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Thermal and Electrical Performance analysis of Rooftop Solar Photovoltaic Power Generator

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Abstract- The solar energy is the vital source of renewable energy used today and nearly eighty percentage of the energy is absorbed by the surroundings. The mathematical modeling of energy and exergy analysis with both the thermal and electrical quality of polycrystalline PV module has been entailed under different seasonal climatic circumstances of Bhubaneswar, Odisha, India. Different parameters like energy, converted power and exergy efficiencies have been estimated. The simulation results clarify that the efficiency of the above-mentioned parameters are changing with respect to the variation in the wind speed, temperature and solar insolations. The data validation has been performed by using artificial neural network. Ambient temperature, cell temperature, wind speed, solar radiation and time are used as input, and thermal and electrical efficiencies are the outputs in ANN structure. It has been evidently observed that the correlation factor and efficiency are higher in training process when compared to the testing process.

Keywords- Energy; Exergy; Solar radiation; Photovoltaic module; Wind speed; ANN;

1. Introduction

In near future, the renewable energy resources will completely replace the fossil fuels for electrical power generation due to pollution free, rich in potential and technological advancement [1, 2]. There are various types of renewable sources but the most significant and widely spreading is solar energy technology using photovoltaic (PV) cells [3-4]. The solar photovoltaic cells are semiconductor materials, which converts the solar radiations into useful electrical energy by using photoelectric effect. Depending upon the insulation used and the performance of solar cells, the energy payback period generally lies between 10 to 15 years [5], but it will be minimized, if the outcomes of solar photovoltaic cells can be increased. So, the optimal performance analyses of solar PV cells are very much necessary. The outcome of PV cells chiefly depends upon design constraints, operational strategy and weather condition of specified area [6]. The intensity of solar irradiances, ambient temperature, solar cell temperature, heat loss, area of PV panel (combination of cells), voltage available at open circuit condition, current at short circuit, voltage and current at maximum power also are the design parameters to be investigated in performance analysis. The energy and exergy analysis which are also the key factors are to be investigated. The amount of energy used and energy process efficiency are very much concerned to the energy analysis [7-8]. The energy efficiency is calculated by considering the ratio between the solar power output and the power actually supplied to the PV module. There are also some deficiencies in energy analysis. The conception regarding the energy is not sensitive to the presumed way of processing and does not differentiate the quality of energy.

Exergy analysis is an analytical technique which utilizes the law of conservation of energy (first law of thermodynamics) and law of non-conservation of entropy (second law of thermodynamics) by considering the losses related to the system [9-16]. The exergy analysis finds its progressive applications during the last decades mainly due to many benefits compared to energy analysis. Therefore, many numbers of input and output parameters are to be evaluated for the accomplishment of energy and exergy analysis. The exergy is the utmost valuable work achievable all through a process which puts the system to the equilibrium state considering environment as the heat reservoir. When the systems and surroundings reach equilibrium, the exergy is zero [17-19]. When there is proper selection of the sources and magnitude of irreversibility, the system's efficiency can be improved.

A lots of experiments has been conducted regarding the performance analysis of systems on different sectors like residential [20], commercial [21], industrial [22-24] and transportation sectors [25]. There are several sectors where the exergy analysis is implemented such as solar heating systems [26-27], water desalination using solar power [28-29], solar refrigeration and air conditioning [30], solar dryer [31] and solar power generation [32]. *K. Sudhakar et al.* [33] have conducted the energy and exergy analysis using the experimental data of 36 W solar photovoltaic modules. It is observed that the exergy efficiency is greatly affected by the PV module temperature. If the heat energy is separated from the surface of photovoltaic panel, the efficiency can be improved. Joshi et al. [34] also have studied the thermal and exergy efficiency of PV and PV-T systems. They have found that exergy efficiency of PVT systems (11.6–16%) is greater than the exergy efficiency of only PV system (8–14%) by using Petela's formula [35]. *S Dubey et al.* [36] have carried out the energy and exergy analysis of PV/T air collectors connected in series. The hourly variation of cell temperature varies inversely with the cell efficiency. Experimental results prove that the solar cell efficiency decreases by 1.6% when the cell temperature increases by 24.4^0C. Sahin et al. [37] also experimented on photovoltaic module for thermal analysis especially exergy efficiency based on the chemical strength of element. At different operating conditions, they provide the comparative analysis of energy, electrical and exergy efficiencies. *Bisquert et al.* [38] has discussed about the physical and chemical properties of solar photovoltaic energy conversion technology and proved that the open-circuit voltage of solar photovoltaic cell depends upon Carnot factor and also the statistical factors. However, *Landsberg and Markvart* [39] also investigated the Carnot factor theory of solar photovoltaic cells and established that the open-circuit voltage is the multiplication of band-gap energy and Carnot efficiency. *Ghoneim* [40] has presented the optimal values of sizing of PV module, orientation and thermal properties of solar energy driven water pumping system in Kuwait climatic condition by developing a computer simulation program. But *Skoplaki et al.* [41] has established a mathematical relation by studying the consequence of solar insolation, wind velocity and air temperature on the solar cell temperature and also overlooked free convection and radiation losses from PV module to the environment. However, *S. Armstrong et al.* [42] have examined the thermal properties of PV modules under variable environmental condition to estimate both the radiative and convective heat losses from the panel and also comparison analysis between the forecasted times constant with measured value under the three different wind speeds.

