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# Effect of Ambient Temperature and Wind Speed on Performance Ratio of Polycrystalline Solar Photovoltaic Module: an Experimental Analysis

Subhash Chandra*[1], Sanjay Agrawal[#], and D.S. Chauhan*

***Abstract –*** *Generation of electricity by clean development mechanism is the key area for researchers, many countries of the world has already shifted towards green energy. Energy is the key factor for the growth of any country. Per capita energy consumption is the significance of the progress of any nation. Recently the penetration of photovoltaic systems has increased to generate the electricity at grid or local level. Although this technology has improved a lot however the performance of these systems is site dependent, which is affected by various environmental parameters like radiation, temperature and wind. An experiment is conducted in laboratory of GLA University, Mathura, India (hot and dry climate zone of India) to emphasis especially on wind effect. Two PV modules of same electrical and mechanical specifications are taken for experiment. To conduct experiment; different months of a year from various seasons are chosen. It has been observed that increased module temperature reduces performance but the cooling mechanism provided bring down the module temperature due to which a net energy gain is 7.69% in considered time. Performance measure indices i.e. PR is improved by 7.14%.*

***Keywords –*** ambient temperature, energy, performance ratio, photovoltaic solar cells, wind speed.

## 1. INTRODUCTION

In the current scenario of growing photovoltaic industry, it is essential to estimate high quality energy yield. In India the backbone of power sector is coal because it contributes maximum in power generation. India is aiming high to achieve the target of 175 GW installed renewable energy capacity by 2022 [1]. Since abundant amount of solar energy is available in India hence to supplement the target, government made a plan to generate 100 GW from solar photovoltaic systems, out of which 40 GW must be generated from rooftop solar photovoltaic systems. State-wise target of solar power is shown in Figure1 [2].

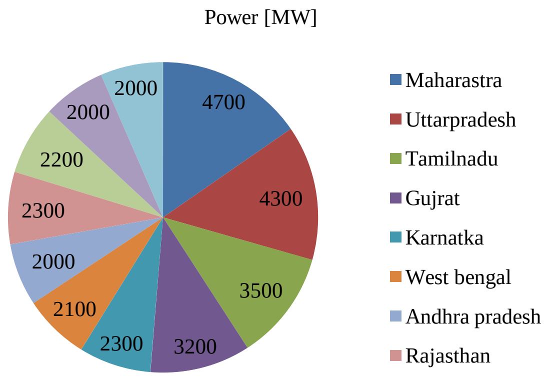


**Fig. 1. State wise target of solar power.**

In order to generate electricity from non-polluting energy sources, many efforts are being made to integrate different renewable energy sources However, PV systems are expected to play a key role for the sustainability of the future [3]. Harnessing of electrical energy from solar energy depends upon geographical location, site conditions, characteristics of solar cell etc. *i.e.* the performance of PV system is highly climate dependent. Many researchers have already contributed a lot to improve the efficiency, actual performance and sizing of PV system [4]. Two well-known parameters *i.e.* radiation and temperature affect the performance of PV system directly. Maximum electricity can be harnessed by maximizing radiation and minimizing temperature. Radiation is module orientation dependent and temperature depends on the semiconductor material used for manufacturing the solar cell. Although tracking methods can be used to get maximum radiation and due to limitations, they are not always beneficial. Since India is in northern hemisphere, and generally the PV modules are placed facing due south (*i.e.* equator facing), as a thumb rule the tilt angle is fixed equal to the latitude of the location to maximize the solar radiation on a tilted surface. Seasonal variation in tilt angle is beneficial for better performance of PV system but in fixed rooftop PV system the optimal tilt angle is equal to latitude [5]. Solar cells are very sensitive to temperature; their power is significantly affected by temperature. For crystalline silicon the voltage temperature coefficient is about – 0.45%/K and current temperature coefficient ranges between 0.04 to 0.09%K. Manufacturers indicate the PV module efficiency under standard test conditions (STC), temperature of module 25°C, solar radiation of 1000w/m$^2$ and air mass ratio AM=1.5 [6]. Large variations can be seen under outdoor conditions, therefore an important impact on efficiency and energy yield is observed. Module efficiency is temperature dependent [7]-[9]. Although a lot of literature is available on PV cell temperature, which can be assumed

