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Research Paper

Empirical modeling of solar radiation exergy for Turkey

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HIGHLIGHTS

- Solar radiation exergy is an important parameter in solar energy applications.
- Empirical models are developed for estimate solar radiation exergy for Turkey.
- The accuracy of the models is evaluated on the basis of statistical indicators.
- The new models can be used to predict global solar radiation exergy.

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ABSTRACT

In this study, three different empirical models are developed to predict the monthly average daily global solar radiation exergy on a horizontal surface for some provinces in different regions of Turkey by using meteorological data from Turkish State Meteorological Services. To indicate the performance of the models, the following statistical test methods are used: the coefficient of determination (R^2), mean bias error (MBE), mean absolute bias error (MABE), mean percent error (MPE), mean absolute percent error (MAPE), root mean square error (RMSE) and the t-statistic method (t_{sta}). By the improved empirical models in this paper do not need exergy-to-energy ratio (ψ) and monthly average daily global solar radiation to calculate solar radiation exergy. Consequently, the average exergy-to-energy ratio (ψ) for all provinces are found to be 0.93 for Turkey. The highest and lowest monthly average daily values of solar radiation exergy are obtained at 23.4 MJ/m^2 day in June and 4 MJ/m^2 day in December, respectively. The empirical models providing the best results here can be reliably used to predict solar radiation exergy in Turkey and in other locations with similar climatic conditions in the world. The predictions of solar radiation exergy from regression models could enable the scientists to design the solar-energy systems precisely.

1. Introduction

Solar radiation reaching the surface of the earth is the most fundamental renewable energy source in nature. Solar energy is one of the most important renewable energy sources such as wind energy, geothermal energy [1–6]. The average daily global solar radiation is the most important parameter for solar energy applications, such as solar furnaces, concentrating collectors, interior illumination of buildings and thermoelectricity [1,7]. In locations where no measured average daily global solar radiation values are available, a common application has been to obtain this parameter by appropriate regression models, which are established using the measured data [1].

Measured data are the best source for proper knowledge of global solar radiation. However, such data are not available to measure global solar radiation at every location. In contrast, the sunshine duration has been measured in almost all meteorological stations for many years. As a result, there have been many studies that have represented the relationship between and developed regression equations for average daily global solar radiation and sunshine duration [8–11]. The first equation developed for predicting monthly average daily global radiation was carried out by Angstrom [12]. In this regression model, sunshine duration data for predicting the global radiation were used. Most of the sunshine based regression equations built to predict the monthly average daily global solar radiation are based on the Angstrom equation [13]. Because of the difficulty in determining clear sky global irradiance, Prescott [14] proposed extraterrestrial radiation intensity values instead of global irradiance [15]. Many types of regression models or methods have been proposed to estimate solar radiation in the literature [1–4,8–49].

As known, exergy is related to the work potential of the energy contained in a system at a specified state [50], and it is a concept that explicitly shows the 'usefulness (quality)' of energy and

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Nomenclature

a, b, c,d	Angström coefficients
a′,b′,c′,d′	Angström coefficients
D	day number starting from first of January
H	monthly average daily global radiation (MJ m^{-2})
H_{exergy}	calculated global solar radiation exergy value (MJ m^{-2})
$H_{p,exergy}$	predicted global solar radiation exergy value (MJ m^{-2})
$H_{exergy,avg}$	average of the calculated global solar radiation exergy value (MJ m^{-2})
$H_{p,exergy,avg}$	average of the predicted global solar radiation exergy value (MJ m^{-2})
R^2	coefficient of determination
H_o	monthly average daily extraterrestrial radiation (MJ m^{-2})
k	total number of observations
MPE	mean percent error
MAPE	mean absolute percent error
MBE	mean bias error
MABE	mean absolute bias error
RMSE	root mean square error
t_{sta}	t-statistic method
G_{sc}	solar constant (W/m^2)
n	monthly average daily sunshine duration
N	monthly average day length
n/N	monthly average relative sunshine duration
T_s	solar radiation temperature
T_o	mean monthly air temperature
W	work
η_e	real energy conversion efficiency of thermal radiation
E_{rad}	solar radiation energy
W_{max}	maximum work
Ex_{rad}	exergy of radiation
$\eta_{e,max}$	maximum conversion efficiency of thermal radiation
φ	latitude of site (°)
δ	solar declination (°)
w_s	mean sunrise hour angle for the month (°)
ψ	exergy-to-energy ratio for solar radiation
α	statistical significant level