In the literatures [43–47], numerous investigators have studied the solar PV performances under different climate conditions. *Jiang et al,* [48] have proposed an assessment model for eight distinctive cities in China. Their researches have clearly noted the appropriateness of artificial neural network based assessment method over regression model for performance evaluation. *Leal et al,* [49] employed three statistical models and two artificial neural network models to estimate the UV solar radiations from daily global radiations. Both the statistical and ANN models have been observed to have good performance with MBE between 0.4 to 2% and RMSE lesser than 5%. For predicting the future data on solar radiations for seven different cities in Turkey a model based on ANN has been developed by *Koca et al,* [50]. The researchers or scientist could use the results to design high efficiency solar devices. *Kolagirou et al,* [51] have utilized the ANN technique for the assessment of results for large solar systems. ANN based methodology has been used to estimate the probable daily energy output for individual operating conditions. *Rai et al,* [52] have developed a simulation structure of ANN based maximum power point tracking (MPPT) controller. *Karamirad et al,* [53] used ANN for predicting the photovoltaic panel characteristics under balanced climate state of affairs. The results obtained from ANN have been compared with analytical four/five parameter structures of the PV module. *Ammar et al,* [54] recommended a PV/T control methodology on the basis of ANN to estimate the behavior of the module. For a measured radiation and ambient temperature, the optimal power operating point computes the optimum mass flow rate of the PV/T. *Mellit et al,* [55] formulated two ANNs methodology with the aid of cloudy and sunny days to assess the generated power of a 50Wp Si–polycrystalline photovoltaic modules. *Almonacid et al,* [56] formulated silicon crystalline PV modules by ANNs which could produce the voltage current curves for any amount of radiance and cell temperature of the PV module. *Yoro et al* [57] have incorporated the ANN based technique to highlight the significance of ANN inputs.

Sozen et al, [58] have calculated the efficiency of ANN based model with date, time, surface temperature etc, as the input to the system. Also, the parameters of the flat plate solar collector have been considered as the output from the system. The results clearly revealed that the maximum as well as minimum deviations are observed to be in the range of 2.5584 and 0.00197 respectively. The efficiency of solar cells has been found to be considerably enhanced for the last few years.

This research work mainly concentrates on thermal performance evaluation of the polycrystalline Silicon photovoltaic module on the basis of energetic and exergetic analysis for four seasons (summer, rainy, winter, autumn) of the year, under the climatic conditions of Bhubaneswar, Odisha. The mathematical model has been developed to analyze the exergy efficiency based on the exergy destruction .Simulation works have been carried out in order to estimate the electrical as well as the operation parameters, design parameters and operating parameters on exergy efficiency have been examined by ANN as a part of performance evaluation.

2. Data with Proposed Methodology

The investigational method of polycrystalline solar panels has been carried out for eight months i.e January and February (winter), April and May (summer), July and August (rainy), October and November (autumn) under distinctive weather condition in Bhubaneswar, Odisha. The location of the case study is at 20° 15'N latitude and 85° 52' E longitudes. The experiments have been conducted for the different months in actual atmospheric environments from 8.00 AM to 5.00 PM. The experimental factors like wind speed, solar irradiance, short circuit current, open circuit voltage, voltage and current with respect to fill factor, ambient temperature, maximum power point, minimum temperature, maximum temperature and average temperature of the photovoltaic module have been considered.

2.1. Thermodynamic analysis of PV Module

A number of mathematical models have been designed for energy and exergy examination of the solar photovoltaic modules.

