FUZZY LOGIC MODELING OF SOLAR RADIATION USED IN PHOTOVOLTAICS

DORIN LEŢ[1], ANDREEA STANCU[1]

[1]*Valahia* University of Targoviste - Multidisciplinary S&T Research Institute, 130082, Dambovita

Abstract: *Knowing the amount of solar radiation on a surface is of key importance to engineers and scientists involved in the design of solar powered systems. Numerous design methods for thermal and photovoltaic systems require as an input monthly average daily radiation on a horizontal surface, in order to predict the energy production of the system on a monthly basis. In applicative studies it is a logical and coherent idea that the solar radiation is directly proportional to the sunshine duration. Usualy solar energy models have linear mathematical forms similar to scientific laws which express linear relationships between two relevant variables. However, planetary boundary layer turbulence, atmospheric turbidity and transmissivity, cloud thickness, and temporal and spatial variations cause embedding of non-linear elements in the solar radiation phenomena. Therefore, the use of simple linear models cannot be justified except statistically without even considering about obtaining the model parameter estimations.*

Keywords: *photovoltaic, solar radiation, fuzzy logic (FL) algorithm,*

1. Introduction

Solar energy is clean, undepletable, and harmless to living organisms on the earth because the harmful short wavelength ultraviolet rays are absorbed before reaching the troposphere by the stratospheric ozone layers and weakened by the air composition and moisture in the troposphere.

Solar radiation emission comes in the form of electromagnetic waves that carry energy at the speed of light. The radiation is absorbed, reflected, or diffused by solid particles in any location of space and especially by earth, which depends on it for many activities such as weather, climate, agriculture, and socio-economic activities. Considering the geometry of earth, its distance from the sun, geographical location of any point on earth, astronomical coordinates, and the composition of the atmosphere, the incoming irradiation at any given point takes different shapes. A significant fraction of the solar radiation is absorbed and reflected back into space through atmospheric events and consequently the solar energy balance of the earth remains the same. These basic concepts, their definitions, and derived astronomical equations provide the foundations of solar energy evaluation at any given location. They are deterministic in the sense that there is no uncertainty about the effect of weather events.

Methodical measurements of diffuse solar energy and the global irradiation incident on a horizontal surface are usually made by a national agency. The measurement network includes pyranometers, solarimeters, or actinography instruments for this purpose. At several locations direct or beam irradiation is measured by a pyrheliometer with a fast-response multi-junction thermopile. Diffuse irradiance is measured at a set of stations by placing a shadow band over a pyranometer. In practice, it is very important to appreciate the order of measurements prior to any modeling study both for solar radiation and sunshine period or daylight. The present state of solar radiation and daylight models is such that they are approaching the accuracy limits set out by the measuring equipment.

Multiple versions of the linear Angstrom Model (AM) are in use widely in solar energy studies for estimation of the global terrestrial solar radiation amounts from the sunshine period data. However, atmospheric turbidity and transmissivity, planetary boundary layer turbulence, cloud thickness, and temporal and spatial variations cause embedding of non-linear elements in the solar radiation phenomena. That's why, the use of simple linear models cannot be actually justified except by statistics and this without thinking about obtaining the model parameter estimations. In the literature, most often the linear models are either modified with the addition of extra terms in the hope of explaining the non-linear features or adjustment of the linear model parameters by relating them to geographical, meteorological, and other variables. Non-linearity in solar radiation and sunshine period relationships is represented initially through classic statistical techniques through the addition of non-linear terms to the basic AM. Some researchers have incorporated the non-linear behavior in the models by expressing the linear model parameters in terms of each other or in terms of sunshine and solar radiation variables. Such models reduce to the classic linear solar radiation models under a set of specific suppositions.

