SOLAR ENERGY ANALYSIS OF A HOME BY CONSIDERING OUTDOOR PARAMETERS

Master of Science Thesis

Özge AYVAZOĞLUYÜKSEL

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MASTER OF SCIENCE THESIS

Graduate School of Sciences
Electrical and Electronics Engineering Program
Supervisor: Assist. Prof. Dr. Ümmühan BAŞARAN FİLİK

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ABSTRACT

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Özge AYVAZOĞLUYÜKSEL

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Anadolu University, Graduate School of Sciences, December, 2016

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In this thesis, solar energy analysis is performed for a home placed in Anadolu University İki Eylül Campus by considering outdoor parameters. Within the scope of this analysis, hourly global solar radiation values on horizontal surface are estimated from measured daily global solar radiation values by using eleven different models. The measured and estimated hourly global solar radiation values are compared and accuracy of the models is evaluated using statistical analysis methods. The obtained results indicate that Collares - Pereira and Rabl model modified by Gueymard (CPRG) has generally the highest accuracy among all considered models. By using Olmo et al. model, the estimated hourly global solar radiation values of CPRG model for horizontal surface are converted to values for inclined surface. In addition, cell temperature of the photovoltaic modules is estimated with seven different models that consider outdoor conditions and panel technical characteristics defined by manufacturers. Hence, based on the estimated cell temperature and global solar radiation values on inclined surface, power generation values of on-grid and off-grid systems are predicted with a model in MATLAB®, and these values are compared with actual power generation values. It is seen that cell temperature values estimated by the standard approach give the best prediction values of power generation.

Keywords: Solar radiation, cell temperature, power generation, estimation, outdoor parameters.

ÖZET

BİR EVİN DIŞ ORTAM PARAMETRELERİ GÖZETİLEREK GÜNEŞ ENERJİSİ ANALİZİ

Özge AYVAZOĞLUYÜKSEL

Elektrik-Elektronik Mühendisliği Anabilim Dalı

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Bu tezde, Anadolu Üniversitesi İki Eylül Kampüsü'ne konumlandırılan bir ev için dış ortam parametreleri gözetilerek güneş enerjisi analizi gerçekleştirilmiştir. Bu analiz kapsamında, yatay yüzeyde saatlik küresel güneş ışınım değerleri, ölçülen günlük küresel güneş ışınım değerlerinden on bir farklı model kullanılarak tahmin edilmiştir. Ölçülen ve tahmin edilen saatlik küresel güneş ışınım değerleri karşılaştırılmıştır ve modellerin doğruluğu istatistiksel analiz yöntemleri kullanılarak değerlendirilmiştir. Elde edilen sonuçlar, Gueymard tarafından modifiye edilen Collares - Pereira ve Rabl (CPRG) modelinin göz önünde bulundurulan tüm modeller arasında genel olarak en yüksek doğruluğa sahip olduğunu göstermektedir. Olmo et al. modeli kullanılarak, CPRG modeli ile yatay yüzey için tahmin edilen saatlik küresel güneş ışınım değerleri eğimli yüzey değerlerine dönüştürülmüştür. Ayrıca, fotovoltaik modüllerin hücre sıcaklığı, dış ortam koşullarını ve üreticiler tarafından tanımlanan panel teknik özelliklerini göz önünde bulunduran yedi farklı model ile tahmin edilmiştir. Böylece, tahmin edilen hücre sıcaklığı ve eğimli yüzeydeki küresel güneş ışınım değerleri esas alınarak, şebeke-bağlantılı ve şebekeden-bağımsız sistemlerin güç üretim değerleri MATLAB® ortamında bir model ile tahmin edilmiştir ve bu değerler gerçek güç üretim değerleri ile karşılaştırılmıştır. Standart yaklaşım ile tahmin edilen hücre sıcaklığı değerlerinin en iyi güç üretim tahmin değerlerini verdiği görülmüştür.

Anahtar Kelimeler: Güneş ışınımı, hücre sıcaklığı, güç üretimi, tahmin, dış ortam parametreleri.

