Intelligent model for solar energy forecasting and its implementation for solar photovoltaic applications

Gulnar Perveen,[1,a)] M. Rizwan,[2,b)] and Nidhi Goel[3,c)]
[1]*Department of Electronics and Communication Engineering, Delhi Technological University, Delhi 110042, India*
[2]*Department of Electrical Engineering, Delhi Technological University, Delhi 110042, India*
[3]*Department of Electronics and Communication Engineering, IGDTUW, Delhi 110006, India*

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As the demand for renewable energy is surging day-by-day, the solar energy data are important for applications in the field of solar photovoltaic (PV) systems. However, there exists a challenge in the collection of data owing to expensive instruments and a limited number of meteorological stations. In addition, the output of the system is largely affected due to variation in sky-conditions; therefore, an intelligent model based on sky-conditions is essential for estimating global solar energy so as to meet the energy requirements. In this work, the sky-based model employing fuzzy logic modelling has been developed and presented to forecast global solar energy using the dew-point as the meteorological parameter along with other known available parameters, namely, sunshine duration, wind speed, ambient temperature, and relative humidity for different sky-conditions, namely, clear sky (type-a), hazy sky (type-b), partially foggy/cloudy sky (type-c), and fully foggy/cloudy sky (type-d) respectively. Simulations have been performed for five meteorological stations across India that represents distinct climate zones such as composite, warm and humid, hot and dry, cold and cloudy, and moderate climate zone respectively, and the performance of the proposed model has been evaluated by using statistical indicators. The applicability of the proposed sky-based model employing fuzzy logic modelling can further be exploited for solar PV systems. The model is implemented in 210 W PV modules in forecasting the power output of solar photovoltaic systems in different sky-conditions. The obtained results reveal that the systems employing fuzzy logic modelling can be implemented for a wide range of applications and provide benefits. Furthermore, to check for accuracy of the proposed model, a comparative analysis has been carried out with the Angstrom model using statistical indicators. The value of the results, however, shows the supremacy of the proposed fuzzy logic prediction model. *Published by AIP Publishing*. https://doi.org/10.1063/1.5027824

NOMENCLATURE

a,b	coefficients [Eq. (A5)] (dimensionless)
e_i	i_{th} estimated data (dimensionless)
G_{sc}	solar constant (W/m^2)
G_T	solar irradiance at standard test condition (STC) (W/m^2)
H_g	global solar radiation (MJ/m^2)
H_o	extraterrestrial solar radiation on horizontal surface (MJ/m^2)
I_s	short circuit current of photovoltaic module at STC (A)

a)Email: gulegulnar@gmail.com.
b)Author to whom correspondence should be addressed: rizwan@dce.ac.in, Tel.: +91 9891558821
c)nnidhi.iitr@gmail.com

L	measured data
L_{max}	highest value of relevant set of data
L_{min}	lowest value of relevant set of data
L_s	normalized/scaled data
m_i	i_{th} measured data (dimensionless)
MPE	mean percentage error (%)
N_{PVP}	photovoltaic arrays in parallel (number)
N_{PVS}	photovoltaic arrays in series (number)
N_{OCT}	temperature of solar panel (^oC)
P_{max}	maximum power of photovoltaic module at maximum power point (MPP) (W)
P_{PV}	output of photovoltaic array in power at MPP (W)
$P_{PV,STC}$	the rated power output of photovoltaic single array at MPP (W)
RMSE	root mean square error (dimensionless)
S	measured sunshine duration (hours)
S_o	maximum possible sunshine duration (hours)
T_{amb}	ambient temperature (°C)
T_d	desired temperature (°C)
T_j	temperature of solar panel (°C)
V_{oc}	open circuit voltage of photovoltaic module at STC (V)
x	number of observed data (dimensionless)
X_{max}	maximum limit of normalized range
X_{min}	minimum limit of normalized range

Greek Symbols

Φ	latitude of the site (^{o})
ω_s	mean sunrise hour angle (^{o})
n_{day}	number of days of the year starting from 1st January (dimensionless)
η_o	optical efficiency (%)
δ	solar declination angle (^{o})
γ	temperature parameter at MPP

I. INTRODUCTION

Due to the growing population of the world, there is a surge in the demand for energy—specifically electricity. The production of electricity contributes the largest share in the emission of greenhouse gases that emanate from the burning of fossil fuel. So, a need has arisen for the clean form of energy, i.e., renewable energy that can contribute to the demand for energy worldwide. Major sources of renewable energy include wind, solar, biomass, and hydro, among which solar energy is the easily foreseeable and predictable form of renewable energy with no greenhouse gas emissions during its generation and its natural flow is also intense as compared to global solar energy use.

In recent times, India has emerged as one of the leading destinations for solar energy based research and applications due to the formation of ISA (International Solar Alliance) in 2016, which is headquartered at NISE (National Institute of Solar Energy). India has influenced many investors from developed countries to excel in the area of solar energy generation. More than 121 countries have joined ISA to exploit the potential of solar energy, thereby reducing the dependence on fossil fuels.

Solar energy is an important parameter for solar photovoltaic applications but the measurement devices of such parameters are not easily available at many of the meteorological centres due to limited spatial coverage and the high cost of the instruments. Therefore, it is viable to forecast global solar energy for such locations where measurements have not been done using meteorological parameters.

Many grid-connected solar power plants have been built using photovoltaics.[1] However, due to the variation in sky conditions, the output of the system is nondeterministic and stochastic. Therefore, an accurate estimation of global solar energy is required for different sky conditions as the accuracy of the system output is greatly affected by the external environmental factors like clouds, dust, moisture, and temperature differences in the atmosphere.

Many previous research studies have focused on providing a forecasting tool in order to predict the photovoltaic power output with good accuracy.[2–5] Most of them were based on autoregressive,[6] autoregressive moving average,[7] and Markov chain.[8] However, such nondeterministic models are inaccurate and found with errors as they are based on the probability estimation. In fact, predicting global solar energy by such models is not easy as it is dependent on mathematical functions. So, to overcome such a drawback, intelligent techniques[9] have been employed for modelling and estimating the solar energy.[10]

Several previous papers have dealt with intelligent modelling techniques, i.e., fuzzy logic based model applied to meteorology. Most of them deal with meteorological predictions like the circulation pattern by fuzzy c-mean,[11] and fuzzy classification of clouds.[12] The concept of fuzzy set theory has been introduced by Zadeh for forecasting solar energy from one of the commonly used parameters like the sunshine duration.[13] Various models have been proposed based on fuzzy modelling of solar irradiance.[14,15] In the past, models have been proposed using the cloudiness index and air temperature data for estimating global solar energy.[16] Fuzzy logic modelling has been proposed for predicting solar energy by using meteorological parameters for clear sky conditions.[17] Most of the previous research studies are based on clear or sunny sky conditions; however, very few literature studies are there that discussed sky-based model like hazy sky, foggy sky, and cloudy sky conditions for predicting global solar energy by employing fuzzy logic modelling.

The objective of the present work is to (i) establish the sky-based model by employing intelligent modelling to estimate global solar energy for each day of the month, defined as clear/sunny sky (type-a), hazy sky (type-b), partially foggy/cloudy sky (type-c), and fully foggy/cloudy sky (type-d) conditions, respectively, using the dew-point as one of the meteorological parameters along with other known available parameters, namely, the sunshine duration, relative humidity, wind speed, and ambient temperature, (ii) carry out simulation for five meteorological stations across India that represents distinct climate zones such as composite, warm and humid, hot and dry, cold and cloudy, and moderate climate zone, respectively, (iii) the performance of the developed sky-based model has been derived by carrying out the comparative analysis of measured data with the estimated data using statistical error tests, (iv) the results obtained by employing the fuzzy logic technique have been further implemented in 210 W HIT (Heterojunction with intrinsic thin layer) PV modules for predicting system power output at maximum power point (MPP) tracking, and (v) further, comparison has been drawn with empirical regression models using statistical indicators to check for accuracy and supremacy of the developed model.

This work is arranged as follows. The methodology where the collection of meteorological data and its normalization is carried out along with mentioning the sky conditions is presented in Sec. II. Section III presents the fuzzy logic modelling for estimating global solar energy. Section IV carries out its implementation for the solar photovoltaic application. Section V is developed to statistical evaluations. Section VI presents results and discussions. Section VII discusses the comparison of the fuzzy logic based model with the Angstrom model. Section VIII brings the conclusion which is followed by Appendix and references.

II. METHODOLOGY

A. Meteorological data

In this work, the recorded hourly data averaged month-wise from the year 2006 to 2016 have been considered which is obtained from IMD (Indian Meteorological Department), NISE (National Institute of Solar Energy), and in collaboration with NIWE (National Institute of Wind Energy).[18,19] The measured data at the meteorological sites include parameters such as the dew-point,, sunshine duration, global solar radiation, wind speed, ambient temperature, and relative humidity respectively.