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to be same as that of PV module temperature and recently it has been reported that wind speed provides natural cooling for PV module, which decreases the Module temperature hence improves the efficiency. Yet the effect of cooling by wind that can be an important factor for estimating the true potential for large PV system is not broadly applied [10]-[13]. In order to collect the hot air, a channel can be made having inlet and outlet port and hot air from outlet port can be used for space heating *i.e.* utilization of both types of energy improves the efficiency of the system [14][15]. In general the performance is assessed by measuring the actual output and comparing it with expected output. The ratio is called performance ratio (PR) usually employed to optimize the performance and for proper maintenance, a healthy system must have a certain PR value depending on the site, where the system is located [16]. Although CUF is an important metrics for performance measurement but it actually does not include various solar PV system parameters, hence less suitable in comparison to PR. Different solar PV systems have PR value in the range of 0.6 - 0.9, depending upon site conditions. The inherent losses present in the system reduces the PR value, detailed losses are weak irradiation losses, temperature losses, DC cable losses, shading losses, dust and snow losses, inverter looses, and others if applicable. Such losses cannot be reduced to zero. However, they can be minimized. In India very little literature is available on energy performance indicators hence a lot of documentation is required [17]-[21].

This paper is intended to help investors and project planners to estimate the true potential of PV system by providing cooling mechanism behind the PV module and also reduces the risk of PV cell damage by decreasing the temperature. An experiment is conducted in the laboratory to analyze the comparative performance of two modules of similar characteristics, a fan is connected behind one module (cooled module), which is powered by module itself. Analysis is done for energy consumed by the fan and gain in energy by cooling mechanism during different months of various seasons of the year. This mechanism is beneficial in actual size estimation in large power plants.

## 2. EXPERIMENTAL SETUP

An experiment is conducted in the solar energy laboratory in GLA University, Mathura, India (27.4924° N, 77.6737° E). The Experimental setup is consisting two polycrystalline type PV modules of 0.353 $m^2$ areas as shown in Figure 3. One of the PV module is cooled by connecting a DC fan below it and powered by itself while another is not cooled. Two modules can be connected in series or parallel for different experiment. Keeping in mind the continuous consumption of energy by the fan, a mechanism of adaptive cooling is chosen, this mechanism consists a temperature sensor and microcontroller. Halogen lights are used to get the variable artificial radiation, which is measured by solar power meter TM 207. It indicates the range in $W/m^2$ and in BTU. It is high precision equipment and its operating temperature ranges between 5°C to 40°C. The instrument operates with a 9 volt battery and below 2000 meter altitude. Its dimensions and weight are 143(l) x 74(w) x 34(h) mm, and 250g., respectively. A prototype of a mini solar power plant kit has been used to measure the temperature, output voltage and current. This kit has two PV modules of same power rating which can be adjusted at desired latitude. The output of the two modules can be measured individually or in series/parallel. AC /DC loads are available to conduct an experiment. Artificial lamps are used for regulated irradiation; a digital anemometer AVM 06 is used to measure the speed of the wind. It has large screen LCD, backlight, auto power off and standard accessories.

**Fig. 2. Experimental setup.**

## 3. METHODOLOGY

The experiment is performed for four and half hours weekly with artificial irradiation in the month of March, May, September and December by keeping one module cooled while another not cooled. Monthly average values are taken to analyze the energy. In experiment, radiation and wind speed are two artificial parameters and controllable while ambient temperature is natural parameter. First of all equal amount of irradiation (G) falls on both modules, which is varied from 50 $W/m^2$ to 500$W/m^2$ in step of 50, at the same instant $T_a$, $T_{mb}$, $V_{oc}$ and $I_{sc}$ of individual PV modules are measured by mini solar power plant kit. After some time, the radiation is increased and measuring steps are repeated, this time $T_{mb}$ of not cooled module is obtained higher than the $T_{mb}$ of cooled module. The concept behind cooling is that when $T_{mb}$ is more than $T_a$, it is sensed by temperature sensor and signal goes to micro controller which makes switch ON and the fan starts cooling in order to bring down the $T_{mb}$. As soon as the $T_{mb}$ becomes closer to or equal to $T_a$, microcontroller turns OFF the switch. Fan speed is also measured to observe its effect on solar cell temperature and thermal energy if collected. For not cooled PV module $T_{mb}$ is theoretically calculated based on approaches given by various researchers and compared with the measured values, while for cooled module $T_{mb}$ is theoretically calculated including wind effect and compared with measured values by temperature sensing device. To observe the effect of wind speed, module temperature is calculated by different approaches and measured also. Mathematical expressions for these approaches are

