Determination of Efficiency of Hybrid Photovoltaic Thermal Air Collectors using Artificial Neural Network Approach for Different PV Technology

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Abstract - In this paper an attempt has been made to determine efficiency of semi transparent hybrid photovoltaic thermal double pass air collector for different PV technology and compare it with single pass air collector using artificial neural network (ANN) technique for New Delhi weather station of India. The MATLAB 7.1 neural networks toolbox has been used for defining and training of ANN for determination of thermal, electrical, overall thermal and overall exergy efficiency of the system. The ANN model uses ambient air temperature, number of sunshine hours, number of clear days, temperature coefficient, cell efficiency, global and diffuse radiation as input parameters. The transfer function, neural network configuration and learning parameters have been selected based on highest convergence during training and testing of network. About 2000 sets of data from four weather stations (Bangalore, Mumbai, Srinagar and Jodhpur) have been given as input for training and data of the fifth weather station (New Delhi) has been used for testing purpose. It has been observed that the best transfer function for a given configuration is logsig. The feed forward back-propagation algorithm has been used in this analysis. Further the results of ANN model have been compared with analytical values on the basis of root mean square error.

Index Terms - Artificial neural network (ANN), Efficiency, Photovoltaic thermal (PVT), Levenberg–Marquardt (LM), Multi-layer perceptron (MLP), Mean Bias Error (MBE), Single pass (SP), Double pass (DP).

1. INTRODUCTION

Due to depleting rate of conventional energy sources there have been sincere efforts all over the world to harness renewable energy resources. Solar energy is one of the significant renewable energy source that can be harnessed using photovoltaic thermal systems. The major applications of solar energy can be classified as: thermal system, which converts solar energy into thermal energy and photovoltaic (PV) system, which converts solar energy into electrical energy. The integrated arrangement for utilizing thermal energy as well as electrical energy, with a photovoltaic module is referred to as the hybrid PVT system. PVT collector produces thermal and electrical energy simultaneously and hence it is referred as hybrid PVT system. The development of sustainable technologies requires an overall evaluation of the product's environmental impacts and benefits. The solar cells currently in the market have undergone the environmental evaluations to be classified as sustainable sources of energy. Over last decade there is rapid increase in PV energy generation devices. The classification for photovoltaic technology available in the market has been given in Table 1. Since late 1990s, new PV technologies have begun to emerge commercially along with more traditional Si-based systems. The emerging non crystalline silicon technologies have started making momentous into solar cell markets. These thin film PV modules still constitute a tiny fraction of the total PV market, but things may change quickly as new manufacturers hit the market each year. (Raugei and Frankl, 2008) have compared energy cost of thin film PV-cells to that of crystalline systems. It has been observed that energy cost has dropped to 1$/W (Fthenakis, 2009). The performance of a PV can be described in terms of its energy conservation efficiency and the percentage of incident solar ray that converts cell into electricity under standard test conditions.

Most parts of India receive abundant quantity of solar energy due to their geographical positions but it is difficult to have measurements from all locations of interest as measuring devices are expensive to purchase, install and maintain. The design of any cost effective system depend on the reliable data for which accurate techniques are required. The ANN methodology is a promising alternative to the traditional approach for estimating solar radiation. (Jiang, 2008) has developed a model for estimation of the monthly mean daily diffuse solar radiation for eight typical cities in China. It has been observed that ANN-based estimation technique is more suitable than the empirical regression models for estimation of solar radiation. (Leal et al., 2011) have measured, analyzed and compared three different statistical models and two ANN models for estimating the daily UV solar radiation from the daily global radiation. It has been observed that the statistical and ANN models have good statistical performance with RMSE lower than 5% and MBE between 0.4 - 2 %. (Koca et al., 2011) have developed an ANN model for estimation of future data on solar radiation for seven cities from Mediterranean region of Anatolia in Turkey. The obtained results indicated that the method could be used by researchers or scientists to design high efficiency solar devices.

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ANN's have also been used for prediction of energy consumption (Ekonomou, 2010; Tso & Yau, 2007; Kalogirou & Bojic, 2000). (Yoro et al., 2009) have applied the ANN method for exergy analysis of thermodynamic systems and presented the performance of the ANN method to emphasize the definition of ANN inputs. (Hui Xie et al., 2009) developed an ANN to determine the performance of solar collectors for Beijing with 10 neurons in the hidden layer considering back propagation learning algorithm and logistic sigmoid transfer function with minimum RMSE. The performance parameters ambient temperature of collector, solar intensity, declination angle, azimuth angle and tilt angle have been used as training data in the input layer for computing efficiency and heating capacity outputs. It has been observed that there is fair agreement between experimental and ANN model for performance prediction of solar collectors. (Caner et al., 2011) have designed an ANN model considering LM based MLP in Matlab nntool module to estimate thermal performances of two types of solar air collectors. The calculated and predicted values of thermal performances have been compared and statistical error analysis has been carried out to evaluate results. Further reliability of ANN has been tested by applying stepwise regression method to the data used in designing. (Almonacid et al., 2011) have compared the results of three classical and ANN methods for estimating the annual energy produced by a PV generator for Solar and Automatic Energy at the University of Jaen. It has been observed that ANN method provides better results than the alternative classical methods in study, as it takes some second order effects such as low irradiance, angular and spectral effects into consideration.