2.1.1. Energy analysis

The energy produced due to the solar radiation (G_s), which is incident upon the solar photovoltaic module having area A_m is estimated according to the formula given below in equation (1) [38, 34].

$$E_{IN} = G_s A_m \tag{1}$$

The power generated from the solar PV panel E_{spv} is expressed in mathematical model as given below in equation (2).

$$E_{spv} = V_{oc} I_{sc} FF \tag{2}$$

Where, V_{oc} is the voltage at open circuit condition, I_{sc} is the current available at short circuit situation and FF is the fill factor of the solar PV module. Fill factor of the solar photovoltaic system is normally defined as the ratio of maximum power ($V_{mp}I_{mp}$) to the power available due to multiplication of both open circuit voltage(V_{oc}) and short circuit current (I_{sc}) and may be expressed as in equation (3) [34].

$$FF = \frac{V_{mp} I_{mp}}{V_{oc} I_{sc}} \tag{3}$$

The energy efficiency is defined as in equation (4).

$$\eta = \frac{V_{oc} I_{sc}}{G_s A_m} \tag{4}$$

2.1.2. Exergy analysis

The exergy efficiency is defined as the output exergy divided by the input exergy as expressed in equation (5) [35]

$$\eta_{EX} = \frac{EX_{OUT}}{EX_{IN}} = 1 - \frac{CV_{irr}}{EX_{IN}} \tag{5}$$

Where, EX_{IN}, EX_{out}, and CV are the exergy as input, exergy as output and irreversibility in the control volume correspondingly. The input exergy includes the intensity exergy of solar radiation. Conferring to R Petela, the input exergy is specified by in equation (6) [35].

$$EX_{IN} = E_{IN}\left[1 - \left(\frac{4}{3}\right)\frac{T_{Amb}}{T_{Solar}} + \frac{1}{3}\left(\frac{T_{Amb}}{T_{Solar}}\right)^4\right] \tag{6}$$

Where, T_{solar} is the temperature of sun in Kelvin. The irreversibility in control volume is given in equation (7).

$$CV_{irr} = \sum\left(EX_{LOSS} + EX_{DEST}\right) \tag{7}$$

The losses produced by the heat leakage are specified by equation (8).

$$EX_{LOSS} = H_{LOSS} A_m \left(T_C - T_{Amb}\right)\left(\frac{T_C - T_{Amb}}{T_C}\right) \tag{8}$$

The total heat loss coefficient of the photovoltaic panel consists of the losses due to convection and radiation. The convective heat transfer coefficient as in equation (9) [59]:

$$H_{Convection} = 2.8 + 3V_{WIND} \tag{9}$$

Where, V_{wind} is the speed of the wind .The radiative heat transfer coefficient could be expressed as in equation (10) [60]

$$H_{Radiation} = \varepsilon_g \sigma \left(T_{SKY} + T_C\right) \left\{T_{SKY}^2 + T_C^2\right\} \tag{10}$$

Where, ε_g and σ are the emissivity of PV panel and the Stefan-Boltzmann constant respectively. The effective temperature of the sky (T_{sky}) is normally lesser than 5-6°C from ambient temperature. The exergy destruction losses are due to heat that caused by temperature deviation of photovoltaic array and reference environmental state. The exergy destruction is expressed by equations (11)-(14).

$$EX_{DEST(Opt)} = E_{IN} \left(\frac{T_{Solar} - T_{Amb}}{T_{Solar}} \right) \left\{ 1 - (\tau\alpha) \right\} \tag{11}$$

$$EX_{DEST(\Delta T_{Solar})} = E_{IN} (\tau\alpha) \left(\frac{1}{T_C} - \frac{1}{T_{Solar}} \right) T_{Amb} \tag{12}$$

$$EX_{DEST(\Delta T_m)} = \frac{m_C T_{Amb} C_p}{\Delta t} \left\{ \ln\left(\frac{T_C}{T_{Amb}} \right) - \frac{T_C - T_{Amb}}{T_C} \right\} \tag{13}$$

$$EX_{DEST(elect)} = V_{oc} I_{sc} - V_{mp} I_{mp} \tag{14}$$

Where, m_c and Δt are the array mass and time interval of the photovoltaic module respectively. The time interval is based on the time step of experimental durations. The specific heat of silicon solar cell (C_p) has been taken in the range of 0.8 to 1.0. The exergy efficiency could be expressed as in equation (15).

$$\eta_{EX} = 1 - \left[\left\{ 1 - (\tau\alpha) \right\} + \frac{EX_{LOSS}}{EX_{IN}} + \frac{EX_{DEST(\Delta T_{Solar})}}{EX_{IN}} + \frac{EX_{DEST(\Delta T_m)}}{EX_{IN}} + \frac{EX_{DEST(elect)}}{EX_{IN}} \right] \tag{15}$$

3. Results and Discussions

Weather related different parameters like the wind speed, solar radiation and ambient temperature have been collected, so also the measured parameters such as open circuit voltage, short circuit current, maximum voltage, maximum current, fill factor, solar cell temperature of the photovoltaic module have been collected. Similarly, power conversion efficiency with the energy and exergy efficiencies for polycrystalline silicon photovoltaic panel have also been considered. Their performances have been plotted against the experimental time from 8 AM to 5PM. The variation in different parameters of polycrystalline solar photovoltaic module against time interval for January and February has been displayed in figures 1 and 2.