$$Tmb = Ta + (TNOCT - TaNOCT) * I/INOCT \quad (1)$$

Although this expression accurately determines the module temperature but it neglects the wind effect. In addition to the irradiance, temperature the wind effect is calculated as:

$$Tmb = Ta + I/INOCT\ (TNOCT - TaNOCT).HwNOCT/Hw.[1 - \eta stc/(\tau.\alpha)(1 - \beta stc.Tstc)] \quad (2)$$

Above two equations are used to calculate theoretical $T_{mb}$ of not cooled module and cooled module. Hence temperature dependent electrical efficiency of both modules can be calculated by:

$$\eta el = \eta stc[1 - \beta stc(Tmb - Ta)] \quad (3)$$

Now the measured value of $T_{mb}$ is used to calculate the actual electrical efficiency by Equation 3.

Electrical efficiency of both modules is given by;

$$\eta = \sum_{j=1}^{n} Pj / A \sum_{j=1}^{n} Ij \quad (4)$$

The PR can be calculated by:

$$PR = \frac{Actual\ KW□}{Expected\ Kw□} \quad (5)$$

Energy gain = Energy generated by cooled module - Energy generated by not cooled module.

Net Energy gain= Energy gain – Energy consumed by fan.

Theoretical and experimental results are compared by calculating, correlation coefficient (r) and root mean square percent deviation (e).

$$r = \frac{N(\sum Xi \times Yi) - (\sum Xi)(\sum Yi)}{\sqrt{N\sum X_i^2 - (\sum X_i)^2}} \frac{1}{\sqrt{N\sum Y_i^2 - (\sum Y_i)^2}} \quad (6)$$

$$e = \sqrt{\frac{(e_i)^2}{N}} \quad \text{Where} \quad e_i = [\frac{Xi - Yi}{Xi}] \times 100 \quad (7)$$

A DC fan of 3W power is used for cooling which is powered by cooled PV module. The energy consumed by the fan is calculated from average ON time in various months. The fan remains ON for more time during summer month while it is very less in winter. Various parameters of a 40W, polycrystalline photovoltaic module are given in Table 1 at STC (G = 1000w/m$^2$, T = 25°C, AM = 1.5). The tilt angle of modules is fixed to local latitude measured by angle finder.

**Table 1: Specification of PV module and setup.**

| Serial No. | Parameter | Value |
|---|---|---|
| 1 | $V_{oc}$ | 22.32 V |
| 2 | $I_{sc}$ | 2.24 A |
| 3 | $V_m$ | 18.1 V |
| 4 | $I_m$ | 2.21 A |
| 5 | $P_m$ | 40 W |
| 6 | NOCT | 47°C |
| 7 | Operating Range | -20°C to 90°C |
| 8 | βstc | -0.43%/°C |
| 9 | Fan rating | 3W |
| 10 | $INOCT$ | 800w/m$^2$ |
| 11 | $TaNOCT$ | 20°C |
| 12 | $\tau.\alpha$ | 0.9 |
| 13 | $\eta stc$ | 11.3% |
| 15 | Ws | 2 m/s |
| 16 | Module Area | 0.353m$^2$ |

## 4. RESULTS AND DISCUSSION

Hourly variation of electrical energy (theoretical and experimental) for not cooled and cooled PV module in the month of March have been shown in Figures 3(a) and (b), respectively. Result for not cooled module show as module temperature increases, significant loss in electrical energy is observed. For not cooled module, experimental energy is 101.29Wh, which is 2.88%. Less than theoretical energy and thermal losses are 7.65%, while for cooled module experimental energy is 108.82Wh., which is 2.85% more than theoretical energy and thermal losses are 1%. It is interesting to note down that this is due to forced cooling of PV module by DC fan. The correlation coefficient and root mean square percentage deviation between theoretical and experimental results are 0.998, 2.59 and 0.999, 2.50 for not cooled and cooled module, respectively.

