the maximum capacity of each 50kW inverter is 55000W.

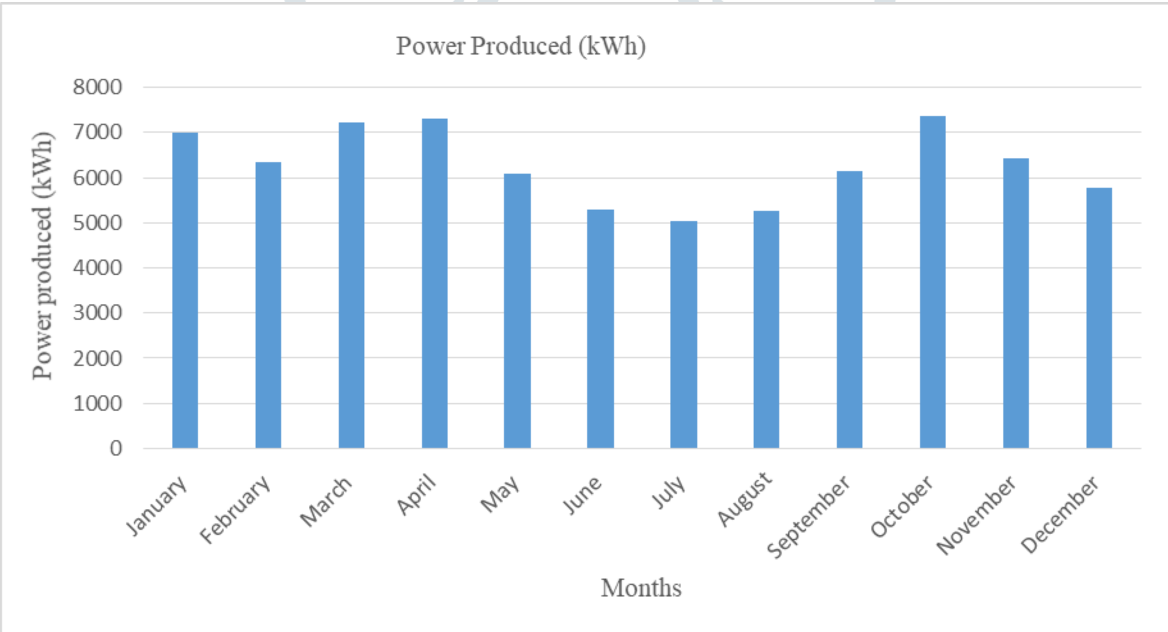

Figure 6. The power produced by a 50 kW section an at Ellora hostel.