The measured data have been obtained for 24 h of duration as per IST (Indian Standard Time). The parameter such as sunshine hours is measured by means of the Campbell-Stokes sunshine recorder and the measurement is done during the availability of sunshine from dawn to dusk as per LAT (Local Apparent Time). Ambient temperature is recorded by using a bimetallic thermograph, and a hygrometer is used to measure the relative humidity and dew point. An electrical anemograph is commonly used to measure wind speed whereas a pyranometer is used to measure global solar energy.

India possesses variation in climates, ranging from hot zones to cold zones with locations of high altitude. The main determining parameters for classifying the climate zones such as relative humidity, ambient temperature, and wind speed are those that most affect the heat exchange between the human body and the surroundings. The two other parameters like solar radiation and dew-point are those that influence the building design.

The criteria for allocating the location to these climate zones depend on weather conditions which prevail for more than 6 months. Based on this condition, Bansal and Minke in 1988 presented the climate zone by evaluating the average of the mean monthly climate data from the 233 different meteorological stations and made it possible to partition/divide the country into five distinct climatic zones as shown in Table I.[20]

B. Normalization

Normalization of the input parameters, namely, sunshine hours, ambient temperature, relative humidity, and wind speed, has been done so to avoid convergence issues and defined in the range of 0.1–0.9 expressed by Eq. (1). The normalization of these parameters has been obtained for five meteorological stations across India and is shown in Tables II–VI

$$Ls = \left(\left(\left(\frac{X_{max} - X_{min})}{(L_{max} - L_{min})}\right) * (L - L_{min})\right) + X_{min}\right), \tag{1}$$

where L is the measured data, L_s is the scaled data, L_{max} is the highest value of the relevant set of data, L_{min} is the lowest value of the relevant set of data, X_{max} is the maximum limit of the normalized range, and X_{min} is the minimum limit of the normalized range.

C. Classification of sky conditions

In this work, the sky-based models can be classified as follows:[21]

1. Sunny/clear sky (type-a)

If the duration of the sunshine hour is equivalent to or greater than 9 hour, and the diffuse component of solar energy is equivalent to or lower than 25% of global solar energy.

TABLE I. Climatic zone.

Climate zone	Latitude (°N)	Longitude (°E)	Meteorological station	Ambient temperature (°C)	Relative humidity (%)	No. of clear days
Composite	28.61	77.2	New Delhi, Delhi	This condition prevails when 6 months or more does not occur within any of the below mentioned category.		
Warm and humid	13.08	80.27	Chennai, Tamil Nadu	>30	>55	<20
Hot and dry	26.28	73.02	Jodhpur, Rajasthan	>30	<55	>20
Cold and cloudy	25.56	91.88	Shillong, Meghalaya	<25	>55	<20
Moderate	18.52	73.85	Pune, Maharashtra	25–30	<75	<20

TABLE II. Meteorological data and their normalization for the composite climate zone (Delhi).

	Global solar radiation (MJ/m^2)		Sunshine hours (h)		Ambient temperature (°C)		Relative humidity (%)		Wind speed (m/s)		Dew-point (°C)	
Month	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized
Jan	15.41	0.34	7.85	0.66	16.06	0.45	63.99	0.46	3.20	0.31	7.58	0.52
Feb	30.21	0.61	7.94	0.59	21.55	0.67	59.94	0.45	3.83	0.42	9.07	0.38
Mar	37.41	0.48	7.34	0.71	26.79	0.44	41.00	0.50	3.98	0.36	11.48	0.69
Apr	40.81	0.67	9.22	0.72	34.21	0.55	21.08	0.51	4.19	0.47	10.84	0.40
May	36.32	0.59	8.85	0.64	35.08	0.59	34.66	0.43	4.28	0.41	15.30	0.60
Jun	32.24	0.63	7.60	0.58	34.92	0.48	47.96	0.55	4.11	0.43	21.93	0.55
Jul	24.58	0.53	4.74	0.38	30.32	0.51	78.49	0.53	2.99	0.50	25.92	0.62
Aug	29.00	0.55	5.93	0.52	29.80	0.53	81.26	0.43	3.55	0.50	26.09	0.57
Sep	34.36	0.66	6.68	0.55	31.24	0.63	61.93	0.32	3.08	0.39	22.77	0.41
Oct	31.28	0.65	9.33	0.71	29.87	0.55	43.95	0.34	3.16	0.44	15.41	0.39
Nov	25.44	0.60	7.20	0.55	24.26	0.71	40.82	0.26	2.93	0.40	8.88	0.37
Dec	23.11	0.72	5.81	0.60	19.21	0.59	61.10	0.42	2.78	0.38	10.09	0.41

TABLE III. Meteorological data and their normalization for the warm and humid climate zone (Chennai, Tamil Nadu).

	Global solar radiation (MJ/m^2)		Sunshine hours (h)		Ambient temperature (°C)		Relative humidity (%)		Wind speed (m/s)		Dew-Point (°C)	
Month	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized
Jan	36.72	0.63	8.94	0.70	27.60	0.65	66.31	0.46	4.43	0.42	16.66	0.66
Feb	42.05	0.54	9.74	0.77	28.80	0.54	68.18	0.57	4.58	0.49	21.80	0.72
Mar	42.90	0.79	9.05	0.66	29.66	0.72	68.90	0.48	5.55	0.47	23.52	0.62
Apr	45.11	0.42	9.37	0.61	31.21	0.73	70.92	0.55	7.45	0.48	25.55	0.68
May	38.89	0.70	8.83	0.63	32.21	0.69	58.13	0.57	6.15	0.57	20.61	0.70
Jun	31.35	0.54	7.61	0.64	31.50	0.61	50.16	0.54	5.21	0.43	15.38	0.51
Jul	34.56	0.56	6.77	0.55	31.15	0.51	64.27	0.55	5.40	0.43	22.66	0.72
Aug	33.74	0.63	5.24	0.53	31.50	0.59	61.22	0.45	5.33	0.57	16.88	0.64
Sep	32.47	0.59	6.16	0.58	30.53	0.61	68.07	0.44	4.59	0.54	21.68	0.71
Oct	35.38	0.66	6.94	0.60	30.61	0.67	61.85	0.41	4.15	0.46	18.11	0.62
Nov	34.61	0.62	6.78	0.61	28.21	0.73	67.61	0.50	4.94	0.45	17.32	0.65
Dec	29.99	0.68	7.30	0.62	26.88	0.72	74.83	0.50	5.68	0.21	17.88	0.65

TABLE IV. Meteorological data and their normalization for the hot and dry climate zone (Jodhpur, Rajasthan).

Month	Global solar radiation (MJ/m^2)		Sunshine hours (h)		Ambient temperature (°C)		Relative humidity (%)		Wind speed (m/s)		Dew-Point (°C)	
	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized
Jan	29.40	0.71	9.23	0.68	21.87	0.54	52.68	0.40	2.96	0.41	11.11	0.52
Feb	25.88	0.58	9.71	0.69	23.29	0.40	43.37	0.32	3.67	0.41	10.49	0.27
Mar	41.57	0.66	9.12	0.65	29.30	0.56	43.78	0.42	3.81	0.46	14.23	0.51
Apr	45.53	0.66	9.87	0.11	33.30	0.39	39.97	0.46	4.51	0.42	10.27	0.46
May	44.67	0.66	11.21	0.72	36.17	0.45	54.05	0.45	6.64	0.45	21.58	0.66
Jun	42.40	0.63	8.94	0.68	35.37	0.42	66.53	0.55	6.94	0.40	28.83	0.55
Jul	34.38	0.55	8.04	0.64	31.72	0.65	51.79	0.51	5.32	0.56	22.05	0.56
Aug	29.27	0.59	8.10	0.68	29.12	0.57	38.74	0.41	4.35	0.47	16.69	0.54
Sep	43.06	0.64	9.73	0.67	31.15	0.43	74.12	0.66	4.63	0.50	24.03	0.65
Oct	38.69	0.73	9.79	0.79	30.19	0.57	61.76	0.48	3.46	0.44	21.28	0.59
Nov	34.81	0.59	9.32	0.77	26.31	0.51	33.59	0.32	2.61	0.40	2.73	0.37
Dec	33.15	0.54	8.50	0.35	23.84	0.60	36.78	0.43	2.84	0.41	7.27	0.52

TABLE V. Meteorological data and their normalization for the cold and cloudy climate zone (Shillong, Meghalaya).