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29/12/2016

STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with "scientific plagiarism detection program" used by Anadolu University, and that "it does not have any plagiarism" whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

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NOMENCLATURE

I	Hourly global solar radiation on horizontal surface (W/m^2)
I_0	Hourly extraterrestrial global solar radiation on horizontal surface (W/m^2)
I_{sol}	Solar constant (W/m^2)
I_φ	Hourly global solar radiation on inclined surface (W/m^2)
H	Daily global solar radiation on horizontal surface (W/m^2)
H_0	Daily extraterrestrial global solar radiation on horizontal surface (W/m^2)
I/H	Ratio of hourly to daily global solar radiation on horizontal surface *(unitless)*
W	Solar hour angle (*degree*)
W_s	Sunrise hour angle (*degree*)
W_0	Sunset hour angle (*degree*)
k_t	Hourly clearness index (*unitless*)
K_t	Daily clearness index *(unitless)*
t_s	Solar time (*hour*)
h_0	Daily average solar elevation outside of the atmosphere (*degree*)
Γ	Day angle (*radians*)
δ	Solar declination angle (*degree*)
ϕ	Latitude (*degree*)
γ	Surface inclination angle (*degree*)
θ_z	Solar zenith angle (*degree*)
θ	Solar incidence angle (*degree*)
S_0	Day length (*hour*)
R	Monthly mean sun-earth distance correction factor *(unitless)*
d	Number of day starting from the first of January *(unitless)*
ρ	Albedo of the underlying surface *(unitless)*
ψ_o	Function that converts the horizontal global solar radiation to the values of tilted surface *(unitless)*
F_c	Multiplying factor *(unitless)*

T_c	Cell/module temperature (^oC)
T_a	Ambient temperature (^oC)
v_w	Local wind speed close to the module (m/s)
v_f	Wind speed measured ten meters above the ground (m/s)
h_w	Wind convection coefficient ($W/(m^2K)$)
u_{PV}	Heat exchange coefficient for the total surface of module ($W^oC^{-1}m^{-2}$)
u_0	Coefficient describing the effect of the radiation on the module temperature ($W\,^oC^{-1}m^{-2}$)
u_1	Cooling by the wind ($W s\,^oC^{-1}m^{-3}$)
η	Efficiency of the solar cells *(unitless)*
β	Temperature coefficient of maximal power of the solar cells ($^oC^{-1}$)
τ	Transmittance of the cover system *(unitless)*
α	Absorption coefficient of the solar cells *(unitless)*
V_t	Thermal voltage (V)
V_{oc}	Open circuit voltage (V)
I_{sc}	Short circuit current (A)
dV_{oc}/dT_c	Voltage temperature coefficient ($^oC^{-1}$)
dI_{sc}/dT_c	Current temperature coefficient ($^oC^{-1}$)
P_m	Maximum power (W)
V_m	Maximum voltage(V)
I_m	Maximum current (A)
v_{oc}	Normalized voltage *(unitless)*
r_s	Normalized resistance *(unitless)*
R_s	Series resistance (ohm)
c_i	i^{th} calculated hourly global solar radiation data (W/m^2)
m_i	i^{th} measured hourly global solar radiation data (W/m^2)
$P_{p,h}$	Power value predicted in the hour (W)
$P_{m,h}$	Power value measured in the hour (W)
n	Number of hourly global solar radiation data ($unitless$)
N	Number of daylight hours ($unitless$)
C_N	Net capacity of the plant (W)

a	Intermediate variable *(unitless)*
b	Intermediate variable *(unitless)*

1. INTRODUCTION

1.1. Overview and Motivation

Energy is the core of the economic and social growth of the countries, and its importance is increasing with technological and industrial developments in the world. Although fossil fuels have many disadvantages especially on environment such as global warming and pollution, they are still the most widely used resource for electrical energy generation. However, people are becoming more aware about the harmful impact of fossil fuels and have started thinking about renewable energy [1]. Among renewable energy resources, solar energy has gathered wide interest because it is sustainable, free, non-polluting and endless. Since solar energy has more advantages than fossil fuels, studies and applications of photovoltaic (PV) systems that convert solar energy to electrical energy are becoming popular in recent years. PV systems are being preferred due to their multiple advantages, for example, having flexibility to store excess generated energy in batteries, not polluting the environment, having simple structures and easy applications [2].

