THE PREDICTION OF SOLAR RADIATION USING FUZZY LOGIC: A CASE STUDY

JWAN ABDULKHALIQ MOHAMMED* and BERIVAN HADI MAHDI**
* Dept. of Computer Science, College of Science, University of Duhok, Kurdistan Region-Iraq
** Branch of Basic Science, College of Agriculture, University of Duhok, Kurdistan Region-Iraq

(Received: May 23, 2018, Accepted for publication: October 22, 2018)

ABSTRACT

Solar energy is used in many applications such as producing agricultural food, renewable energy, and heating and lighting systems... etc. Nowadays, countries all over the world, especially the developing countries are facing a great challenge which is providing sustainable energy for consumers. Electricity is the most common type of energy that is used by consumers in which oil or nuclear power is used to produce sufficient amount of electricity for the constant increase of the population in the present. However, both oil and nuclear energy negatively affect the global warming; therefore, solar energy is aspired by many countries to decrease the effects of the global warming and produce renewable sources of energy. The aim of this study is to predict the use of solar radiation for solar energy to produce electricity in Duhok city due to the fact that “national electricity” is not enough for the great number of consumers; as a result, people depend on “local or private generators” which mainly depend on oil to produce electricity. Fuzzy logic approach is used to estimate the solar radiation. The four fuzzy systems are created using the available data in Duhok City in 2016. Daily observations for temperature, humidity and wind speed for four seasons are analyzed to estimate the solar radiation. The predicted outputs of fuzzy logic system are compared with the actual solar radiation. In addition, the fuzzy system approach is evaluated using Mean Absolute Percentage Error (MAPE) and Absolute Percentage Error (APE). The outcomes of MAPE and APE are 5.86%, 1.54%, 2.76% and 1.52 for four seasons (winter, summer, spring and fall), respectively. According to the results, the performance of fuzzy system is reasonably effective in predicting the solar radiation.

KEYWORDS: Fuzzy logic, Solar radiation, Prediction, Membership functions

INTRODUCTION

Forecasting defined as the process of predicting the value of a variable or variables in the future (Yazdani et al., 2014). Solar radiation is defined as “the radiation, or energy emitted by the sun in the form of electromagnetic radiation in the wavelength range of the measuring instrument”. One of the most significant green sources is solar radiation which is recently used in some countries. Solar radiation is usually measured very well in sunny and clear days than cloudy days. Coops and others (Coops et al., 2000) have conclude that the location of a specific area and meteorological parameters or weather conditions affect the solar radiation. Consequently, the precise prediction of any energy production in solar systems includes the precise estimation of solar radiation which relies on various atmospheric parameters. Recently, many research studies have been evolved to attempt to estimate solar radiation utilizing artificial intelligence mechanisms and meteorological parameters such as wind speed, temperature and humidity ...etc. One of the significant mechanisms is fuzzy logic.

A membership function in fuzzy sets is used as the representation of continuous nature of data. One of the controlling technologies in Artificial Intelligence (AI) is the theory of fuzzy set which is broadly used in load forecasting. For instance, normal linguistic variables can be modeled at cognitive level, which are ambiguous at the cognitive level (Pujar, 2010; Ibrahim, 2003). There are many uncertainties in load forecasting like the difference in temperature, rainfall, wind speed, atmosphere pressure and solar radiation which cannot be numerically specified precisely (Mordjaoui et al., 2010). For this reason, the most convenient method to be used, under such conditions, is the fuzzy logic approach.
In the literatures many techniques of forecasting have been evolved. These comprise artificial neural network (ANN), the ARMA model, exponential smoothing, data mining models, linear regression and fuzzy logic (Filik et al., 2011; Ismail et al., 2011). Amongst these techniques, ANN and fuzzy logic are widely utilized. Because of the distinct characteristics of fuzzy logic, the fuzzy logic overcomes ANN (Karwade and Ali, 2015). For example, there is a reasonable variation among the weather factors and solar radiation; the fuzzy logic system can treat the variation with low estimation error.

