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Research Article

TEMPERATURE AND PRESSURE BASED ESTIMATION OF DAILY GLOBAL SOLAR RADIATION OVER TURKEY USING FUZZY LOGIC MODELING

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ABSTRACT

In this paper, a fuzzy logic model (FLM) for the prediction and modeling of daily average solar radiation over Turkey is developed. The daily values of ambient temperature and relative pressure durations as meteorological data are utilized for our FLM. These data for estimating solar radiation are generally obtained easily. Moreover, the calculated daily solar radiation values by using the FLM for selected twelve cities are compared with the actual data and the national database of selected cities. For similarity tests, the most common statistical procedures (MAE, RMSE, MSE, MAPE and R^2) are utilized. The fuzzy logic based models show the stable processor different meteorological data introduced to the operation for modeling of daily average solar radiation.

INTRODUCTION

Most of the world's energy needs are met by burning fossil energy sources, with a small contribution from nuclear power. Worldwide energy demand has increased year by year over the last twenty years. The burning of coal, oil and natural gas to generate power causes environmental pollution although modern technology can limit the amount emitted. Environmental pollution due to toxic gas (CO) emissions, acid rain due to the emission of (SO_2) and (NO_X), global warming due to the production of large quantities of (CO_2) and (CH_4) and radioactive waste products are some of the major factors requiring attention to reduce harmful effects to the planet. Renewable energy, such as hydroelectricity, solar, wind, geothermal, tidal, wave and biomass based technologies are inexhaustible and there is a continuous and free supply. Among other renewable energy sources, solar and wind energy are the two most available sources. Utilization of the solar energy for electrical power generation is being given serious consideration around the world. Installation of solar panels on rooftops and building cladding using solar cells can provide considerable energy, cutting down the pollution due to the burning of fossil fuels. Turkey lies in a sunny belt between 36° and 42°N latitudes. The country has a high potential for solar radiation, with yearly average solar energy being about 4.18kWh/(m^2day) and the daily average duration of sunshine being approximately 7.5 hours (Ulgen and Hepbasli 2003),(Bakirci 2015). Therefore, the solar energy potential of the country is very high. The daily global solar radiation coming from a horizontal surface and as well as the duration of daily sunshine are evaluated by a number of meteorological stations in Turkey (Kaygusuz and Sarı 2003),(Sözen and Arcaklioğlu 2005). The prediction and performance of solar energy systems using simulation methods usually requires weather data (Mohammadi, Shamshirband *et al*. 2016). These methods can create a number of problems due to there being potential significant variances between the recurrent days of the year. Moreover, the determination of solar radiation is a very difficult process as determination apparatuses are required to be continually calibrated and maintained (Ozturk 2015). The different methodologies for the determination of hourly global solar energy coming on the horizontal surface per day have been elaborated upon and proposed by many researchers both theoretically and experimentally.

Rizwan *et al*. (Rizwan, Jamil *et al*. 2014) have submitted an FLM that estimates the hourly basis of global solar radiation for smart grid applications in New Delhi, Jodhpur, Kolkata and Shillong stations. In their paper, they measured meteorological data as the duration of sunshine and ambient temperatures, and

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the geographical indicators of the selected stations were taken as input indicators. They compared the outputs from the FLM with the measured meteorological data and announced that the percentage error was within the allowable limit.

Paulescu *et al*. (Paulescu, Gravila *et al*. 2008) have presented FLM based algorithms for the global solar radiation determination. They have found as the FLM is an accurate alternative to classical approaches to determine quantities of solar energy. In their paper, the beam, diffuse and direct atmospheric transmittances, geographical and time coordinates are used as input parameters for the fuzzy logic based model.
Chen *et al*. (Chen, Gooi *et al*. 2013) analyzed global solar radiation estimating techniques based on the fuzzy logic model and the artificial neural network (ANN) model to obtain a good correctness in different ambient cases. They classified the ambient cases and reference temperature indicators as different fuzzy series based on the fuzzy codes. Moreover, they compared the output results from development techniques with different models and found that these models were adequate for determining daily global solar energy. Gomez and Casanovas (Gomez and Casanovas 2003) proposed a model based on fuzzy logic to determine solar radiation on an inclined plane. Their FLM included notions from earlier design studies, and although dissimilar to these design studies, our paper considers non-disjunctive environment status. The main disadvantage of their fuzzy model is that the correctness of the prediction outputs was not as good as that of the ANN in only one ambient situation.