2. Fuzzy Logic Modeling

The records of solar radiation and sunshine period during a day are uncertain and abstract. Using a *fuzzy logic* (FL) algorithm can be benefic for dealing with these uncertainties and estimating the amount of solar radiation. The most important advantage of *fuzzy logic models* (FLM) is their capacity to describe the knowledge in a descriptive human-like mode, by use of simple logical rules with linguistic variables. Any AM or other types of regression equations are substituted by a set of fuzzy base rules. Some indirect assumptions exist in all the model formulations as follows:

a) Excluding the scatter diagram of H versus S, in many applications, a linear regression line is fitted to data at hand according to a linear model where coefficients depend loosely on the variations in the sunshine period.

b) Unfortunately, a linear model that estimates the global radiation on a horizontal surface at earth's level, does not give indications about the normal incidence and tilted surface global radiation because diffuse and direct radiation components are not considered.

c) The modeling is mainly done by relating global irradiation to the sunshine period by ignoring some of the meteorological factors such as the RH, maximum temperature, air quality, latitude, elevation above sea level, *etc.* Each one of these factors contributes to the relationship between H and S and their neglect introduces some errors in the estimations. For instance, the AM assumes that if all of the other meteorological factors are constant then the global horizontal irradiation is proportional to the sunshine period only. The effects of other meteorological variables appear as deviations from the straight line fit on a scatter diagram. Using a FL model, there are no parameters but all the uncertainties and model complications are included in form of IF-THEN iterations in the descriptive fuzzy inference procedure.

d) The system's dynamic response is not considered due to the complexities because the regression technique is based on restrictive assumptions. However, in the FLM there are no assumptions involved in the global irradiation estimation from the sunshine period data. This is because the regression method does not provide dynamic estimation of the coefficients from available data.

3. Fuzzy building blocks

The *"fuzzy sets"* theory was introduced in 1965. At that time it was not well accepted into the literature since many uncertainty techniques such as probability theory, statistics, and stochastic processes were commonly employed at that time. FL has been developed further since then and it is now used for automatic control of commercial products such as washing machines, cameras, and robotics. The key idea in FL is the allowance of partial belonging of any object to different subsets of the universal set instead of belonging to a single set completely. Partial belonging to a set can be described numerically by a membership function (MF) which assumes values between 0 and 1.0 inclusive. For instance, Figure 1 shows typical MFs for small, medium, and large class sizes in a universe, U.

Consequently, these verbal assignments are the fuzzy subsets of the universal set. In this figure set values with less than 2 are definitely "small," those between 4 and 6 are certainly "medium," and values larger than 8 are definitely large. However, intermediate values such as 2.2 are in between, that is, it partially belongs to subsets "small" and "medium." In fuzzy terminology 2.2 has an MF value of 0.9 in "small" and 0.1 in "medium" but 0.0 in "large."

Amongst the ways to assign MFs to fuzzy variables there can be mentioned: intuition, inference, rank ordering, angular fuzzy sets, neural networks, genetic algorithms, inductive reasoning, *etc.* The intuition approach is used rather commonly because it is derived from the capacity of humans to develop MFs through their own innate intelligence and understanding and because it involves contextual and semantic knowledge about an issue.

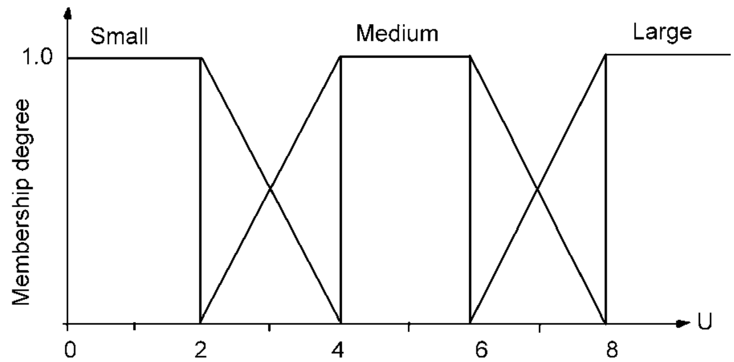

Figure 1. Fuzzy subsets.

In applications fuzzy MFs may take many forms but preferably a simple straight line function. Triangular functions with equal base widths are the simplest possible ones. For instance, in Figure 2 the whole universe of temperature, T, space is subdivided into four subsets with verbal attachments "cold," "cool," "warm," and "hot," associated with different MFs.

