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Influence of Artificial and Natural Cooling on Performance Parameters of a Solar PV System: A Case Study

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ABSTRACT Contribution of renewable energy in overall power generation is eagerly welcomed by all nations to mitigate the carbon emission. Solar Photovoltaic based power generation is a rapid progressing technology. Although drop in efficiency due to rise in Photovoltaic (PV) module temperature, is yet a significant loss which is highly site dependent. The most common approach does not include natural wind cooling effect while others are not commonly applied to estimate the module temperature during performance evaluation, which leads to error in forecasting, large area requirement for same power generation, more money investment as well as large payback period. Temperature and natural wind cooling highly affects the PV module performance, thus it becomes important to study and evaluate the performance of PV module in local conditions. In this work an attempt is made to observe the effect of natural cooling on PV module performance. The case study includes the performance ratio for simulation and experimental conditions considering artificial cooling. On another hand performance ratio is also evaluated for simulation and experimental conditions considering natural cooling. This study evaluates various errors, invested cost, annual units, annual recovery, payback time and return on investment to emphasize on local site dependent performance. An improved performance for various performance parameters is observed considering the natural cooling effect.

INDEX TERMS Artificial cooling, energy efficiency, module backside temperature, natural cooling, performance ratio.

ABBREVIATION

PV	Photovoltaic
ANN	Artificial Neural Network
NN	Neural Network
NOCT	Nominal Operating Cell Temperature
MSE	Mean Square Error
SDE	Standard Deviation Error
MBE	Mean Biased Error
RMSE	Root Mean Square Error
PR	Performance Ratio

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LIST OF SYMBOLS

η_{stc}	Module efficiency in standard test condition
η_{td}	Temperature dependent electrical efficiency
P_o	Output electrical power
P_i	Input solar power
A	Area of PV module
I	Irradiance
T_m	PV module back side temperature
T_a	Ambient temperature
V_{oc}	Open circuit voltage
I_{sc}	Short circuit current
V_w	Wind Speed
U_{PV}, U_o, U_1	Constants

T_{NOCT}	Nominal operating cell tempreature
I_{NOCT}	Radiation at NOCT
τ_{α}	Transmittivity and absorptivity product
E	Annual average energy
β	Power temperature coefficient
H_w	Wind convection coefficient
F	Total amount to be paid
i	Annual interest rate
P	Loan amount
n	Total number of years

I. INTRODUCTION

In the present scenario of grid connected photovoltaic (PV), trend of installation of large rating PV system is in full swing. Countries over the globe are focusing to reduce the dependency on fossil fuels and supporting the clean development mechanism. India is also one of them which is actually targeting to generate 175 GW from renewable sources by 2022. This will be the 33% of total demand at that time and most important is that out of 175 GW, 100 GW will be generated from PV systems. Luckily India has potential, lying on tropic of cancer but this potential is identified and emphasized in last 4 to 5 years. The international solar alliance is launched in 2015. According to the availability of solar radiation, target has been assigned to different states. Presently India is in top five countries in the electricity from alternating sources by generating approx 76 GW [1]. Significant contribution has seen in electricity generation from solar PV. Government has taken good initiatives especially for solar energy like solar roof top systems, solar based water pump, solar park etc [2], [3]. A comparative chart for progress in renewable energy is shown in figure 1.

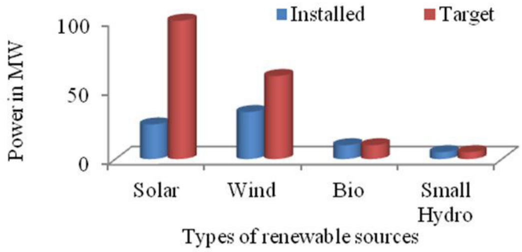

FIGURE 1. Progress in renewable energy.

Solar power plants are most sensitive to climate dependent parameters; hence project planners are always in ambiguous state before the installation. The PV modules can be selected for a roof top, isolated or grid connected applications, thus it will be beneficial to analyze the site dependent performance rather than generalized performance. In the country like India, climate conditions are drastically region and season dependent. These parameters are radiation, temperature and wind speed at any location. North and West zone of India are rich in solar radiation but suffers from temperature variation while Central and South zone is having good wind speed but suffers from land area problem due to lower latitude.

