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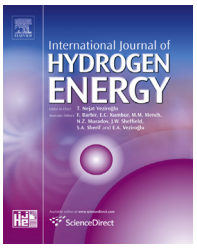

Prediction of horizontal diffuse solar radiation using clearness index based empirical models; A case study

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ABSTRACT

Diffuse solar radiation is an important factor for design and simulation processes of the photovoltaic (PV) panels as well as other solar systems. Nowadays, hydrogen generation can be accomplished by harnessing solar energy via PV systems to electrolyze the water in a clean and environmentally friendly manner. In this study, 13 existing functional forms of the clearness index based diffuse radiation models, reported so far in the literature, have been firstly categorized on the basis of how they correlate: (1) the diffuse fraction and (2) diffuse coefficient with clearness index as the sole input variable. Then in a case study, by utilizing the long term global and diffuse solar data, in overall 26 new models have been established for both daily and monthly mean daily predictions for the city of Kerman, Iran. The performances of the new established models have been evaluated using different well-known statistical indicators. For the daily based prediction, the diffuse fraction model with linear form is the most suitable one with root mean square error (*RMSE*) and correlation coefficient (*R*) of 1.3081 MJ/m^2 and 0.8767, while for the monthly mean daily prediction, the diffuse coefficient model again with linear form provides the utmost accuracy, for which *RMSE* and *R* are 0.5391 MJ/m^2 and 0.9258, respectively. The employment of these only clearness index based models for any solar system application, in particular solar hydrogen production, is convenient; given that the knowledge of clearness index only requires the global solar radiation data.

Introduction

Owing to the economical and technological developments as well as the needs to a more comfortable life across the globe, the worldwide energy demand is increasing substantially. The main current sources of fossil fuels reserves such as oil, gas and coal are depletable. More importantly, the large scale utilizations of fossil fuels in recent decades have brought some serious environmental concerns comprising greenhouse gas emissions, global warming and environmental pollution. Thus, enhancing the security of power supply chain

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Nomenclature

G_{sc}	solar constant (equal to 1367 W/m^2)
H	global solar radiation on horizontal surface, MJ/m^2
H_d	diffuse solar radiation on horizontal surface, MJ/m^2
$H_{di,p}$, $H_{di,m}$	ith predicted and measured values of H_d, MJ/m^2
$\overline{H}_{d,p}$, $\overline{H}_{d,m}$	averages of the predicted and measured values of H_d, MJ/m^2
H_o	extraterrestrial solar radiation on horizontal surface, MJ/m^2
$K_{df} = (H_d/H)$	diffuse fraction or cloudiness index (dimensionless)
$K_{dc} = (H_d/H_o)$	diffuse coefficient or diffuse transmittance index (dimensionless)
$Kt = (H/H_o)$	clearness index (dimensionless)
MABE	mean absolute bias error, MJ/m^2
MAPE	mean absolute percentage error, %
n_{day}	day number counted from 1st January
N	maximum possible sunshine hours, h
RMSE	root mean square error, MJ/m^2
RSE	relative standard error
R	correlation coefficient

Greek letters

α	solar altitude angle, deg
δ	solar declination angle, deg
Φ	latitude of the location, deg
ω_s	sunset hour angle, deg

and reducing the emissions of hazardous greenhouse gases seem to be highly essential [1,2]. In this regard, many industrial and non-industrial countries are looking toward the utilization of clean and renewable energy sources to reduce the dependency on fossil fuels and diminish the existing negative environmental issues. In fact, in light of offering a practical solution for the aforementioned issues, the appropriate utilization of renewable energy sources would be of particular interest [3]. Renewable energies are free, clean, environmentally preferable and inexhaustible. These make them proper alternatives or supplements for fossil fuel sources. Among renewables, solar energy is the most attractive and promising option due to its broad availability across the globe [4,5].

In recent years, hydrogen as a fuel, has attracted a considerable attention. Hydrogen is regarded as a high efficiency and low polluting fuel that can be utilized in different applications such as transportation, heating and power generation, particularly in the locations with difficult accessibility to the electricity [6]. Hydrogen is an element which is abundantly available in the universe, therefore it may continually and securely sustain the worldwide trade energy systems in an environmentally preferable manner [6]. In fact, because of worldwide availability of the hydrogen, all of the continents and nations can generate, trade and utilize hydrogen; however, hydrogen must be generated since it is found in combination with other elements.

Technically, there are several ways to produce hydrogen such as reforming the natural gas, liquefying the petroleum gas or gasoline, gasifying the coal, electrolyzing the water by means of fossil fuels, nuclear energy or different types of renewable energy sources including the solar, wind and biomass. Furthermore, photocatalytic splitting of water as well as thermo-chemical cycles are other technologies for hydrogen generation [7–10]. Nevertheless, generating hydrogen from renewable energies sources is considered as an appealing target for a gradual evolution to a clean economy and a more sustainable and smart energy mix [11,12]. Hydrogen can be generated by utilization of solar energy via photovoltaic (PV) modules to electrolyze the water without emission of carbon dioxide or other hazardous gases and dependency to fossil fuels [13–15]. In this combined system, the requisite electrical energy for the electrolyzer is supplied by the PV generator [9,16–19]. Due to such importance, many investigations have been recently carried out in this regard [17–25].

For designing and developing the solar-hydrogen energy based systems, knowledge of diffuse solar radiation is a prerequisite. In fact, for sizing, adjusting, simulating and monitoring the PV panels at a particular location, the terrestrial beam and diffuse solar radiation components are needed [26–30]. The PV panels are typically mounted as inclined solar surfaces; thus, after obtaining the amount of diffuse solar radiation on a horizontal surface it is required to determine its amount on an inclined surface. Nevertheless, due to technical and financial issues the diffuse radiation data are not easily available in many regions [31,32]. Therefore, diffuse solar radiation should be predicted based on available input variables. In this context, many empirical models have been proposed so far using various input variables [33–46]. In a recent review paper, Khorasanizadeh and Mohammadi have introduced and categorized the typical input variables as well as different functional forms utilized so far for solar diffuse prediction across the globe [47]. Among the input variables, the global solar radiation is one of the most important ones [48]. The ratio of global solar radiation to extraterrestrial solar radiation (i.e. the clearness index) is highly correlated with diffuse radiation. Liu and Jordan [48] made the first attempt to develop a proper correlation between diffuse radiation and clearness index. From then a big number of empirical models with different functional forms have been suggested to estimate diffuse radiation based upon clearness index as the sole input element. The main benefit of clearness index-based empirical models is that only availability of measured global solar radiation is adequate to predict diffuse radiation. Furthermore, such models have a high generalization capability so that when they are developed for a location, their application can be extended to nearby areas and other regions with similar weather conditions [49].

The main aim of this investigation, is to establish and introduce accurate clearness based diffuse solar radiation models for developing and designing PV systems intended for hydrogen generation in the city of Kerman, Iran, as a case study. To fullfil this objective, 13 reported functional forms of clearness index based horizontal diffuse solar radiation models in the literature are categorized into two classifications: (1) the diffuse fraction or cloudiness index (i.e. the ratio

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