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An Introduction to Solar Energy, Solar Radiation, and their Measurement Methods: A Review Study

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Abstract
The amount of solar radiation is one of the important climatic parameters that has a direct and close relationship with many hydrological and meteorological processes. This parameter is a fundamental element for designing and developing various solar energy systems and conducting applied solar energy research. To estimate the amount of solar radiation, researchers have proposed various models that eliminate the need for expensive equipment in meteorological stations. When measured data is not available, meteorological parameters such as maximum and minimum temperatures, wind speed, sunshine hours, rainfall, air pressure, and humidity can be used at different meteorological stations. In this review article, a series of research conducted in this field will be discussed.

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INTRODUCTION

The radiant energy of the sun is a source of promising and renewable energy on the planet (Basurto et al., 2019). Solar radiation is a crucial parameter used in hydrology, water resources management, water balance models, and plant growth simulation models (Ball, Purcell & Carey, 2004; Seyedian et al., 2017; Besharat, Dehghan & Faghih, 2013; Huang et al., 2021; Budyko, 1969; Islam et al., 2009). The amount of total solar radiation (GSR) is the most important parameter in the design and development of various solar energy systems, which affects numerous water and soil processes, including evaporation, snowmelt, and plant growth (Tiris & Erdalli, 1997; Bagheri, Moradi & Bagheri, 2013; Sabziparvar & Bayat Varkeshi, 2019; HoushmandRad & Mokhtari, 2022). The concept of total radiation refers to the amount of solar energy absorbed by a horizontal surface within a specific period of time in a given region (Almorox & Hontoria, 2004; Wang et al., 2011).The first and most important need in solar energy application designs is the accurate observation and estimation of solar radiation components. Unfortunately, in some countries around the world, there are insufficient solar radiation measurement stations, and in some cases, the measurements are of poor quality.

In developing countries (such as Iran), direct measurement of GSR is usually done in limited sites, and in some cases, the measurements are not of the desired quality; because in these countries, the number of meteorological stations is limited, and in addition, expensive equipment is needed to directly obtain the amount of solar radiation (Tiris & Erdalli, 1997; Bagheri, Moradi & Bagheri, 2013; Chen et al., 2004). To overcome this problem, numerous studies have aimed to predict the amount of solar radiation using geographical and meteorological parameters, such as minimum and maximum temperatures, sunny hours, relative humidity, altitude, rainfall, and wind speed, by various researchers (Bristow & Campbell, 1984). These studies have led to the presentation of different models for evaluating solar radiation (Almorox, 2011).

Literature Review

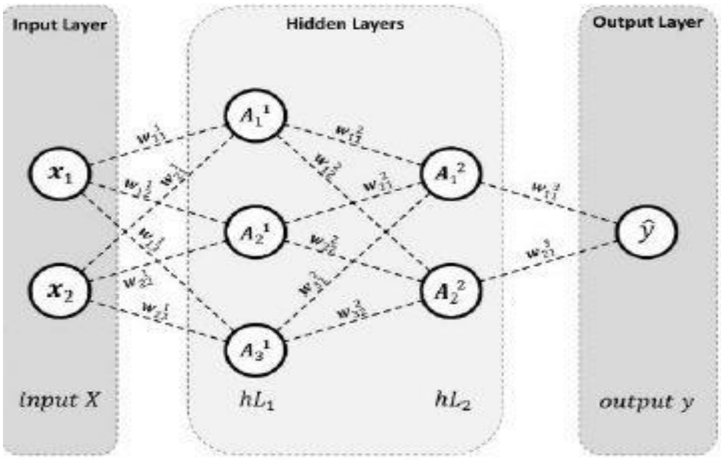
An extensive and practical study of solar energy has been conducted since the 1970s in most parts of the world. According to the climatic and geographical conditions of different regions, suitable models have been proposed. The significant difference in geographical latitude in Iran is a significant factor in the substantial variation in solar radiation across the country. Appropriate modeling to estimate solar energy in different regions of the country, and its correct use, will play a crucial role in determining the country's required energy (Bagheri, Moradi, & Bagheri, 2013).