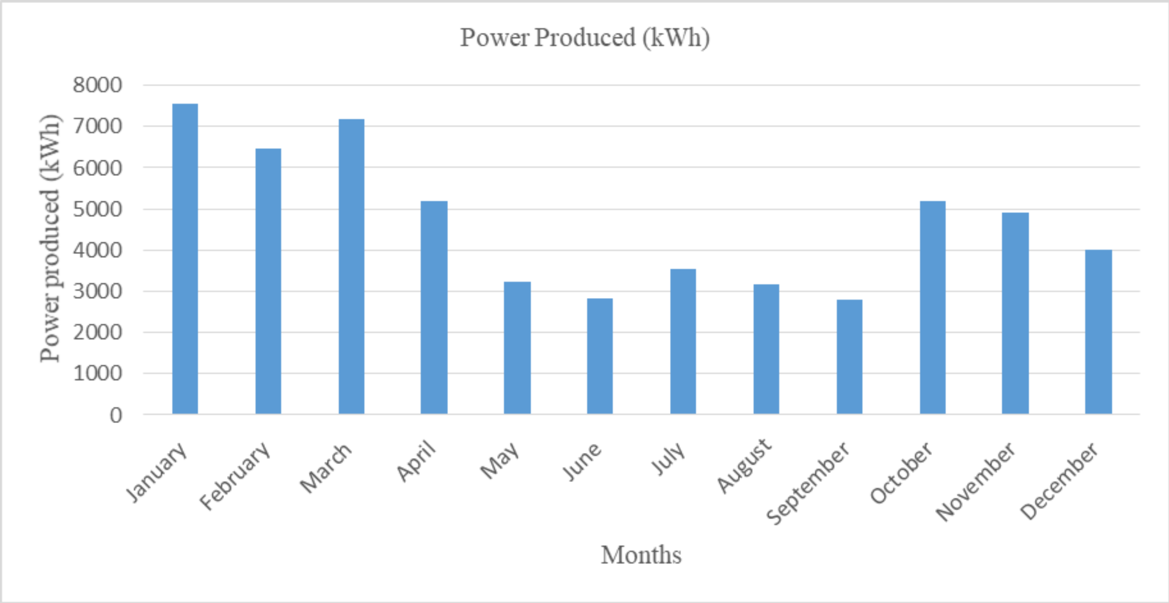

Figure 7. The power produced at Ellora building (50 kW inverter B).

4.2 Climate condition.

Temperature, irradiance and sunny

Climate condition is one of the factors which affects the power produced by a solar panel, and in 2018 the following data were recorded from weather station of latitude and longitude of JNTUA Anantapur 14.6515° N, 77.6081° E . Figure 9 shows the number of sunny days, partial cloud days and overcast days. Figure 10 shows the average monthly amount of solar radiation falling on the unit square meter per day (kWh/m^2/day). Figure 11 shows the average maximum temperature and an average temperature of each month from January to December (NASA POWER, 2018).

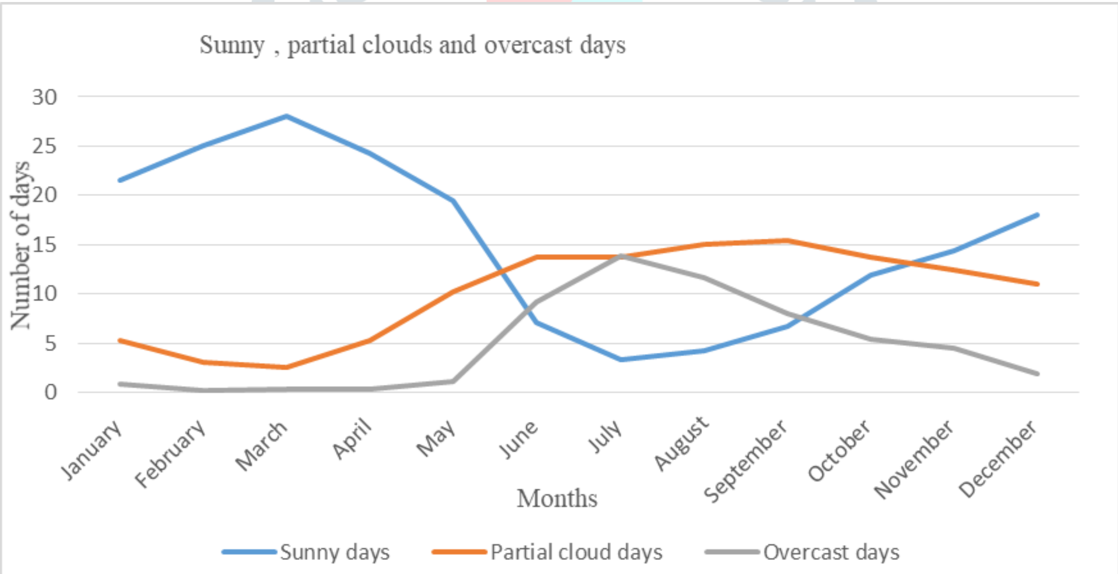

Figure 8. 2018 sunny, cloudy and overcast days.