	Global solar radiation (MJ/m^2)		Sunshine hours (h)		Ambient temperature (^oC)		Relative humidity (%)		Wind speed (m/s)		Dew-Point (^oC)	
Month	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized
Jan	25.67	0.66	7.46	0.63	18.84	0.59	60.40	0.42	2.78	0.52	10.36	0.67
Feb	31.89	0.66	6.49	0.57	22.13	0.47	54.03	0.50	3.23	0.39	12.16	0.42
Mar	34.11	0.64	7.22	0.63	25.34	0.50	50.56	0.40	3.69	0.52	13.69	0.51
Apr	32.93	0.60	3.79	0.32	25.77	0.50	66.78	0.51	4.09	0.36	18.79	0.51
May	33.66	0.52	4.84	0.48	27.20	0.54	74.97	0.55	4.35	0.36	22.31	0.53
Jun	31.45	0.66	4.18	0.49	28.14	0.72	79.62	0.29	6.21	0.53	24.26	0.61
Jul	14.12	0.5	3.25	0.4	27.19	0.4	82.34	0.6	3.19	0.3	23.84	0.7
Aug	22.09	0.56	2.50	0.44	27.04	0.57	84.82	0.52	3.98	0.45	24.30	0.61
Sep	19.58	0.53	3.29	0.39	27.15	0.43	82.38	0.52	2.72	0.38	23.80	0.65
Oct	22.37	0.46	5.87	0.56	26.31	0.45	71.68	0.50	2.01	0.34	20.75	0.54
Nov	19.46	0.47	7.06	0.63	23.76	0.43	63.47	0.51	1.78	0.27	16.35	0.50
Dec	20.43	0.56	7.60	0.63	21.35	0.50	61.23	0.56	2.56	0.45	17.25	0.52

TABLE VI. Meteorological data and their normalization for the moderate climate zone (Pune, Maharashtra).

	Global solar radiation (MJ/m^2)		Sunshine hours (h)		Ambient temperature (°C)		Relative humidity (%)		Wind speed (m/s)		Dew-point (°C)	
Month	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized	Measured	Normalized
Jan	21.43	0.45	9.50	0.53	22.91	0.56	43.38	0.38	2.42	0.33	9.01	0.39
Feb	19.44	0.61	10.21	0.73	27.01	0.56	40.73	0.49	2.83	0.45	11.50	0.49
Mar	27.62	0.46	9.90	0.69	29.08	0.49	38.98	0.52	2.98	0.43	13.77	0.48
Apr	25.99	0.62	9.97	0.65	30.73	0.51	39.98	0.41	3.14	0.40	16.28	0.46
May	22.09	0.59	10.83	0.72	30.47	0.50	48.62	0.60	4.32	0.50	18.94	0.55
Jun	18.69	0.54	5.07	0.50	26.74	0.52	68.87	0.56	4.25	0.47	20.56	0.55
Jul	16.30	0.51	4.27	0.28	24.56	0.45	80.48	0.53	4.17	0.39	20.93	0.40
Aug	17.32	0.58	4.00	0.44	24.70	0.54	77.79	0.46	4.77	0.43	20.55	0.59
Sep	17.25	0.46	5.57	0.53	25.01	0.41	73.36	0.54	3.79	0.42	19.76	0.50
Oct	10.90	0.47	7.67	0.59	24.63	0.61	65.41	0.46	2.25	0.36	18.09	0.51
Nov	13.81	0.44	8.46	0.61	21.82	0.46	53.75	0.62	2.14	0.47	11.45	0.30
Dec	25.56	0.48	8.74	0.70	24.59	0.62	43.51	0.51	2.70	0.31	10.85	0.40

2. Hazy sky (type-b)

If the duration of the sunshine hour is between 7 and 9 hours, and the diffuse component of solar energy is lower than 50% or greater than 25% of global solar energy.

3. Partially foggy/cloudy sky (type-c)

If the duration of the sunshine hour is between 5 and 7 hour, and the diffuse component of solar energy is lower than 75% or greater than 50% of global solar energy.

4. Fully foggy/cloudy sky (type-d)

If the duration of the sunshine hour is lower than 5 hour, and the diffuse component of solar energy is greater than 75% of global solar energy.

III. FUZZY LOGIC MODELLING FOR SOLAR ENERGY FORECASTING

The proposed sky-based model by employing fuzzy logic modelling to forecast global solar energy using meteorological parameters is implemented for the distinct climate zone across India as discussed in Table I.

Three variables, namely, low, medium, and high, are defined in the proposed model. The key task is the membership function assignment. Here, five membership functions have been defined using fuzzy terms defined as very low, low-medium/low, medium-high/medium, high/high-high, and very high which lie in the range of 0.1–0.9 and a set of rules are described in the fuzzy inference system for estimating global solar energy for each day of the month. The fuzzy membership function for wind speed and sunshine duration is presented inFigs. 1 and 2, respectively.

The defined fuzzy rules have been implemented using the fuzzy logic toolbox of MATLAB for developing the model to estimate global solar energy as shown in Fig. 3.

IV. IMPLEMENTING FUZZY LOGIC MODELLING FOR SOLAR PHOTOVOLTAIC APPLICATION

Generation of power from photovoltaic systems depends on sky-conditions,, solar irradiance, cell temperature, and the topographical position. In this work, the HIT (Heterojunction with intrinsic thin layer) photovoltaic module of 210 W power output is chosen and operated at maximum power point tracking. Since the generation of PV power is greatly influenced by solar irradiance and temperature, so only these parameters are used in this paper. The data which include solar irradiance, cell temperature, and photovoltaic power output is obtained and arranged within 1 h. The data are collected on the daily basis as the availability of solar irradiance during the summer

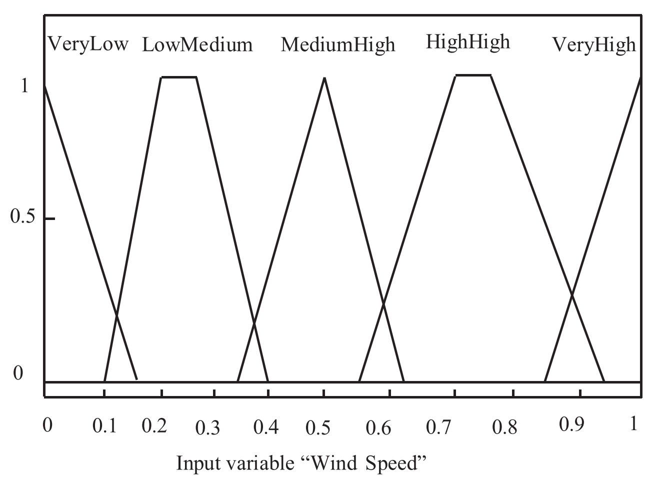

FIG. 1. Graphical representation of fuzzy logic membership functions for wind speed.

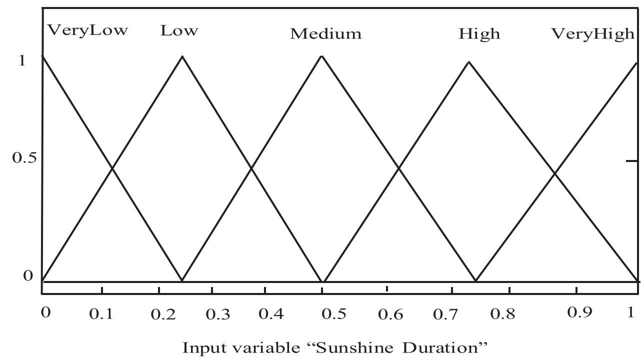

FIG. 2. Graphical representation of fuzzy logic membership functions for the sunshine duration.

season is from morning 6:00 A.M. till evening 18:00 P.M. In the winter season, the variation is from morning 8:00 A.M. till evening 17:00 P.M.

Fuzzy logic modelling has been employed for the prediction of the power output from the solar PV system. The fuzzy system takes solar irradiance, temperature, and weather descriptions as the input follow the process of Fuzzification and rule evaluation, and finally produces output power for forecasting.

Specification details of 210 W HIT photovoltaic modules are as follows:

The efficiency of the module: 16.7%
The efficiency of cell: 18.9%
Short circuit current: 5.57 A
Open circuit voltage: 50.9 V
Ambient operating temperature: −4 °F to 115 °F
N_{OCT} (Normal operating cell temperature): 114.8 °F

Based on the standard test conditions (STC) and influence by input parameters such as solar irradiance and cell temperature, the generation from the photovoltaic system can be defined as follows:[22]

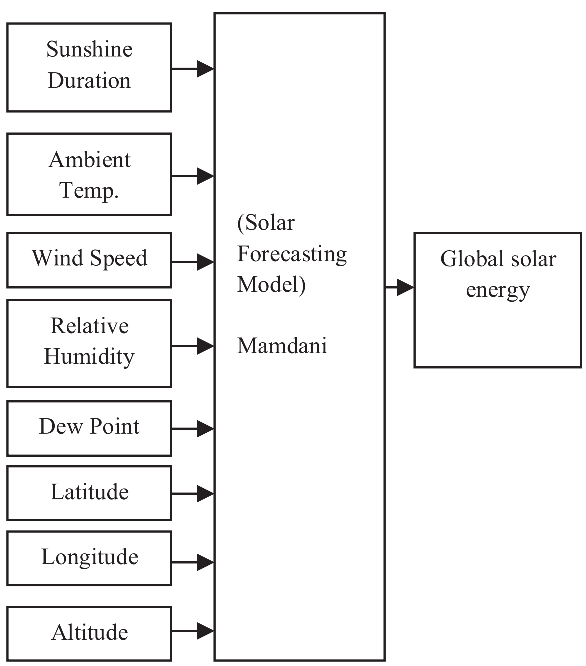

FIG. 3. Model-based on fuzzy logic technique for estimating global solar energy.

$$\mathrm{P_{PV}} = \left[P_{PV,STC}\,\mathrm{X}\,\frac{G_T}{1000}X\left[1-\gamma\,\mathrm{X}\,(T_j - 25)\right]\right]\mathrm{X}\,N_{PVs}\,\mathrm{X}\,N_{PVp}\,, \tag{2}$$

and

$$T_j = T_{amb} + \frac{G_T}{800}X\,(N_{OCT} - 20), \tag{3}$$

where $\mathrm{P_{PV,STC}}$ is the rated power output of the photovoltaic system of the single array at the MPP, $\mathrm{P_{PV}}$ is the power output of the photovoltaic array at the MPP, $\mathrm{G_T}$ is the solar irradiance in $\mathrm{W/m^2}$ at the STC, $\mathrm{N_{PVS}}$ is the photovoltaic arrays in series in number, γ is a temperature parameter at the MPP, $\mathrm{N_{PVP}}$ is the photovoltaic arrays in parallel in number, $\mathrm{T_{amb}}$ is the ambient temperature in °C, $\mathrm{T_j}$ is the temperature of the solar panel in °C, and $\mathrm{N_{OCT}}$ is a constant.