matter, in addition to ‘what is consumed’ in the course of energy transfer or conversion steps. The concept of ‘Energy’ does not show these quality and consumption aspects, because it is a concept aimed at ‘quantity’; this quantity, being subject to a conservation law, cannot be consumed according to the first law of thermodynamics. The concept of ‘Exergy’ provides further understanding of ‘how a system works’, by pinpointing the subsystems where energy is degraded. An understanding of exergy consumption principles will lead us to a better understanding of resource and environment issues [51,52].

Currently, the conversion of solar energy into useful energy, such as mechanical and electrical energy, does not play a crucial role in the energy budget of most countries. However, this energy conversion will become more important in the future because of its environmentally friendly standing. Thus, it is crucial to have these thermodynamic tools ready for action when the demand increases. Given a fixed environment, exergy is the fraction of the incoming energy that is fully convertible into mechanical or electrical energy. Mechanical and electrical energy are completely exergy; they are fully convertible into all other energy types. Solar energy is not fully convertible because of its entropy content; therefore, its exergy content is less than 100%. Thus, the energetic conversion efficiency of a solar conversion device will not be 100%, even if there were an ideal, fully reversible conversion. The exergy content of solar radiation arriving on earth is between 50 and 80% of its energy flux, depending on the atmospheric conditions [53].

In analyzing solar energy application systems using an exergy analysis method, the calculation of the exergy of solar radiation is very important. Over a period of more than 20 years, many papers considering different approaches to this calculation have been published [53–56]. For example, a thermodynamic model was developed by Zamfirescu and Dincer [57] to study the exergetic content of incident solar radiation reaching the Earth’s surface that can be used to produce work through a dually cascaded thermodynamic cycle. Joshi et al. [58] developed a solar exergy map concept and conduct a comprehensive case study to show how it is utilized and how it is significant for practical solar applications.

The aim of many papers in the literature is to estimate the global solar radiation using empirical models or methods. However, empirical models or methods have not been reported in literature only in relation to the estimation of solar radiation exergy. Therefore, the main objective of this study is to predict the global solar radiation exergy using sunshine duration based on the Angstrom–Prescott method in Turkey. Also, this study proves that regression modeling can be used prediction of solar exergy.

The advantage of proposed approach used this study, by the developed regression models in this study do not require exergy-to-energy ratio (ψ) and monthly average daily global solar radiation to calculate solar radiation exergy.

2. Modeling

Many empirical models have been found in the literature, such as linear, quadratic and cubic regression models, to estimate the solar irradiation on a horizontal surface from the observed the monthly average daily hours of bright sunshine and the calculated extraterrestrial radiation and monthly average day length. The first recommended regression model (Table 1) is the linear form known as the Angstrom-Prescott model, which is most commonly used model [12,14]. The second quadratic and third cubic regression models were derived by Akinoglu and Ecevit [36] and Bahel [37], respectively. In this study, the value of the monthly average daily global solar radiation exergy value is determined on a horizontal surface “H_{exergy}” to replace the energy “H” in Table 1.

H is the monthly average daily global radiation on a horizontal surface, and Ho is the monthly average daily extraterrestrial radiation on a horizontal surface. The ratio between the observed monthly average daily sunshine duration (n) and the monthly average day length (N) is known as the relative sunshine duration, and a, b, c and d are the regression coefficients.

The monthly average daily extraterrestrial radiation on a horizontal surface (H_o) can be computed from the following equation [59]:

$$H_o = \frac{24 \times 3600 G_{sc}}{\pi}\left[1 + 0.033\cos\left(\frac{360D}{365}\right)\right] \times \left[\cos\varphi\cos\delta\sin w_s + \frac{2\pi w_s}{360}\sin\varphi\sin\delta\right] \quad (1)$$

where G_{sc} is the solar constant (1367 W/m^2) which is expressed as the energy from the sun per unit time received on the unit of area perpendicular to the direction of sun’s rays, at mean earth–sun