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Annual Optimum Tilt Angle Prediction of Solar Collector using PSO Estimator

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Abstract: The amount of solar flux falls on solar collector depends on tilt angle and orientation of collector from the surface. By efficiently regulating the tilt and orientation of solar collector unnecessary loss in potential power can be minimized. In general, for north hemisphere, south facing of the collector is considered as optimum orientation. There are several metrological and geographical factorswhich affect the optimum tilt angle.In this paper, the PSO estimator has been proposed in order to find optimum tilt angle on annual basis. The results of PSO estimators are compared with ANN estimator and satellite (RETScreen software) data.Toevaluate the performance of proposed model MBE, RMSE, Error range, percentage annual error as well as direct method of statistical study have been carried out. During annual tilt angle prediction the annual percentage errorsof proposed method and RETScreensoftware data are 0.03% and 7.03% respectively with respect to ANN results.Finally, the average percentage error indicates that the proposed estimator gives better prediction as compared to satellite based results for collecting maximum solar flux at surface of solar collector.

Keywords: Solar Collector, PSO, ANN.

1. Introduction

The development of solar technologies is the pressing need of the world in order to address the global challenges of energy security, climate change and sustainable development. In fact, the most parts of tropical country like India, clear sunny weather are experienced more than 250 days in a year. The India is geographically located in the equatorial sun belt of the earth, thus it receives abundant solar energy from the sun. The most preferable equipments in order to utilize the solar energy are Flat Plat Collector (FPC) and Photovoltaic Array (PVA).The solar flux falls on these solar collectorsor panelsdependon the tilt angle from horizontal surface. In other words, the amount of radiation absorbed by solar collector or panel is affected by their orientation and angle of tilt with the horizontal surface. It has been seen that often solar data are given at horizontal surface and also it is not possible to measure the performance of solar equipments at different tilt angle in large countries like India.

Although, the solar radiation calculation is highly nonlinear, stochastic and site specific, several complex models areavailable in literature. Further, these modelspredict solar radiation in terms ofclimate parameters such as sunshine hour, relative humidity, cloud layer, maximum temperature etc.[1]-[3], [7]. Theproposed model from different researchers helps to derive the optimum tilt angle at any location around the world from available metrological data on horizontal surface[4] and [5].In [1] a number of equations related to mean monthly global solar radiant exposure $\left(E_g\right)$ available in literature have been reviewed. And it has been observed that the original Angstrom type regression equation which relates E_g to clear day's radiation at site and average possible sunshine hour ratio are modified by different researchers. These modified model are classified such as linear, polynomial, other (nonlinear, exponential and logarithm term) models. In [7] author has proposed an empirical formula to predict optimum tilt angle, hour angle and orientationof solar panel based on generic surface with respect to position of sun. In [8]-[11] authors have proposed different empirical formulas to derive optimum tilt angle of solar panel around the world from available metrological data on horizontal surface.In [19] the monthly, seasonal, and annual optimum tilt angles for solar collectors in six different climatic zones of China are computed using empirical model and the measured weather data from China's meteorological stations over a 16-year period from 1994 to 2009, including air-dry bulb temperature, relative humidity, wind velocity, and global solar radiation data.

Recently, the soft-computing techniques such as ANN, GA, ANFIS, and PSO etc. becoming popular in solar energy estimation problems of optimization.The ANN to determine optimum tilt angle of solar collector (β_{opt}) has been widely used in solar energy estimation problems [12]-[14]. In [12] the author has taken Eg (monthly mean daily solar irradiance), ϕ (Latitude of the site in degree), ground albedo$\left(\rho\right)$and E_L Elevation of the site in (meter)) as input to ANN model and predicted the optimum tilt angle. Where, Mubiru and Banda [13] have developed ANN based model to predict direct solar irradiance. This proposed ANN model takes sunshine hour, cloud cover, maximum temperature, latitude, longitude as well as altitude of site as input parameters. In [14] author has proposed ANN model to predict direct beam radiation on horizontal surface based on five input parameters such as global solar irradiance, maximum temperature, latitude, longitude and altitude of site. In [15] author has proposed an ANN estimator to predict periodic optimum tilt angle from available input data such as $E_{g(monthly)}, \phi,$ and E_L . Here, ρ is not taken into account because the variation in ρ is negligible and mostly considered as constant. In [20] author has proposed generalized regression NN (GRNN) model to predict hourly solar radiation by taking hour angle, sunset angle and mean daily solar radiation as input to ANN. To train the GRNN model five year data have been collected using solar radiation transmitter. The results of GRNN model have been compared with existing empirical and statistical models.The ANN model is suitable only if accurate target data to train the ANN is available. But for large country like India due to geographical and astrological variations, accurate and reliable data collection is always not feasible. For reliable data collection it is utmost importance to measure solar radiation data in different part of country. On other hand, the network of radiation measuring stations should be modernized as well as monitored.