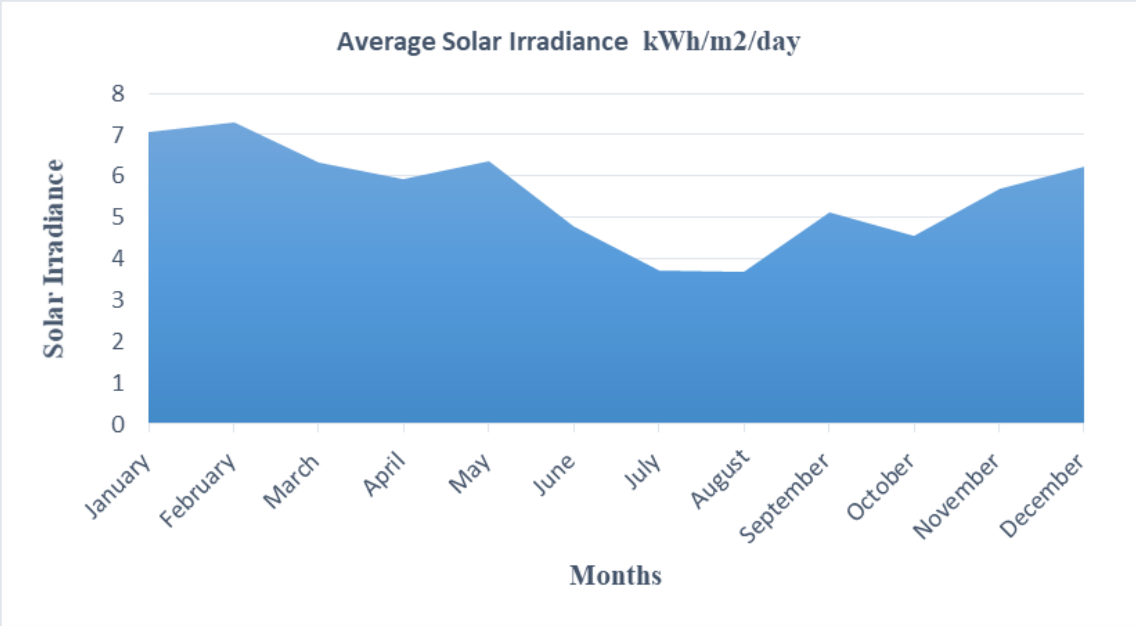

Figure 9. Average monthly solar radiation kWh/m^2/day.

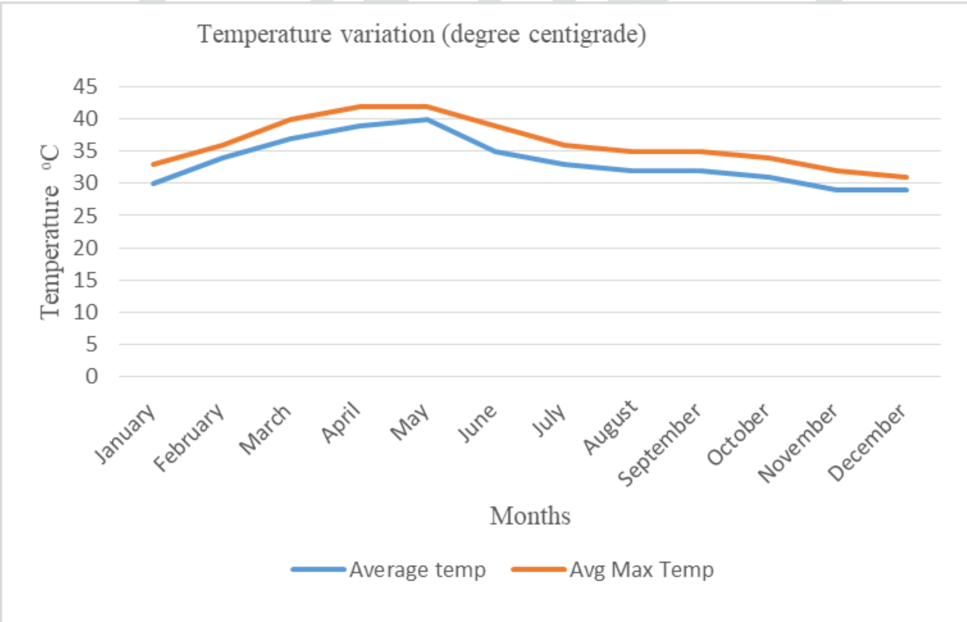

Figure 10. Average surrounding temperature (in degree centigrade).

4.3 Discussion of the findings and analysis

4.3.1 Low power production

The data shows that the production is low from May to August , this is due to the following reasons.

i. During March to mid-June, there is a high average temperature in the range of 35^{0}C- 40^{0}C which affects the production of the power plant.

ii. The number of sunny days is more, but the problem is ambient temperature which affects the power production negatively from the plant.

iii. From June to September the solar irradiance is low compared to other months also the number of days which are partial clouds, and overcast are high; this leads to low production of power.