In a study comparing solar energy accumulated annually in earth and current fossil reserves, it is found that solar energy amount is 516 times more than oil reserves and 157 times more than coal reserves [3]. Therefore, we should efficiently take advantage of the solar energy which is provided to us at no cost and is limitless [4]. Along with being limitless, the industrial generation of electrical energy using PV systems requires less labor and machines, and they have lower carbon emission. This situation increases the importance of PV systems. Whereas, when fossil sources are used to generate the energy, the heat generated in combustion moves into atmosphere, and increases the earth's temperature that causes melting of glaciers, droughts and rise of seas [5]. In addition, energy consumption in the world is increasing rapidly because of increase in population, economical developments and rapid urbanizations. Under these circumstances, required precautions must be taken to prevent the electricity deficit that would appear in following years, meet the energy demand sufficiently and avoid serious problems that stem from heat increase. Thus, in our majorly foreign-dependent country, all the problems can only be solved if appropriate energy plannings for future are adopted including use of in particular solar energy, in heating, lighting and some other fields.

Global solar radiation data has an important role on solar energy applications because accurate information on availability of the solar resources for the considered application is often required [6]. The data should be recent, reliable and available for design, optimization and performance evaluation of solar technologies for any particular location [7]. The measurement of solar radiation data is generally available in some specific areas due to difficulty in solar radiation measurements in terms of cost of measuring equipment, maintenance and calibration requirements [8]. Therefore, solar radiation estimation techniques have come into prominence due to the increasing need for electrical energy generation with solar energy applications. When actual measured values are not available in a region, global solar radiation data are estimated by using appropriate models.

In some solar studies, hourly global solar radiation data on horizontal surfaces in a particular region are needed where measured daily global solar radiation values are available. Therefore, global solar radiation decomposition models are performed to estimate hourly solar radiation values from daily solar radiation values. As stated in [9], the existing daily global solar radiation decomposition models are divided into three main groups. The first kind of models considers the solar hour angle, day length and solar time. In this group, Whillier model, Liu and Jordan model, Collares-Pereira and Rabl (CPR) model, CPRG model, Garg and Garg model and Gueymard model are included [10]. In [11], Whillier model is proposed to estimate hourly radiation values from daily values by assuming constant weather conditions as if there is no atmosphere. Then, the radiation formula developed in Whillier model is slightly simplified in [12] and obtained as Liu and Jordan model. CPR model is developed in [13] by giving a significant correction to Liu and Jordan model after adding atmospheric effect. Also, CPR model is modified to estimate hourly global solar radiation from the daily value in [14] which results in the occurance of CPRG model. Garg and Garg model is proposed in [15] by modifying Liu and Jordan model to obtain hourly global solar radiation values for four Indian stations. Finally, Gueymard model is developed in [16] by modifying CPR model. In the model, it is observed that asymmetries of morning and afternoon can affect the performance of the model's result.

The second kind of models assumes that there is a random variation in weather conditions and axial symmetric distribution between hourly global solar radiation of morning and afternoon times which results in a normal distribution. The models of the second type include Jain model 1, Jain model 2, Baig et al. model and Shazly model. These models consider the normal distribution [9]. Within the models, Jain models are proposed in [17] and [18] by considering the daily global solar radiation decomposition models in the form of Gaussian function. Then, Baig et al. [19] and Shazly [20] models are performed by applying a correction factor to Jain model.

The most common model in the third group of models is Newell model. In the model proposed in [21], a simplification is given to CPR model, which completely considers neither the variability of hourly solar radiation, nor the randomness of weather conditions.