(Ashhab, 2007) has used ANN technique for forecasting photovoltaic solar integrated system efficiencies. (Sozen et al., 2008) have developed an ANN model to determine the efficiency of flat plate solar collectors. The collector surface temperature, date, time, solar radiation, declination angle, azimuth angle and tilt angle have been used as the input and efficiency of flat plate solar collector has been used as the output with Logistic sigmoid transfer function in the network. The results have shown that the maximum and minimum deviations were found to be 2.558484 and 0.001969 respectively. Efficiency of solar cells has significantly improved over the last few decades. However realized values are much lower than the theoretical limits.

In this paper efficiency of a semi transparent single and double pass air collector for different PV technology have been evaluated considering four types of weather conditions defined as (Singh, 2005). Table 2 shows the number of clear days in different weather condition for New Delhi weather station. The data of solar radiations for different climates for four weather stations (Bangalore, Mumbai, Srinagar and Jodhpur) obtained from Indian Metrological Department, Pune have been used for training and data of the fifth weather station (New Delhi) has been used for testing purpose. The results of ANN models for semi transparent hybrid PVT single and double pass air collector for different PV technology have been compared with analytical values on the basis of RMSE.

2. ARTIFICIAL NEURAL NETWORK

2.1. Theory

ANN models are computer programs designed to follow human information processing capability like knowledge processing, prediction and classifications. The ability of ANN to learn from examples provides quick responses to new information. ANN's although implemented on computers but they are not programmed to perform specific tasks rather trained with respect to data sets until they learn patterns which have been used as inputs. Once they are trained, new patterns may be presented to networks for prediction or classification. ANN model has three types of layers: input, hidden and output layer. The neurons in layers are connected together in a network topology. The input neurons receive data from the external environment, the hidden neurons receive signals from neurons in the preceding layer, and the output neurons send information back to the external environment. The information is passed through neurons along with interconnections. An incoming connection has input value and weight associated with it and the output of the unit is function of the summed value. After summation, the net input of the neurons is combined with the previous state of the neurons to produce a new activation value. The activation is then passed through an output or a transfer function that generates the actual neuron output. The transfer function modifies the value of the output signal. This function can be either a simple threshold function that only produces output if the combined input is greater than the threshold value, or it can be a continuous function that changes the output based on the weight of the combined input. When the signal reaches to the last node, an appropriate output is generated. This output when compared to the desired output gives the error. Error during learning is called MSE. This error is back propagated to nodes to readjust the weights through adaptation learning function. The complete cycle is called an iteration and the set of inputs are called epoch. Many epochs are applied to get the desired output and train the network. In training data accuracy is vital for the development of an efficient model that can provide accurate prediction. Once the network is trained the same can be used for estimation and analytical purpose. The trained model is assumed to be successful if the model gives good results for that test set. To insure that ANN models provide correct prediction or classifications, the prediction results produced by ANN models can be validated against expert predictions for the same cases or it can be validated against the results of other computer programs.

2.2. Description And Design Of Ann

ANN modeling has been done to estimate electrical, thermal, overall thermal and exergy efficiency from the arrangement shown in Figure 1(a) and (b) for single and double pass respectively. The ANN model uses ambient air temperature, number of sunshine hour, number of clear days, temperature coefficient, module efficiency, global and diffuse radiation as input parameters and thermal, electrical, overall thermal and exergy efficiency as output parameters for the experimental setup is shown in Figure 3 (a) and (b).

Figure2 (a) and (b) represents the typical layout of the ANN, which shows the network nodes along with biases and weights for single and double pass respectively. The network type is selected as feed forward back propagation. The ANN model has four-layer feed forward back propagation neural network architecture, input layer of seven neurons, two hidden layer of twenty and twenty five neurons for single and double pass air collector respectively and an output layer of four neurons. The hidden layers has 'tan-sigmoid' activation function, Φ defined by the logistic function as

$\phi = 1/1 - e^{n}$, where n is the corresponding input.

For the output layer, a logsig activation function is used. The inputs have been normalized in the (0, 1) range. A set of 2000 epochs has been taken for training purpose. The MATLAB Neural Network Toolbox is used for the implementation of the feedforward network. The supervised training technique back propagation algorithm has been used. TRAINLM has been selected as training function and

MSE has been taken as the performance function. This training function updates the weights and bias values in accordance with LM optimization. In order to train the network the data of solar radiations for different climates has been obtained from Indian Metrological Department, Pune.