Therefore selection of module technology should be across all the climate dependent parameters for better performance is a challenge, researches show that crystalline module technology may be preferred for windy locations where temperature impact is less [4], [5].

The polycrystalline module technology is less efficient and less sensible to temperature variations hence it may be a good option for high temperature but rich in radiation zones. Local wind speed provides natural cooling for the module and brings down the module temperature which improves the performance [6]. The generalized approach to estimate the module temperature does not include the local wind speed although can play a significant role in determining the true performance [7]–[9]. It is also found that very high wind speed does not mean very high efficiency because temperature dependent losses can not reduced to zero they can only minimized. Few researchers proposed the approach of hybrid PV / Thermal system for performance improvement. They suggested collecting the thermal energy behind the module and utilizing this for low grade thermal applications. Thus co generation of energy improves the performance of the system [10]–[15]. Forecasting of solar irradiance variability, to predict the solar PV performance becomes important in order to ensure the stability of the power grid, not only stability forecasting is also helpful for project planners. The World Meteorological Organization provides detailed guidelines on measurement in addition to the instruments used.

Artificial Neural Network (ANN) is co domain of the Artificial Intelligence. It may have any structure like radial basis network, multi layer perceptron, support vector machine and hopefield.ANN basically perform two tasks Regression and Pattern recognition, both are useful. In regression, and input is mapped with output in non linear manner. During the training, weights of neural network are updated to compute the forecast. With the inclusion of different climate dependent parameters and hybrid models, forecast error is continuously reduced [16]–[20]. Although several researchers have enlightened us regarding the performance of solar PV system but since its performance is highly site dependent, therefore true potential of system can be analyzed at local level only [21], [22]. In order to obtain true performance an experimental approach is applied in laboratory as well as in outdoor conditions. Also the data is used to form the Neural Network in MATLAB using NN Tool for simulated performance as shown in table 1.

This paper presents the detailed experimental analysis of a solar PV system in outdoor conditions. In which the performance of PV system is compared in artificial and natural conditions. The rest of the paper is organized as, section II elaborates the simulation and experimental findings of a solar PV module under artificial cooling. Further, analogous experiment is performed in natural cooling on a roof mounted 50 kW system. Section III presents various steps followed in the experiment conduction, as well as details of the

TABLE 1. Specification of NN tool used.

Parameter	Narration
Network structure	Two layer
Number of Network input	Number of problem input
Number of Network output	Number of problem output
Transfer Function	Log-Sigmoid
Performance parameter	Mean square error
Training parameter	Levenberg-Marquardt backpropagation

TABLE 2. Specification of PV module and setup.

Parameter	Value
V_{oc}	22.32 V
I_{sc}	2.24 A
V_m	18.1 V
I_m	2.21 A
P_m	40 W
$NOCT$	47^oC
Temperature range	-20^oC to 90^oC
Power Temperature Coefficient	$-0.43\%/^oC$
Rating of fan	3 W
I_{NOCT}	800 W/m^2
T^a_{NOCT}	20^oC
$\tau.\alpha$	0.9
η_{stc}	11.3%
Wind Speed (W_s)	2 m/s
Module Surface Area	0.353 m^2

instruments used for the same is briefed. Section IV provides the findings of this case study, where as section V concludes the paper with the emphasis on inclusion of natural wind cooling influence during the performance estimation.

II. INDOOR AND OUTDOOR EXPERIMENT

This experiment is conducted in the solar energy laboratory in the department of electrical engineering situated in GLA University, Mathura, India in northern hemisphere (27.4924° N and 77.6737° E). The experimental setup is consisting of two polycrystalline type electrically and mechanically same PV modules of 0.353 m^2 areas as shown in figure 2. The output of two modules can be assessed either individually or in series/parallel. AC /DC loads are available to conduct the experiment. Artificial lamps are used to regulate the irradiation with a digital anemometer AVM 06 to measure the speed of the wind. When module temperature rises above reference temperature, fan becomes ON otherwise OFF. This mechanism saves the power. Solar power kit also contains inverter mechanism through which DC/AC conversion is possible thus this kit mimic the DC/AC solar PV system. For measuring the temperature, a sensor is also available. Solar power meter TM- 207 is used. It indicates the range in W/m^2 and in BTU also. It is high precision equipment and its operating temperature ranges between 50^oC to 400^oC. Specifications for Used PV module are shown in table 2.