Mohammadi *et al*. (Mohammadi, Shamshirband *et al*. 2015) studied an adaptive neuro-fuzzy system (ANFIS) to determine of the daily global solar radiation coming onto a horizontal surface. They used the days of a year as the input parameter. For this goal, the long-term evaluated daily global solar radiation values for Tabass in Iran were used for the neuro fuzzy-based model. Moreover, they tested the supposed model by using some statistical methods, such as the bias error (BE), mean absolute percentage error (MAPE), root mean square error (RMSE) and the correlation coefficient (R^2).

Piri and Kisi (Piri and Kisi 2015) analyzed the ANFIS and neural network autoregressive approach with exogenous input (NN-ARX) techniques to determine the daily global solar radiation values in two different areas with different ambient conditions in Iran. They also compared the suggested approach with the Angstrom, Hargreaves and Samani approaches by using the same input indicators. The measurement studies of daily average solar radiation were made at only a limited number of sites. Hence, it is important to improve approaches to determining the solar radiation on the basis of the more readily available meteorological data. The objective of this paper is to estimate the daily average solar radiation potentials in Turkey based on the FLM using the meteorological data of twelve stations. The daily average values of solar radiation for the selected cities are also calculated for each day of a typical month. The calculated daily values are compared with the actual data.

Figure 1 Area of study.

Solar Radiation Parameters

To use simulation models to predict the output from systems under the influence of solar radiation, hourly data values are usually required. Twelve stations in different locations and climates covering Turkey, such as Tekirdağ, Izmir, Denizli, Zonguldak, Bilecik, Burdur, Samsun, Kayseri, Antakya, Artvin, Elaziğ and Van, were selected for this paper and their locations are illustrated in **Fig 1**. In the determination of daily global solar radiation, geographical and meteorological indicators play a significant role (Çelik, Teke *et al*. 2016),(Kisi 2014). The FLM can utilize ambient temperature and pressure, latitude, longitude, altitude, month, duration of sunshine and wind velocity, which can be categorized into two group indicators for the prediction of daily global solar radiation values:

- meteorological; and
- geographical.

Meteorological data for twelve stations are given that cover the several climatic locations of Turkey and their features are given in **Table 1**. The geographic indicators, such as longitude, latitude and altitude, and data period for selected cities, are given in this table. A total period of six years of daily solar radiation in Turkey (2005 to 2010), which is available at the data library of the Turkish State Meteorological Service (DMI), is used.

Fuzzy Logic Approach

The concept of the fuzzy set originates from the observation made by Zadeh (Zadeh 1996) to order classes of objects encountered in the real world that do not have precisely defined criteria of belonging. These classes of objects are present both in the mental representations of reality and in the terminology used in natural language and therefore absent in the usual mathematical representations that make use of the binary logic of exact formulas of differential equations and so on. In this regard, the mathematician A. Sangalli (Mohammadi, Shamshirband *et al*. 2016) states that: “In the ideal world of mathematics things are certain and precise; but in the real world precision and absolute certainty are very rare goods".

Nowadays, fuzzy set theory is defined as that discipline which contains concepts and techniques that form a mathematical structure capable of manipulating the vague and blurred concepts present in the processes of human thought. The purpose is to provide a formal approach so as to be able to manage incomplete and gradual information as expressed by natural language. In general, fuzzy theory includes all those

disciplines that use the basic concepts of fuzzy sets, including:

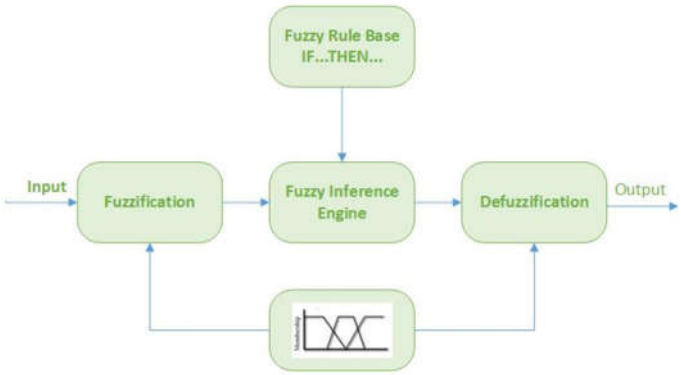

Figure 2 Components and information flow in a fuzzy rule-based system.