When global radiation values can be measured, they are generally obtained on horizontal surfaces. However, in solar studies, PV systems are mounted on inclined surfaces to maximize the amount of solar radiation that falls on the solar panels [22]. Information of the amount of global solar radiation on inclined surfaces is necessary for a variety of purposes such as in solar energy engineering studies, energy balance estimations at the earth surface, or the modeling of topographic solar radiation using satellite data [23]. Most importantly, global solar radiation values on tilted surfaces where solar panels are mounted on have to be determined to predict power values that solar panels should generate. Therefore, horizontal global solar radiation intensities should be converted to global solar radiation values on the inclined surface by using appropriate models. The global solar radiation on the inclined surface has three components as direct radiation, diffuse radiation and ground reflected radiation [24]. The direct radiation on a tilted surface can be obtained with an easy mathematical relationship between horizontal and tilted surfaces. Similarly, the ground reflected radiation can accurately be computed by using an isotropic model. However, it is not possible to compute diffuse radiation as easy as other components because diffuse radiation includes the radiation comes from all points of the sky which results in a non-singular angle for that radiation [25]. Hence, many models have been developed to estimate diffuse radiation on tilted surfaces, and these models are generally divided into two groups. Isotropic models are included in the first group of models and these models assume that there is a uniform diffuse radiation over the sky which results in independence of zenith and azimuth angles. Another type of models that estimate diffuse radiation on inclined surfaces is called as anisotropic models. As the name implies, these models assume that diffuse radiation is anisotropic over the sky [26].

As mentioned before, there are a lot of models that estimate tilted global solar radiation from horizontal values. Most of models require global and direct or diffuse radiation on horizontal surface to find global radiation on tilted surfaces [27]. In Liu and Jordan model proposed in [28], it is assumed that diffuse solar radiation is isotropic and a relationship is provided for diffuse radiation on tilted surfaces. The effects of horizon brightening and circumsolar radiation are considered by adding a factor to Liu and Jordan model and proposed as Temps and Coulson model in [29]. Hay model is proposed in [30] by assuming the linearity of isotropic and circumsolar contributions to the diffuse radiation. The model that is provided in [29] is modified to obtain an anisotropic model, so Klucher model is developed in [31]. Then, Ma and Iqbal model is proposed in [32] by dividing diffuse radiation into radiations emitted by the circumsolar region and rest of the sky. Hay model is adjusted to find the corresponding relationship between diffuse radiation on horizontal and inclined surfaces, and results in Skartveit and Olseth model in [33]. Gueymard model is proposed in [34] by assuming that the radiance of a partially cloudy sky is a weighted sum of the clear and overcast sky's radiances. As in [33], Reindl et al. model is obtained in [35] with the modification of Hay model by adding the horizon brightening term used in Temps and Coulson model with a modulating function. Then, a model named as Perez et al. is proposed in [36] based on the three components as mathematical representation of the sky dome, a parametric representation of the radiation conditions and a statistical component between these two. However, if this model is used for global radiation estimation on tilted surface, a lot of coefficients have to be determined. In [37], the relative ability of Liu and Jordan, Klucher, and Hay models are analyzed and it is concluded that this ability changes with time of year and climatic conditions of the site while estimating global solar radiation on tilted surface. Also, in [38], Liu and Jordan, and Hay models are compared to determine the total global radiation on tilted surface in Amman, Jordan. Muneer model in [39] includes tilt factor depending on the radiance distribution index to estimate diffuse radiation intensity. Comparison and modification of developed models are considered in some studies (e.g. [40–42]) for specific regions. In [23], a simple model is developed to estimate global solar radiation values on inclined surfaces and named as Olmo et al. model. The model only requires the horizontal global radiance, solar incidence and zenith angles as input parameters with no need of diffuse and direct radiations. In [43] and [44], accuracy of different models is evaluated to estimate diffuse radiation from the measured horizontal global and diffuse radiation in Spain. In addition, eight different models are evaluated in [45] to estimate global solar radiation on 45^o south-facing and 40^o west-facing surfaces in Iran. In [46], the authors combine their two previous studies and compare it with Olmo et al. model to obtain global solar radiation on inclined surfaces from horizontal values directly. In [47], eleven different models are tested by considering measured data of horizontal global and diffuse radiation, normal incidence direct and global radiation on surface tilted 40^o. Also, different models are evaluated in [48] to estimate diffuse or global solar radiation on different inclined surfaces by using the measured horizontal values therein.