4.3.2 High power production

The power production is high from January to mid-April and from mid-August to December. The following are reasons

i. The solar irradiance starts to increase from January to mid-April and from September to December which indicates the high power production in the graphs.

ii. The average temperature starts to decrease, and the effect of temperature on the solar cell starts to decrease. Hence the efficiency of the system improves.

iii. From September to December the number of overcasts is low, and this indicates more power production.

4.3.3 Problems associated with the power plant

During data analysis of the power plant data, some frequent inverter errors and problems were observed these problems could be categorised as permanent and temporary problems. Some of these problems are:

4.3.4 Overvoltage error (AC voltage high)

This error causes the frequent disconnection of the system to the grid; this indicates that the power produced will not be sent to the grid. This lowers the power which is supposed to be exported to the grid.

4.3.5 Solar panel cleanness

If the solar panel has debris or dust which indicates that there is no frequent cleaning, solar dirtiness lowers the power production of the system. Accumulation of dirt or particles like dust (soiling) lowers the absorptivity of the solar cell which leads to lower power production. The experiment below was performed to check the effect of dust or dirt accumulation on the power output, in Table 3 the 50 W panel was used to analyse the power output before dirt accumulation and after dirt accumulation, the experiment shows that the efficiency of the panel was reduced by 42.34%, the results are shown in Table 3.

Table 2.Experimental data on the effect of dirt accumulation on the solar panel

Effect of dust contamination on the PV power output				
s/n	voltage (V)	current(A)	power (W)	Condition
1	18	0.062	1.11	Clean solar panel
2	18	0.06	1.08	
3	18	0.06	1.08	
4	16.2	0.04	0.648	With dust contamination
5	16	0.04	0.64	
6	16	0.04	0.64	

4.4 Performance measures.

4.4.1. Capacity of utilisation (C.U.F)

The capacity of the utilisation of the solar power plant is calculated from equation 7 and represented in Table 4.

Table 3. The capacity of the utilisation of the solar power plant

Sub section	50 kW (Main b)	10kW (main b)	50kW (A)	50kW (B)
CUF	0.16493379	0.167579909	0.171990868	0.128127854
Average CUF		0.158158105		

Main b = Main building.

From the data collected and Table 4, the solar power plant overall production is determined; therefore the overall capacity of utilisation is 15.8158105%. The CUF value is low compared to the data provided by the ministry of new and renewable energy (MNRE) of the overall average capacity of utilisation factor in India. The ministry of energy report of 2018 shows that the capacity of the utilisation of power plants in India ranges from 15-19%. Hence the Ellora hostel substation is not performing well.

4.4.2. Performance ratio of the power plant

The overall performance ratio of the power plant was computed, and the results are shown in Table 5, sometimes the PR is regarded as a quality factor also PR is stated as a relationship between the actual and theoretical energy outputs of the solar plant. The computed value of the performance ratio is shown in Table 5; equation 5 is used to calculate the performance ratio.\

Table 4.Annual performance ratio of Subsection A and subsections B.

Parameter	The main building (A)	Ellora hostel (B)
Number of panels	260	558
Area of panel (m^2)	1.31175	1.31175
Efficiency of panel	0.15	0.15
Annual radiation (kWh/m2)	2031.225	2031.225
Nominal power output (kWh)	103913.92	223015.2513
Actual power produced (kWh)	86921	153900
Performance ratio	0.84	0.6900873
Percentage PR	84%	69%

From Table 5 the performance ratio for main building subsection power plant is 84% and 69% for Ellora hostel. This evaluation shows that the Ellora hostel does not perform well because of frequent disconnection from the grid, dirt contamination on the panel, broken solar panels and poor maintenance of the power plant in general as shown in Figure 12.

Figure 11. The current condition of Ellora hostel subsection Solar panels

5.0. Conclusion and Recommendation

5.1 Conclusion

The power plant is performing well in a few months while other months are experiencing low production. From the analysis of power plant data, the performance ratio of the power plant is 84% for subsection A and the 69% for subsection B. This indicates that, the Ellora hostel subsection is underperforming in comparison to the main building power plant subsection .the capacity of utilization of the power plant is 15% which is the lowest compared to the CUF of power plants in India, but the lowest was observed in subsection B Ellora hostel. Various problems were observed in the power plants such as frequent disconnection from the grid, taking half a minute to reconnect back to the grid after each disconnection which lowers the production, low solar panels maintenance. The experiment was conducted to check the effect of dirt/ dust accumulation on the plant, and the results show that the power production was lowered by 42.34%. The performance of the power plant can be improved by ensuring the proper maintenance of the power plant and avoiding to put a low clearance between the panel and the concrete surface.