In this paper, solar prediction for future planning utilizing fuzzy logic system is suggested and the following aims can be fulfilled; the first aim is to develop a rule base to identify precise solar prediction and the second aim is to develop a fuzzy logic model to predict a future solar. Fuzzy logic approach is utilized to show the highly nonlinear relationships (using membership function) between weather factors and their outcomes on the highest load on a month basis of the year (Fan et al., 2007). There are many factors that affect solar radiation such as temperature, humidity, wind speed, cloud cover, pressure ... etc. However, temperature, humidity and wind speed were utilized as inputs to the fuzzy logic because they have direct influence on solar radiation when the solar radiation is an output.

METHODOLOGY

Description of Study Area

Duhok governorate is located in north of Kurdistan, region of Iraq. (43.20 – 44.10) longitude, (36.40 – 37.20) latitude, close to both Syrian & Turkish borders. Duhok city is surrounded by two series of mountains, Zawa Mountain from the south and Bekher Mountain from the north, while it is rather plain from east and west sides. Basically, there are four seasons in Duhok city –KRG and the climate of Duhok is moderate; it is sunny hot in summer, cold and wet in winter and spring and fall are partly sunny and wet. In general, summer and winter are longer than the other seasons, where summer starts from June to the beginning of September and winter starts from October to the end February. Thus, fall is September and spring starts from March to the end of May.

Method of Data Collection

The data (the inputs and output parameter) is gathered from the Weather Station of College of Agriculture in Sumel, University of Duhok for four seasons in Duhok city in 2016 for four seasons (winter, summer, fall, and spring). This was the only available data for the study. This data are temperature, humidity and wind speed for inputs and solar radiation for output.

Fuzzy System (FSs)

FSs are also known as fuzzy model, fuzzy logic controller and rule-based system. FSs consist of multiple-valued logics in which more than two values can be true. The values of variables can be approximate between 0 and 1 depending on reasoning. The main notion of fuzzy set was initially introduced by Lotfi Zadeh in 1965 (Ali et al., 2016). The theory of fuzzy set can be regarded as a generalized classical set theory (Jantakoon, 2016). Generally, in the classical set theory, there are two options for an element which may belong to a specific set or not. Thus, the crisp value is the aspect that determines the degree of being a member in a particular set. Yet, the degree of a membership of an element in fuzzy set theory may vary permanently. The scope of the fuzzy set is between \( \{0,1\} \) (Zadeh, 1965). In fuzzy logic, linguistics terms are used to express the values of variables. The input and output variables are connected utilized fuzzy IF-THEN rules, where the IF part represents the fuzzy antecedent and the Then part represents the fuzzy consequent, that also takes the form of fuzzy set. The format of creating rules is similar to human reasoning because it is based on the ‘IF-THEN’ expressions.

FSs include four major phases, the fuzzification, the fuzzy rule base, the fuzzy inference engine and the defuzzification. The block diagram in Figure 1 shows the procedure of the fuzzy system.
The first phase is fuzzification method which converts the crisp values into fuzzy values using membership functions. Triangular membership functions are used in this study for input and output variables. The second phase, the fuzzy rule base is formed using the fuzzy operator and input and output variables. The fuzzy system includes input variables which are temperature, humidity and wind speed. Output is solar radiation. The AND and OR operators are used to correlate the input variables (Bunnoon, 2011). The third phase is the fuzzy inference engine which includes the application of the membership functions of inputs and the fuzzy rules base to maintain the membership function of output. This operation is called the implication method through which a fuzzy set of output by giving a number for each input. Then, the aggregation process is applied to join membership functions of each rule and get one output fuzzy set (Yazdanbakhsh and Dick, 2017). The final phase is defuzzification method which converts the output fuzzy set into a crisp value using Center Of Area method (COA) which is the most common defuzzification method (Swaroop and Abdulqader, 2012). Three well-known models exist in FSs which are Sugeno-type, Mamdani-type and Tsukamoto-type. This study concentrates only on Mamdani-type because it is more convenient for the aims of this study.