The following parameters are set while training the feed forward neural network: training pattern 2000, learning rate 0.001, MSE training goal has been set as 0.005, number of training iterations 1250, momentum 0.94. The training patterns are presented repeatedly to the ANN model and the adjustment is performed after each iteration whenever the network's computed output is different from the desired output. After several adjustments to the network parameters, the network converged to a threshold of 0.00001 using hidden nodes. The accuracy of the trained ANN model was validated using other sets of data, which are different from those used for the training process and the mean square error is 0.005 The RMSE varies from 0.0568 to 4.7633% for different output parameters. The results demonstrate that the ANN based model developed in this work can predict the efficiency at any point in time with high accuracy.

3. THEORETICAL ANALYSIS OF AIR COLLECTOR

3.1 Single Pass Air Collector

The cross sectional view of semi transparent single pass air collector has been shown in Figure 3(a).There is a provision of duct below the PV module. The air is passed through one end of the duct and gets warm by picking the thermal energy from the back side of the PV module and exit from the other end of the duct. The duct has been insulated to minimize the heat loss.

3.2 Double Pass Air Collector

The cross sectional view of semi transparent hybrid PV module double pass collector, has been shown in Figure 3(b). There is provision for two ducts. The two ducts are connected in series at the end. The air flows in the upper duct get exposed to the solar radiation. Due to exposure, the temperature of the air in the outer duct increases. The heated air is circulated through the inner duct and gets further heated due to increase in the temperature of semi transparent PV module. Thus this useful thermal energy obtained, from hybrid PVT pass air collector can be used in building for space heating in cold climatic condition.

3.3. Thermal Energy And Exergy Analysis

The hourly rate of useful thermal energy of semi transparent hybrid PVT air collector is calculated as

$$(\dot{q}_u) = \dot{m}_a C_a \left(T_{f_o} - T_{fi}\right) \tag{1}$$

The daily thermal energy output in kWh of the semi transparent hybrid PVT air collector can be expressed as

$$Q_{thdaily} = \sum_{i=1}^{N} \frac{\dot{q}_{ui}}{1000} \tag{1a}$$

The monthly thermal energy output in kWh of the semi transparent hybrid PVT air collector can be expressed as

$$Q_{thmonthly} = \sum_{j=1}^{n_o} Q_{thdaily\ j} \tag{1b}$$

The annual thermal energy output can be evaluated by using hourly equation

$$Q_{thannual} = \sum_{k=1}^{12} \frac{\dot{q}_u}{1000} \times N \times n_0 \tag{1c}$$

The annual exergy of semi transparent hybrid PVT air collector is calculated as

$$Ex_{thannual} = Q_{thannual}\left[1 - \frac{\overline{T}_a + 273}{\overline{T}_{fo} + 273}\right] \tag{2}$$

The expression for outlet air temperature (T_{f_o}) in Eq. (2) is given by Kamthania et al. [17, 18].

The thermal efficiency of semi transparent hybrid PVT air collector can be expressed as

$$\eta_{th} = \frac{\sum \dot{q}_u}{\sum I(t) \times b \times L} \tag{3}$$

3.4 Electrical and Equivalent Thermal Analysis

The hourly electrical energy can be written as

$$E_{el} = \eta_{el} \times A \times I(t) \tag{4}$$

The annual electrical energy can be obtained as

$$\left(E_{el}\right)_{annual} = \eta_{el} \times A \times I(t)_{avg} \times N \times n_0 \tag{5}$$

The temperature dependent electrical efficiency of PV system can be written as

$$\eta_{el} = \eta_o\left[1 - \beta\left(T_c - T_a\right)\right] \tag{6}$$

where, T_a is 25°C (under Standard test condition) and value of cell efficiency (η_o) and temperature coefficient (β) for different PV technology is given in Table 3.
The equivalent thermal energy can be calculated as

$$E_{thannual} = \frac{\left(E_{el}\right)_{annual}}{0.38} \quad (7)$$

The 0.38 is the conversion factor from thermal to electrical energy for thermal power plants by Huang et al. [19].

3.5. Overall Thermal Energy and Energy Analysis

The overall thermal energy can be obtained from Eqs. (1c) and (7) and is expressed as

$$\left(Q_{ov}\right)_{th} = Q_{thannual} + E_{thannual} \quad (8)$$

The overall thermal efficiency of semi transparent hybrid PVT air collector can be expressed as

$$\eta_{ovth} = \eta_{th} + \frac{\eta_{el}}{0.38} \quad (9)$$

where, is calculated from Eq.(3) and from Eq.(6)

3.6. Overall Exergy

The annual exergy can be obtained from Eqs. (2) and (5)

$$Ex_{annual} = Ex_{thannual} + \left(E_{el}\right)_{annual} \quad (10)$$

The exergy efficiency of semi transparent hybrid PVT air collector can be expressed as

$$\eta_{ex} = \eta_{th}\left[1 - \frac{T_a + 273}{T_{fo} + 273}\right] \quad (11)$$

The overall exergy efficiency of semi transparent hybrid PVT air collector can be expressed as

$$\eta_{ovex} = \eta_{ex} + \eta_{el} \quad (12)$$

For more details, please refer the paper written by Kamthania et al. [17, 18].