Another important factor other than global solar radiation, which considerably affects the power generation of solar panels is temperature. Since solar cells are semi-conductors, the current and voltage of these cells are significantly affected by temperature. Hence, temperature plays a vital role on power generation process in PV systems. Increase in PV cell temperature causes open-circuit voltage to decrease significantly and increase short-circuit current slightly. Solar panel manufacturers provide limited information and assume that solar panels operate under standard test conditions, which considers cell temperature of $25°C$, solar radiance of 1000 W/m^2 and air mass of 1.5. However, these conditions are not generally valid when dynamic change of weather conditions are considered. Therefore, the estimation and analysis of cell temperature have received wide attention in recent years to predict power generation and accordingly efficiency of solar panels. With the aid of related studies, power generation of PV systems is able to be analyzed depending on dynamic change of outdoor parameters.

The temperature of the PV cell is assumed as the same with the temperature of PV module [49]. Hence, power generation values of PV modules can be analyzed on the basis of cells in terms of temperature. In a study, three different PV technologies are analyzed and it is concluded that energy generation of solar systems are decreased by 2 to 10 % at high module temperatures [50]. This situation increases the importance of cell temperature estimation methods. It is not possible to measure cell temperature of solar panels directly for many PV systems. Therefore, the physical relationship between the PV cell temperature, global solar radiation on the surface of panels and other meteorological parameters such as wind speed should be analyzed with the help of related methods.

In literature, there are some methods used to estimate cell temperature of PV systems. A standard approach is developed in [51] which is based on only ambient temperature and global radiation on the surface. This method does not consider the effect of wind or other meteorological parameters on cell temperature. Within Mattei et al. models in [49], two different parametrizations of heat exchange coefficient are defined for the module surface to calculate cell temperature depending on wind speed. In addition, two different equations of wind convection coefficient are defined to integrate wind data in the standard formula, which are named as Skoplaki et al. models in [52]. Kurtz et al. model, defined in [53], does not take into account different PV technologies, and considers only ambient temperature, global solar radiation and wind speed. A simple empirical model proposed in [54] is used and some constants are described depending on PV technologies within Koehl et al. model in [55].

Information on actual power generation values of solar energy systems are essential to associate demand and source side dynamics efficiently. Before installation of PV systems, this information should be obtained to optimize the system size that is required to meet energy demand and analyze the whole system. Therefore, after obtaining tilted global solar radiation and cell temperature, these values can be basically used to predict power values that solar panels should generate in ideal.

As indicated in [56], the methods which are preferred for prediction of power generation can be classified into three main groups as physical, statistical and hybrid methods. In physical models, output power mainly depends on the global solar radiation and ambient temperature. More complex models will require some other outdoor parameters. Since solar panel systems are assumed under nominal operating conditions, related parameters should be estimated to obtain actual power output values. In some studies (e.g. [57–60]), the current and voltage relationships of solar systems with the aid of different methods are analyzed, and the efficiency of the considered methods are compared under different solar radiation and temperature values. Also, in [61], current and voltage characteristics of the systems depending on different modelling methods are defined. In [62] where efficiency and complexity of the models are compared, five different models are used to predict energy generation of fields of almost 5 MW. It is concluded that simple models (four- or five-parameter) are more accurate than the more complex ones. In [63], a five-parameter model is evaluated to analyze open circuit voltage, short circuit current and maximum power point on a single panel, string and array. It is analyzed that the model can be applied to strings and arrays other than single panels by using a derating factor. Finally, four- and five-parameter models are compared in [64] by applying measured cell temperature values based on 120 W monocrystalline solar panels to calculate operating currents.