**Fuzzification**

Fuzzification is the operation that converts crisp values of input variables into fuzzy values (Cornelis and Kerre, 2003). Linguistic terms are the use of words in artificial or natural language to represent information with several degree of ambiguity (Jeon et al., 2009).

In this study, solar radiation is an output, while temperature, humidity and wind speed are inputs. Each variable has its linguistic terms and it will be classified based on the degree of vagueness. Solar radiation is classified into VeryLow, Low, LittleLow, and Medium. Temperature is classified into Low, Medium, and High. Humidity is categorized into Dry, Medium, and Wet, and wind speed into VeryLow, Low, Medium, and High.

The below equation is a triangular membership function which is used to evaluate linguistic expressions for variables and their membership functions.

\[
\mu_A(x) = \begin{cases} 
0, & x \leq a \\
\frac{x-a}{m-a}, & a < x \leq m \\
1, & x \geq b 
\end{cases}
\]

Where a is the minimum limit, b is the maximum limit and m is the value between a and b.

**Membership Functions (MFs)**

Membership function is the graphical representation which determines how each value in the input space can be transformed to membership value which is between 0 and 1. Input space is normally known as the universe of discourse (µ), that involve all of relevant elements for every specific application (Hong and Lee, 1996).

Hence, the solar radiation, temperature, humidity and wind speed are considered as the universe of discourse or fuzzy sets. Then, these fuzzy sets are categorized into linguistic variables which have been mentioned in the previous section (Cornelis and Kerre, 2003).

There are several sorts of MFs like gaussion, trapezoidal, triangular, sigmoid and bell-shaped. However, triangular membership functions have been used for this study due to their simplicity. In addition, simple formulas and computational efficiency are used in these MFs. Plus, they have straight lines segment, so they can be easily implemented in FSs (Bauer, 2018).
In this study, triangular membership functions are used to fuzzify the crisp values. Figure (2) shows the membership functions and ranges for each variable in the fuzzy system, the ranges of parameters have been adopted from the above mentioned weather station. Overlap among antecedent membership functions is essential to decrease the sensitive errors. As shown in the below figure (2), the overlap occurs between membership functions when their scopes partly cover each other. In other words, if a crisp number is entered to the system, it belongs to more than one fuzzy numbers.
Rule base (RS)

This part of the fuzzy system considers one of the important steps for the whole procedure. The rule base links between input parameters and the required output. RS is used to demonstrate the connection between input and output for the real issue using “linguistic terms” (Cordón et al., 2001). Each rule in the rule base is written as shown in the following equation:

“If A is C then B is D” (2)

According to equation (2), the IF-THEN rule contains two parts, where A and B are named antecedent (input parameter) and consequent (output) in the same order, while C and D are linguistic terms as mentioned in the fuzzy system section. However, in each part more than two variables can be connected using logical operators such as OR, AND and NOT (Surmann and Selenschtschikow, 2002).

In this work, the following steps are adopted:

1- Three input variables (temperature, humidity and wind speed) with logical AND operator are used for the antecedent part. For the consequent part only one output variable (solar radiation) is used. Equation (3) illustrates the two parts of the IF-THEN.

IF Temperature is Low AND Humidity is Medium AND Wind Speed is High THEN Solar Radiation is Medium

Where Temperature, Humidity and Wind speed are linguistic variables and Low, Medium, High and Medium are linguistic terms.

2- The antecedent part is placed into the fuzzy inference engine. If the rule is fired, then the inference engine calculates the membership functions of the input variables using equation (1). According to equation (3), since AND operation is used then the minimum value of membership functions in the antecedent part will be taken. The result of this stage is produced first by using the implication method followed by an aggregation of the outputs of each rule to make a single fuzzy set (Jantakoon, 2016).