4. SYSTEM AND DATA COLLECTION

The analytical model has been derived for the experiential setup installed at the Solar energy park of IIT, New Delhi as shown in Figure3 (a) and (b). The equations are derived for the analytical model of various performance parameters (thermal, electrical, overall thermal and exergy efficiency) considering a, b, c and d type climatic conditions for different weather stations. The ambient air temperature, number of sunshine hours, number of clear days, temperature coefficient, cell efficiency, global and diffuse radiation have been used as input for training of ANN. Climatic data and results of four weather stations (Bangalore, Mumbai, Srinagar and Jodhpur) have been used for training purpose and the data of the fifth weather station (New Delhi) has been used for testing purpose of the ANN model.

5. METHODOLOGY

The ANN has been defined in MATLAB 7.1 neural network toolbox as per the above mentioned parameters. The initial values of the weights have been defined and an incremental input is given to the network for estimating the outputs. When the outputs are closure to result matrix and the calculated MSE is within specified limits the iterations are terminated and the values of weights are recorded. If the output matrix is close to desired results then the network is trained otherwise the same procedure is repeated with new weight matrix. Thus value obtained through ANN model are compared with analytical result for New Delhi weather station. The RMSE deviation has been calculated using the following equation.

$$RMSE = \left(\sqrt{\frac{\sum\left(X_i - Y_i\right)^2}{n}}\right) \times 100 \quad (13)$$

6. RESULTS AND DISCUSSION

ANN helps in analysis and estimation studies before putting the Solar project at place. The purpose of this study is to develop an ANN model for performance analysis of a semi transparent hybrid PVT single and double pass air collector for different PV technologies. The training cities have been chosen as Banglore, Mumbai, Srinagar and Jodhpur and test city is New Delhi. The performance parameters calculated from ANN, are compared with the results obtained from analytical study.

Figure 4 shows MSE curve for a typical iteration, the performance of the network has been shown against the goal set for the network. MSE has been taken as the performance function with MSE training goal set as 0.005. It has been observed that LM with 20 and 25 neurons in the hidden layer for single and double pass air collector respectively and 4 neurons in input and output layer is the most suitable algorithm with set MSE value for single and double pass air collector respectively.

The RMSE measures the average magnitude of error. It is better to have lower RMSE values. The RMSE has been calculated using Eq.13. The RSME values of the performance parameters calculated from both ANN model and analytical study considering a, b c and d type weather conditions have been shown in Table 4. According to the results the deviation are in the range of 0.056-4.763% for different output parameters. It has been observed that RMSE for electrical efficiency, overall thermal efficiency and overall exergy efficiency varies from 0.056 to 0.211 %, 4.068 to 4.763% and 0.298 to 0.580% respectively.

Fig 5(a) shows monthly variation of electrical efficiency of single pass air collector for different PV technologies. The minimum electrical efficiency for different PV technology is in the month of May due to maximum solar radiation and minimum in the month of January due to low solar radiation. With the increase of solar radiation the cell temperature increases and there is decrease in the electrical efficiency of solar cell. The monthly electrical efficiency is maximum for HIT and minimum for a-Si. Fig 5(b) shows monthly variation of electrical efficiency of double pass air collector for different PV technologies. The monthly electrical efficiency is maximum for HIT and minimum for a-Si due to same reason as discussed in Figure 5(a).

Figure 6, 7 and 8 shows deviations of various performance parameters for single and double pass air collector of different PV technology. It is observed that double pass air collector have higher values as compared to single pass air collector. Further it is also observed that that maximum value of electrical, overall thermal and overall exergy efficiency are obtained for 'HIT' PV technology whereas minimum value of electrical, overall thermal and overall exergy efficiency have been obtained for 'a-Si' type for New Delhi weather station. The values obtained from ANN model are very close to the analytical values.

CONCLUSION

In this paper ANN models have been developed using MATLAB 7.1 neural networks toolbox for performance analysis of a semi transparent hybrid PVT double pass air collector for different PV technology. The ANN model is based on feed forward back propagation algorithm with two hidden layer. The LM with 25 and 20 neurons for single and double pass air collector respectively in the hidden layer and 4 neurons in input and output layer is the most suitable algorithm with MSE value of 0.005. It has been observed that analytical and ANN model have fair agreement with RMSE value lower than 5%. Further it is also observed that it is advantageous to use ANN as compared to traditional method due to speed, simplicity and ability to learn from examples.