For outdoor experiment, another module which is used in real time system of 50 kW installed in university campus, main block, chosen to observe the actual performance as shown in figure 3. The details of this polycrystalline module are given in table 3.

FIGURE 2. Laboratory experimental setup.

TABLE 3. Specification of PV module used in natural condition.

Parameter	Value
V_{oc}	45.35 V
I_{sc}	8.93 A
V_m	35.87 V
I_m	8.36 A
P_m	300 W
$NOCT$	47^oC
Temperature range	-20^oC to 90^oC
Power Temperature Coefficient	$-0.43\%/^oC$
I_{NOCT}	800 W/m^2
T^a_{NOCT}	20^oC
$\tau.\alpha$	0.9
η_{stc}	14.8%
Wind Speed (W_s)	2 m/s
Module Surface Area	2007×991 m^2

III. METHODOLOGY & INSTRUMENTS USED

To perform the experiment in laboratory, following steps are executed

1) First of all halogen irradiation comes on module, this radiation is ranging from 50 W/m^2 to 500 W/m^2 in incremental step of 50, instantaneously Ta, Tm, Voc and Isc of PV module are measured by experimental setup. With the progress of time, new values of radiation are used and measuring steps are repeated. The theoretical value of Tmb is computed as (Standard Approach)
$$T_m = T_a + \frac{NOCT - 20}{I_{NOCT}} I$$
2) For cooling purpose, a DC fan 3 W, 12 V, 0.25 A is connected on the back side of module.
3) In order to decide the wind speed, fan is run on different speeds and the effect on the module temperature as well as on efficiency is observed.
4) Percentage drop in electrical efficiency is noted with Percentage thermal losses. Also the fan speed is noted at which thermal losses becomes constant.
5) In above sequence to consider the effect of summer, winter, spring and rainy season, experiment is

FIGURE 3. String of PV module of a 50 kW system.

performed in different months of the year like December, March, May and September. Ten samples on every Sunday of each month are measured and their average values are used for analysis.

6) The Energy is computed with help of measured and theoretical module temperature i.e. theoretical energy from various approaches available in literature and experimental energy is obtained.
$E = \eta_{td} IAt$
Where,
$\eta_{td} = \eta_{stc}[1 - \beta(T_m - T_a)]$
η_{td} is temperature dependent electrical efficiency.
7) With the help of obtained energy, the feed forward neural network is formed. In which 70 % data is used to train the neural network, 10% for validation and 20 % for test purpose, Mean square error is the measuring performance parameter. Thus output of neural network is the energy, known as simulated energy.
8) Mean Square Error MSE $= [\frac{1}{N}\sum_{k=1}^{N} e_k^2]$
9) Standard Deviation Error
SDE $= [\frac{1}{N-1}\sum_{k=1}^{N}(e_k - \bar{e}_k)^2]^{\frac{1}{2}}$
10) Mean Biased Error, MBE $= [\frac{1}{N}\sum_{k=1}^{N} e_k]$
11) Error $e_k = Y_{Simulated}^k - Y_{theoritical}^k$
12) Annual Energy units are calculated using
$Annual \quad Energy = \sum_{i=1}^{12}\sum_{j=1}^{180} E_{ij}$
$Annual \quad units = \frac{\sum_{i=1}^{12}\sum_{j=1}^{180} E_{ij}}{1000}$
13) Performance Ratio, PR $= \frac{kWh_{actual}}{kWh_{stc}}$

The important highlights are

- The various kinds of errors are evaluated with respect to the simulated performance, the standard (conventional, which does not include wind effect) approach has maximum errors and does not motivate for soft computing based forecasting.
- Since performance by standard approach is inferior in comparison to other approaches hence project planners do not feel enthusiastic.
- The performance evaluated by experimental approach having least errors with respect to simulated performance hence emphasize on forecasting with improved performance parameters. Here project planners do not hesitate.