Defuzzification

The results of the fuzzy inference engine are fuzzy values which are produced using the aggregation of all membership functions that are operated by the inference engine. The defuzzification process is used to achieve crisp equivalent which is the output of fuzzy logic system (Ronald and Sari, 2014). There are several methods of defuzzification such as Center of Sums Method (COS), Center of gravity (COG) / Centroid of Area (COA) Method, Bisector of Area Method (BOA), Weighted Average Method and Maxima Methods. In this study, a numerical prediction is produced using the centroid of area (COA) which is the most popular method. COA is calculated using the following equation:
\[ x^* = \frac{\sum_{i=1}^{n} x_i \cdot \mu(x_i)}{\sum_{i=1}^{n} \mu(x_i)} \]

Where \( x^* \) is crisp value, \( \mu(x_i) \) is the membership function, \( n \) indicates the number of elements in the sample. This prediction is sensitive to all the rules applied.

**Error Measurements**

\[ \text{APE} = \left| \frac{\text{actual}(i) - \text{forecast}(i)}{\text{actual}(i)} \right| \times 100\% \]

Where \( \text{actual}(i) \) represents the actual solar radiation in the sample, \( \text{forecast}(i) \) indicates the predicted solar radiation in FS.

**MAPE**

\[ \text{MAPE} = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{\text{actual}(i) - \text{forecast}(i)}{\text{actual}(i)} \right| \times 100\% \]

Where \( \text{actual}(i) \) refers to the actual solar radiation in the sample, \( \text{forecast}(i) \) represents the predicted solar radiation in FS, and \( n \) represents the number of elements in the sample.

**RESULTS AND DISCUSSIONS**

The inputs used for the prediction of solar radiation are: temperature, humidity and wind speed. To make one record in the fuzzy system, the values of these inputs were organized as string split by a comma. Thereafter, such records were normalized and fuzzified to be utilized to create the rules for anticipation by the fuzzy system. The prediction of solar radiation is done for four seasons in Duhok city in 2016. The variation between the predicted and actual solar radiation is shown in Figures 3-6:

![Fig. (3): The actual and predicted solar radiation for winter season in 2016](Image)
Figures (3-6) present the details of actual and predicted solar radiation for the four seasons in 2016. As shown in the figures 4 and 5, there is no difference between the actual and predicted solar radiation. However, figures 3 and 6 show that there is a little variation between the actual and predicted solar radiation.

Tables 1-4 present the actual and predicted solar radiation for four seasons in 2016 and the APE and MAPE are computed for the sample data set using the equations (3) and (4) respectively:
Table (1): Temperature, humidity, wind speed, actual and predicted solar radiation for winter in 2016

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>Humidity %</th>
<th>Windspeed m/s</th>
<th>Actual w/m</th>
<th>Predicted w/m</th>
<th>APE %</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>73.8</td>
<td>2.7</td>
<td>103.2</td>
<td>112</td>
<td>8.527131783</td>
</tr>
<tr>
<td>11.6</td>
<td>70</td>
<td>1</td>
<td>90</td>
<td>81.9</td>
<td>9</td>
</tr>
<tr>
<td>13.6</td>
<td>78</td>
<td>0.2</td>
<td>120</td>
<td>112</td>
<td>6.666666667</td>
</tr>
<tr>
<td>14.5</td>
<td>70</td>
<td>0.6</td>
<td>116</td>
<td>111</td>
<td>4.310344828</td>
</tr>
<tr>
<td>13.4</td>
<td>67</td>
<td>2</td>
<td>88</td>
<td>81.4</td>
<td>7.5</td>
</tr>
<tr>
<td>12.7</td>
<td>85</td>
<td>3.6</td>
<td>55.7</td>
<td>53.7</td>
<td>3.590664273</td>
</tr>
<tr>
<td>16.4</td>
<td>78.2</td>
<td>0.5</td>
<td>121</td>
<td>113</td>
<td>6.61570248</td>
</tr>
<tr>
<td>14.8</td>
<td>66</td>
<td>4.5</td>
<td>26</td>
<td>23.7</td>
<td>8.846153846</td>
</tr>
<tr>
<td>14.6</td>
<td>68.8</td>
<td>1.1</td>
<td>107</td>
<td>106</td>
<td>0.934579439</td>
</tr>
<tr>
<td>11.4</td>
<td>71</td>
<td>0.6</td>
<td>80</td>
<td>82.1</td>
<td>2.625</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>58.61211108</td>
<td></td>
</tr>
</tbody>
</table>