The average power output of the solar photovoltaic system can be predicted by employing the fuzzy logic technique and is presented in Fig. 4.

V. STATISTICAL EVALUATION

For evaluation of the models, statistical error tests have been carried out, namely, mean percentage error and mean bias error for result comparison.

Mean Percentage Error (MPE) is described as the variation of the forecasted data with the measured data, and the relationship is given by

$$\mathrm{MPE} = \frac{1}{x}\sum\nolimits_{i=1}^{x}\left(\frac{e_i - m_i}{m_i}\right), \tag{4}$$

where x is the number of observed data, and m_i and e_i are the i_{th} measured and estimated data, respectively.

Mean Bias Error (MBE) is expressed by the following equation:

$$\mathrm{MBE} = \frac{1}{x}\sum_{i=1}^{x}(e_i - m_i), \tag{5}$$

where x is the number of observed data, and m_i and e_i are the i_{th} measured and estimated data, respectively. On comparing the measured and the estimated values, the long-term performance can be obtained for correlations, and its ideal value is "zero."

VI. RESULTS AND DISCUSSION

The sky-based model employing fuzzy logic modelling has been developed and presented for predicting global solar energy using meteorological parameters such as the dew-point besides using other commonly known parameters like the sunshine duration, ambient temperature, wind speed, and relative humidity for the distinct climate zone across India. The results obtained using intelligent modelling are then compared with the measured data for five meteorological stations across India that represents the distinct climate zone, namely, composite climate, hot and dry, warm and humid, cold and cloudy, and moderate climate zone, respectively. The performance of the proposed model is then evaluated based on statistical indicators and is presented in Table VII.

Based on the results obtained in Table VII, the following can be briefly summarized:

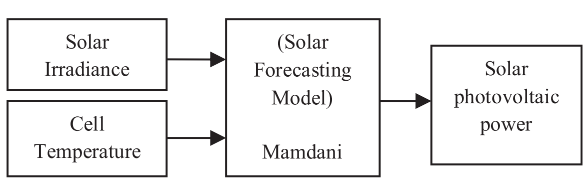

FIG. 4. Model based on fuzzy logic technique for estimating the photovoltaic system power output.

TABLE VII. Estimated global solar energy by employing fuzzy logic modelling for different sky-conditions along with statistical error for the distinct climate zone across India.

Climate zone	Sky conditions	H_g (MJ/m^2)		Sunshine hours (h)	MPE (%)	MBE (%)
		Measured	Fuzzy			
New Delhi (Composite)	Clear/sunny sky (type-a)	29.96	30.20	9.30	1.94	0.24
	Hazy sky (type-b)	29.71	29.76	8.09	0.22	0.05
	Partially foggy/cloudy sky (type-c)	23.93	23.88	6.30	1.96	−0.05
	Fully foggy/cloudy sky (type-d)	23.13	22.54	0.30	−2.56	−0.59
Chennai (Warm and humid)	Clear/sunny sky (type-a)	38.60	36.80	10.28	−4.32	−1.80
	Hazy sky (type-b)	32.98	36.49	8.58	6.82	0.07
	Partially foggy/cloudy sky (type-c)	37.93	37.50	6.61	−0.80	−0.43
	Fully foggy/cloudy sky (type-d)	34.79	35.73	2.26	5.79	0.94
Jodhpur (Hot and dry)	Clear/sunny sky (type-a)	38.63	37.81	12.36	−1.23	−0.82
	Hazy sky (type-b)	36.93	36.35	8.67	1.39	−0.57
	Partially foggy/cloudy sky (type-c)	35.35	31.72	6.63	−7.90	−3.63
	Fully foggy/cloudy sky (type-d)	36.56	38.58	2.84	4.39	2.02
Shillong (Cold and cloudy)	Clear/sunny sky (type-a)	31.30	30.12	9.546	−2.74	−1.18
	Hazy sky (type-b)	24.48	25.45	7.256	5.77	0.97
	Partially foggy/cloudy sky (type-c)	26.25	26.25	4.443	9.05	−0.002
	Fully foggy/cloudy sky (type-d)	32.68	32.41	1.200	0.36	−0.30
Pune (Moderate)	Clear/sunny sky (type-a)	20.25	20.61	10.12	4.75	0.28
	Hazy sky (type-b)	19.70	19.68	8.46	0.89	0.26
	Partially foggy/cloudy sky (type-c)	18.89	18.94	6.08	1.78	0.04
	Fully foggy/cloudy sky (type-d)	16.42	16.01	2.85	−0.89	−0.41

A. Clear/sunny sky (type-a) condition

It is observed that by employing fuzzy logic modelling for estimating global solar energy, the minimum value of mean percentage error for this model is 1.23% which is obtained for the Jodhpur station representing hot and dry climate zones as shown by the computed data presented in Table VII.

This is due to the fact that the climatic condition of Jodhpur is hot and dry as the variation in relative humidity is from 33% to 74% as shown in measured data presented in Table IV, which is generally low, because of low water surface bodies and vegetation.

The sky is generally clear, with high solar irradiance during daytime as the surrounding atmosphere got heated up quite fast. In addition to this, the average hours of the bright sunshine throughout the year is 12.36 h, which is much higher as compared to other meteorological stations as shown by the computed data presented in Table VII. During the night as well, the sky is generally clear; therefore, the heat absorbed by the surface during the daytime got dissipated to the upper atmospheric layer quickly. Hence, during the night the ambient temperature is low which makes it much cooler than during the daytime. Jodhpur is also well-known as the 'Sun City' for clear and sunny weather which prevails throughout the year.

B. Hazy sky (type-b) condition

It is observed from Table VII that the minimum value of mean percentage error by employing fuzzy logic modelling for this model is 0.22% which is obtained for the Delhi composite climate zone.

The reason behind is the presence of high humidity which shows the variation from 35% to 61% during dry periods and 64% to 81% during wet periods as shown in measured data presented in Table II. In addition, the intensity of solar radiation is quite high during summer and low during monsoon as the average of the bright sunshine hours computed throughout the year is 8.09 h, as shown by computed data presented in Table VII, which is comparatively less as compared to that in the hot and dry climate zone. The sky is generally dull and overcast during monsoon and hazy during summer.

C. Partially foggy/cloudy sky (type-c) condition

It can be seen in Table VII that the minimum average forecasting precision by employing fuzzy logic modelling for this model is 0.80% in mean percentage error for the Chennai station, which represents the warm and humid climate zone.

This is due to the fact that the diffuse radiation component of solar energy is comparatively higher because of cloud cover as the average bright sunshine is 6.61 h only. The reason might be the presence of clouds because of which the heat dissipation from the surface of the earth to the sky during night time is minimal. Hence, the sky is partially cloudy as ambient temperature varies from 30 to 35 °C at daytime and 25 to 30 °C at night time during summer which is quite low. During winter, the variation in maximum ambient temperature is from 25 to 30 °C during the day and 20 to 25 °C during the night. A typical feature of this zone is the relative humidity varying from 58% to 74% throughout the year, which is generally high, as shown by measured data presented in Table III.

D. Fully foggy/cloudy sky (type-d) condition

It is observed that the minimum value of mean percentage error employing fuzzy logic modelling for this model is 0.36% for the Shillong station, which represents the cold and cloudy climate zone as shown by computed data presented in Table VII.

The reason behind is that the intensity of solar insolation is quite low during winter because of the presence of the diffuse component of solar energy which makes winters extremely cold. The summers are comparatively quite pleasant as the variation in maximum air temperature lies between 25 and 30 °C during daytime and 17–27 °C during the night, whereas the winters are comparatively chilly. In addition, the relative humidity shows variation from 50% to 85% which is generally high, as shown by measured data presented in Table V. Sky is generally overcast and cloudy throughout the year except during short summer as the daily average hours of the bright sunshine is 1.20 h only as shown by the measured data presented in Table VII.