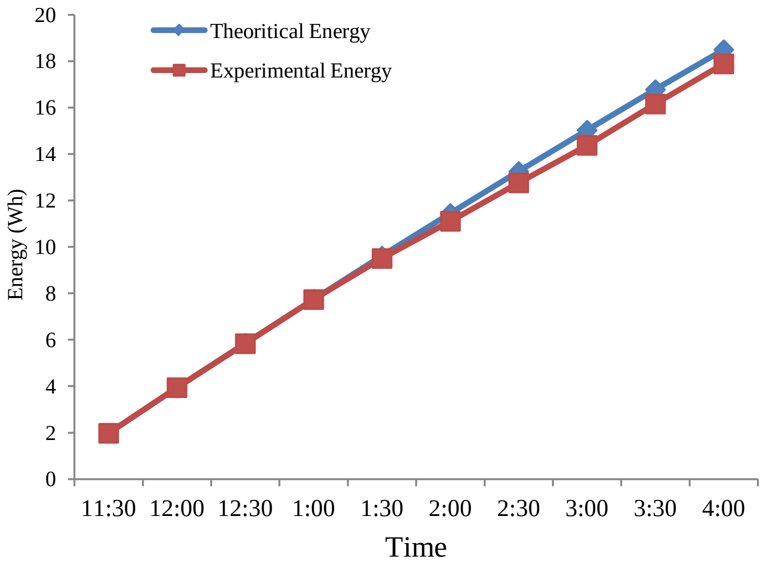


**Fig. 3(a). Hourly variation in theoretical and experimental energy in the month of March for not cooled module. r = 0.998, e = 2.59.**

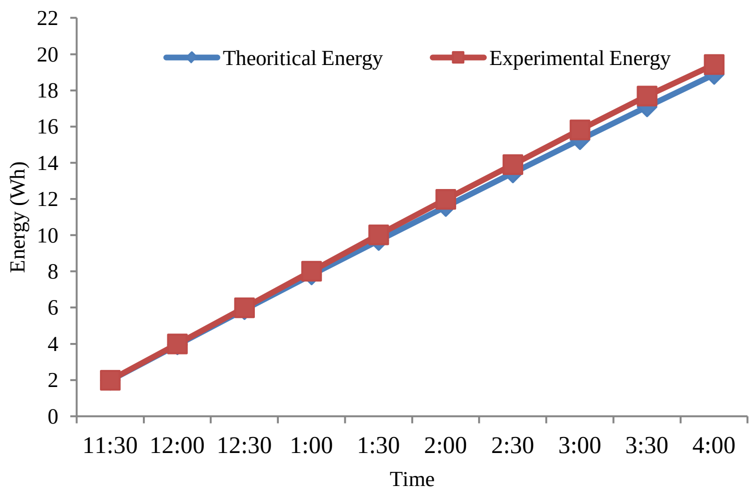


**Fig. 3(b). Hourly variation in theoretical and experimental energy in the month of March for cooled module. r = 0.999, e =2.50.**

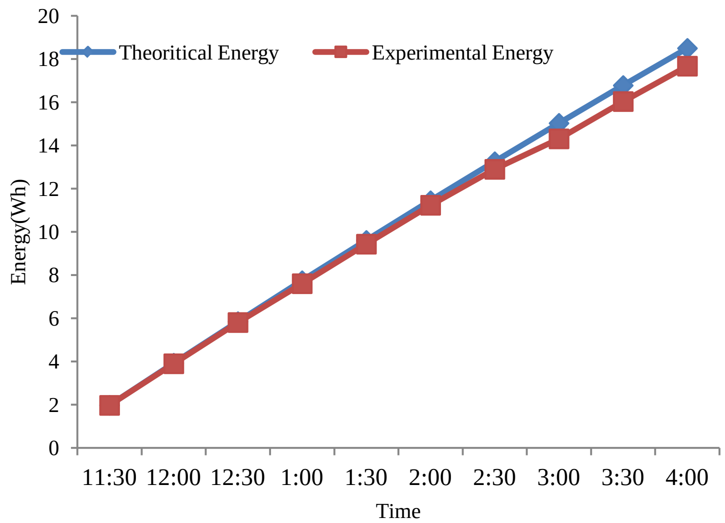


**Fig. 4(a). Hourly variation in theoretical and experimental energy in the month of May for not cooled module. r = 0.997, e = 2.83.**