REFERENCES

[1]. M. Raugei and P. Frankl, "Life cycle impacts and costs of photovoltaic systems: current state of the art and future outlooks", *Energy*, Vol. 34, 392–9, 2009.

[2]. V. Fthenakis, "Sustainability of Photovoltaics: the case for thin film solar cells", *Renewable & Sustainable Energy Reviews*, Vol. 13, 2746–50, 2009.

[3]. H. N. Singh and G. N. Tiwari, "Evaluation of cloudiness/haziness factor for composite climate", *Energy*, Vol. 30, 1589-1601, 2005.

[4]. Y. Jiang, "Prediction of monthly mean daily diffuse solar radiation using artificial neural networks and comparison with other empirical models", *Energy Policy*, Vol. 36, 3833-3837, 2008.

[5]. S. S. Leal, C. Tíba and R. Piacentini, "Daily UV radiation modeling with the usage of statistical correlations and artificial neural networks", *Renewable Energy*, Vol. 36, 3337-3344, 2011.

[6]. A. Koca, H. F. Oztop., Y. Varol, and G. O. Koca, "Estimation of solar radiation using artificial neural networks with different input parameters for Mediterranean region of Anatolia in Turkey", *Expert Systems with Applications*, Vol.38, No.7, 8756-8762, 2011.

[7]. E. Ekonomou, "Greek long-term energy consumption prediction using artificial neural networks", *Energy*, Vol. 35, 512-517, 2010.

[8]. G. K. F. Tso and K. K. W. Yau, "Predicting electricity energy consumption: a comparison of regression analysis, decision tree and neural network", *Energy*, Vol.32, No.9, 1761-1768, 2007.

[9]. S.A. Kalogirou, and M. Bojic, "Artificial neural networks for the prediction of the energy consumption of a passive solar building," *Energy*, Vol. 25, 479-491, 2000.

[10]. Y. Yoru, T. H. Karakoc and A. Hepbasli, "Application of artificial neural network method to exergy analysis of thermodynamic systems", *8th International Conference on Machine Learning and Applications*, Miami Beach, Florida, 13-15, 2009.

[11]. H. Xie, L. Liu, M. Fei, and H. Fan, "Performance prediction of solar collectors using artificial neural networks", *International Conference on Artificial Intelligence and Computational Intelligence*, Vol. 2, 573-576, 2009.

[12]. M. S. Ashhab, "Thermal photovoltaic solar integrated system analysis using neural networks", *Third international conference on thermal engineering: theory and applications*, Amman-Jordan; 593–6, 2007.

[13]. A. Sencan and G. Ozdemir, "Comparison of thermal performances predicted and experimental of solar air collector". *Journal Applied Science*, Vol.7, 3721-3728, 2007.

[14]. M. Caner, E. Gedik and A. Kecebas, "Investigation on thermal performance calculation of two type solar air collectors using artificial neural network", *Expert Systems with Applications*, Vol. 38, No. 3, 1668-1674.

[15]. F. Almonacid, C. Rus, P. Pérez-Higueras, L. Hontoria, "Calculation of the energy provided by a PV generator. Comparative study: Conventional methods vs. artificial neural networks", *Energy*, Vol. 36, 375-384, 2011.

[16]. Adnan So¨zen, Tayfun Menlik and Sinan Unvar, "Determination of efficiency of flat-plate solar collectors using neural network approach", *Expert Systems with Applications*, Vol. 35, 1533–1539, 2008.

[17]. D. Kamthania, S. Nayak and G. N. Tiwari, "Performance evaluation of a hybrid photovoltaic thermal double pass facade for space heating", *Energy and Buildings*, Vol. 43, No.9, 2274-2281, 2011.

[18]. D. Kamthania, S. Nayak, G. N. Tiwari, "Energy and Exergy Analysis of a Hybrid Photovoltaic Thermal Double Pass Air Collector", *Applied Solar Energy*, Vol. 47, No.3, 199–206, 2011.

[19]. B. J. Huang, T.H. Lin, and W.C. Hung, "Performance evaluation of solar photovoltaic/thermal system", *Solar Energy*, Vol. 70, No. 5, 443-448, 2011.