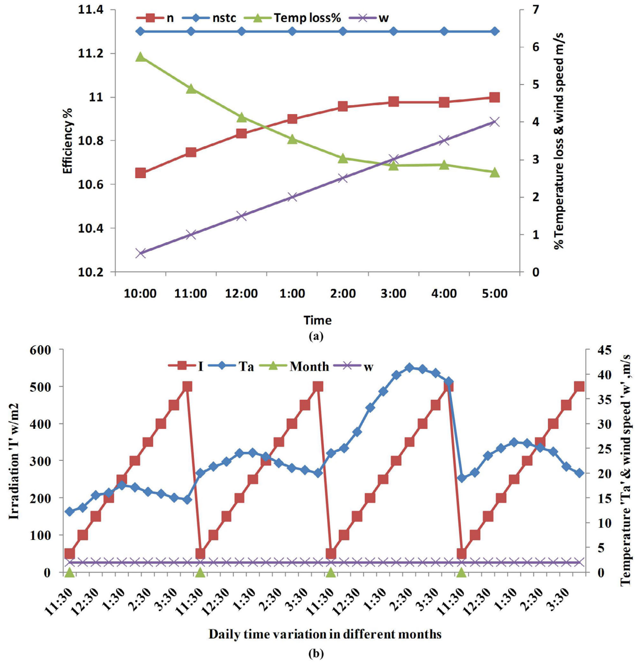

FIGURE 4. (a) Hourly variation showing electrical efficiency, wind speed and thermal losses of cooled module at radiation 500 W/m^2, (b) Hourly variation in radiation, temperature and wind speed for various months.

From the existing literature the PV module temperature including wind effect can be estimated by different approaches as given below,

This was given by E. Skoplaki, where Hw is heat transfer coefficient, can be given by

$$T_m = T_a + \frac{I}{I_{NOCT}}(T_{NOCT} - T_{aNOCT})\hat{A} \tag{1}$$

where $\hat{A}$ and H_w are defined in Eq. (2) and (3) respectively,

$$\hat{A} = \frac{H_{wNOCT}}{H_w}[1 - \frac{\eta_{stc}}{\tau\alpha}(1 - \beta T_{stc})] \tag{2}$$

$$H_w = a + bV_w \tag{3}$$

Koehl used another approach

$$T_m = T_a + \frac{I}{U_o + U_1 V_w} \tag{4}$$

Mattei calculated module temperature by

$$T_m = \frac{U_{pv}T_a + I[\alpha\tau - \eta_{stc}(1 - \beta T_{stc})]}{U_{pv} + \beta\eta_{stc} I} \tag{5}$$

Kurtz neglected the material type and told that

$$T_m = T_a + Ie^{-3.473 - 0.0594 v_w} \tag{6}$$

IV. RESULT AND DISCUSSION

In order to choose the appropriate speed of the cooling fan, an experiment is conducted, in which for a constant radiation, fan speed is varied from 1 m/s to 5 m/s. It is observed that