In paper [16]GA and Lagrange Multiplier algorithm has been proposed to maximize the photovoltaic panel output. Where, the GA gives initial population at optimal power and then it is feed to Lagrange Multiplier algorithm to find the PV module output power.The

[17]presented the β_{opt} calculation for fixed flat solar panel based on Genetic Algorithm (GA) and Simulated-Annealing (SA) methods. The relation between incident angle of sun and its radiation intensity on solar cell has been presented. The climate data of different sites of Taiwan have been used by GA and SA to obtain the optimum tilt angle β_{opt}. In [18] and [23] existing radiation data sources and software have been reviewed.Noteworthy, the radiation datacould be obtained from various sources, such as IMD, NREL, Meteonorm, NASA, WRDC (World Radiation Data Centre) RETscreen and so on. Noteworthy, the data from the above sources varies over a wide range, depending on whether it is collected from monitoring stations, extrapolated, or derived from satellite information. In above sources inaccuracies arise in micro-climates and areas near mountains, large bodies of water, or snow cover. Further, it has been reported that the weather estimation made by NASA, WRDC and high quality research base such as RETscreen have inaccuracy 19-20%, 6-12% and 3-6% respectively.

The objective of present work is to propose a cost function for PSO estimatorto determine optimum tilt angle such that maximum total mean daily solar irradianceon solar collector surface could be collected. In this paper the annual model of expected irradiance in (MJ/m^2) are presented. The optimum tilt angle of south facing collectors of Indian citiesare calculated on the basis of mean (monthly) global solar irradiance data obtained by Metrological center India[22].The proposed estimator results are compared with ANN [15] and the results reported in article [18].Further, the results of PSO estimators are analyzed based on statistical error tests [17].

2. Modeling of solar irradiance estimator at tilted surface

Generally, the sensors are horizontally placed in order to measure direct solar irradiance at Metrological centers. However, for capturing maximum solar energy the collectors are normally kept in tilted position. Hence, it becomes necessary to derive total solar radiant exposure from available Periodicvalues of global solar irradiance and diffuse irradiance on the tilted panel surface. Sometimes, global solar irradiation data may either not be available or not be desired form. In such case a typical empirical regression (1) suggested by Gopinathan[3] can be considered when data on sunshine hours are available.

$$\frac{E_g}{E_{go}} = a_1 + b_1\left(\frac{S}{S_{\max}}\right) \qquad \text{-(1)}$$

Where,S and $S_{max}$are the Monthly mean and maximum possible Sunshine hour per day at horizontal surface respectively. Further, the $a_1, b_1 = f\{\phi, E_L, S, S_{max}\}$ are regression constants can be obtained by (2-3) [7, 22].

$$a_1 = -0.309 + 0.539\cos\phi - 0.0693E_L + 0.290\left(\frac{S}{S_{\max}}\right) \qquad \text{-(2)}$$

$$b_1 = 1.527 + 1.027\cos\phi + 0.0926E_L - 0.359\left(\frac{S}{S_{\max}}\right) \qquad \text{-(3)}$$

The extraterrestrial solar radiation on a horizontal panel for dn^{th}day is given as [7,9 and 12]

$$E_{go} = \frac{24}{\pi}G_{sc}\left(1 + 0.033\cos\left(\frac{2\pi \times dn}{365}\right)\right) \qquad \text{-(4)}$$

Where, Solar constant G_{SC} =4.921 MJ/m^2/hr.