NOMENCLATURE

n	number of samples
N	number of sunshine hour in a day
n_o	number of clear days in a month
$Q_{thannual}$	annual rate of useful thermal energy (kWh)
$(E_{el})_{annual}$	annual rate of useful electrical energy (kWh)
$(Q_{ov})_{th}$	overall thermal energy (kWh)
$Ex_{thannual}$	overall exergy (kWh)

T_a	ambient temperature (°C)
T_c	solar cell temperature (°C)
T_{fo}	outlet air temperature of inner duct (°C)
η_{el}	electrical efficiency (%)
η_{ovth}	overall thermal efficiency (%)
η_{ovex}	electrical efficiency (%)
η_0	cell efficiency (%)
β	Temperature coefficient ((°C^{-1})
X_i	predicted values
Y_i	calculated values

ABBREVIATIONS

a	ambient air
c	solar cell
el	electrical
ov	overall
th	thermal

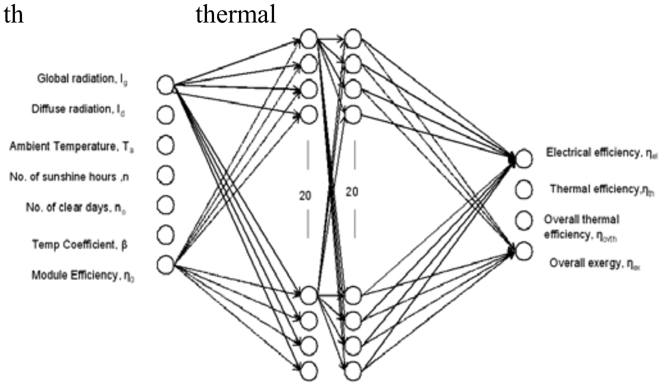

Figure 1(a): Input, output and hidden layers of ANN for single pass air collector

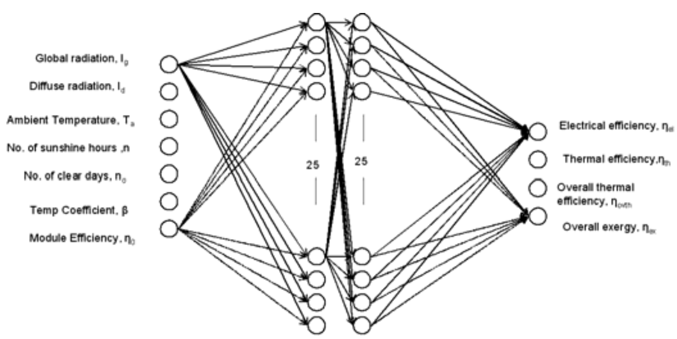

Figure 1(b): Input, output and hidden layers of ANN for double pass air collector.

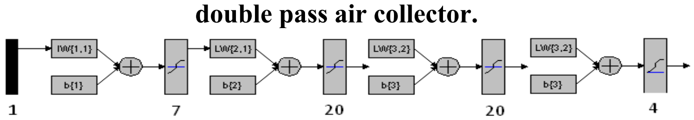

Figure 2 (a): Typical arrangement of ANN for single pass air collector.

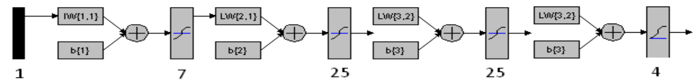

Figure 2 (b). Typical arrangement of ANN for double pass air collector.

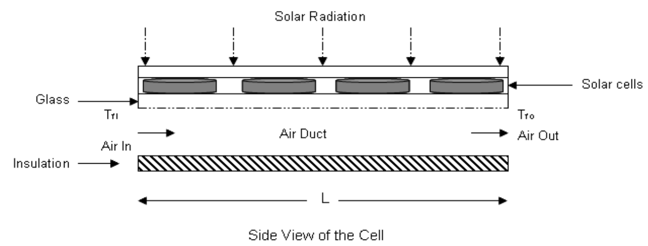

Figure 3(a): Schematic diagram of hybrid photovoltaic thermal single pass air collector.

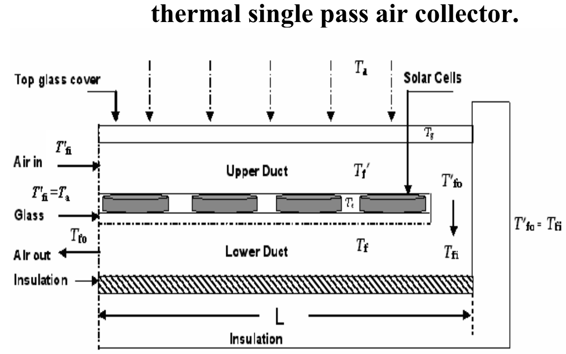

Figure 3(b): Schematic diagram of a hybrid photovoltaic thermal double pass air collector

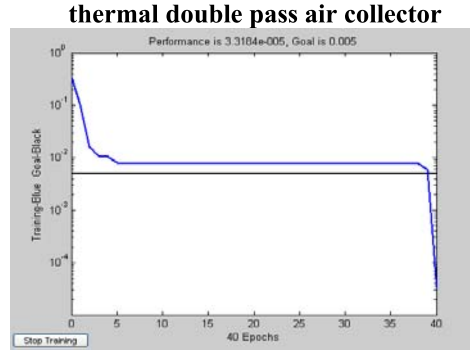

Figure 4: MSE obtained in the training of the network.