Studies have been done to estimate the total amount of radiant energy received on a horizontal surface. The first empirical relationship to calculate GSR based on sunshine hours over a long period was presented by Angstrom (1924) (Seyedian et al., 2017; Angstrom, 1924). By using atmospheric data, such as sunshine hours, he developed a simple model to estimate the total amount of solar radiation reaching the Earth's horizontal surface. After Angstrom, many researchers attempted to improve and modify the Angstrom model, whose conversion coefficients and input data were dependent on climatic conditions (Prescott, 1940). Prescott improved the Angstrom model, and his proposed model is known as the Angstrom-Prescott model. Page (1979) presented the coefficient of the Angstrom-Prescott model in a way that can be used everywhere in the world. Ogelman et al. (1984) modified the results of the Angstrom-Prescott equation by using the quadratic relationship. Almorox and Hontoria (2004) presented a power relationship based on the n/N ratio (n: number of sunny hours, N: maximum number of sunny hours). They demonstrated that the results are in good agreement with actual values, making them suitable for estimating monthly solar radiation. Wanxiang et al. (2014), in order to estimate solar radiation, studied 108 different relationships based on the n/N ratio in Shanghai, China, and selected three relationships as the best relationships. Yin et al. (2008) showed that Angstrom's relationship is suitable for estimating radiation in China in order to predict evaporation-transpiration. Bahel et al. (1987) developed a general relationship based on radiation data and sunshine hours for 48 stations, representing diverse geographical and meteorological conditions worldwide.

In Ninomiya's research (1994), the effect of rainy days is also considered. Burari et al. (2001) employed a solar radiation estimation model with specific regression coefficients tailored to the Bauchi region. Chandel et al. (2005) proposed a model based on temperature. Saffaripour and Mehrabian (2008) analyzed the analytical models of other researchers and calibrated some of these models for the climatic conditions of Iran according to the experimental data; also, they investigated the combined effect of geometrical, geographical, astronomical, and meteorological factors on the amount of solar radiation received in Yazd city by using the compound regression method, and by presenting a seven-parameter model, they predicted the intensity of the total daily radiation very accurately.

Research Methodology

Artificial Neural Network (ANN): Artificial neural networks are computational methods that, through a learning process using simple processors called neurons, identify inherent relationships within data and map input spaces to desired output spaces (Figure 1) (Huang et al., 2021). In designing artificial neural networks, a structure inspired by human bio-structure is adopted to enable learning, generalization, and decision-making capabilities (Abbassi et al., 2023; Habibi et al., 2022; Mobasseri & Janghorban, 2024; Mobasseri et al., 2022; Mobasseri et al., 2020; Mobasseri et al., 2024). Hidden layers process information from the input layer and pass it to the output layer. Training involves adjusting connection weights so that predicted values match observed values within an acceptable margin (Sabziparvar & Bayat Varkeshi, 2019). These trained networks can then predict outputs for new datasets.



Figu 1. A sample of artificial neural network with two hidden layers (Rahbar et al., 2020).

Adaptive Neuro–Fuzzy Inference System (ANFIS): ANFIS combines neural network algorithms and fuzzy logic to create a non-linear mapping between input and output spaces. Its strength lies in the combination of fuzzy linguistic capabilities with the numerical power of neural networks for complex process modeling (V & K, 2008). In recent years, AI techniques such as ANN and ANFIS have been widely used for simulating complex phenomena including solar radiation prediction, due to its non-linear nature and dependence on atmospheric parameters (Caudill, 1987).

Application of ANN in Solar Radiation Modeling: The use of ANN for solar radiation prediction was first proposed by Kalogirou et al. (Kalogirou et al., 1998). Subsequent studies demonstrated the effectiveness of ANN in various countries: Fadare (Fadare, 2009) highlighted its superiority in predicting solar radiation; Alfa et al. (Alfa et al., 2001) successfully predicted hourly solar radiation in Nigeria; Sozen et al. (Sözen et al., 2004) applied it for radiation potential zoning in Turkey; Jiya and Alfa (Jiya & Alfa, 2002) also utilized ANN for zoning; Mellit et al. (Mellit et al., 2006) used an adaptive microwave network; and Moghaddamnia et al. (Moghaddamnia et al., 2009) applied gamma test for parameter selection before ANN and ANFIS modeling. Rehman and Mohandes (Rehman & Mohandes, 2009) found that combining relative humidity and average temperature provides the most accurate estimation.