MAPE 5.861211108

Table (2): Temperature, humidity, wind speed, actual and predicted solar radiation for summer 2016

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>Humidity %</th>
<th>Windspeed m/s</th>
<th>Actual w/m</th>
<th>Predicted w/m</th>
<th>APE %</th>
</tr>
</thead>
<tbody>
<tr>
<td>44.1</td>
<td>20.4</td>
<td>2.6</td>
<td>256</td>
<td>259</td>
<td>1.171875</td>
</tr>
<tr>
<td>44.2</td>
<td>19.8</td>
<td>5</td>
<td>263</td>
<td>260</td>
<td>1.140684411</td>
</tr>
<tr>
<td>43.3</td>
<td>24.7</td>
<td>2.4</td>
<td>241</td>
<td>246</td>
<td>2.07488797</td>
</tr>
<tr>
<td>43.2</td>
<td>21.6</td>
<td>1</td>
<td>230</td>
<td>235</td>
<td>2.173913043</td>
</tr>
<tr>
<td>44.7</td>
<td>18.4</td>
<td>1.6</td>
<td>230</td>
<td>234</td>
<td>1.739130435</td>
</tr>
<tr>
<td>42.6</td>
<td>21.5</td>
<td>1.9</td>
<td>240</td>
<td>242</td>
<td>0.833333333</td>
</tr>
<tr>
<td>45.5</td>
<td>20.6</td>
<td>1</td>
<td>212</td>
<td>214</td>
<td>0.943396226</td>
</tr>
<tr>
<td>44.6</td>
<td>16.2</td>
<td>4.5</td>
<td>246</td>
<td>240</td>
<td>2.43902439</td>
</tr>
<tr>
<td>45.4</td>
<td>15.4</td>
<td>3.1</td>
<td>208</td>
<td>205</td>
<td>1.442307692</td>
</tr>
<tr>
<td>45.9</td>
<td>16.3</td>
<td>4.4</td>
<td>202</td>
<td>205</td>
<td>1.485148515</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15.44350184</td>
<td></td>
</tr>
</tbody>
</table>

MAPE 1.544350184

Table (3): Temperature, humidity, wind speed, actual and predicted solar radiation for spring 2016

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>Humidity %</th>
<th>Windspeed m/s</th>
<th>Actual w/m</th>
<th>Predicted w/m</th>
<th>APE %</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.2</td>
<td>65.8</td>
<td>1.1</td>
<td>189</td>
<td>187</td>
<td>1.058201058</td>
</tr>
<tr>
<td>23.9</td>
<td>55.8</td>
<td>1</td>
<td>193</td>
<td>188</td>
<td>2.590673575</td>
</tr>
<tr>
<td>21.1</td>
<td>72.5</td>
<td>1</td>
<td>183</td>
<td>187</td>
<td>2.18579235</td>
</tr>
<tr>
<td>18.2</td>
<td>72.7</td>
<td>1.1</td>
<td>201</td>
<td>189</td>
<td>5.970149254</td>
</tr>
<tr>
<td>22.2</td>
<td>71.6</td>
<td>1</td>
<td>195</td>
<td>189</td>
<td>3.076923077</td>
</tr>
<tr>
<td>22.7</td>
<td>69.3</td>
<td>1</td>
<td>200</td>
<td>189</td>
<td>5.5</td>
</tr>
<tr>
<td>15.3</td>
<td>84.7</td>
<td>2.4</td>
<td>147</td>
<td>149</td>
<td>1.360544218</td>
</tr>
<tr>
<td>22</td>
<td>57.2</td>
<td>4.9</td>
<td>178</td>
<td>179</td>
<td>0.561797753</td>
</tr>
<tr>
<td>18.3</td>
<td>80.6</td>
<td>2.6</td>
<td>125</td>
<td>131</td>
<td>4.8</td>
</tr>
<tr>
<td>15.5</td>
<td>82.7</td>
<td>0.8</td>
<td>188</td>
<td>187</td>
<td>0.531914894</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>27.83599618</td>
<td></td>
</tr>
</tbody>
</table>