5.2 Recommendations

There are so many factors which affect the performance of power plant such as frequent disconnection from the grid, errors such as Ac voltage high and others, all of these factors do not affect the performance at a high percentage. Hence the dirt accumulation on the panels affects the performance at a high percentage; the frequent cleaning should be conducted to avoid the effect of low production.

The inverter setting should be rechecked to avoid taking so long to reconnect back to the grid instead of taking more than 30 seconds after each disconnection; this will prevent the power loss due to being out of the grid. Replacing the broken solar panels so as to avoid low power production since more than three solar panels was found broken at Ellora substation.

REFERENCES

Abbas Ghasemi, V. N. (2011). *Energy and Environment.* New YorkVaughn: Taylor & Francis Group.

Austalia, T. s. (2019). Effects of shading. *Solar panels*.

D.Goswami, Y. (2015). *Principles of Solar Engineering (third edition).* London & NewYork: Tayler & Francis Group.

Decker B, J. U. (2012). Perfomance of 170 grid connected pv plants in Northern Germany. *Analysis of yields and optmization potentials* , 4-6.

ECA, M. o. (2010). *The energy conservation (Amendment) Act 2010.* New Delhi.

Energy, C. C. (2001). *A guide to photovoltaic sysytem design and installation.* Califonia.

Foster, R. (2010). *Solar Energy (Renewable Energy and the Environment).* London & New York: Taylor & Francis Group .

IEA-PVPS. (2007). Photovoltaic power system program . *cost and perfomance trends in grid connected photovoltaic systems and case studies* .

IEC60502, I. s. (2004). Power cables with extruded insulation. *INTERNATIONAL ELECTROTECHNICAL COMMISSION*.

IEC61724-1. (2017). *Standard for PV monitoring systems .*

Kalogirou, S. (2009). processes and systems. In *Solar energy engineering* (pp. chapter 9 pages 469–517.).

Kymakis E, K. S. (2009). perfomanace analysis of a grid connected photovoltaic. *Energy Convers Manage*, 50.

Ministry of power, G. o. (2018). *The annual growth in power generation during recent years.* New Delhi: Ministry of power.

MinistryOfNewandRenewable. (2015). *Solar / Green Cities.* Solar Energy . Lodhi Road,New Delhi-110 003, India: https://mnre.gov.in/.

NATCOM. (2017). *United Nations Framework Convention on Climate Change.*

Nayfeh. (2004). Thin film silicon nanoparticle UV photodetector . In Nayfeh, *Photonics Technology Volume 16* (pp. Pages 1927-1929,). IEEE.

Power, M. o. (2001). *Energy conservation act 2001.* New Delhi.

PVeducation. (2019). Mismatch Effects in Arrays.

Review, W. P. (2019). *India Population.* http://worldpopulationreview.com/countries/india/.

Roger A, M. a. (2004). *Photovoltaic Systems Engineering (second edition).* NEW YORK : CRC PRESS NY .

Schenck, N. (2010). PV theory II. *Photovoltaic system sizing and design*, chap 7.

SEI, S. E. (2007). Design and Installation Manual. *Design and Installation of solar systems*.

Shaharin Anwar Sulaiman, A. K. (2014). Influence of Dirt Accumulation on Performance of PV Panels. *The International Conference on Technologies and Materials for Renewable Energy, Environment*.

Sun, N. A. (2019). *Maximum Power Point Tracking (MPPT) Solar Charge Controllers.* Arizona.

Synergy_Enviro. (2018). Analyze the Solar Irradiance at Anantapur, Andhra Pradesh.

Trishan Esram, S. M. (JUNE 2007). Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques. *IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 22*.

Tyler J. Formica, H. A. (2017). The Effect of Inverter Failures on the Return on Investment of Solar Photovoltaic Systems.