1. Mathematics fuzzy: Here the concepts of classical mathematics are extended to replace classical sets with fuzzy sets.
2. Fuzzy logic and artificial intelligence: The former allows propositions to take true values in the interval [0, 1]. This generalization makes it possible to deduce inaccurate conclusions from inaccurate premises. In the field of artificial intelligence, on the other hand, expert systems are developed using approximate reasoning and fuzzy information.
3. Fuzzy systems: Such systems include fuzzy control and fuzzy approaches in both signal processing and communications.
4. Fuzzy decision making: This discipline deals with optimization problems in the presence of soft constraints.

Table 1 Geographical parameters of considered cities in Turkey.

Cities	Longitude(E°)	Latitude(N°)	Altitude(m)
Tekirdag	40.59	27.29	4
Izmir	27.10	38.26	29
Denizli	37.47	29.05	05
Zonguldak	41.27	31.48	136
Bilecik	40.09	29.58	526
Burdur	30.18	37.43	957
Samsun	36.18	41.17	4
Kayseri	35.29	38.54	1093
Antakya	36.15	36.07	100
Artvin	41.49	41.11	628
Elazığ	38.40	39.13	1105
Van	4.17	38.27	1661

The Construction of a Fuzzy System

Given the universe of speech *S*, a fuzzy set *A* in *S* is characterized by a membership function $\mu_A(x)$ which associates to each element of *S* a real number in [0,1]. That is:

$\mu_A(x): S \to [0,1] \quad for \quad x \in S.$

Using a different notation, the membership function relating to the fuzzy set *A* can be written in the form $A: S \to [0,1] \quad with \quad x \in S$, we will use both notations. When *S* is a continuous universe, then the fuzzy set A is commonly written as:

$$A(x) = \int_u \frac{\mu_A(x)}{x},$$

where $\int_u$ is not the well-known integral symbol, but indicates the set of pairs $(\mu_A(x), x)$ present in *S*. If *S* is a discrete set, then *A* can be written as:

$$A(x) = \sum \frac{\mu_A(x)}{x}.$$

A triangular fuzzy number $x = [a, b, c]$ in [0,1] is a fuzzy set whose membership function is a triangle, whose vertices are represented by the points $(a, 0), (b, 1) \quad and \quad (c, 0)$. A fuzzy partition is a succession of fuzzy sets $\{A_1, \ldots\ldots, A_n\}$ defined in S such that $\forall i \in N$ we have:

1. $A_i \neq \emptyset$ and $A_i \neq S$.
2. $\sum_{i=1}^{n} A_i(x) = 1, \quad \forall x \in S.$

Suppose that S and T are two universes of discourse with the peculiarity:

$S = S_1 \times S_2 \times \ldots \times S_n \subset R^n \quad and \quad T \subset R.$

Let $x = (x_1, \ldots, x_n)$ and y elements of S and T, respectively,and also assume that the fuzzy rules base of the system we want to construct, with which the problem is represented linguistically such that the rule will have the following form:

$r_j = if \ x_1 \ is \ A_1^j \ and \ldots and \ x_n \ is \ A_n^j, then \ y \ is \ C^j \ for \ j = 1, \ldots, m.$ (1)

Where $x_1, \ldots, x_n$ are the linguistic variables of the inputs and y is the linguistic variable of the output, while A_i^j and C^l are respectively the fuzzy set in S_i and T. They represent, respectively, the linguistic value of the linguistic variable x_i and linguistic variable y in the rule r_j. The rules inside the base of fuzzy rules ought to have the following properties:

1. Completeness, where, for $\forall x \in S$ there is at least one rule in the fuzzy rule base such that $A_i(x_i) \neq 0$ for $i = 1, \ldots, N$.
2. Consistency: If in the fuzzy rules base, there are no rules with the part *if*, and the part *then* different.