The second group consists of statistical methods which are based on the concept of persistence or stochastic time series. The most common method used to estimate future values of time series, is the machine learning method. As stated in [65], during the application process of these methods in [66–68], artificial neural network (ANN) are used for prediction of the fluctuating energy supply. Also as stated in [65], in statistical methods, patterns are recognized by using training data sets which means that there is a need of historical data about weather estimation, power generation and environmental conditions to train ANN and predict power generation values of renewable energy systems.

In the third group, combinations of two or more prescribed methods are included and named as hybrid models. The methods are combined to overcome the disadvantages of individual methods [69].

Prediction of output power of solar based systems is essential for PV applications. A very common way to obtain power values that solar panels should generate is to consider global radiation incident on panel surface which has a specific angle, and ambient temperature to obtain module temperature. These parameters which are needed to be obtained for solar energy analysis and studies, affect the power generation of solar panels. Therefore, a detailed solar energy analysis plays a significant role on future's power system studies. This analysis should include estimation of horizontal and tilted global solar radiation, cell temperature, and power generation of the whole system that meets the energy demand of a home.

1.2. Thesis Goals and Contribution

In this thesis, it is aimed to perform solar energy analysis of Renewable Energy Research Home (RERH) built within the scope of Scientific Research Project in İki Eylül Campus in Eskişehir. In accordance with this purpose, in addition to hourly global solar radiation on horizontal and tilted surfaces, cell temperature values are estimated to predict output power of solar systems depending on outdoor parameters.

The thesis contributes to the literature in an important point. In the light of [70–72], studies presented in this thesis, include a detailed solar energy analysis along with a real-time home by considering outdoor parameters in Eskişehir. It should be noted that, this is the first study which considers the comprehensive analysis of solar energy in Eskişehir region.

In future, it is expected to be more common to design and implement solar systems to satisfy the energy demand efficiently, so it is crucial to get information about actual power generation of solar panels before installation. By analyzing and applying accurate models for the considered region, solar energy analysis can be performed to have an idea about determination of number of panels that meet the required energy to minimize the cost and system sizing.

1.3. Thesis Outline

The thesis is structured as follows: Chapter 2 gives the background information about the input parameters of solar energy analysis. In Section 2.1, eleven different daily global solar radiation decomposition models are discussed. In Section 2.2, the considered model used for global solar radiation estimation on tilted surface is explained. In Section 2.3, cell temperature estimation methods are compared by emphasizing seven different models based on tilted global solar radiation obtained in the previous section, measured ambient temperature and wind speed. In Section 2.4, a mathematical model which is used to obtain power generation values of both on-grid and off-grid solar panels by using the obtained parameters, is defined.

In Chapter 3, description of the current system and simulation results are discussed in detail. In Section 3.1, RERH that consists of on-grid solar panels, off-grid solar panels and wind turbine is explained. In Section 3.2, simulations are evaluated by using selected statistical analysis methods depending on the measured hourly global solar radiation values on horizontal surface. In Section 3.3, predicted power generation values of on-grid and off-grid systems are compared with the actual power values. Also, the results are presented with related figures and tables.

In Chapter 4, the results are concluded. In addition, future expectations are explained.

2. BACKGROUND

In this chapter, methods used for solar energy analysis of RERH are described. In Section 2.1, the considered models that estimate hourly global solar radiation values from the daily global solar radiation values on horizontal surface are discussed. In Section 2.2, the selected model for estimation of global solar radiation on tilted surface is given. The methods used for estimation of an another parameter, cell temperature, are indicated in Section 2.3. In the last section, the considered power generation model is described, which is based on the technical specifications of solar panels and the parameters found in Section 2.1, 2.2 and 2.3.

2.1. Global Solar Radiation Estimation on Horizontal Surface

Global solar radiation data in a particular region are essential for solar energy applications because electricity generation from PV panel is directly affected by solar radiation [73]. The data must be available, reliable and accurate for planning, projection and continuity of the system. Due to the maintenance and calibration requirements and the cost of the equipment used for measurements, solar radiation estimation techniques are considered as an important issue [74]. There are lots of models performed for estimation of hourly global radiation by using daily global radiation values. The existing daily global solar radiation decomposition models are mainly categorized in three groups as explained in Section 1.1.