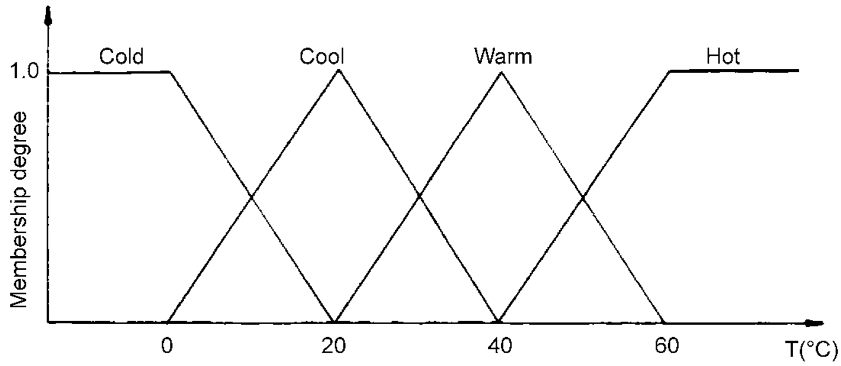

Figure 2. Membership functions for the fuzzy linguistic word "temperature".

Solar radiation at the earth's surface is a random process and therefore it involves uncertainty. Furthermore, if the form of uncertainty happens to arise because of imprecision, ambiguity, or vagueness then the variable is fuzzy and can be represented by an MF.

4. Fuzzy applications for Solar Radiation

Considering the following fuzzy logical propositions in the forms of IF-THEN statements and the solar energy variables of sunshine period and solar radiation described in terms of linguistic variables such as "long," "high," "short," and "small":

IF sunshine period is "long" THEN the solar radiation amount is "high."

IF sunshine period is "short" THEN the solar radiation amount is "small."

The two propositions are satisfied logically by a simple AM. These linguistic variables are only a certain part set of the whole variability domain, *i. e.,* of the full set. It can be understood from this argument that a set of relationships is required between two variables as exemplified in Figure 3.

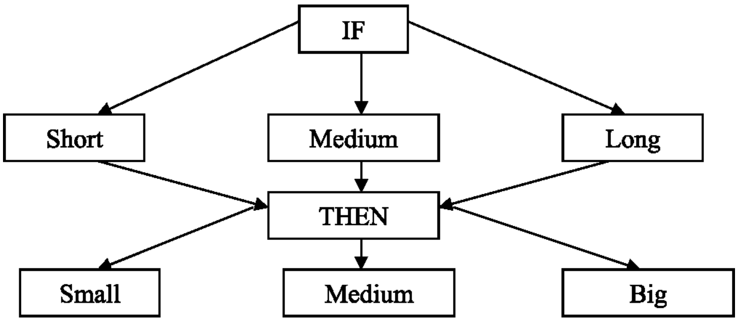

Figure 3. Linguistic words and relationships

Figure3 represents the architecture of a two-variable fuzzy proposition collection. The first three boxes on the same line represent sunshine period linguistic words; the second line represents three words for the solar radiation. Hence, it is possible to infer 3 x 3 = 9 different IF-THEN propositions, the question reised in this figure: whether the boundaries between the linguistic words in each line are distinct from each other or there may be some overlaps. Logically, it is not possible to draw crisp boundaries between subsequent words. For this purpose, Figure 3 can be rendered into a more realistically valid architectural form as shown in Figure 4 where there are interferences (shaded areas) between the sunshine period (solar radiation) linguistic words on the same line. The overlapping areas between the atomic words indicate fuzzy regions.