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Moreover, to simplify the calculation, Klein has suggested that the E_{go} (Extraterrestrial solar radiation on horizontal surface for dn^{th} day) in middle of the each month is nearly equal to the monthly mean value [3].The hour angle (in degree) corresponding to sunrise or sunset on the horizontal surface is given by (5)

$$\bar{\omega} = \left[\cos^{-1}\left(\tan\phi\tan\delta\right)\right] \quad -(5)$$

Therefore, the corresponding sunshine hour is

$$\bar{S} = \frac{2}{15}\left[\cos^{-1}\left(\tan\phi\tan\delta\right)\right] \quad -(6)$$

The angle made by the line joining the centers of the sun and earth with the projection of this line on the equatorial plane, is known as declination angle ( ). There are four models (formulas from model-1 to model-4) are proposed in literature to calculated declination angle, all these formulas are assumption based. In fact, all these four models have no significant difference as far as declination angle calculation is concern.

Model-1: The declination angle $\delta = 23.45\sin\left[\frac{2\pi\left(284+dn\right)}{365}\right]$ (7-a)

Model-2: $\delta = \sin^{-1}\left[\sin(23.45)\times\cos\left(\frac{2\pi(dn-173)}{365.25}\right)\right]$ (7-b)

In equation (7-a) and (7-b) *dn*=1 at 1^{st} Jan of every year*[3][6].*

Model-3: Rble's model of inclination angle [5] is given in equation (7-c)

$$\delta = \sin^{-1}\left[-\sin(23.27)\times\cos\left(\frac{2\pi D}{365.25}\right)\right] \quad (7\text{-c})$$

Where D- time after winter solstice (i.e. D count starts from 22 DEC onwards)

Model-4: This is a data driven model for which data is obtained from Indian Metrological Center Pune (Ref Table-7) [22]

The downward solar radiant energy scatted by the suspended particle, air molecules and the clouds. Many researchers have developed empirical for estimating E_d/E_g ratio for various part of world [5, 7, 9, and 22]. In this case the prediction of mean monthly daily diffuse irradiance (E_d) on horizontal surface from (8 and 9) is most suitable than other predictors because in fact diffuse components are much larger in India [1-3].

$$\frac{E_d}{E_g} = 0.8677 - 0.7365\left(\frac{S}{S_{max}}\right) \quad -(8)$$

$$or \ \frac{E_d}{E_g} = 1.411 - 1.696\left(\frac{E_g}{E_{go}}\right) \quad -(9)$$

A. Solar Irradiance on Tilted Surface

The total solar irradiance $\boldsymbol{E_{gs}}$ on tilted panel is the summation of direct-beam, diffuse and ground reflected radiations on the inclined surface. The $\boldsymbol{E_{gs}}$ for sharp south facing $\gamma = 0^\circ$ can be expressed as (10)[15]

$$E_{gs} = \left(E_g - E_d\right)\left[\frac{\omega_s \sin\delta \sin(\phi-\beta) + \cos\delta\cos\omega\cos(\phi-\beta)}{\omega_s \sin\delta\sin\phi + \cos\delta\cos\omega_s\cos\phi}\right] + E_d\left(\frac{(1+\beta)}{2}\right) + E_g\left(\frac{\rho(1-\beta)}{2}\right) \quad -(10)$$

3. Optimum tilt angle forecasting of solar collectorusing pso estimator

The Particle Swarm Optimization (PSO) is a stochastic optimizationtechnique based on social behavior of bee swarmingor fish schooling. This method has been proven effective fornon-derivable objective function as well as its implementationis very easy. In PSO each particle adjust its position in searchspace by its own as well as other particle flying experience tofind the best global solution for each particle. The performanceof each swarm can be improved by defining initial populationrange of each swarm such that each particle closely boundsto the expected domain of feasible region [25],[26]. A realcoded PSO estimator is proposed to find the optimum tiltangle of Solar Collector based on mean monthly global and diffusesolar irradiance during uncertain climate changes at differentlocations in India. The mathematical model of optimizationproblem can be described as follow:

$$\min or\ \max f\left\{X, E_{gs}\right\} \quad -(11)$$

Where, X is some equality and Non equality constraints and$\boldsymbol{E_{gs}}$ is the objective function to be maximize i.e. ($E_{gsmax}$is the Maximum solar radiation collection by solar collector on tilted surface in MJ/m^2/day)