In this thesis, daily global solar radiation decomposition models included in all groups are performed to obtain hourly global solar radiation values on horizontal surface from the daily values in Eskişehir, Turkey. Measured hourly and daily global solar radiation values of nine months of 2016 are recorded. Hourly global solar radiation values are estimated from the measured daily global solar radiation values by performing eleven different models.

2.1.1. Whillier Model

The model is proposed in [11] to estimate hourly global solar radiation on horizontal surfaces from the daily values to study long-term average solar radiation. Since the main interest is long-term estimation here, atmospheric transmission that can change instantly is assumed as constant. The ratio of hourly to daily global solar radiation on horizontal surface is given by:

$$\frac{I}{H} = \frac{\pi}{24} \cdot \frac{\frac{24}{\pi} \sin \frac{\pi}{24} \cos W - \cos W_s}{\sin W_s - \frac{\pi W_s}{180} \cos W_s} \ . \tag{2.1}$$

Day angle (Γ) and solar declination angle (δ) are defined as in (2.2) and (2.3) respectively:

$$\Gamma = \frac{2\pi \left(d - 1\right)}{365} \ , \tag{2.2}$$

$$\begin{aligned} \delta = \left(\frac{180}{\pi}\right) \Big(&0.006918 - 0.399912 \cos(\Gamma) + 0.070257 \sin(\Gamma) \\ &- 0.006758 \cos(2\Gamma) + 0.000907 \sin(2\Gamma) \\ &- 0.002697 \cos(3\Gamma) + 0.00148 \sin(3\Gamma)\Big) \ . \end{aligned} \tag{2.3}$$

Therefore, sunrise hour angle (W_s) and solar hour angle (W) used in (2.1) are described as follows:

$$W_s = \arccos\left(- \tan \delta \tan \phi\right) \ , \tag{2.4}$$

$$W = \frac{360 \left(t_s - 12\right)}{24} \ . \tag{2.5}$$

In (2.4), since δ and latitude (ϕ) are constant, W_s will remain the same in a day. Unlike W_s, W changes depending on the hour of the day. Since atmospheric transmission is considered as a constant value, and any related parameter is included in (2.1), the hourly to daily global solar radiation ratio is a function of the theoretical maximum possible duration of sunshine for the particular latitude and time of year involved.

2.1.2. Liu and Jordan Model

In [12], it is aimed to determine long-term average hourly and daily sums of diffuse radiations. For these purposes, total amount of hourly global solar radiation that includes direct and diffuse radiations is needed. Therefore, the ratio of hourly to daily global solar radiation formula defined in (2.1) is slightly simplified to obtain an equality as follows:

$$\frac{I}{H} = \frac{\pi}{24} \cdot \frac{\cos W - \cos W_s}{\sin W_s - \frac{\pi W_s}{180} \cos W_s} \tag{2.6}$$

where W_s and W values are calculated as in (2.4) and (2.5) respectively. Since $(\frac{24}{\pi}\sin\frac{\pi}{24})$ is approximately equal to 1, the model nearly gives the same results with Whillier model [9]. Hence, Liu and Jordan model may be known as Whillier - Liu and Jordan model.

2.1.3. CPR Model

The equation expressed in (2.6) is modified in [13] by realizing that atmospheric effect of direct and global radiation has a dependency upon hour angle. Two years of individual hourly radiation values from four U.S. stations and the data involved in [12] are used, so the formula defined in (2.6) which ignores atmospheric effect is adjusted. In the developed model, Liu and Jordan approach is confirmed by emphasizing that hourly global solar radiation can be estimated with hour angle and mean daily total global radiation directly. The model is a widely used daily global solar radiation decomposition model and described by:

$$\frac{I}{H} = \frac{\pi}{24}\left(a + b\cos W\right)\frac{\cos W - \cos W_s}{\sin W_s - \frac{\pi W_s}{180}\cos W_s} \tag{2.7}$$

where W_s and W values are found as in (2.4) and (2.5) respectively. Also, a and b are linear functions of $(W_s - 60°)$ and defined as [75]:

$$a = 0.4090 + 0.5016\sin\left(W_s - 60°\right)\ , \tag{2.8}$$

$$b = 0.6609 - 0.4767\sin\left(W_s - 60°\right)\ . \tag{2.9}$$

When equations in (2.6) and (2.7) are compared, it is seen that atmospheric attenuation depending on hour angle is considered in (2.7) by adding the term of $a + b\cos W$ in (2.6).