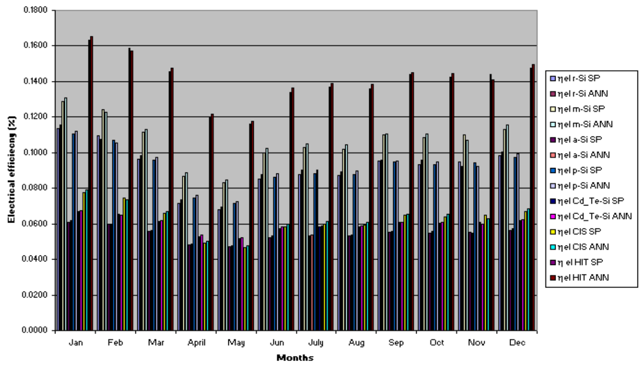

Figure 5 (a): Monthly variation of electrical efficiency of single pass air collector for different PV technology

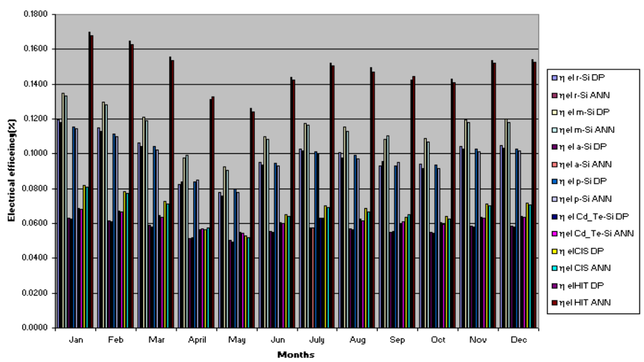

Figure 5(b): Monthly variation of electrical efficiency of double pass air collector for different PV technology

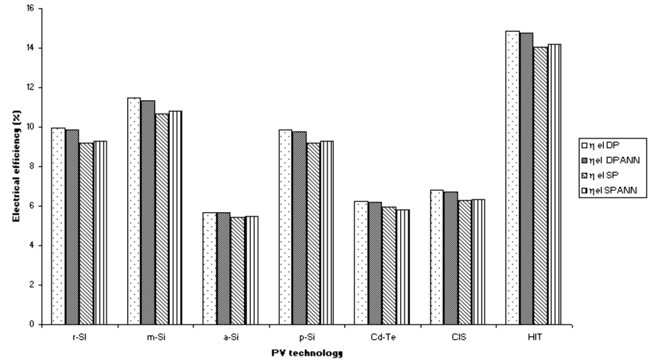

Figure 6: Annual variation of electrical efficiency of single and double pass air collector of different PV technology

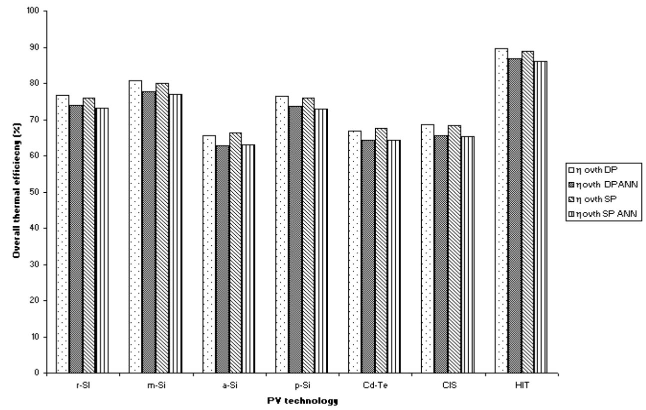

Figure 7: Annual variation of overall thermal efficiency of single and double pass air collector of different PV technology

Type of weather conditions	January	February	March	April	May	June	July	August	September	October	November	December
a	3	3	5	4	4	3	2	2	7	5	6	3
b	8	4	6	7	9	4	3	3	3	10	10	7
c	11	12	12	14	12	14	10	7	10	13	12	13
d	9	9	8	5	6	9	17	19	10	3	2	8

Table 2: Number of clear days fall in different weather condition for New Delhi weather station

PV Technology	Module efficiency η_o (%)	Temperature Coefficient β ($^oC^{-1}$)
Ribbon cast Si (r-Si)	12.00	0.0045
Mono-crystalline silicon (m-Si)	13.50	0.0040
Amorphous silicon (a-Si)	6.30	0.0026
Polycrystalline silicom (p-Si)	11.60	0.0040
Cadmium telluride (Cd-Te)	6.90	0.0026
Copper indium diselenide (CIS)	8.20	0.0045
Heterojunction with **I**ntrinsic **T**hin-layer (HIT)	17	0.0033

Table 3: Specification for various silicon and non silicon based PV modules.