In addition, the graphical representation showing the comparison of measured data with the estimated data has been presented in Figs. 5–9 for different sky-conditions for five meteorological stations across India, respectively.

As shown in Figs. 5–9, the predicted data obtained by employing fuzzy logic modelling for different sky-conditions are almost the same as the measured data and the model performance is observed to be satisfactory.

The sunny/clear sky (type-a) model performs best for the Jodhpur station which represents the hot and dry climate zone, as the predicted data exactly match the measured data as shown in Fig. 7(a).

The hazy sky (type-b) model shows the best results for the New Delhi station which represents composite climate zone, as the predicted data exactly match the measured data as shown in Fig. 5(b).

Similarly, the partially foggy/cloudy sky (type-c) model is best for the Chennai station which represents the warm and humid climate zone, as the predicted data exactly match the measured data as shown in Fig. 6(c).

Also, the fully foggy/cloudy sky (type-d) model is best for the Shillong station which represents the cold and cloudy climate zone, as the predicted data exactly match the measured data as shown in Fig. 7(d).

The obtained results are further simulated for solar photovoltaic applications. In this section, the solar radiation data collected from IMD and NISE are used to assess the proposed fuzzy logic model. In the present work, the HIT (Heterojunction with intrinsic thin layer) PV module of 210 W is selected and operated at maximum power point tracking. The data in the input layer comprise cell temperature, solar irradiance, and sky information obtained from NISE and the output layer is the power. The forecasted solar photovoltaic system power output

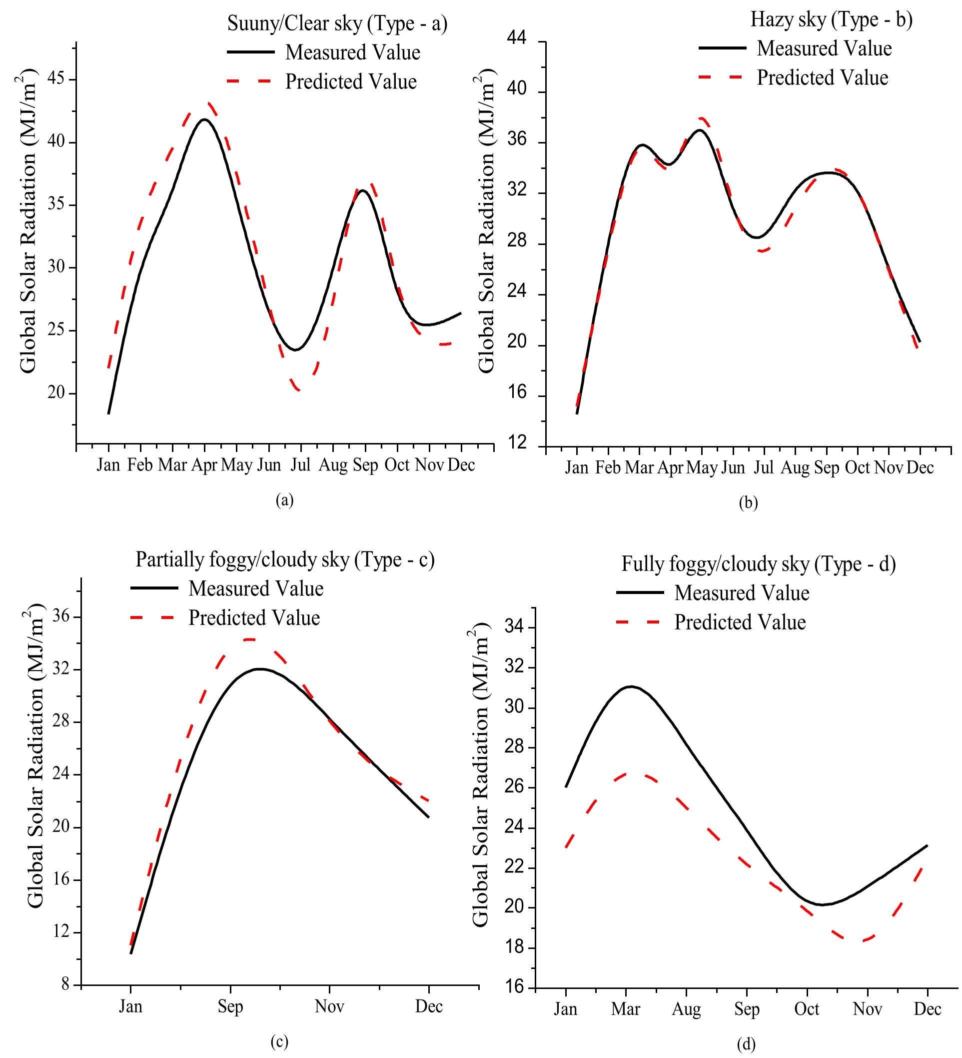

FIG. 5. Comparison of measured data with the forecasted data of global solar energy for composite climate (Delhi).

employing the fuzzy logic technique obtained month-wise for year 2012 for a given solar irradiance level and cell temperature is presented in Table VIII for the Delhi composite climate zone.

Table VIII shows that the mean percentage error (MPE) of the solar photovoltaic system power output averaged month-wise is 0.0581% by employing fuzzy logic modelling, which is within the permissible error limit.

Furthermore, the different sky-conditions affect different forecast behaviour of solar radiation. Pure sunny, hazy, partially foggy/cloudy, and fully foggy/cloudy models are considered and performance has been evaluated based on statistical indicators and results are presented in Table IX. Normally, the day considered here is the combination of different periods of hazy, sunny, partially foggy/cloudy, and fully foggy/cloudy sky-conditions considered during daytime.

In one sunny/clear day, the variation between the measured and the forecasted data using the proposed fuzzy logic methodology is shown in Fig. 11(a). The time considered is from morning 7:00 A.M. till evening 18:00 P.M. As compared to the factor of temperature, here the factor of time plays a major role that mostly affects the solar radiation. The average of mean percentage error calculated between the measured and the forecasted data is observed to be 0.0741% for the sunny-sky model as presented in Table IX.

In one hazy day, the variation between the measured and the forecasted data using the proposed fuzzy logic methodology is shown in Fig. 11(b). The time considered is from morning

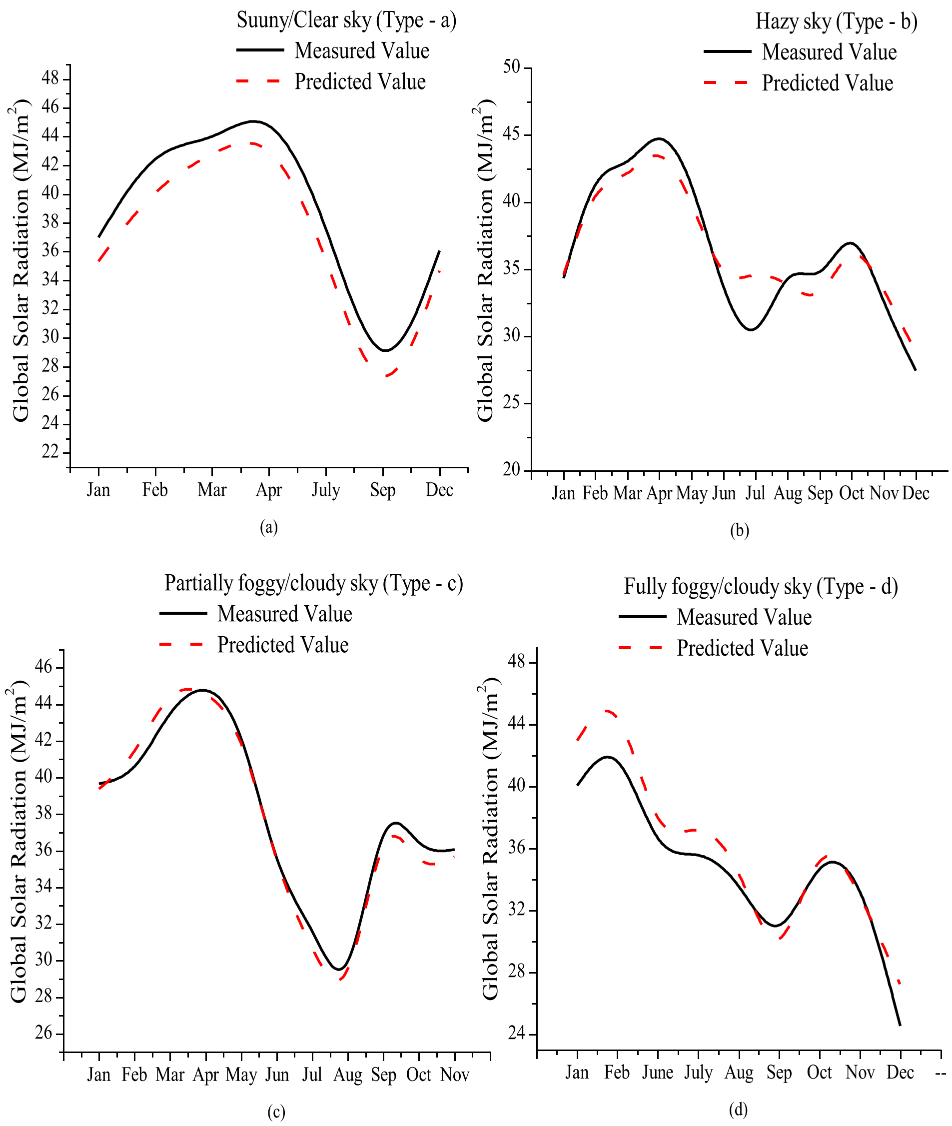

FIG. 6. Comparison of measured data with the forecasted data of global solar energy for warm and humid climate (Chennai, Tamil Nadu).