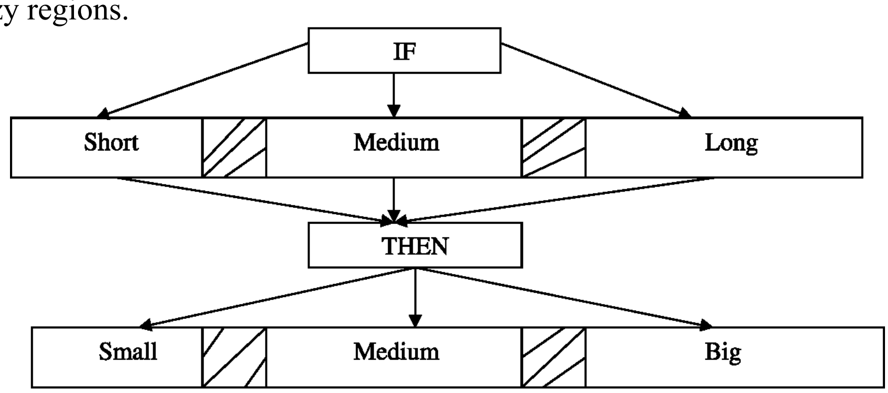

Figure 4. Fuzzy boundary linguistic words and relationships

It's reasonable to assume that as the linguistic word domain moves away from the interference locations they represent more of the linguistic word meaning. For instance, medium sunshine period linguistic word has two interference regions and, therefore, one can assume comfortably that the middle locations in the "medium" word domain are more genuine mediums. This last statement reflects a triangular type of medium appartenence to the medium region. On the contrary, the words that are located on both sides of the line, such as short and long or small and big, have only one interference region. This means that the appartenence into these words will increase as one move's away from the interference region. Likewise, this gives again the impression of a triangular appartenence but with its greatest belonging at the far edges from the interference regions. Such appartenence is attached with certain numbers that vary between zero and one. In such a terminology zero represents nonappartenence to the word concerned, whereas one corresponds to the full appartenence. These appartenence numbers are referred to as the membership degree (MD) in fuzzy sets.

Models with the architectural form of Figure 4 are already present for solar radiation estimation. In such an approach there is no mathematical equation included. However, in engineering applications simple and linear equations are required for rapid calculations. For this purpose, the architecture in Figure 5 can be changed into the one in Figure 6 with crisp mathematical forms after the THEN part of the logical. In FL terminology, the premises of the productions are vague in terms of fuzzy subsets whereas the consequent parts are adopted in the form of the simplest linear partial mathematical equations.

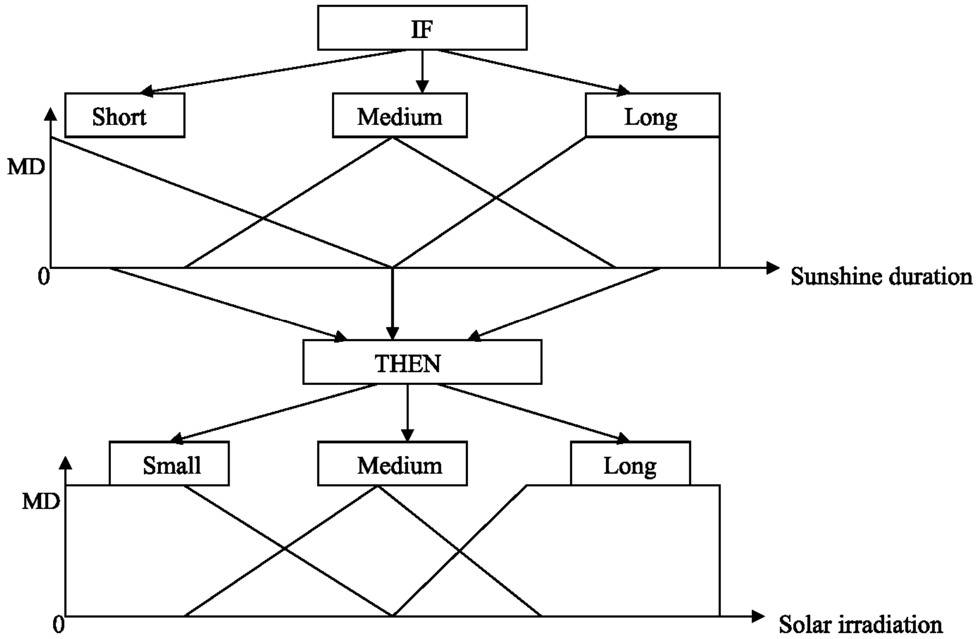

Figure 5. Fuzzy sets and relationships.