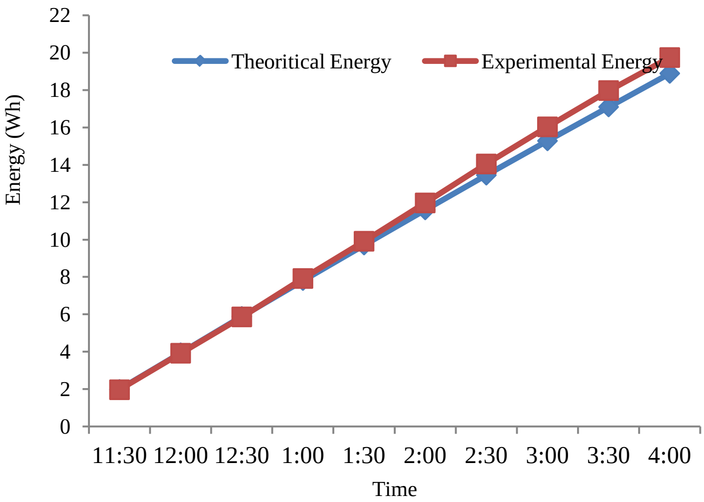


**Fig. 4(b). Hourly variation in theoretical and experimental energy in the month of May for cooled module. r = 0.998, e = 3.28.**

In the month of May, which is very hot and thermal, losses are maximum as shown in Figures 4(a) and 4(b), the not-cooled module has experimental energy of 100.88 Wh which is 3.84% less than theoretical estimated energy due to 8 % thermal losses. Here it is important to observe the effect of cooling mechanism, which shows that experimental energy is 109 Wh, 3.8% more than theoretical energy with reduced thermal losses about 0.08%. The correlation coefficient and root mean square percentage deviation between theoretical and experimental results are 0.997, 2.83 and 0.998, 3.28 for not cooled and cooled module, respectively

In the Indian climate, September is the last month of rainy season, due to rain temperature comes down and thermal losses reduced little bit naturally, however significant losses are there as shown in Figures 5(a) and 5(b). Experimental energy is 102.39 Wh which is 2.82% less than estimated energy with thermal losses 7.6%. On the other hand the module with cooling mechanism produces 109 Wh energy practically which is 3.8% more than theoretical energy. The correlation coefficient and root mean square percentage deviation between theoretical and experimental results are 0.997, 2.73 and 0.999, 2.95 for not cooled and cooled module, respectively.

Figures 6(a) and 6(b) shows the variation in theoretical energy and experimental energy in the month of December, which is the last and coldest month of the year in India. During this thermal losses are minimum *i.e.* 7% and experimental energy is 2.8% less than theoretical energy, while for cooled module the experimental energy is 108.83 Wh, 2.8% more than theoretical energy. The correlation coefficient and root mean square percentage deviation between theoretical and experimental results are 0.998, 2.73 and 0.999, 2.78 for not cooled and cooled module. Thermal losses degrades maximum, the performance of the photovoltaic system as we have seen that during the year these losses are always more than 5%. For not cooled module a significant amount of energy is lost in the form of heat which can be recovered and thermal losses are reduced below 5% by proposed adaptive cooling mechanism in the cooled module.