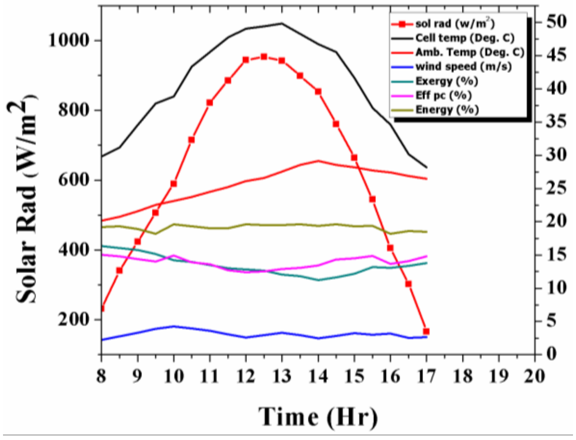

Fig 1. Time dependent parametrical variation for one day of January

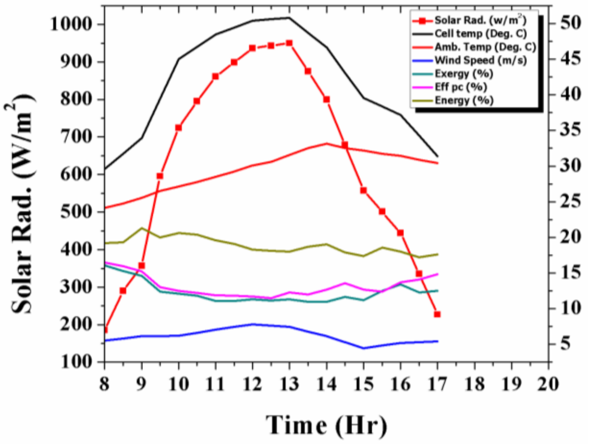

Fig 2. Time dependent parametrical variation for one day of February

It has been perceived from the figures that the solar irradiance varies slowly and reaches the peak value at mid-day and then decreases slowly during afternoon. Consequently, the efficiencies have been observed to be fluctuating for the entire day. Therefore, the variations of all these three efficiencies have been found to be affected inversely by the solar radiation and also by both the temperatures.

The rise in solar cell temperature greatly affects the output of solar photovoltaic module. The exergy efficiency varies more regularly than that of energy efficiency, when the wind speed increases beyond cut-in speed. During day time, the energy efficiency increases more compared to the exergy efficiency. According to first law of thermodynamics, the energy efficiency signifies quantity of energy rather than quality of energy. The power conversion, average energy and exergy efficiencies are found to be 13.15%, 18.11% and 13.05% respectively for January month.

The same type of change has been occurred in all the parameters which is described in Figure 2. There is less fluctuation in the month of February compared to the month of January. Also, the average energy, power conversion and exergy efficiencies for the month of February have been found to be 18.85%, 13.58% and 13.72%. From figures 1 and 2, it is also evident that all the efficiencies for February are higher than those in January.