Estimation Procedure: Meteorological parameters such as minimum and maximum temperature, relative humidity, wind speed, and sunshine hours are commonly used as input for ANN and ANFIS models. Networks are trained on historical data to adjust weights for minimizing prediction errors, and the trained models are then validated using independent datasets.

Research findings

(Lazzús et al, 2011) demonstrated, using wind speed, relative humidity, and air and soil temperatures, that the neural network has a remarkable ability in hourly estimation of solar radiation. AbdulAzeez (AbdulAzeez, 2011) estimated the monthly mean solar radiation using a neural network with reasonable accuracy, incorporating data from sundial, maximum temperature, and relative humidity. SabziParvar and Bayat (Sabziparvar & Bayat Varkeshi, 2019) conducted research to evaluate artificial intelligence models for predicting the total amount of solar radiation reaching the horizontal surface of the Earth. In that study, an artificial neural network and an Adaptive Neuro-Fuzzy Inference System were employed to simulate the total amount of solar radiation. The information used included minimum temperature, maximum temperature, average relative humidity, sunny hours, and daily solar radiation recorded at four similar stations in the country (Isfahan, Kerman, Urmia, and Shiraz) from 1992 to 2006. Their results indicated that the amount of solar radiation can be predicted by using intelligent models. Additionally, the predicted results of the artificial neural network were more accurate than those of the neural-fuzzy inference system. Also, using the linear regression model, the most effective factors affecting the amount of solar radiation at each station were identified. The results of their research indicate that in all the studied stations, the parameter of sunny hours had the most significant effect on the amount of solar radiation. Additionally, in most stations, the minimum air temperature and average relative humidity had the least effect on the total amount of solar radiation. Bagheri et al. (Moradi, & Bagheri, 2013) presented a new method to estimate the daily average solar radiation on a horizontal surface for a given month, based on the Angstrom model and using the bees algorithm with programming in the MATLAB software environment. They calculated the experimental coefficients of the Angstrom model for four different climatic regions of Iran in the MATLAB software environment. They presented the average daily amount of total solar radiation estimated by the proposed method for each month in the sample areas. To validate their results, they used the results obtained from the proposed method in conjunction with other methods to determine solar radiation for all four sample regions of Iran.

Table 1. The proposed BA coefficients and its corresponding R^2 & RMSE values

City	A	B	R^2	RMSE
Hamedan	0.36710	0.30821	0.9912	0.0011
Khur and Biabanak	0.3329	0.39008	0.9908	0.0014
Mashhad	0.32846	0.30162	0.9786	0.0175
Tabriz	0.33372	0.42148	0.9745	0.0194

Table 2. Comparison between BA and SRT outputs

City	Method	A	B	R^2	The difference between the values R^2 (%)
Hamedan	BA	0.36710	0.30821	0.9912	2.58
	SRT	0.38250	0.24580	0.9662	
Mashhad	BA	0.32846	0.30162	0.9786	7.06
	SRT	0.32200	0.31100	0.9140	
Tabriz	BA	0.33372	0.42148	0.9745	8.84
	SRT	0.33870	0.42140	0.8953	
Khur and Biabanak	BA	0.3329	0.39008	0.9908	4.81
	SRT	0.4101	0.3154	0.9453	