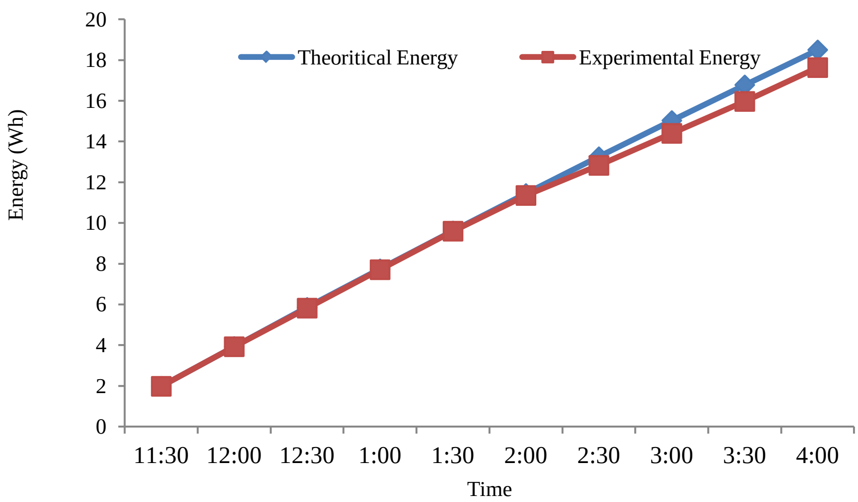


**Fig. 5(a). Hourly variation in theoretical and experimental energy in the month of September for not cooled module. r = 0.997, e = 2.73.**

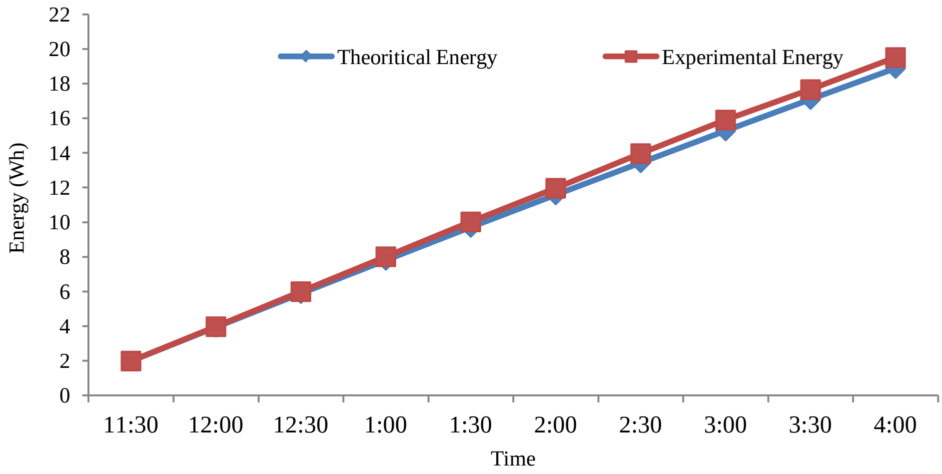


**Fig. 5(b). Hourly variation in theoretical and experimental energy in the month of September for cooled module. r = 0.999, e = 2.95.**

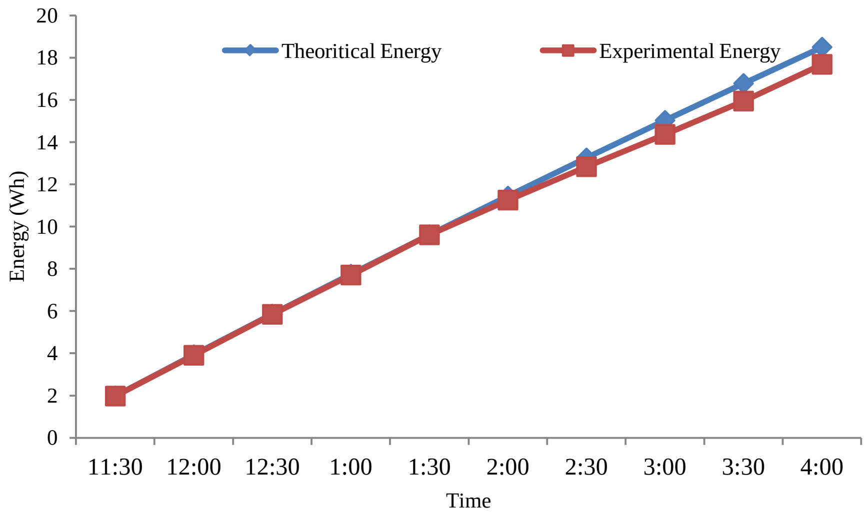


**Fig. 6(a). Hourly variation in theoretical and experimental energy in the month of December for not cooled module. r = 0.998, e = 2.73.**