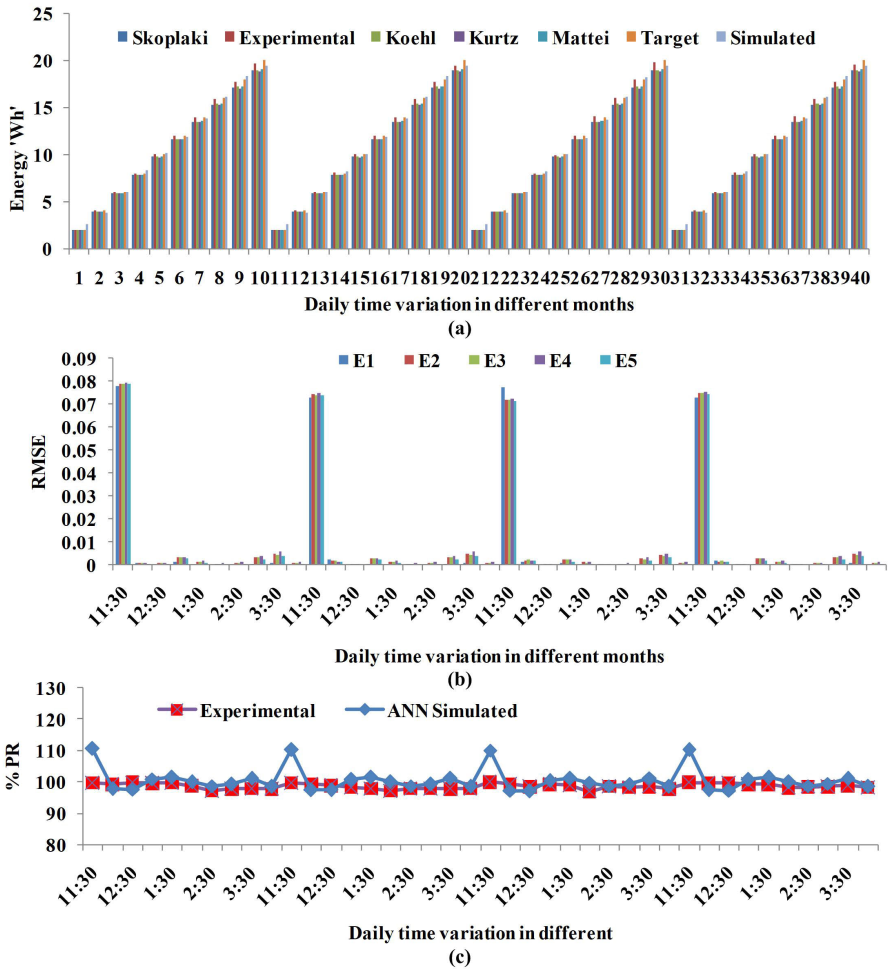

FIGURE 5. **(a) Daily variation in energy of cooled module during various months, (b) Daily variations in root mean square error in energy of cooled module during various months, and (c) Instantaneous performance ratio obtained by different methods considering wind effect.**

suitable fan speed is the function of ambient temperature and radiation. In various cases performed, suitable fan speed is 2 m/s which occur at 500 W/m^2 because above this speed the efficiency of the module becomes constant as shown in figure 4. Also thermal losses are reduced but cannot brought up to zero.

The artificial irradiance obtained from halogen lights are controlled manually and varied from. 50 W/m^2 to 500 W/m^2 measured with the help of solar power meter. Due to the experimental setup limitations, radiation is not increased over 500 W/m^2. Average ambient temperature values are calculated from the data and considered for different months, first ten values are for December, and next ten are for March. Similarly next values are for May and September month with same interval. In the month of March and September moderate temperature is found while it is high in May and low in December. Based on the module temperature reduction during trial, fan speed is chosen 2 m/s as shown in figure 4.

Annual average of target energy is 438.77 Wh, experimental energy 435.96 Wh, simulated energy 439.37 Wh, theoritical energy from various methods is Skoplaki 422.41Wh, Koehl 423.27Wh, Kurtz 420.58Wh, Mattei 424.11Wh. Simulated energy is 0.61% more than experimental energy In figure 5 it is important to observe that in every sample of various months the experimental energy is more than the theoretical energy from various approaches and closer to target energy and simulation energy too.

In figure 5, E1, E2,E3, E4 and E5 are root mean square error between simulated, experimental, simulated, skoplaki calculated, simulated, Koehl calculated, simulated, Kurtz calculated and simulated, Mattie calculated respectively. Total E1 is found 8.91 % because neural network is unable to predict accurate energy during morning time while accurately determines at higher temperatures. Total E2, E3, E4 and E5 are 9.46%, 9.39%, 9.63% and 9.33% respectively.

Site dependent performance ratio (PR) forecasted by ANN is very close to experimental PR. Observation of both PR graphs in figure 5, it seen that ANN simulated PR almost follow the experimental PR at all instant except that during morning session in each month of the year. Annual average

TABLE 4. Specification of instruments used.

Instrument name	Description
Solar Power Meter	Solar power meter model number TM -207 has been used to measure the radiation. It indicates the range in W/m^2 and in BTU also. It is high precision equipment and its operating temperature ranges between 50^oC to 400^oC. The instrument operates with a 9 volt battery and below 2000 meter altitude. Its dimensions and weight are 143(l) × 74(w) × 34(h) mm, and 250 g respectively.
Angle Finder	The angle finder having magnetic base which is easy to use. It measures angles accurately and quickly from 0- 90 degrees in any quadrant. It has accuracy within ½ of 10. By this instrument, latitude can be measured.
Anemometer	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
Mini Solar Power Measurement kit	A prototype of mini solar power plant kit has been used to measure the temperature, output voltage and current. Although the setup can also be used for measuring the shading effects, maximum power point finding, DC to AC conversion and performance analysis of solar Photovoltaic systems.

of simulated PR is 98.6% while experimental PR 98.2%. Here with the laboratory experiment various important observations are drawn, first, the module temperature is brought down by providing cooling mechanism. Although one cannot completely overcome from thermal losses. Second, these thermal losses cannot be completely reduced, also these losses are radiation and temperature dependent hence appropriate speed of the fan will be site dependent. Third, the PV module performs better event in low radiation condition provided that its temperature should be reduced. Fourth, Among various theoretical approaches available. Mattie approach is better suitable because energy calculated from this approach is closer to experimental energy. Fifth, overall performance and health of the system is also forecasted by ANN techniques because simulated values of energy are not far from experimental values.