Source: Bagheri et al, 2013

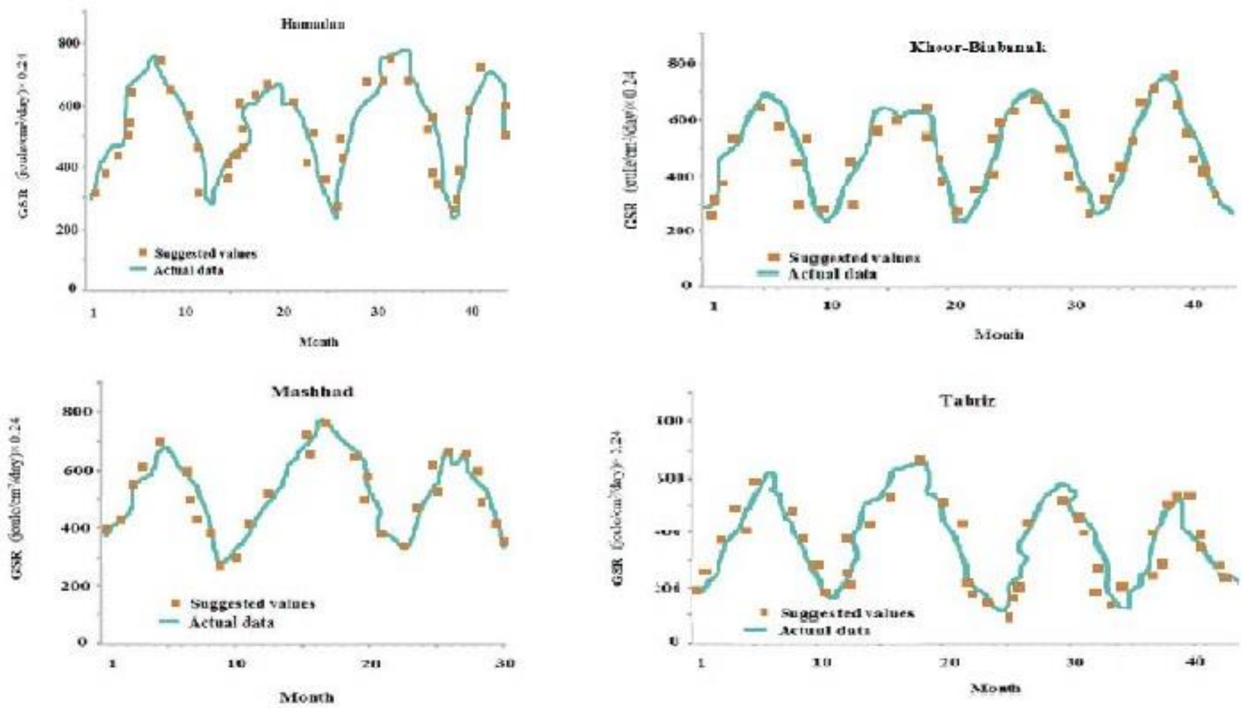


Fig 2. Comparison between average daily GSR values in the month predicted by BA and actual values in four sample cities (Bagheri et al, 2013)

Gamma test: Gamma test was first proposed by Koncar (1997) and later developed by many researchers such as Durrant (2001). Gamma test is a non-linear modeling tool that can be used to check the appropriate combination of input parameters to model the output data and create a model. It is also a developer tool for estimating the mean squared error resulting from the modeling of various phenomena using observational data sets. Gamma test estimates the mean square of the output error for different combinations of parameters:

$$\gamma = A\delta + \Gamma \qquad (1)$$

There is useful information on the regression of relation (1). The width from the origin of the line indicates the value of gamma (Γ), which represents that part of the variance of the output data that cannot be estimated by the model. The slope of the regression line indicates the complexity of the model, and the steeper this slope is, the more complex the model is. The results of the gamma test can be checked by another parameter ($Vratio$), obtained by equation (2):

$$V_{ratio}=\frac{\Gamma}{(y)\sigma 2} \qquad (2)$$

The denominator of the fraction is the variance of the output values (y) and (V_{ratio}) is a number between zero and one that shows the constant error value. Seyedian et al. (2017) collected meteorological data, including maximum and minimum temperatures, wind speeds, solar hours, rainfall, air pressure, and humidity, at six meteorological stations in Mashhad, Isfahan, Ramsar, Zahedan, Urmia, and Shiraz. Using the gamma test, they determined the meteorological parameters that affect solar radiation at each station. The results of their research showed that, in all stations, maximum temperature and sunshine hours are among the parameters affecting solar radiation. Additionally, at five stations, air pressure and wind speed are also among the parameters that affect solar radiation. The most important influencing parameters differ at each station; therefore, wind speed in four stations and sun hours in three stations are the first and second most important factors. Examining the parameters revealed that the maximum temperature has a significant impact on solar radiation, but compared to sun hours and wind speed, these are less important parameters (Tables 3, 4, and 5).