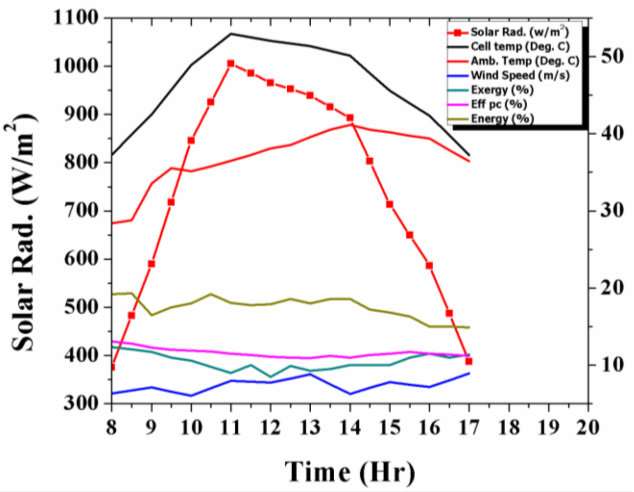

Fig 3. Time dependent parametrical variation for one day of April

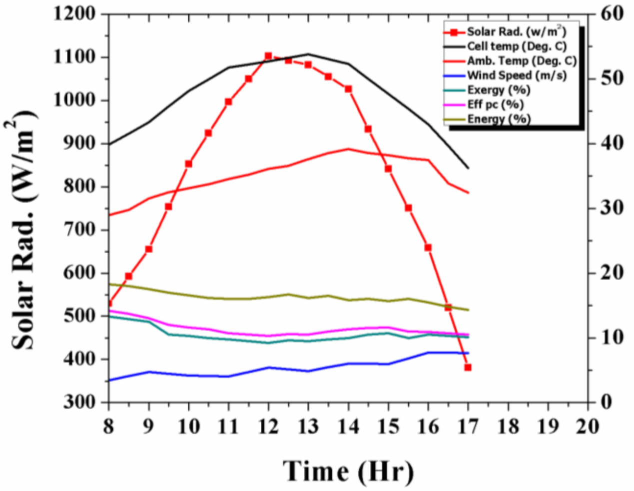

Fig 4. Time dependent parametrical variation for one day of May

Moreover, the power exchange efficiency and energy efficiency of April month are higher in magnitude compared to the month of May. Similarly, the fluctuation in the exergy efficiency and the energy efficiency during 10.30–3.00 hrs, are found to be more which compared to that during 11.30-01.30 hrs, during the May month that is expressed in terms of ambient air temperature, solar cell temperature and wind speed as mentioned in the preceding sections. The power conversion, average energy, exergy efficiencies are 11.47%, 17.07%, and 10.02% for April, but they are around 11.11%, 6.54% and 10.13% for May.

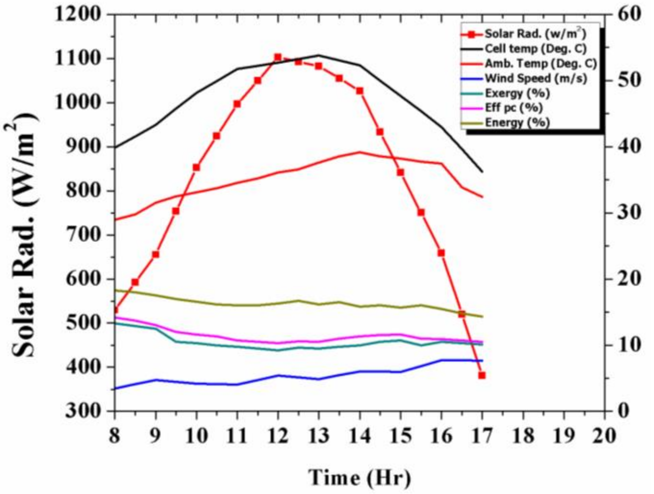

Fig 5. Time dependent parametrical variation for one day of July

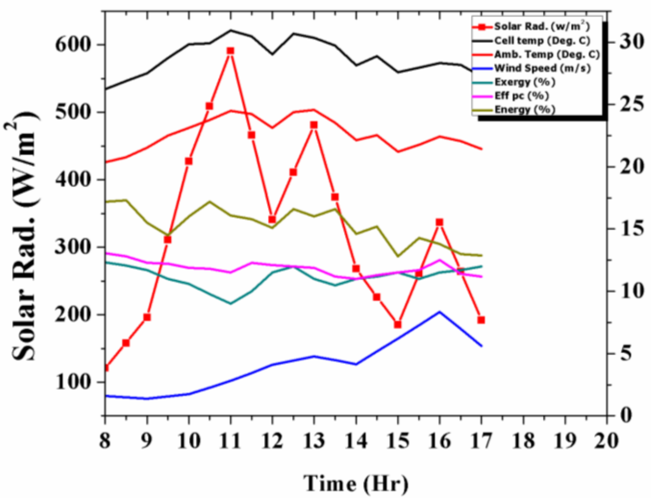

Fig 6. Time dependent parametrical variation for one day of August

The deviation in solar irradiance and three types of efficiencies versus experimental time duration for the polycrystalline photovoltaic module during the months of July and August has been depicted in figures 5 and 6 respectively. It has been clearly demonstrated that a severe depression has occurred in all the three efficiencies at 11.20 A.M. for the month of July and at around 9.30 A.M. for the month of August and again at around 3.00 P.M. The sharp fall in solar radiation at that particular instant produces a sudden dip in efficiencies, thereby resulting in sharp decrease of output to input ratios. The efficiencies of power exchange, energy and exergy are 16.22%, 11.31% and 10.70% respectively for July month, but they are in the range of 11.12%, 16.30% and 9.03% respectively for August month.