Described the form of the fuzzy rules, one will have to specify the way in which a real value of the input is transformed by the system into a fuzzy set. This task is entrusted to fuzzification. In practice, this operation is defined as a way of associating a value $x^* \in S \subset R^n$ to a fuzzy set A' defined in S. In the case under examination, the fuzzy set triangular and trapezoidal membership function will be used, which is given as follows:

$$\mu_{A'}(x) = \begin{cases} 0, & x \leq a, \\ \frac{x-a}{b-a}, & a \leq x \leq b, \\ \frac{c-x}{c-b}, & b \leq x \leq c, \\ 0, & c \leq x. \end{cases} \quad (2)$$

and

$$\mu_{A'}(x) = \begin{cases} 0, & x \leq a, \\ \frac{x-a}{b-a}, & a \leq x \leq b, \\ 1, & b \leq x \leq c, \\ \frac{d-x}{d-c}, & c \leq x \leq d, \\ 0, & d \leq x. \end{cases} \quad (3)$$

MATERIALS AND METHODS

The data series utilized for the development of the fuzzy logic based approach contains the daily global solar radiation measurements of 12 cities in Turkey. The quantities of the

daily global solar energy data coming from these areas of investigation have been saved hourly between 2005 and 2010. The analyzed provinces are randomly selected from 141 present stations covering the entire country. In these meteorological terminals, the global solar radiation rate coming onto a horizontal surface is determined hourly using pyranometers calibrated in the DMI calibration office, which is accredited by the Turkish Accreditation Agency in Ankara, Turkey (Demirhan 2014),(Bakirci 2009). The daily global solar radiation data were measured during the same period of the month or year.

Statistical Approaches Used for Comparison

The statistic provides numerous parameters or combination indices to quantify and qualify the differences between observations and predictions and therefore be taken as a reference to establish the overall goodness of a series of predictions. The conformity of the approaches is investigated based on the common statistical error tests, including the mean absolute error (MAE), mean square relative error (MSE), root mean square error (RMSE), mean absolute percentage error (MAPE) and the coefficient of determination (R^2) (Şenkal 2010). The MAE, MSE, RMSE, MAPE and R^2 are defined as follows (Willmott and Matsuura 2005):

The Mean Absolute Error (MAE)

The Mean Absolute Error is given by:

$$\mathrm{MAE} = \frac{\sum_{t=1}^{n} |G_{i,c} - G_{i,m}|}{n} \quad (4)$$

It allows the estimation of the average absolute forecast error, but it does not provide information on the sign of such errors. It is important to consider this indicator together with the bias (the average error) where:

$$\mathrm{Bias} = \frac{\sum_{t=1}^{n} (G_{i,c} - G_{i,m})}{n}$$

Mean square relative error (MSE)

The formula for calculating the value of MSE is as follows:

$$\mathrm{MSE} = \frac{\sum_{t=1}^{n} (G_{i,c} - G_{i,m})^2}{n} \quad (5)$$

Its square root provides a further statistical index, the so-called Root Mean Square Error (RMSE or Root Mean Square Deviation, RMSD). The MSE and RMSE are not dimensional quantities, but they do assume the unit of measure of the considered quantity (RMSE) and its square (MSE).

Root mean square error (RMSE)

The Root Mean Square Error (or RMSE) is a measure of quantitative performance commonly used to evaluate demand forecasting methods. In this context, the RMSE consists of the square root of the sum of the quadratic errors. In comparison with the MAE, the RMSE amplifies and penalizes with greater force those errors of greater magnitude. The calculation formula of the RMSE is as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{t=1}^{n} (G_{i,c} - G_{i,m})^2}{n}} \quad (6)$$

Mean absolute percentage error (MAPE)

The mean absolute percentage error (MAPE) is a measure of the prediction accuracy of a prognostication methodology in statistics, as an example in trend estimation. It always expresses accuracy as a proportion and is outlined by the formula:

$$\mathrm{MAPE} = \frac{\sum_{t=1}^{n} \left| \frac{G_{i,c} - G_{i,m}}{G_{i,m}} \right|}{n} \quad (7)$$

Coefficient of determination (R^2)

The coefficient of determination is a proportion between the variability of the data and the correctness of the statistical model used. It measures the fraction of the variance of the dependent variable

Table 2 Statistical results.