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3.1. Imposed Parametric Constrains

The imposed parametric constraints in this paper for sharp south facing PV array are as follows:

$$dn^{\min} \le dn \le dn^{\max} \Rightarrow 1 \le dn \le 365 \quad -(12)$$

$$\beta^{\min} \le \beta \le \beta^{\max} \Rightarrow 0^\circ \le \beta \le 90^\circ \quad -(13)$$

$$\gamma = 0^\circ;\ \text{Surface azimuth angle in Degree} \quad -(14)$$

$$\rho = 0.2 \quad -(15)$$

In this work the performance of swarms are made better by putting parametric constraints (lower and upper bound constraints) as shown in (12-15), but linear and nonlinear constraints are not taken into account. In PSOeach particle moves about the cost surface with a velocity. The velocities of particles are controlled by ω inertia weight. By decreasing ω global search converges to local search. The particle updates their velocities and position based on the global and local best solution by(16-18).Therefore, the new position of particle can be predicted by following:

$$v_n^{j+1} = \omega v_n^j + C_2 r_1\left(P_{LB_n}^j - P_n^j\right) + C_1 r_2\left(P_{GB_n}^j - P_n^j\right) \quad -(16)$$

$$\omega = \omega^{\max} - \frac{\left(\omega^{\max} - \omega^{\min}\right)}{I_{ter}^{\max}} \times I_{ter} \quad -(17)$$

Therefore, thenewposition of particle can be predictedbyfollowing:

$$p_n^{j+1} = p_n^j + v_n^{j+1} \quad -(18)$$

The[26]demonstratedthattheparticle swarmisonlystable ifthefollowingconditions aresatisfied:

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Condition-1: $0<(C_1+C_2)<4$

Condition-2: $\left\{\frac{(C_1+C_2)}{2}-1\right\}<C_0<+1$

Where,C_0,C_1 and C_2 are inertia, social attraction and cognitive attraction of the particles respectively. Although, the above conditions ensures the convergence of system but that may not be global minimum. By selecting inertia weight tactfully optimal global solution can be achieved in lesser number of iterations. Here, ω decreases linearly from 0.9 to 0.4 during simulation [25]. The boundary constraint of particle can be managed by either 'Penalize' or 'Reflect' or 'Soft' or 'Absorb' option [26]. In this paper 'Soft' boundary constraint has been taken which sets fitness scores to infinity if particles leave problem bounds. The 'soft' boundary option saves the simulation time since infeasible points are not evaluated.

3.2.PSO Input Parameters

Theselectedinputparametersandtheir imposedparametricconstraintareasfollows:

$$X=[\ ,E_L,\ ,S,dn,\ E_g]$$

Where,dnis a day oftheyear(dn= 1onJan 1st anddn=365onDec 31st)

3.3. Problem Formulation

The objective of this work is to propose a cost function in order to maximize the solar energy collection on annual basis by adjusting tilt angle β of solar collector of cities of India. Hence, optimum tilt angle β_{opt} can be obtained by maximizing the cost function $E_{gs}(\beta_i)$ calculated from (10) for each city. Therefore, the fitness function to be optimized is obtained by taking harmonic mean of (10) for each of the latitude. The harmonics mean gives largest weight to smallest item and smallest weight to largest item.

$$F_\Delta(X_i)=\left[\frac{\sum_{i=1}^{N}\left(\varepsilon_{(\Delta)}\{\phi,\beta,\delta,\omega_s\}+\mu_{(\Delta)}\{\beta\}+\kappa_{(\Delta)}\{\rho,\beta\}\right)^{-1}}{N}\right]^{-1} \quad -(19)$$

With, $\Delta=(C\times 1)$ $C\in\{1, 2, ...23\}$ number of cities under study, $N\in\{12\}$ number of months. Here, $\varepsilon_\Delta,\kappa_\Delta$ and μ_Δ are the arbitrary functions of corresponding variables.