MAPE 2.763599618
As evident from Tables 1-4, there have been few variations of the predicted solar radiation value from the actual. The APE and MAPE are used to evaluate the performance of fuzzy logic approach. The results of APE and MAPE were comparatively low for all seasons. Therefore, the prediction model is effective and dependable and can be utilized for solar radiation prediction.

**CONCLUSION**

In this study, fuzzy system has achieved a good performance in predicting the solar radiation. The amount of accuracy for the four seasons was reasonably acceptable. However, the performance of this system can be improved, if more than one dataset are available. Fuzzy inference engine was the most effective part of the fuzzy system. This part is responsible for the application of implication method and aggregation method which consider the backbone of the fuzzy system.

**REFERENCES**


الخلاصة:

يتم استخدام الطاقة الشمسية في تطبيقات مفيدة عديدة مثل في انتاج المنتجات الزراعية الغذائية. التأكد من أن الطاقة المتجددة وتنظيم بيئة الحياة والبيئة. حاليا، أن جميع دول العالم، وخاصة الدول النامية، تواجه تحديات كبيرة في توفير مصدر مستدام للمستهلكين. الطاقة الكهربائية هي من أكثر أنواع الطاقة شيوعاً وأكثرها استعمالاً من قبل المستهلكين.

ولذا فإن استخدام البترول والطاقة النووية تأتي كأفضل سلسلة على التغيير المناخي والاحتياج الحراري لكوكب الأرض. ولهذا فإن الغلب الدور في تأمين وانتاج الطاقة الشمسية لنخيل تأثيرات ظاهرة الاحتباس الحراري على كوكب الأرض، واتجاه مصدر لطاقة نظيفة ومستدامة ومتجددة.

هذا المنهج من هذه الدراسة هو النموذج البسيط للطاقة الشمسية في انتاج الطاقة الكهربائية في مدينة دهوك، وذلك لكون الطاقة الكهربائية المسماة باشهعة الشمس كمصدر للطاقة الشمسية في المملكة المتحدة. وبالتالي، فإن المستهلكين يعتمدون أعمدة كبيراً من مولدات الطاقة الكهربائية الشخصية أو مولدات الطاقة الكهربائية التي يمكنها أن يكونوا من النوع الذي يستخدم البترول في تشغيل هذه المولدات لانتاج الكهرباء.

تم استخدام نظام المنطق المضبب في هذه الدراسة للتنبؤ باشعة الشمس، حيث تم بناء أربعة نماذج منظمة مضبحة باستخدام البيانات المتاحة لسنة 2012 في محافظة دهوك. تم تحليل القراءات اليومية للحرارة والرطوبة وسرعة الرياح لدوجerot كل فصل من فصول السنة لتخمين اشعة الشمس. كما تم مقارنة نتائج نموذج المنطق المضبب مع أشعة الشمس الفعلية. بالإضافة إلى ذلك، تم تقييم النظام المضبب باستخدام ال (MAPE) و (APE) لاستخدام ال (الشمس، الصيف، الربيع والخريف)، على التوالي، وموجبة هذه النتائج، فإن أداء النظام المضبب هو فعال نسبياً في النتيجة باشعة الشمس.