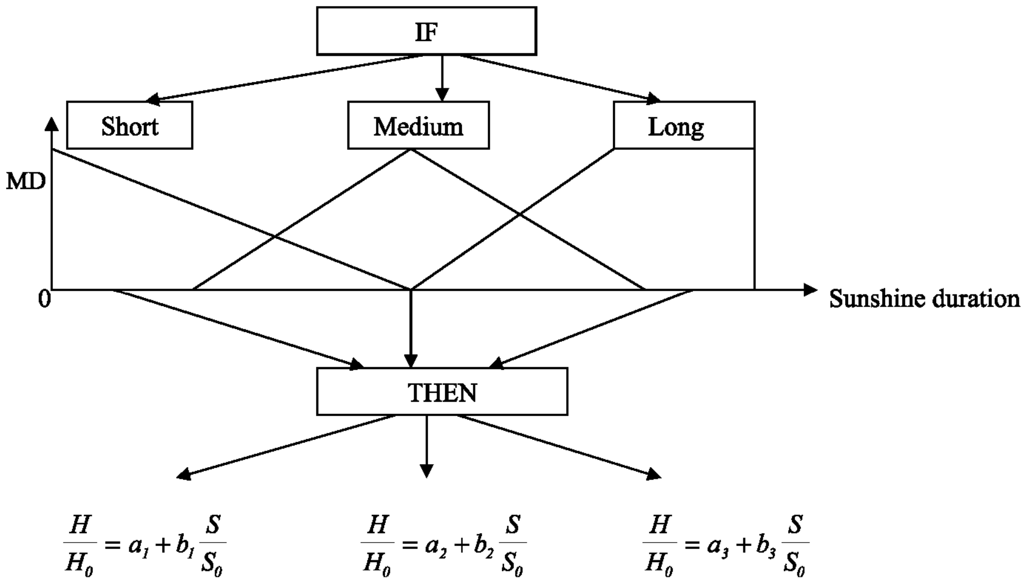

Figure 6. Mathematical relationships of the consequent parts.

The mathematical formulations in the consequent part are adopted similar to the AM. Although the AM is globally fitted to the S/S_0 versus H/H_0 scatter diagram, the architecture in Figure 6 provides a piece-wise linear approach. These two cases are shown in Figure 7.

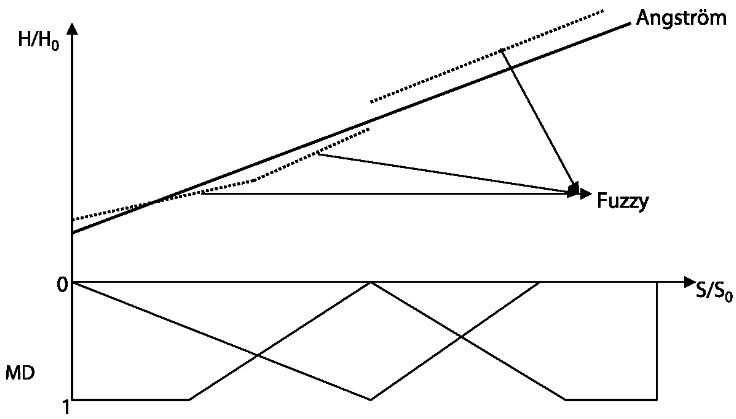

Figure 7. Angstrom and fuzzy solar radiation estimation models

It is possible to write down the three possible propositions that emerge from Figure 6 as

IF sunshine period is "short" THEN $\frac{H}{H_0} = a_1 + b_1 \frac{S}{S_0}$

IF sunshine period is "medium" THEN $\frac{H}{H_0} = a_2 + b_2 \frac{S}{S_0}$

IF sunshine period is "long" THEN $\frac{H}{H_0} = a_3 + b_3 \frac{S}{S_0}$

Therefore, the relationship between the radiation and sunshine period is deduced from the measurements linguistically. Without dividing by H_0 and S_0 salient features of H and S scatter diagram are plotted in Figure 8 for the purpose of fuzzy irradiation estimation based on hipotetical data. To this end, the extraterrestrial solar radiation, H, and sunshine period hours are first fuzzified into fuzzy subsets so as to cover the whole range of changes.