10:00 A.M. till evening 16:00 P.M. In a hazy-sky day, the sun rays will get obstructed and the factor of temperature affects the solar irradiance most as compared to the time factor, which is not the same as in the case of sunny day. The maximum value of solar irradiance is 519.54 W/m^2 and the averaged of mean percentage error between the measured and the forecasted data is 0.0031% for the hazy-sky model as presented in Table IX.

In one partially foggy/cloudy day, the variation between the measured and the forecasted data using the proposed fuzzy logic methodology is shown in Fig. 11(c). The time considered is from morning 8:00 A.M. till evening 19:00 P.M. The sunshine is partially absorbed by the photovoltaic and partially by the cloud. Here, the solar radiation has a close relationship with both the temperature factor and the time factor. The average of mean percentage error between the measured and the forecasted data for this studied partially foggy/cloudy sky model is 0.0072% as presented in Table IX.

In one fully foggy/cloudy day, the variation between the measured and forecasted data using the proposed fuzzy logic methodology is shown in Fig. 11(d). The time considered is

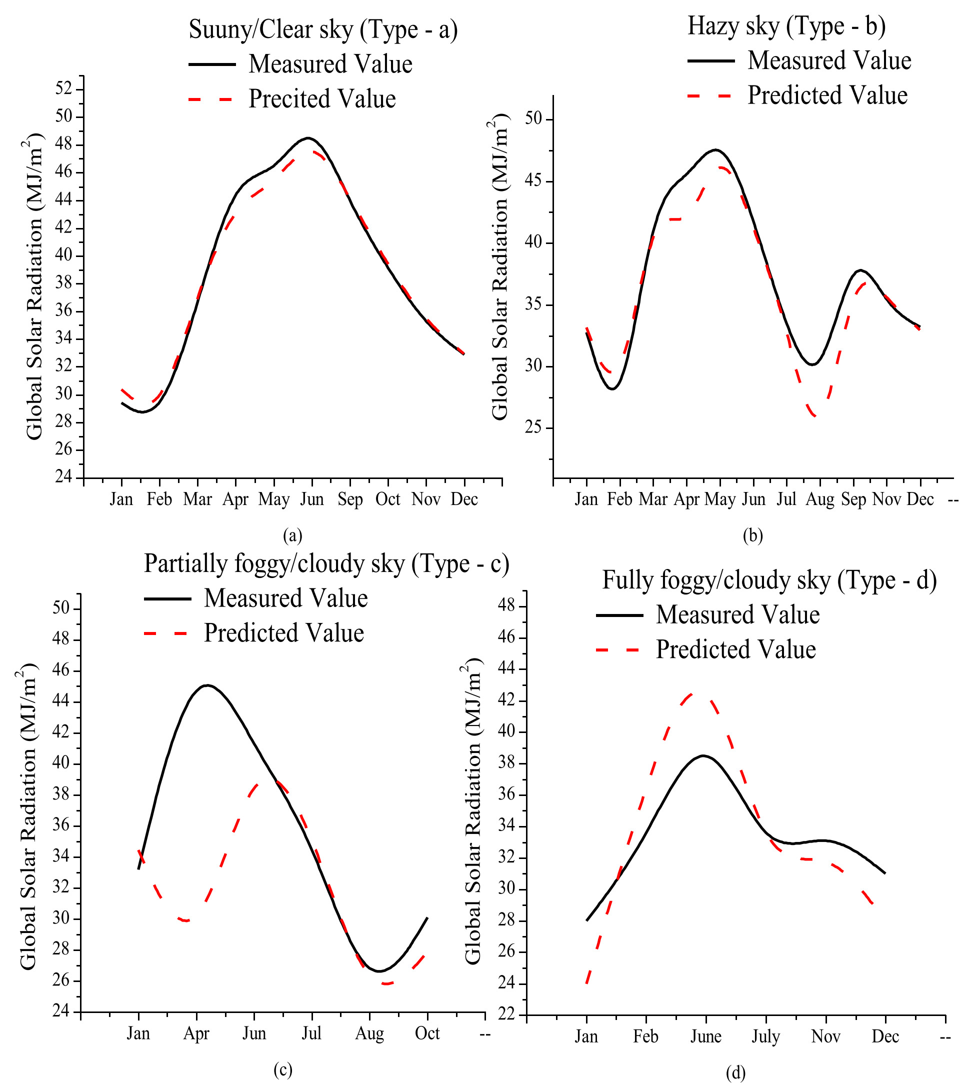

FIG. 7. Comparison of measured data with the forecasted data of global solar energy for hot and dry climate (Jodhpur, Rajasthan).

from morning 9:00 A.M. to evening 15:00 P.M. The maximum value of solar irradiance is 164.25 W/m^2. In this, the sun rays will get fully blocked by the presence of cloud and both the factor of time and temperature will affect the solar radiation. The average of mean percentage error between the measured and forecasted data for this fully foggy/cloudy sky model is 0.0077% as presented in Table IX.

From Table IX, it is observed that out of the four models, especially the sunny-sky and hazy-sky model perform well in forecasting of power of a solar photovoltaic system in the Delhi composite climate zone. In addition, the industrial requirements have been satisfied as the short term photovoltaic power forecasting MPE is not greater than 20%. However, for each of the sky-models, the mean percentage error fluctuates, as presented in Fig. 10.

The variation in mean percentage error for different sky-conditions between the measured and predicted data during day time is shown in Fig. 10. The variations in the error is highest for the sunny/clear sky model in comparison to other sky-conditions, the reason behind is that the average value of solar insolation is relatively large as compared to other sky conditions.

For the Delhi composite climate zone, the hazy-sky model gives the best results with a mean percentage error of 0.0031%, followed by the sunny-sky model, partially foggy/cloudy

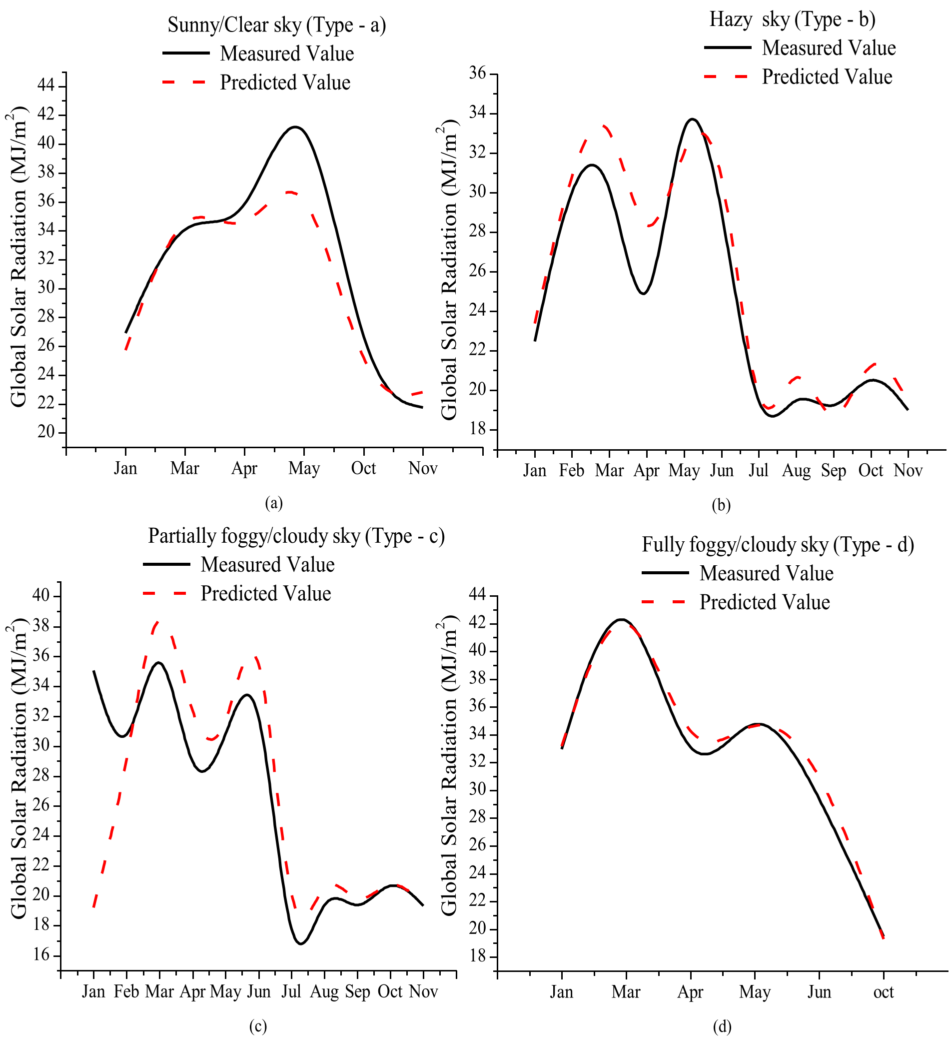

FIG. 8. Comparison of measured data with the forecasted data of global solar energy for cold and cloudy climate (Shillong, Meghalaya).

sky model, and fully foggy/cloudy sky model with a mean percentage error of 0.0741%, 0.0072%, and 0.0077%, respectively, as shown in Table IX. After the study, the average value of forecasting errors of the proposed model is 0.0027% in mean percentage error for the sample photovoltaic installation. The following graph further demonstrates the variation in the measured and the forecasted data for different sky-conditions as shown in Fig. 11.