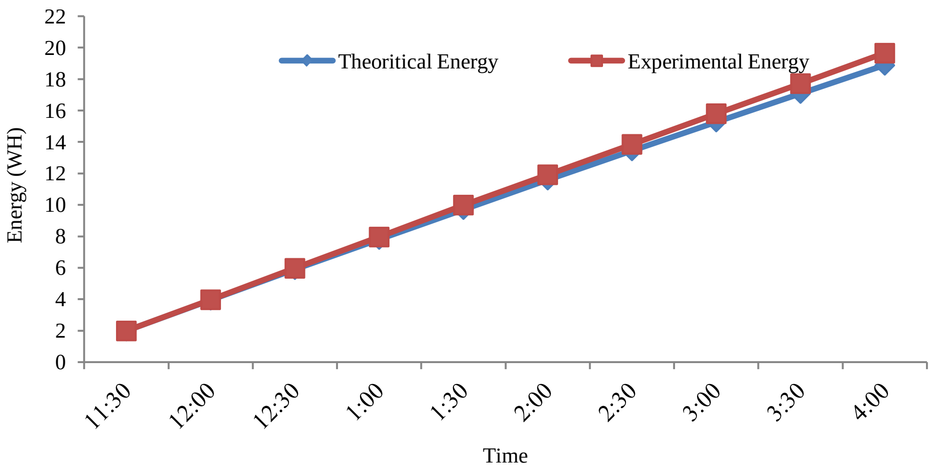


**Fig. 6(b). Hourly variation in theoretical and experimental energy in the month of December for cooled module. r = 0.999, e = 2.78**

It is observed that for not cooled module we always estimate more energy than actual energy delivered by module and thermal losses also more than 5% indicating significant loss in energy. While for cooled module estimated energy is less than actual delivered and thermal losses are also less than 5%.

In Figure 7, the bar diagram is used to show the monthly average variation in measured energy of not cooled and cooled module. The average energy gain is 6.93%, 9.0%, 7.92% and 6.93%, respectively in March, May, September and December and net energy gain in these months is 7.69%. The correlation coefficient and root mean square percentage deviation between theoretical and experimental results are 0.998, 2.73 and 0.999, 2.78 for not cooled and cooled module, respectively.

Since the fan used for cooling is powered by the cooled module so it is more important to analyze the energy consumed by fan and final gain or loss. To save the energy consumption by the fan, adaptive mechanism for cooling is used *i.e.* average ON time is maximum in the month of May because of high module temperature and minimum in the month of December. Hence in the month of May, 20% more energy consumed by the fan than the gain, while in the month of December energy gain is 80.6% more than the energy consumed by the fan. This energy gain and energy consumed by the fan is shown in Figure 8.

Performance ratio is an indicator for the performance of the system and maintenance, for a standalone systems PR value ranges 0.6 to 0.9. For hot zones thermal losses during summer can degrade performance of system as shown in Figure 9 PR value range is 0.57 to 0.58 for not cooled module while for cooled module it is improved to 0.67.