The sunshine period is considered at the maximum for 12h and its subdivision into 7 subsets as S_1, S_2, S_3, S_4, S_5, S_6, and S_7 is considered to have triangular membership functions represented in Figure 9.

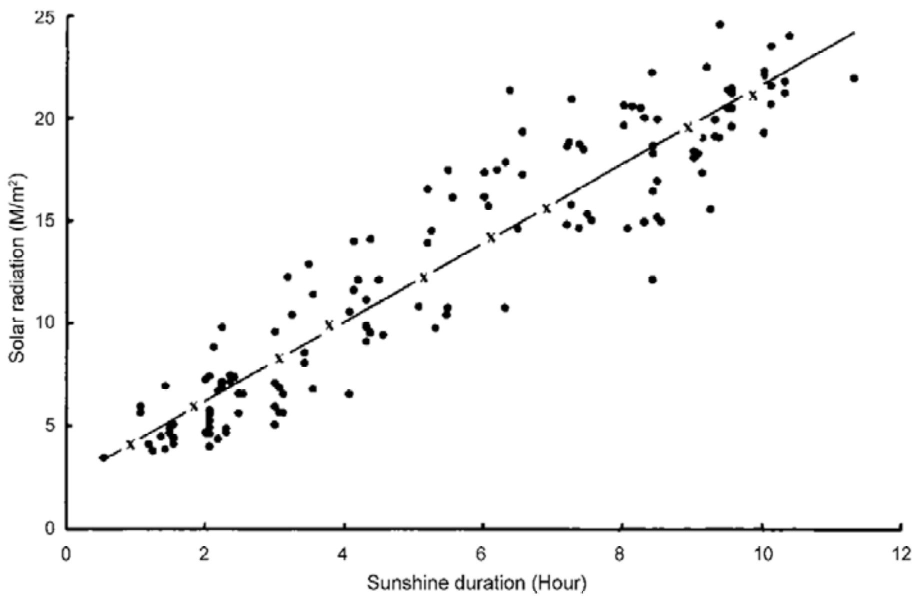

Figure 8. H versus S scatter diagrams at stations with crosses indicating fuzzy solutions.

However, subsets of fuzzy changes in the solar radiation domain will depend on the location and elevation of the station and accordingly fuzzy partitions will be different for different sites. Since solar irradiance data are continuous, and change slightly and smoothly over very large distances, the fuzzy partitions of solar irradiance are expected to be slightly different for different sites. The reason for adopting seven, contrary to what is recommended as a rule of thumb which in practice is five, is due to the error minimization in the estimation. Once the *fuzzy rule base* inference machine is set up it is straightforward to play with the number of fuzzy partitions on the computer until the best fit is obtained.

The domain of radiation change is observed from the past records and at each station the irradiation values assume 600 cal/cm^2 per month. Due to different latitudes there are three slightly different fuzzy set partitions as shown in Figure 10, respectively. The solar radiation fuzzy sets are labeled as H_1, H_2, H_3, H_4, $H5$, H_6, and H_7 in increasing magnitude.