Cities	MAE	RMSE	R^2
Tekirdag	0.228	0.357	0.849
Izmir	0.207	0.299	0.815
Denizli	0.212	0.281	0.814
Zonguldak	0.309	0.43	0.8289
Bilecik	0.249	0.378	0.8224
Burdur	0.191	0.290	0.8140
Samsun	0.212	0.269	0.8049
Kayseri	0.258	0.451	0.8376
Antakya	0.159	0.216	0.866
Artvin	0.222	0.284	0.844
Elazig	0.547	0.830	0.8920
Van	0.140	0.183	0.8751

expressed by regression. There is no agreed definition of (R^2). In simple linear regressions, it is simply the square of the correlation coefficient:

$$R^2 = 1 - \frac{\sum_{t=1}^{n} (G_{i,c} - G_{i,m})^2}{\sum_{t=1}^{n} (G_{i,m})^2} \quad (8)$$

where $G_{i,m}$ is the i^{th} measured global radiation, $G_{i,c}$ the i^{th} calculated global radiation and n the total number of measurements. In this paper, the predictive performances of the proposed models are evaluated using the MAE, RMSE and R^2. The RMSE presents some important data on the short-term effects of the relationships by providing a similarity of the real deflection between the calculated and measured values session by session. On the other hand, several great errors in the sum could generate an important increase in the RMSE data. The MAE presents some significant data on long-term performance. The positive values of the MAE provide the average quantity of overprediction in the calculated value, whereas the negative values show an underdetermination of daily global solar radiation. The main barrier in this model is the overprediction of any individual observational concerns under the prediction in a separate observation. For the proposed approaches be a good estimator, the mean values of all the errors terms, i.e. MAE, MAPE, and RMSE, should be at a minimum, and R^2 should be as high as possible (Iqbal 2012).

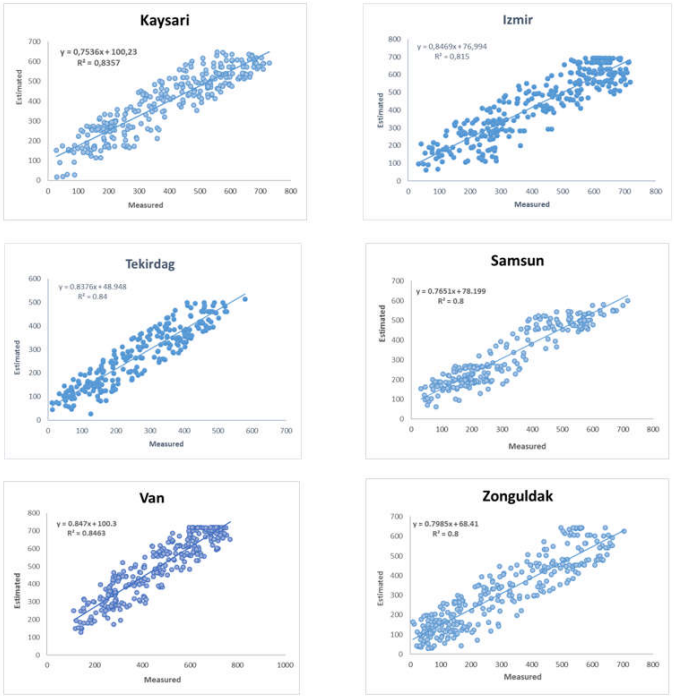

Figure 3 Variation of observed and estimated solar radiation values for the cities(Antakya,Artvin,Bilecik,Burdur,Denizli and Elazig).

RESULTS AND DISCUSSION

The determination of daily average solar radiation is an important indicator for a region as the utilization of solar energy spreads in many different fields. To estimate the daily global solar radiation at various stations in Turkey, a fuzzy logic model has been written in MATLAB Toolbox. Two meteorological parameters include:

*the daily values of ambient temperature; and
* the relative pressure duration of 12 evaluated cities for a year being used for the fuzzy logic based approach.