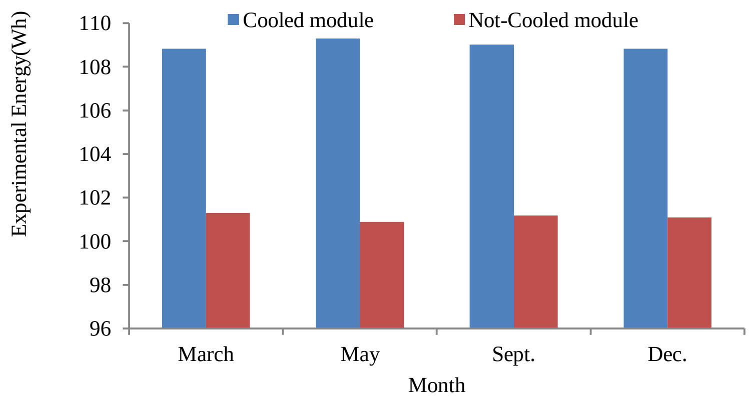


**Fig. 7. Difference in experimental energy in various months for not cooled and cooled module.**

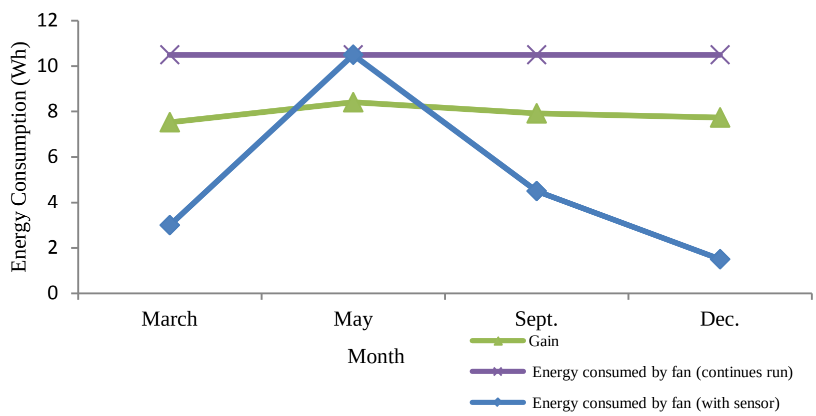


**Fig. 8. Average energy consumed by fan and gain in various months.**

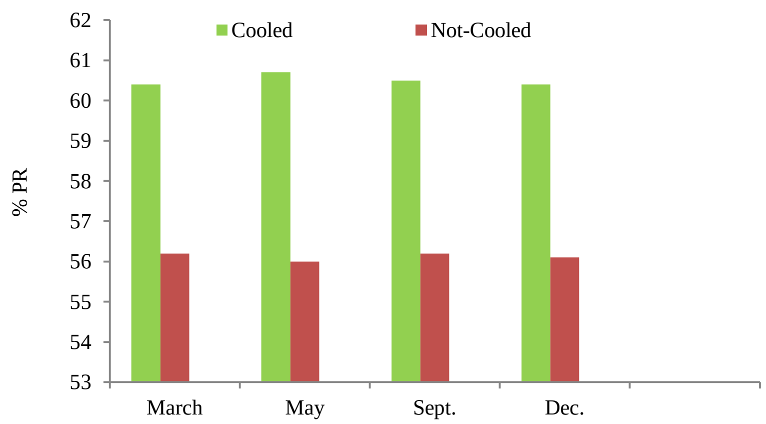


**Fig. 9. Performance ratio variation in various months for not cooled and cooled module.**

## 5. CONCLUSION

Ambient temperature is an important natural parameter for electrical efficiency and thermal losses, the wind can play a role of performance booster by reducing module temperature. At windy locations, the average wind speed must be considered before estimating the performance and PV system size that will reduce the cost and payback period. Module technology of high electrical efficiency can be suitable options for average high temperature and good windy locations in comparison to less efficient module technology having low power temperature coefficient. Experimental result show that even artificial cooling mechanism is beneficial in terms of energy gain.

In cold regions, which are more suitable for BIPV systems because of light electrical load, the BIPV system can have the mechanism of forced cooling and due to this generated thermal energy can be utilized for space heating, swimming pool, bathroom hand drawer *etc*. Thus utilizing both types of energy system efficiency is improved. Generally, due to temperature de-rating it becomes difficult to estimate the actual size of inverter, because of variation in DC input side for a system without storage. This mechanism provides less variation in output voltage hence inverter size can be estimated near true value.

## NOMENCLATURE

| | |
|---|---|
| $V_m$ | Maximum voltage of module |
| STC | Standard Test Conditions |
| $I_m$ | Maximum current of module |
| AM | Air Mass Ratio |
| $P_m$ | Maximum power of module |
| PV | Photovoltaic |
| βstc | Temperature coefficient of power |
| I | Irradiation |
| NOCT | Nominal operating cell temperature |
| Ta | Ambient temperature |
| Tmb | Module back side temperature |
| $W_s$ | Wind speed |
| $V_{oc}$ | Open circuit voltage of module |
| $I_{sc}$ | Short circuit current of module |
| *Hw* | wind conviction coefficient |
| $\tau.\alpha$ | Transmittivity and absorptivity product |
| CUF | Capacity utilization factor |
| PR | Performance ratio |

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