Taking a lead from all these laboratory experiments, when the experiment is conducted in real climate condition on a 50 KWp grid connected PV system. Here average values of all three natural parameters are considered for experimental performance, which are taken from Mateonorm. In figure 6 monthly mean values of total radiation G, atmospheric temperature Ta and speed of wind Vs are plotted on both vertical axes. The minimum and maximum mean values of radiation ranges from 300 W/m^2 to 800 W/m^2 and temperature is 14 ^oC to 32 ^oC in the month of December and May respectively. The wind variation is recorded from 1m/s to 3 m/s with annual mean 2 m/s. As usual expected that drop in radiation is seen in the month of July and August due to cloudy conditions while temperature does not. The annual average energy variation is shown in figure 6. The key point is to consider that actual energy which is measured from experimental procedure is always more than the energy if module temperature is estimated by standard approach i.e. more drop in power is estimated due to over estimation of module temperature. Although the gain in average energy seems less in the month of December, January and February but significant gain is observed in the month of May and June. This correlates that the regions of high temperature are important to analyze this approach. Overall energy is more than the estimated, hence performance is

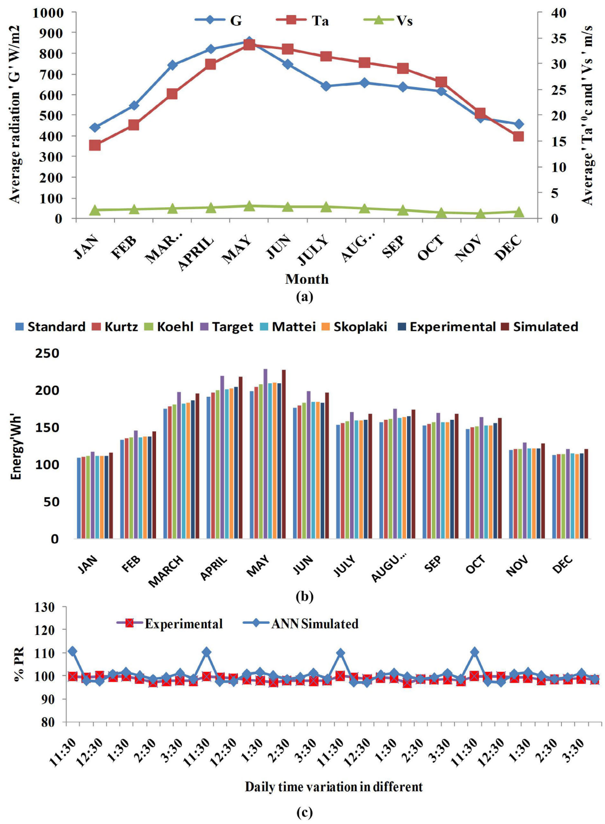

FIGURE 6. (a) Monthly average variations in radiation, ambient temperature and wind speed, (b) Monthly variations in average energy estimated from different methods, and (c) Monthly performance ratio obtained by different methods considering wind effect.

underestimated which can be easily avoided by correct estimation of temperature.

Site dependent performance ratio (PR) forecasted by ANN is not too close to experimental PR as it was in indoor condition. Observation of both PR graphs in figure 6, it is seen that monthly average ANN simulated PR is always more than the experimental PR during the complete year. Annual average of ANN simulated PR is 98.03% while experimental PR 95.9%. The reason of anomaly in two PR values may be because of modules which were considered for testing in indoor and

TABLE 5. Various types of errors in energy obtained from different methods.

Methods	MSE	RMSE	MBE	SDE
Standard	306.5	17.5	16.3	6.5
Kurtz	203.9	14.3	13.3	5.1
Koehl	149.1	12.2	11.5	4.1
Mattei	117	10.8	10.1	3.7
Skloplaki	117.2	10.8	10.3	3.4
Experimental	98.4	9.9	9.2	3.8

outdoor are different also in laboratory for radiation, artificial halogen lights are used. Here it is also important to note that two different data collecting source like temperature sensor in laboratory and temperature data logger in outdoor conditions are used.