Table 3. Average data used to estimate solar radiation

	Zahedan	Shiraz	Ramsar	Urmia	Mashad	Isfehan
Number of days	4725	2384	2400	4079	4624	5488
Minimum temperature (ºC)	10.9	10.8	14.0	5.8	9.6	9.7
Maximum temperature (ºC)	27.2	26.5	20.2	18.5	23.1	24.5
Sunshine duration (hr)	9.4	9.4	4.6	8.3	8.6	9.3
Air pressure (mb)	862.1	850.9	1017.4	867.4	903.0	843.6
Relative humidity (%)	28.8	37.7	83.2	57.1	49.6	34.9
Rainfall (mm)	0.2	0.6	3.3	0.7	0.7	0.4
Wind speed (m/s)	3.3	1.8	1.8	1.9	2.5	1.5
Cloudiness	1.5	1.7	4.7	2.6	3.0	1.8
Solar radiation ($MJm^{-2}d^{-1}$)	7.6	7.3	5.5	5.4	6.7	6.2

Table 4. Parameters affecting on solar radiation

Station	Cloudiness	Wind Speed	Rainfall	Relative humidity	Air pressure	Sunshine duration	Maximum temperature	Minimum temperature
Isfehan				✓	✓	✓	✓	
Mashad	✓	✓				✓	✓	✓
Urmia	✓	✓			✓	✓	✓	
Ramsar	✓	✓				✓	✓	
Shiraz	✓	✓			✓	✓	✓	
Zahedan	✓			✓	✓	✓	✓	

Table 5. Ranking parameters effect on solar radiation in the stations

Station	Parameters	Gamma(Γ)	Slop (A)	Error	V_{ratio}
	All	0.171	0.342	0.0079	0.683
	All-RH	0.179	-0.601	0.0042	0.790
Isfehan	All-n	0.192	0.088	0.0048	0.768
	All-p	0.187	-0.591	0.0083	0.748
	All-T_{max}	0.186	0.086	0.0088	0.745
	All	0.165	0.192	0.0062	0.663
	All-n	0.205	-0.329	0.0028	0.820
Mashad	All-w	0.180	0.294	0.0083	0.719
	All-T_{min}	0.176	0.095	0.0111	0.706
	All-Cl	0.170	0.548	0.0064	0.679
	All-Tmax	0.168	0.194	0.0058	0.672
	All	0.174	0.146	0.0075	0.695
	All-p	0.179	0.254	0.0068	0.714
Urmia	All-w	0.183	0.108	0.0045	0.734
	All-n	0.191	0.241	0.0060	0.765
	All-Cl	0.195	-0.093	0.0053	0.781
	All-T_{max}	0.186	0.147	0.0062	0.745
	All	0.179	0.302	0.0088	0.716
	All-w	0.230	-0.056	0.0052	0.919
Ramsar	All-n	0.208	0.029	0.0047	0.832
	All-T_{max}	0.199	0.245	0.0079	0.795
	All-Cl	0.186	0.401	0.0101	0.746
	All	0.150	0.348	0.0176	0.598
	All-w	0.209	-0.351	0.0131	0.835
Shiraz	All-p	0.192	-0.136	0.0077	0.770
	All-Cl	0.195	0.115	0.0121	0.780

Station	Parameters	Gamma(Γ)	Slop (A)	Error	V_{ratio}
	All-T_{max}	0.190	-0.014	0.0128	0.762
	All-n	0.190	0.147	0.0124	0.761
	All	0.194	0.198	0.0074	0.775
	All-RH	0.217	-0.062	0.0055	0.868
Zahedan	All-Tmax	0.211	-0.019	0.0050	0.844
	All-p	0.211	0.129	0.0081	0.844
	All-n	0.208	0.260	0.0050	0.832
	All-Cl	0.199	0.364	0.0068	0.799

Minimum temperature (Tmin), maximum temperature (Tmax), sunny hours (n), air pressure (P), relative humidity (RH), rainfall (R), wind speed (R) and solar radiation (Rs) in six stations of the country Is. The number of days with data and the average of the studied parameters are given in Table 1.

Results

This review article examines several studies conducted in the field of solar radiation, along with an analysis of their results. Considering the importance of radiation in the applied sciences of solar energy and the numerous problems associated with measuring this parameter, as well as the success of innovative models in predicting complex parameters, the need to utilize intelligent neural models in predicting the radiation parameter becomes increasingly important. Therefore, several user methods have been introduced in this field, including Artificial Neural Networks, Adaptive Neuro-Fuzzy Inference Systems, and the gamma test. This article provides a brief introduction to the field of solar energy, introducing researchers to some standard methods in the field.

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