From Fig. 11, it is learnt that the hazy-sky model (Type-b) shown in Fig. 11(b) outperforms other models as the measured data exactly match the estimated data for the Delhi composite climate zone.

However, for Figs. 11(c) and 11(d), there are significant differences between the measured and the estimated data in partially foggy/cloudy and fully foggy/cloudy models. In the present case, the solar photovoltaic system is installed at NISE, Delhi, where the sunny and hazy day is present during most of the year.

VII. COMPARISON OF THE FUZZY LOGIC BASED MODEL WITH EMPIRICAL REGRESSION MODELS

Empirical models have been developed using the above-mentioned meteorological parameters through linear regression analysis for widely changing climatic conditions across India and are reported in Appendix. The performance of models has been measured using mean

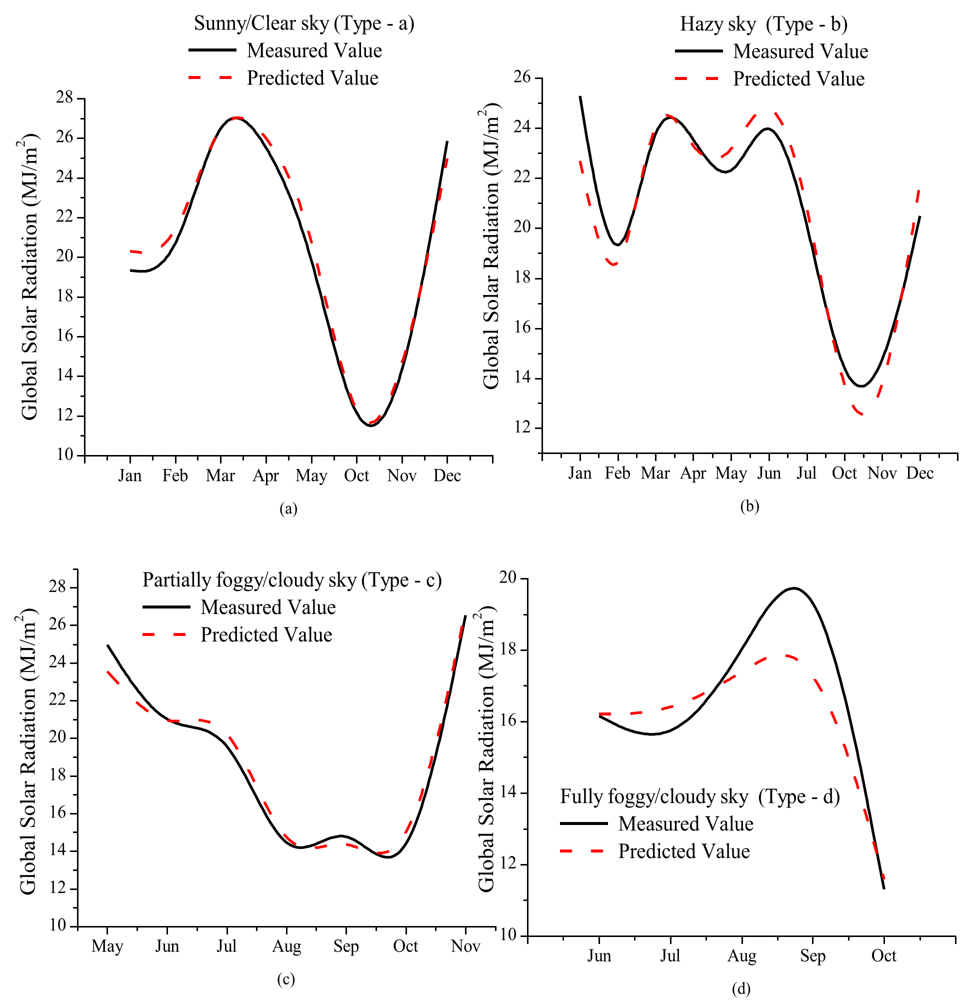

FIG. 9. Comparative analysis of measured and predicted data of global solar energy for moderate climate (Pune, Maharashtra).

TABLE VIII. Forecasted power of the solar photovoltaic system employing 210 W HIT (Heterojunction with an intrinsic thin layer) PV modules averaged month-wise in the Delhi composite climate zone.

					Power (W)		
Month	Solar irradiance (W/m^2)	V_{oc} (V)	I_{sc} (A)	Cell temperature (^{o}C)	Measured	Forecasted	MPE (%)
Jan	361.15	81.47	0.42	28.14	20.80	19.79	−0.0064
Feb	461.52	82.03	0.61	35.69	30.15	30.02	0.0060
Mar	548.24	83.64	0.62	40.12	31.56	31.25	0.0100
April	575.12	79.62	0.60	42.53	30.23	32.56	0.1500
May	559.67	77.35	0.59	46.22	31.05	35.19	0.1938
June	537.17	76.92	0.55	45.24	26.20	26.00	0.0166
July	537.81	76.66	0.05	48.28	24.45	25.72	0.0023
Aug	428.80	76.90	0.47	53.27	22.33	22.59	0.0308
Sep	437.51	77.78	0.50	51.62	23.80	23.99	0.0378
Oct	466.57	78.74	0.63	53.21	29.92	29.40	−0.0090
Nov	369.82	78.48	0.44	45.08	20.85	20.65	−0.0173
Dec	370.84	80.66	0.47	43.36	25.53	32.57	0.2827
Avg.	471.18	79.19	0.50	44.40	26.41	27.48	0.0581

TABLE IX. Forecasted power of a solar photovoltaic system using 210 W HIT PV modules for different sky-conditions in the Delhi composite climate zone.

Sky-conditions	Time (h)	Cell temperature (°C)	Solar irradiance (W/m^2)	Power (W)		MPE (%)
				Measured	Forecasted	
Sunny/clear sky (type-a)	7:00	34.11	140.93	7.00	7.03	0.0036
	8:00	40.55	273.76	15.00	15.00	−0.0002
	9:00	48.14	486.12	30.33	30.34	0.1749
	10:00	52.23	625.25	41.67	41.66	0.1210
	11:00	57.79	783.13	54.17	54.18	0.1271
	12:00	62.86	875.34	60.50	60.50	0.0702
	13:00	64.69	888.95	61.17	61.18	−0.0060
	14:00	63.91	744.96	42.00	42.00	−0.3153
	15:00	61.55	726.73	46.33	46.33	0.3563
	16:00	58.04	549.15	31.50	31.51	−0.3178
	17:00	52.72	361.60	19.33	19.33	−0.4892
	18:00	48.83	204.59	9.80	9.80	−0.6141
	Avg.	53.79	555.04	34.90	34.90	−0.0741
Hazy sky (type-b)	10:00	40.83	123.10	7.00	7.12	0.0218
	11:00	44.49	146.12	9.67	9.70	0.0040
	12:00	43.56	307.56	24.17	24.20	0.0031
	13:00	52.55	519.54	45.50	45.46	−0.0008
	14:00	42.40	467.65	37.33	37.40	0.0018
	15:00	49.36	313.06	21.50	21.50	0.0003
	16:00	41.05	185.35	10.20	10.09	−0.0082
	Avg.	44.89	294.62	22.20	22.21	0.0031
Partially foggy/cloudy sky (type-c)	8:00	45.79	134.08	10.25	10.26	0.0024
	9:00	47.49	179.69	13.00	12.99	−0.0021
	10:00	52.07	355.98	30.33	30.14	−0.0063
	11:00	55.57	463.45	40.17	40.78	0.0130
	12:00	58.38	547.32	44.67	44.39	−0.0117
	13:00	59.96	519.74	33.00	31.40	−0.0372
	14:00	55.52	492.69	41.00	40.93	−0.0001
	15:00	61.30	647.10	52.00	51.69	−0.0105
	16:00	59.64	562.02	34.67	35.16	0.0094
	17:00	50.88	299.99	18.17	18.22	0.0049
	18:00	50.73	235.30	12.83	12.65	−0.0158
	19:00	47.99	156.43	6.50	7.23	0.1405
	Avg.	53.78	382.82	28.05	27.99	0.0072
Fully foggy/cloudy sky (type-d)	9:00	19.08	170.77	10.67	10.75	0.0120
	10:00	19.02	74.87	10.67	10.62	−0.0030
	11:00	23.29	96.49	9.00	8.72	−0.0042
	12:00	18.50	41.20	8.00	8.10	0.0105
	13:00	18.57	140.77	10.33	10.46	0.0500
	14:00	18.59	87.31	11.17	11.14	0.0067
	15:00	17.86	164.25	11.00	10.83	−0.0183
	Avg.	19.27	110.81	10.12	10.09	0.0077

percentage error. The developed model based on the fuzzy logic technique is then compared with the empirical models and the obtained results are shown in Table X.