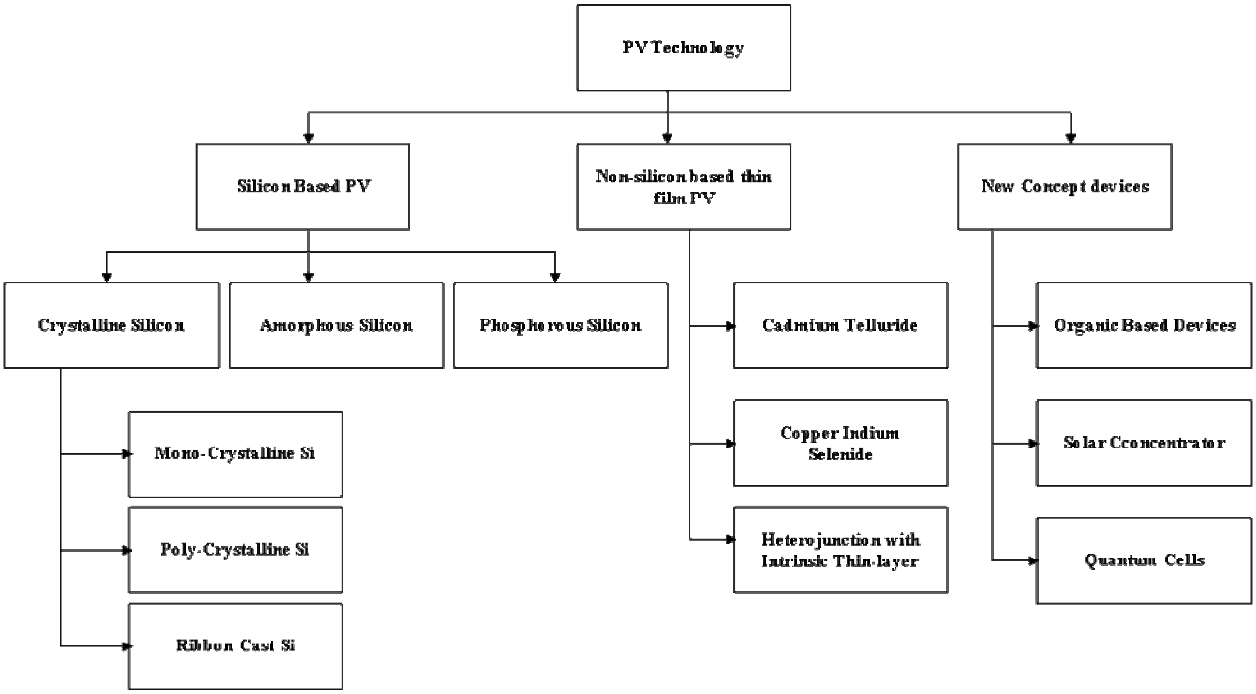

Table 1: Classification of photovoltaic on the basis of PV technology

PV Technology	Electrical Efficiency		Overall Thermal Efficiency		Overall Energy Efficiency	
	DP	SP	DP	SP	DP	SP
r-SI	0.1874	0.2031	4.1898	4.5260	0.5753	0.4125
m-Si	0.1874	0.2031	4.1898	4.5260	0.5753	0.4125
a-Si	0.0568	0.0616	4.0682	4.7633	0.4826	0.2939
p-Si	0.1610	0.1745	4.1632	4.5725	0.5553	0.3873
Cd-Te	0.0622	0.0675	4.0727	4.7532	0.4861	0.2984
CIS	0.1280	0.1388	4.1314	4.6317	0.5312	0.3565
HIT	0.1947	0.2110	4.1973	4.5133	0.5809	0.4195

Table 4: RMSE calculations of electrical, overall thermal and energy efficiency for different PV technologies for single and double pass air collector

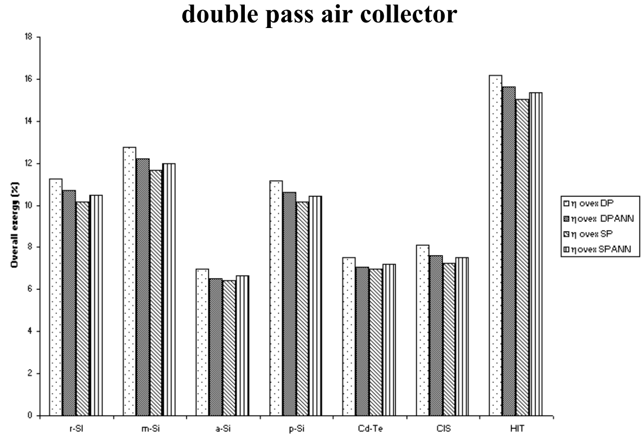

Figure 8: Annual variation of overall energy of single and double pass air collector of different PV technology