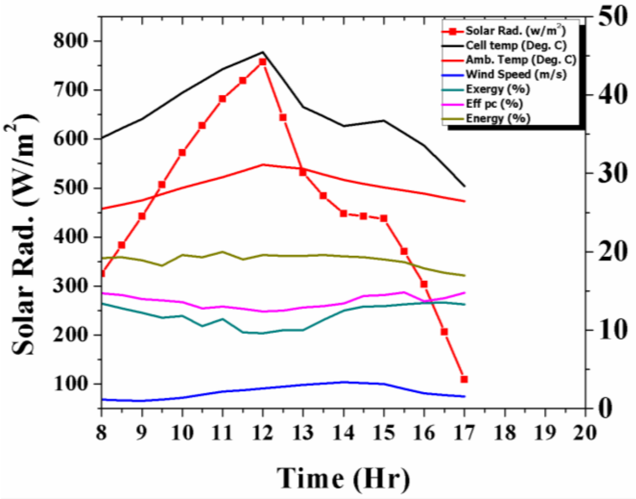

Fig 7. Time dependent parametrical variation for one day of October

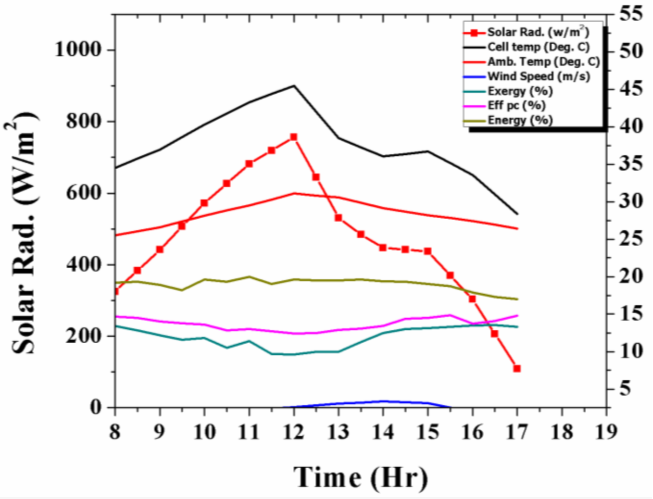

Fig 8. Time dependent parametrical variation for one day of November

The relation of power exchange, energy, exergy efficiencies and solar irradiance with hourly time interval have been clearly discussed in figures 7-8 respectively, for October and November months. The strength of solar insolation is observed as higher in magnitude during these two months. So, comparatively better ranges of efficiencies with minor deviations are obtained from the analysis. On the other hand, the module temperature increases because of higher solar strength; thereby the losses also have increased correspondingly. As a result of this, the exergy efficiency decreases considerably during middle hour of the day.

The power conversion, average energy and exergy efficiencies are observed to be 12.26%, 18.09% and 11.17% respectively, for October month, whereas they are observed to be 11.03%, 15.15% and 10.50% respectively, for November month. For October month every efficiency has been observed to be with lesser fluctuations. Their ranges are found to be higher than those for November month, which could be formally expressed in terms of solar irradiance, solar cell temperature and air temperature.

3.1. Data Evaluation with ANN

In the diverse field of contemporary science and technology, artificial neural networks (ANNs) have been extensively employed. ANNs show physical and mathematical variations. Due to the presence of number of layers, structural variations arise and consequently the connections among the nodes cause variations. Usually the structures of ANN have three layers as follows, the input layer, the hidden layer, and the output layer. Variety of nodes within the input layer is adequate for the number of data given to artificial neural network and variety of nodes at the output layer is adequate for the amount of data that could be taken from ANN. Node variety of the hidden layer is found by experimentation. The learning capability of ANN advances due to variety of nodes and therefore the connection increase, but it takes quite longer time duration for training the artificial neural network.

The inputs are processed in the following manner each and every data is summed up after it is multiplied by its corresponding weight and hence subjected to activation functions. Thereby, the information which can be transferred to successive layer is obtained. The algorithmic programs have been developed for training ANN and therefore variety of activation functions that are commonly employed at the nodes, output are the mathematical variations. Activation functions generally comprise of exponential functions, thereby non-linear modeling could be easily attained.

Based on ANNs purpose of usage, several algorithms have been developed. Training of ANNs is carried out with best–known data. The testing is done with data that are not utilized in training, Even though, training takes an extended time they offer selections in short span of time throughout the operation. They are employed extensively in modeling non-linear systems, because of their capability of learning, generalization, tolerating the faults and learning from the faulty samples. This back propagation algorithm is the most widely employed methodology in artificial neural networks.