3.4. Pseudo-code of PSO Implementation

The pseudo code to implantation of Particle Swarm Optimization algorithm is as follows:

Begin

- Select the number of variable to be optimized for each city
- Select number of swarm particles (population size) and generations (maximum no of iterations), as well as set $C_1,\ C_2\ and\ \omega_{\min}\ and\ \omega_{\max}$ and terminating criteria.
- Impose the parameter constraints (lower bound, upper bound and other constraints if any).
- Randomly initialize the swarm position (p_n^j) and velocity $\left(v_n^j\right)$ of each particle.

Here:

- Randomly generate population.

Next:

- Impose Constraints: Is satisfied?
  - ❖ **No**
    - Remove the population and go to next population set.
    - Go to: **Next**
  - ❖ **Yes**
    - Evaluate fitness function using (19).
    - Determine P_{LBn}^j and P_{GBn}^j for each particle of each city.
- Is terminating Criteria reached?
  - ❖ **No**
    - Update the swarm position and velocity using (16-18).
    - Update the inertia weight.
    - Update P_{LBn}^j and P_{GBn}^j for each particle if its current value is better
    - Go to :**Here**
  - ❖ **Yes**
    - *Compute the best value of* $\mathbf{E}_{gs(max)}$*and corresponding independent variable.*

4. Optimum tilt angle forcasting of soalr collector using pso estimator

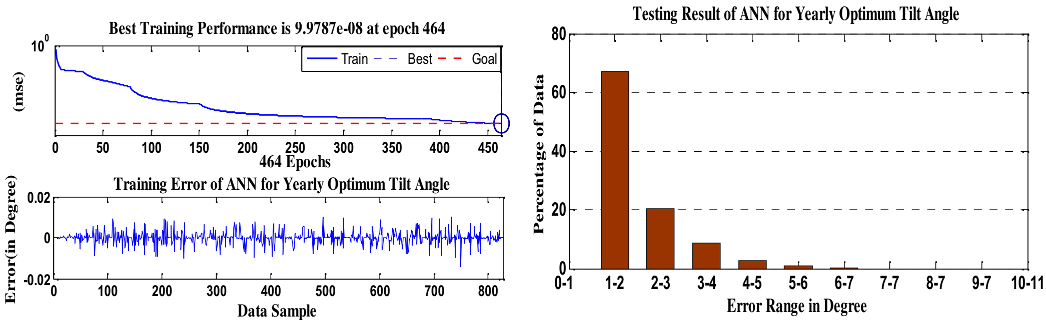
In this section a data driven approach (such as ANN) to forecast the optimum tile angle of solar collector has been discussed. Here, theauthor has refereed ANN model, training and testing data as well as results from [15]. Where, the MLP structure has four layers: input layer, two hidden layer and one output layer and Levenbeg-Marquardt algorithm are considered to train the ANN.

The mathematical model of proposed ANN MLP structure with dimension of input, weight, bias of neuron and activation transfer function of each hidden layer is given by (20). Where, $P_{j\times 1} \in \left\{H_{g_{Jan}}, H_{g_{Feb}} ....H_{g_{Dec}}, \phi, E_L\right\}$ $with\ j \in \{1,2,.....14\}$ number of the inputs at input layer of ANN.

$$\beta_i^{opt} = \left[W_{i\times 20}^3 \cdot \tan\left\{W_{20\times 35}^2 \cdot \log\left(W_{35\times j}^1 . P_{j\times 1} + b_{35\times 1}^1\right) + b_{20\times 1}^2\right\} + b_{i\times 1}^3\right] \qquad \text{-(20)}$$

Where i=1 is the number of neurons in output Layer for annual tilt angle respectively.To train the ANN the measured data are obtained from Indian Metrological Department, Pune.The detailed description of training pattern and analysis of results are presented in [15].