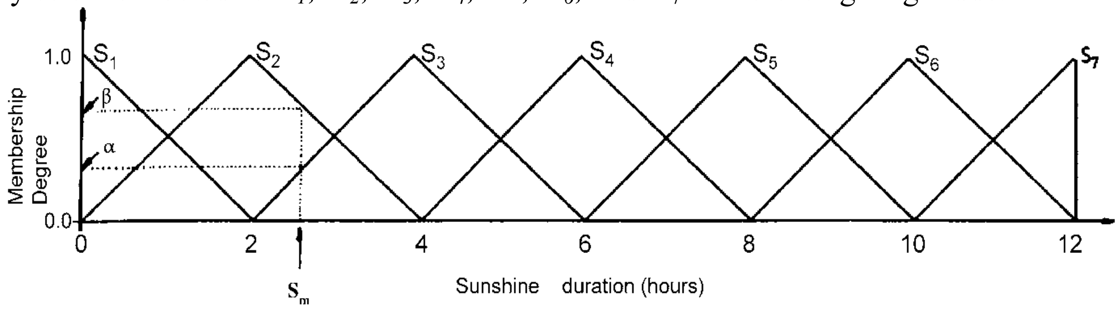

Figure 9. Fuzzy subsets for sunshine duration

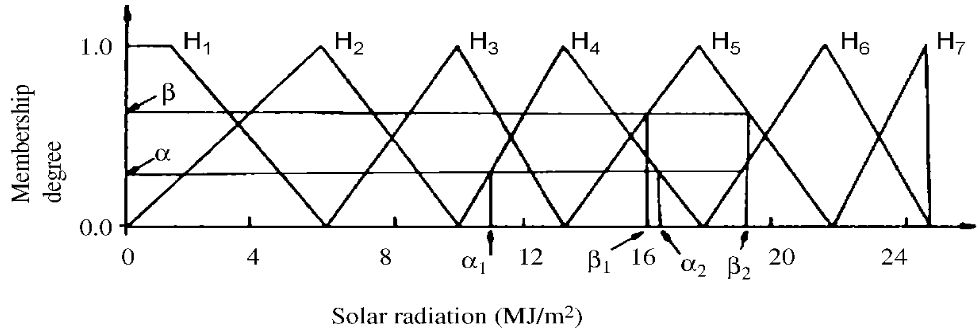

Figure 10. Fuzzy subsets for radiation at different stations.

Irradiation and sunshine period fuzzy subsets are combined with each other through the following fuzzy rule bases:

IF S is S_i and S_{i+1} THEN H is Hi and H_{i+1} (i = 1, 2, 3, 4, 5, 6). (1)

For a given sunshine period measurement, S_m, there are two successive sunshine period fuzzy subsets (see Figure 9). Once the fuzzy subsets of irradiation and sunshine period data are recorded, it is possible to perform the application for the estimation of irradiation amount from a given sunshine period measurement through the following steps:

1. Locate the measured sunshine period amount S_m on the horizontal axis in Figure 9. It is possible to find two successive fuzzy subsets, for instance, S_2 and S_3
2. Find the MDs, namely, α and β corresponding to these two successive sunshine period fuzzy subsets. It is important to notice at this stage that by definition $\alpha + \beta = 1.0$
3. Enter the radiation fuzzy subset domain by considering a and β membership degrees as shown, for instance, in Figure 10

4. Since α in Figure 9 came from S_4, in Figure 10 it should yield two values, namely α_1 and α_2 from the corresponding H_4 fuzzy subset in the irradiation domain. Similarly, β_1 and β_2 are obtained from H_5 as shown in the same figure. In fact, H_4 and H_5 together present the fuzzy consequent, *i. e.*, answer to the irradiation estimation in the form of a fuzzy subset union as is shown Figure 11

5. For the defuzzification of the fuzzy set in Figure 11, first of all the arithmetical averages of the lower and upper values from each fuzzy subsets are calculated as

$$\overline{\alpha} = \frac{\alpha_1 + \alpha_2}{2} \; and \; \overline{\beta} = \frac{\beta_1 + \beta_2}{2} \tag{2}$$