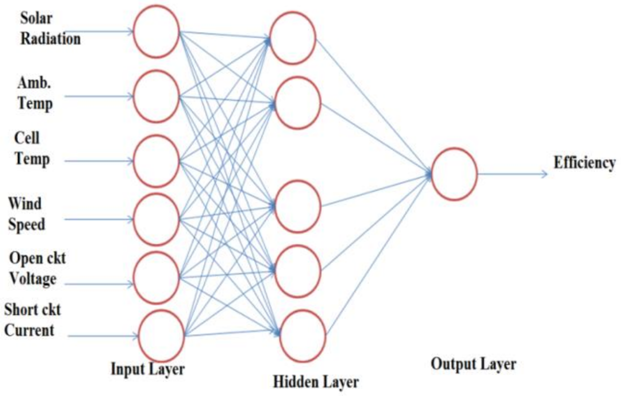

Fig 9. Structure of ANN

3.2. Outcome Analysis

The chief objective of this research work is to come-out with a model of artificial neural network for the investigation of performance of a flat plate collector for dissimilar photovoltaic technologies. The performance parameters calculated from the artificial neural network are then successively tallied with the outcomes that are found from the methodical analysis. Four experiments have been conducted by taking one day each of different months like February, May, August and November. The forecast accuracy can be evaluated and also the average of squaring of errors can be measured by the help of above function. The average magnitude of error is estimated by the root mean square error (RMSE) and it is quite better to have lower values of RMSE. The root mean square error (RMSE) is the standard deviation of the differences between forecasted/predicted values and target values.

The quality of forecasting value can be measured by taking some assumptions.

Let, *S (t)* is the target vale of time series and $S_f(t)$ is the forecasted value with series length *n*.

$$RMSE = \frac{1}{S_{\max} - S_{\min}} \sqrt{\frac{\sum_{i=1}^{n} \{S(t) - S_f(t)\}^2}{n}} \tag{16}$$

Where, S_{max} and S_{min} are the maximum and minimum measured values.

An additional forecast evaluator usually used is the mean absolute error (MAE) which is having same value to the root mean squared error, although somewhat lesser in magnitude.

$$MAE = \frac{1}{S_{\max} - S_{\min}} \frac{\sum_{i=1}^{n} \{S(t) - S_f(t)\}}{n} \tag{17}$$

The RMSE data of different parameters which are calculated from analytical study and ANN model taking into account four type of seasonal weather condition such as: a (winter), b (summer), c (rainy) and d (autumn) are tabulated in Table 1.. In experiment 1, one day of February month is taken with 10 minutes interval. It has been clearly observed from the results obtained from ANN analysis that, the correlation factor and efficiency are higher in training process when compared to the testing process. The RMSE obtained is 0.1957 for training and 0.2541 for testing the data. The second experiment has been conducted with the data for the month of May. It is found that the correlation factor is 0.9861 in case of training but 0.6955 for testing, with larger difference in efficiency of 96% in training and 45% in testing. The RMSE obtained from training is 0.3061 and 0.4094 in case of testing process. The MAE is also found to be 0.2311 for training and 0.3128 for testing .

Table 1. Performance evaluation of ANN model

Experiments	Performance	Correlation Factor	Efficiency	RMSE	MAE
Expt. 1	**Training**	**0.9933**	**98.6006**	**0.1957**	**0.1410**
	Testing	**0.9149**	**82.8755**	**0.2541**	**0.1783**
Expt. 2	**Training**	**0.9861**	**96.9061**	**0.3061**	**0.2311**
	Testing	**0.6955**	**45.3842**	**0.4094**	**0.3128**
Expt. 3	**Training**	**0.9864**	**97.2257**	**0.2810**	**0.2187**
	Testing	**0.8291**	**67.0710**	**0.2707**	**0.2050**
Expt. 4	**Training**	**0.9779**	**95.5949**	**0.3573**	**0.2870**
	Testing	**0.7981**	**63.5698**	**0.2847**	**0.2254**