The MSE (Mean Square Error) of training annual β_{opt} is shown in Fig.1; it reaches to its best training performance of 9.9787E-08 at 464 epochs. Where, the absolute training error of annual ANN estimator is found less than 0.01. For this training 828 data samples of 23 cities are taken which are not considered for testing.



(a) (b)

Fig.1. Training and Testing Results of Annual Optimum Tilt angle of Selected Cities of India using ANN [15]

5. Results and discussion

In this paper the annual optimum tile angles are predicted for selected cities of India using ANN [15] and PSO estimator. In particular, to train the ANN the solar radiation data of India are considered by taking average on a monthly basis for period of 11 years (1991-2001) from Indian Meteorology Department (IMD) Pune, India [22].Also, the annual solar radiation results of PSO have been compared with ANN and results of report [18].

5.1.Testing Results of ANN Estimator [15]

The ANN test results of annual optimum are shown in Fig.1(b) in which percentage of data against range of error has been plotted. As it can be seen in Fig.3, the 96% of testing sample of ANN has error less than 3-4 degree which is well within acceptance range. As shown in Table-I the proposed ANN approach has better ability to locate the optimum solution then other methods.

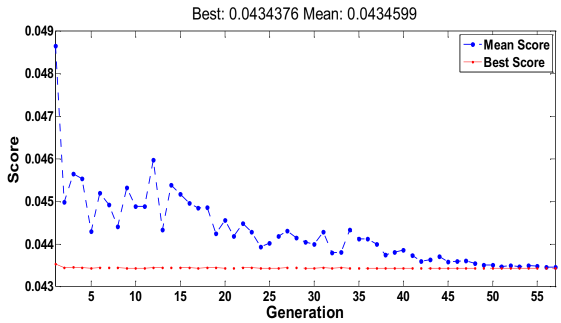


Fig.2. Annual Optimum Tilt angle of Selected Cities of India using PSO

5.2. Result of PSO Estimator

Based on analysis presented in section-II and section-III several MATLAB program were developed to calculate the maximum total solar irradiance E_{gsmax} for $\gamma = 0^\circ$ using (7-10). The optimum tilt angle was calculated by searching for the value at which maximum solar energy could be collected.

The convergence behavior of fitness value of PSO estimator for annual basis is shown in Fig.2. The best score of PSO fitness function reaches to 0.04344 at 55 generations. The best individual score in degree among 55 trials are shown. As shown in Table-I the proposed PSO approach has ability to locate the optimum solution then other methods.

Table I
Optimum tilt angle (in degree) and corresponding total solar irradiance *egsmax*(in mj/m^2)collection on annual basis using ann and pso estimator

Location	β_{opt}			***Egsmax***			**Location**	β_{opt}			***Egsmax***		
	ANN	**PSO**	**RET**	**ANN**	**PSO**	***RET***		**ANN**	**PSO**	**RET**	**ANN**	**PSO**	**RET**
MNC	11.66	10.51	8.30	18.42	18.43	13.39	BHV	24.82	25.50	21.75	19.53	19.53	28.05
TRV	10.16	10.94	8.43	18.43	18.43	26.62	KLK	22.74	21.73	22.65	19.63	19.62	22.14
PBL	16.32	16.60	11.67	18.58	18.58	23.28	AHM	25.67	25.83	23.07	19.71	19.71	26.33
BNG	15.49	16.57	12.97	18.68	18.68	26.92	BHP	27.03	26.95	23.28	19.74	19.74	25.74
CHN	11.55	11.27	13.00	18.67	18.66	26.38	RNC	24.00	25.47	23.32	19.73	19.74	23.13
GOA	20.71	20.72	15.48	18.85	18.85	22.81	VNS	24.24	24.24	25.30	20.00	20.00	24.01
HYD	20.08	20.74	17.45	19.05	19.05	27.90	SHL	28.82	28.62	25.57	20.09	20.09	22.34
VSK	19.85	20.08	17.68	19.07	19.07	25.24	PTN	24.90	24.88	25.60	20.06	20.06	23.77
PNE	21.93	22.25	18.53	19.16	19.16	26.62	JDP	27.70	28.11	26.30	20.20	20.20	27.16
MMB	21.17	20.94	19.12	19.22	19.22	24.75	JPR	26.96	27.01	26.82	20.27	20.27	27.16
NGP	23.87	23.78	21.10	19.45	19.45	25.20	NDL	27.06	26.92	28.48	20.55	20.54	25.05

Note: RET Data is taken from report [24], where latitude of the site is considered as optimum tilt angle.