For this purpose, the fuzzy logic based approach is trained with the one year averaged measured meteorological data taken from February 2005 to November 2008. The meteorological data are also tested with one years averaged measured meteorological data taken from February 2009 to November 2010. The output value is the daily global solar radiation, which is measured in CAL/cm^2. It is important to observe that the fuzzy logic based model is recognized from a series of numerical inputs. Therefore, it is necessary to have the adequate input indicators, representative of all feasible daily global solar radiation. The determining approaches of how many input indicators are required to build the FLM supplying suitable outputs are the main subject of this paper. The correctness and possibility of investigating the FLM technique are evaluated based on the investigation of different statistical models, such as R^2, MAE and RMSE. The error results for different regions in Turkey are illustrated comparatively in Table 2.

A number of different objective functions are examined to determine the most suitable model. After training studies, the FLM is examined to determine the daily global solar radiation over Turkey. In addition, the correlation plots for estimated outputs from the FLM and the measured solar radiation values are illustrated in Fig 3 and 4, respectively. It is clearly seen that all output results show good agreement between measurement data and FLM outputs. The provided results illustrate that the defined fuzzy logic based model supplies sufficient efficiencies. Additionally, the acceptable results were found using the fuzzy logic approaches, as shown in Table 2, and An example, effects of the inputs on outputs can be shown in Fig 5.

The variations between the output values of different cities are probably due to monthly changes of the solar energy apparently created by the grade of cloud cover, availability of water vapor, the ozone layer, and ambient atmospheric dust that varies from one region to another. The lowest RMSE (0.183CAL/cm^2) and MAE (0.14CAL/cm^2) were obtained for Van and the highest R^2 (0.892) was calculated for Elazig. These results demonstrate the good rate of correlation outputs between measured and determined daily global solar radiation. Therefore, the fuzzy logic based models should be used as an alternative approach to determining the daily global solar radiation outputs for the provinces, where methodological measurements do not exist. The proposed model can be used in determining solar radiation for any province where it is necessary to install solar energy based electricity generation systems. Furthermore, the proposed methods can be used for daily global solar radiation maps for provinces and countries.

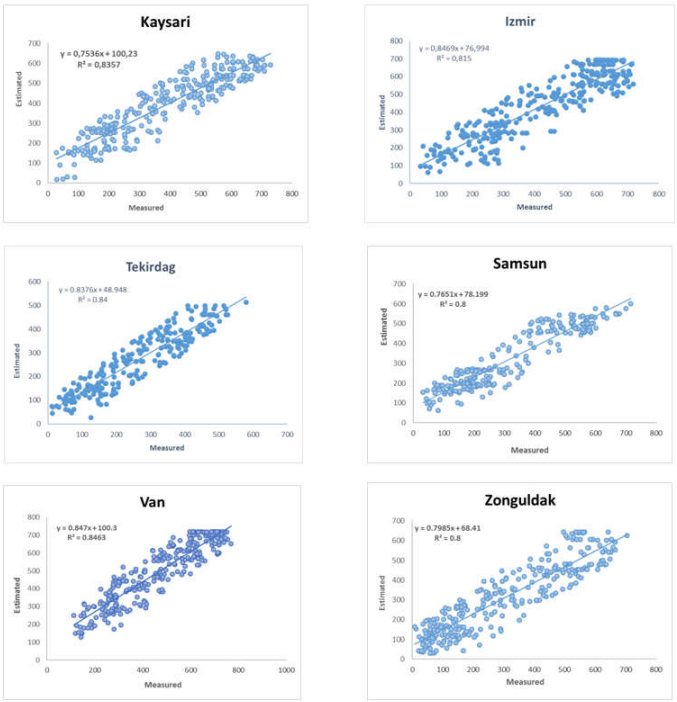

Figure 4 Variation of observed and estimated solar radiation values for the cities(Izmir,Kaysari,Tekirdag,Samsun,Van and Zonguldag).