In table 4 it is interesting to note that MSE, RMSE, MBE and SDE are lower for experimental method and maximum for standard method because here wind effect is neglected hence true module temperature is estimated in remaining methods module temperature is evaluated considering wind effect which clearly indicates that errors between simulated energy and theoretical energy is decreasing. Simulated values of energy are giving closer look about the true performance in real climate conditions. Therefore results support for the inclusion of wind effect during evaluation of the module temperature. Thus, a project planner can obtain near true performance and better estimate the cost invested. All the errors are calculated with respect to simulated values. Also from now onwards only one theoretical approach (Standard) will be considered with experimental and simulated approaches because it is widely used.

Annual energy units from various approaches are calculated for a 50 kWp system which is installed in the university campus by using the module which is considered for experiment. Experimentally the system gives 372048 units while theoretical calculation gives 355544 units and simulated units are 393466. If per unit cost is 3 Rs then annual recovery is also shown in figure 7. Annual recovery from experimental approach is more than theoretical.

In the case study carried out for 50 kWp DC/AC PV power system is installed with capital cost of Rs. 1500000/ and 180 modules are used to generate required amount of power. Here cost of solar electricity based on market is considered Rs 30/watt. If the investor took loan on 12% annual simple interest rate and agrees to pay in 10 years, then he has to pay F amount as given below

$$F = P(1+i)^n$$

Where P is basic amount

i is interest rate

n is total time.

Total amount to paid by investor is Rs. 4658772/.

Now take a look on the life cycle of the PV system. Investors will be interested on the payback period and return on investment.

Payback period = Invested Cost / Annual Recovery

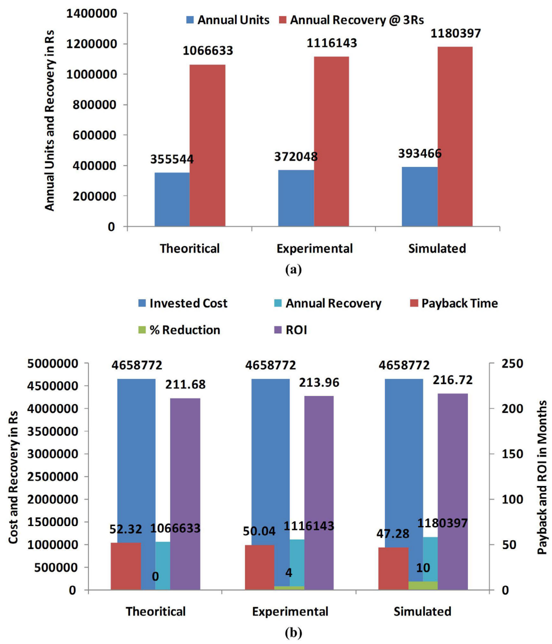

FIGURE 7. (a) Annual energy units and return from various approaches, (b) Comparative chart for different parameters from various approaches.

Return on Investment period = Assumed Life (22 Years) – Payback Period Reduction in Payback Period w.r. t. theoretical

Comparative results, taking as theoretical values reference are shown in figure 7, which clearly indicate that performance parameters evaluated from soft computing approach can give closer idea to the investors. There is 4% and 10% reduction in payback period from experimental approach and soft computing based approach respectively in comparison to theoretical approach for considered location.

V. CONCLUSION

The goal of the study was to analyze the influence of cooling on the performance considering various factors such as, errors, invested cost, annual units, annual recovery, pay back time and return on investment. The case study evaluates a 50 kW PV system, the performance ratio considering artificial cooling for simulation and experimental conditions were 98.6% and 98.2% respectively. While, the performance ratio evaluated considering natural cooling for simulation and experimental conditions were 98.03% and 95.9% respectively. The significant findings of the study are highlighted below,

1) Natural wind speed brings the module temperature down hence its efficiency improves.
2) The optimum wind speed depends on the local atmospheric temperature and radiation.
3) PV module performs well even in lower radiation region if good speed natural wind is present.
4) Collected thermal energy is co energy which also improves efficiency.
5) Module performance can be forecasted nearly true values if its module temperature is estimated considering local climate conditions.
6) A project planner can have better idea about various performance parameters.
7) Actual overall performance strictly depends on local site parameters. Therefore models may be developed for micro level performance rather than generalized model.

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