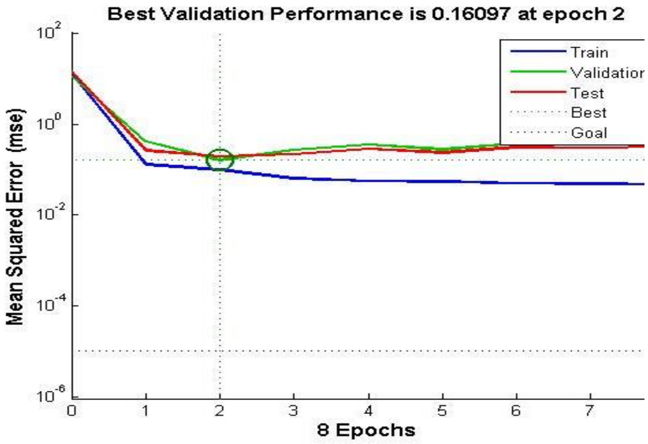

Fig 10. Validation performances

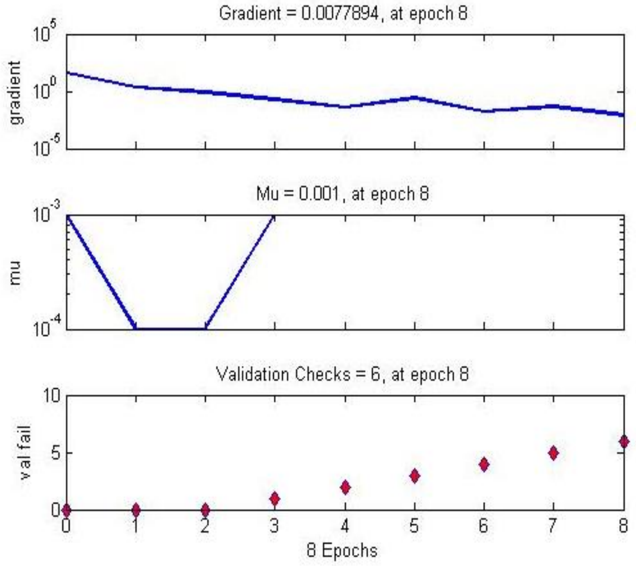

Fig 11. Validation checking

Based on the results obtained, the deviations are found to be in the range of 0.02%-2.417% for different output parameters. By considering different parameters for one day of the month of February , the results depict the best validation performance as 0.16097 at period 2 as seen in figure 10, and the gradient is 0.0077894 at period 8 and the validation checks is 6 at period 8 as depicted in figure 11.

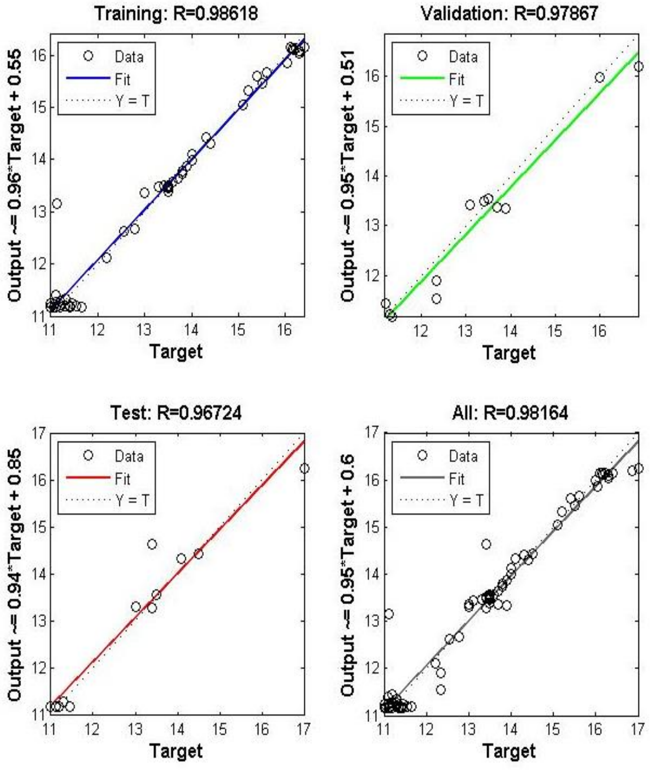

Fig 12. Overall Regression analysis

The output is 96% of target value and the regression R=0.98618 is obtained in the training process. But, in testing process the output is found to be 94% of the target, with the regression value of 0.96724. For validation, the output is obtained as 95% of the target value and the regression value is 0.97867. Nevertheless, the overall regression is obtained as 98% as described in figure 12.

4. Conclusions

The performance analysis based on exergetic as well as energetic analysis of polycrystalline solar photovoltaic module has been carried out during specific month of the year 2015. Due to irregular manner of solar radiation and wind speed, there is a greater variation in all the efficiencies during different months. From the results of different experiments, it is evidently found that the efficiencies are attaining their highest value in the month of February, whereas lowest value is attained during the month of August. Therefore, the performance of polycrystalline silicon photovoltaic panel has been observed to be highest in the month of February. In this paper, the data validation is done by artificial neural network models using MATLAB@13 for performance analysis of the solar PV module. It is clearly observed from the simulation results, that the correlation factor and efficiency is higher in training process when compared to the testing process. The RMSE is obtained as 0.1957 for training and 0.2541 for testing with the MAE of 0.1410 for training and 0.1783 for testing the data. Furthermore, it has also been found that it is advantages to employ artificial neural network when compared to the traditional methodologies because of its betterment in speed and simplicity.

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