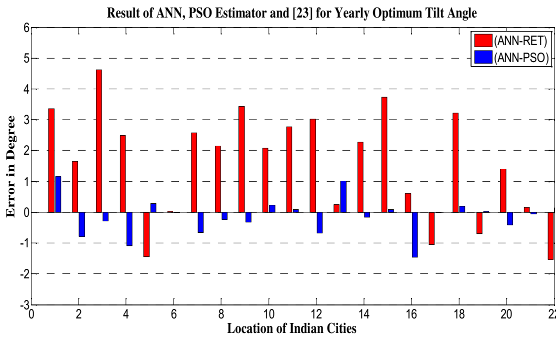


Fig.3. Error Plot of Annual Optimum Tilt angle of (ANN-PSO) Estimator and results reported in [23] of Indian cities

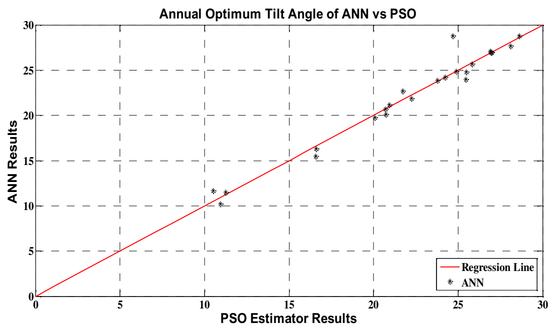


Fig.4. Annual Optimum Tilt angle of ANN versus PSO Estimator Results

5.3. Statistical Error Analysis

The statistical method to assess agreement of two quantitative methods such as PSO-ANN for prediction of optimum has been presented. Where, results obtained by PSO estimator have been compared with ANN results as well as the results reported in article [18]. Meanwhile, the error plot of these methods is presented in Fig.3. To assess the performance of proposed model statistical indicators such as MBE, RMSE, Error range, percentage annual are reported in Table-II. It is noticeable that in article [18] the latitude of the Sites has been considered as optimum tilt angle. Further, Table-I shows that prediction of maximum solar irradiance by ANN estimator is less than other methods, because the ANN is trained and tested with the experimented data unlike other methods.

In direct comparison method of statistical study it could be answered that whether one method of estimation might replace the other with sufficient accuracy. The merits of this approach are that the data will always cluster around a regression line and for comparing two methods it is much more informative. Fig.4 shows the scatter plot between ANN-PSO results with line of equality for annual period respectively. The merit of this approach is that the data will always cluster around line of regression which is more informative for comparing two methods.

TABLE II
COMPARISON OF DATA AND MODEL DRIVEN ESTIMATOR RESULTS ON ANNUAL BASIS

Parameter	Method	Annual % Error	Error Range		MBE	RMSE
β_{opt}	PSO	0.03	-1.47	1.15	0.05	1.06
	RET	7.03	-1.54	4.61	1.29	2.63
Egmax	PSO	-`1.20	-2.50	2.66	-0.22	1.47
	RET	-27.10	-8.80	5.07	-5.31	6.08
Note:1) The ANN estimator results are taken as reference[15]. 2) RET results are refereed from [23]						

6. Conclusion

The particle swarm optimization approach has been adopted to predict the optimum tilt angle of solar collector such the maximum solar energy could be collected. It is also noticeable that the performance of PSO estimator depends on the cost function formulation and selection of appropriate model input. The PSO estimator results are compared with data driven approach such as ANN. Forannual optimum solar data estimation, PSO estimator results are compared with ANN and RETScreen software results. From statistical study it also can be concluded that the PSO estimator results do not differ from data driven approach. Hence, proposed model can be used to forecast the optimum tilt angle and energy collection by solar collector. Further, this scheme could be considered more effective than ANN, if the target data for training are vague, missing or not available.

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