Table X shows that the fuzzy logic based model has less value of mean percentage error for all meteorological stations. So, the comparison result shows that the model developed by

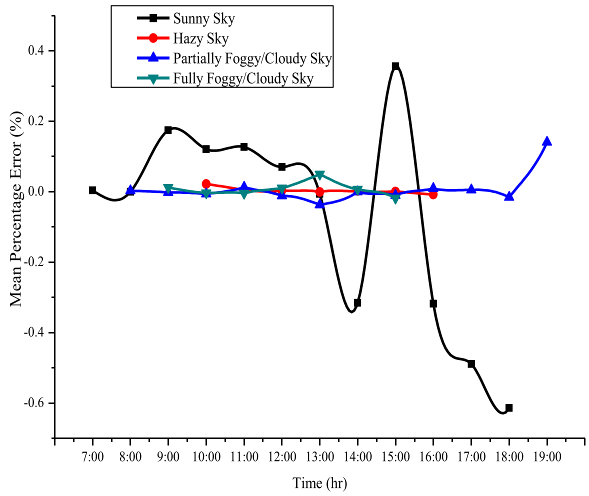

FIG. 10. Mean percentage error of four forecasting sky-based models.

implementing fuzzy logic modelling provides the best result which is accurate and convenient as compared to empirical regression models.

VIII. CONCLUSIONS

In the present work, sky-based models have been developed and presented using fuzzy logic modelling for estimating global solar energy for five meteorological stations across India that represents the distinct climate zone. The meteorological parameters such as the dew-point are considered besides using other known available parameters, namely, the sunshine duration, relative humidity, ambient temperature, and wind speed for different climatic zones. Since there is always ambiguity in climatic conditions, it is difficult to predict the solar energy accurately by using mathematical equations and regression techniques at particular location for different

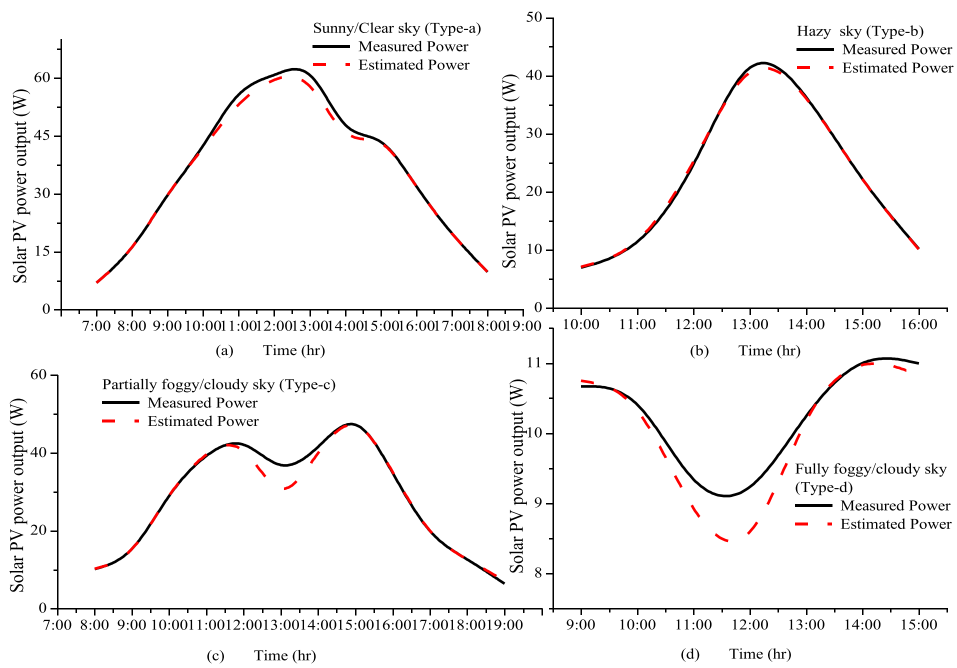

FIG. 11. Graphical representation of the estimated power of a 210 W solar photovoltaic system for different sky-conditions for the composite climate of India (Delhi).

TABLE X. Comparison of the proposed fuzzy logic based model with the Angstrom model.

		Fuzzy		Angstrom	
Station	Measured H_g (MJ/m^2)	H_g (MJ/m^2)	MPE	H_g (MJ/m^2)	MPE
New Delhi (Composite)	18.27	18.28	0.41	18.29	0.70
Chennai (Warm and humid)	19.53	19.51	0.37	19.59	2.25
Jodhpur (Hot and dry)	20.41	20.44	0.02	20.27	0.41
Shillong (Cold and cloudy)	16.45	16.49	0.68	16.88	1.94
Pune (Moderate)	19.36	19.33	0.06	19.86	2.40

sky-conditions. However, such problems may be overcome by employing fuzzy logic modelling for sky-based models using meteorological parameters for different climatic zones across India. Two criteria, namely, mean percentage error and mean bias error, are used to verify the forecasting errors of the proposed modelling approach. Numerical results revealed that the proposed fuzzy logic modelling approach achieves better accuracy and is convenient than the traditional regression methods.

Fuzzy logic modelling has been implemented for solar PV applications as well and a sky-based model employing fuzzy logic modelling has been presented for 1 h ahead power output forecasting of solar photovoltaic systems based upon the principle of fuzzy logic modelling and the characteristics of weather/sky classification. The results obtained through correlation analysis show that the forecasting error of the proposed model is 0.0027% (MPE) for the sample photovoltaic installation. The fuzzy logic approach favours results for the application of the sky-based model in forecasting of photovoltaic power of solar PV systems.

The proposed sky-based model employing fuzzy logic modelling may be further implemented for solar thermal applications that would be helpful for estimating the output of the solar thermal system.

APPENDIX: BRIEF DESCRIPTION OF CONVENTIONAL METHOD

A number of methods have been reported using empirical relationships to estimate global solar radiation, and daily total extraterrestrial radiation H_o is often included in the relationships. H_o was calculated using standard geometric procedures.[23,24] To calculate H_o and S_o at different locations, a program in MATLAB been developed.

The daily extra-terrestrial radiation H_o has been worked out by using the following relation:

$$H_O = \frac{24\times 3600}{\pi} G_{SC}\left(1 + 0.033\cos\frac{360 n_{day}}{365}\right)\times\left(\cos\Phi\cos\delta\sin\omega_s\frac{\pi\omega_s}{180}\sin\Phi\sin\delta\right), \tag{A1}$$

$$\boldsymbol{\delta} = 23.45\,\sin\left[\frac{360}{365}(n_{day}+284)\right], \tag{A2}$$

$$\omega_s = \cos^{-1}(-\tan\Phi\tan\delta). \tag{A3}$$

The value of S_o can be computed from Cooper's formula

$$S_o = \frac{2}{15}\cos^{-1}(-\tan\Phi\tan\delta), \tag{A4}$$

where G_{sc} is the solar constant, assumed equal to 1367 W/m^2, Φ is the latitude of the site, δ is the solar declination angle, ω_s is the mean sunrise hour angle, and n_{day} is the number of days of the year starting from January onwards. First of January, n_{day} is equal to 1 and for 31st of December it is 365. S is the monthly mean of the daily hours of bright sunshine; and S_o is the maximum daily hours of sunshine or day length.

1. Angstrom-type model

The first theoretical model for predicting global solar energy based on the duration of sunshine hours has been proposed by Angstrom in 1924.[25] The original form of the Angstrom-Prescott model is

$$H_g/H_o = a + b * (S/S_o), \tag{A5}$$

where a and b are the regression coefficients calculated for each month. In this paper, the above model in its original formulation is used, where regression analysis has been carried out with input parameters, namely, sunshine duration per hour (S/S_o), ambient temperature, dew-point, wind speed, and relative humidity, while the output parameter is the clearness index (H_g/H_o). The estimated global solar energy is obtained by multiplying the estimated clearness index by H_o where H_g is the global solar radiation and H_o is the extra-terrestrial radiation on a horizontal surface.

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