6. The radiation estimation value, H_e, is calculated as the weighted average of these two simple arithmetic averages as

$$H_e = \alpha\overline{\alpha} + \beta\overline{\beta} \tag{3}$$

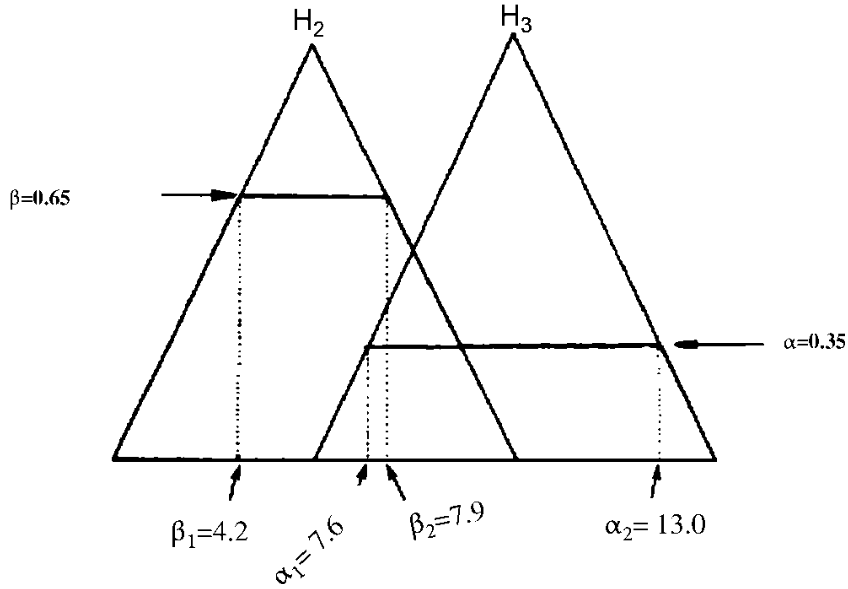

Figure 11. Fuzzy irradiation estimation compound subset

It is to be noticed at this stage that the right hand side of this expression is a function of radiation (see Figure 10). Hence, it is possible to execute these steps for each sunshine period measurement which leads to either fuzzy subset estimation in a vague form similar to Figure 11 or after its *defuzzification* by Eq. 3 to a single irradiation estimation value. The final results in the form of defuzzified irradiation estimations are shown in Figure 8 by crosses. It is obvious that these crosses lie within almost the central parts of scatter diagram for any given sunshine period measurement. Hence, the proposed method of fuzzy estimation leads to irradiation estimations either in a vague form similar to fuzzy subset in Figure 11 or as a defuzzified value.

5. Considerations

Solar energy is expected to be the foundation of a sustainable energy economy, because sunlight is the most abundant renewable energy resource. Additionally, solar energy can be harnessed in an almost infinite variety of ways beginning with simple solar cookers now used in different parts of the world. There is a vast amount of literature about the use of solar energy both in engineering and architectural design procedures and projects.

The practical applications and beneficial uses of solar radiation require consideration of engineering aspects in order that the use of the solar energy is efficient and sustainable. Designing of solar installations requires the determination of solar radiation incident on the plane of the solar collector. Sloped solar collectors receive direct, diffuse, and reflected solar radiation. In order to calculate the total solar radiation, it is necessary to know their components. The relationship between monthly average daily diffuse and global solar radiations incident on horizontal surface, H_d/H is the most significant variable. This relationship can be found from direct meteorological observations or through an empirical relationship. It is also necessary to know how the power density will vary during the day, from season to season.

In general, modeling the solar radiation arriving at the top of the atmosphere can simply be considered as the product of the solar constant I_0 and the astronomical factor f (R) of annual average 1.0, proportional to R^{-2} (inverse distance square), where R is the distance of the earth from the sun. However, for the modeling of solar radiation at the earth's land surfaces, it is usually adequate to assume that the diffuse radiation is isotropic (the same intensity in all directions from the sky). Diffuse sky irradiance under cloud-free conditions may be estimated by assuming an isotropic sky and calculating the proportion of the sky seen from a point (that is using the equivalent of the view-shed operation in GIS). Under cloudy or partly cloudy conditions, diffuse radiation is anisotropic which may be explicitly modeled, but in practice this is computationally expensive to achieve as the diffuse radiation from different portions of the sky must be calculated. In order to calculate actual solar flux, field data from pyranometers (which measure actual incoming solar flux at a station), atmospheric optical data, or atmospheric profiling (sounding) must be used.

Although there are multiple regression models that relate the solar radiation to variables such as sunshine duration, humidity, temperature, elevation, etc., they are based on the restrictive assumptions as required by the regression technique methodology. Such regression models do not exhibit variations in an elastic manner, but rather in a deterministic form. They provide a mathematical relationship, but, due to an increase in the number of variables, the error source might also increase and the model reliability becomes questionable.

The accuracy of the solar radiation mathematical models is important not only in the final stages of projects, but particularly in the initial stages prior to any systematic model construction work. Apart from the scatter diagram inspections, examination of residuals (model errors) is also recommended after the model establishment.

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