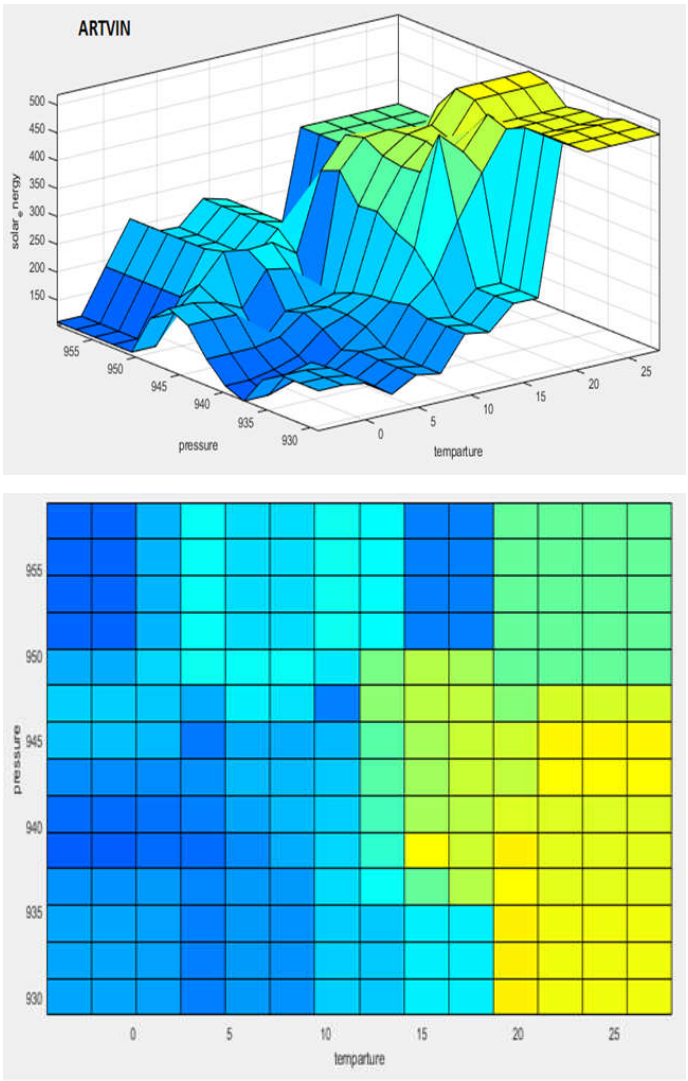

Figure 5 Effects of the inputs on outputs for Artvin city. These graphics created using Fuzzy Logic Toolbox-FIS Editor-Surface Viewer in Matlab R2011a. The 3D graphic created using plot type"surface" and the 2D graphic created using plot type"Psuedo-Color".

CONCLUSION

Turkey is a country with an abundance of solar energy throughout the year for clean energy applications based on solar radiation. In this paper, the monthly average daily global radiation incident on a horizontal surface is determined using the FLM also in addition to the daily solar radiation for 12 months for individual years being used for the FLM approach. The meteorological data, such as daily values of ambient temperature and relative pressure duration of the evaluated cities for a year, are evaluated as input entry indicators. The FLM application for predicting the daily average solar radiation should fill the gap for the assessment of the efficiency of many applications of solar power processes at a certain site. The proposed novel methodology can provide more simplicity than many empirical models to evaluate solar radiation possibilities in provinces where a network of monitoring centers has not yet been installed in the country. The following concluding remarks are drawn from this paper:

- The ensured outputs in this study show that the FLM based approach for solar energy is suitable for the determination of the daily average solar radiation in an investigated region;
- The FLM can be used to determine solar radiation from measured meteorological data for a selected region; and
- The major originality of this paper is the selection of input parameters, such as ambient temperature and relative pressure. These meteorological data are measured easily. Moreover, it can be illustrated that the input indicators are accurate on R^2 outputs.

FLM	fuzzy logic model
DMI	State Meteorological Service of Turkey
MAE	mean absolute error
RMSE	root mean square error
MSE	mean square relative error
MAPE	mean absolute percentage error
R^2	coefficient of determination
ANN	artificial neural network
ANFIS	neuro fuzzy system.
$G_{i,m}$	the i^{th} measured global radiation
$G_{i,c}$	the i^{th} calculated global radiation
n	the total number of the measurements.

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