2.1.4. CPRG Model

The adaptability of CPR model is confirmed and a slight correction to CPR model is proposed to ensure consistency through renormalization in [14]. The correlation for hourly to daily global solar radiation on horizontal surface is defined as:

$$\frac{I}{H} = \frac{\left(a + b\cos W\right) r_o}{f_c}\ . \tag{2.10}$$

W, a and b included in (2.10) are defined as in (2.5), (2.8) and (2.9) respectively, and the other parameters are defined as follows:

$$f_c = a + 0.5\ b\ \frac{\frac{\pi W_s}{180} - \sin W_s \cos W_s}{\sin W_s - \frac{\pi W_s}{180} \cos W_s}\ , \tag{2.11}$$

$$r_o = \frac{\pi}{24} \cdot \frac{\cos W - \cos W_s}{\sin W_s - \frac{\pi W_s}{180} \cos W_s} \tag{2.12}$$

where W_s is obtained as in (2.4).

2.1.5. Garg and Garg Model

Liu and Jordan model is evaluated for various Indian stations in [15], and it is analyzed that the model is not accurate to estimate hourly global solar radiation values for the average day of each month. Therefore, a model is proposed in [15] to obtain hourly global solar radiation values, which provides the following relationship:

$$\frac{I}{H} = \frac{\pi}{24} \cdot \frac{\cos W - \cos W_s}{\sin W_s - \frac{\pi W_s}{180} \cos W_s} - 0.008 \sin 3 \left(\frac{\pi W_s}{180} - 0.65 \right) \tag{2.13}$$

where W_s and W values are obtained as in (2.4) and (2.5) respectively. As shown in (2.13), a term of $0.008 \sin 3 \left(\frac{\pi W_s}{180} - 0.65 \right)$ is added to the relationship in (2.6) to increase the accuracy of global solar radiation estimation for average day of each month.

2.1.6. Gueymard Model

Since most of models consider limited number of data for computation, universal applicability of these models are restricted. For this reason, a large dataset of 135 stations with different climate characteristics and latitudes are considered, and a model is developed based on the modification of CPR model in [16]. In the model, it is analyzed that asymmetries of the different times of a day may have an effect on model results. Within the scope of this model, daily extraterrestrial global solar radiation on horizontal surface (H_0) is needed and obtained as:

$$H_0 = \frac{24}{\pi} W_s R I_{sol} \sin(h_0)\ . \tag{2.14}$$

In (2.14), W_s is found as in (2.4), monthly average sun-earth distance correction factor (R) is selected from the table in [16] for the corresponding month, solar constant (I_{sol}) is accepted as 1367 W/m^2, and sine function of daily-average solar elevation outside of the atmosphere ($sin(h_0)$) is defined as:

$$\sin(h_0) = \frac{qA(W_s)}{\frac{\pi W_s}{180}} \tag{2.15}$$

where q and $A(W_s)$ are calculated as in (2.16) and (2.17) respectively:

$$q = \cos\phi\cos\delta \ , \tag{2.16}$$

$$A(W_s) = \sin W_s - \frac{\pi W_s}{180}\cos W_s \ . \tag{2.17}$$

After H_0 is found, daily clearness index (K_t) is obtained by dividing total daily global solar radiation to daily extraterrestrial global solar radiation on horizontal surface as:

$$K_t = H/H_0 \ . \tag{2.18}$$

In addition, since earth rotates at 15 degrees for an hour, day length (S_0) is defined as a function of W_s:

$$S_0 = \frac{2}{15}W_s \tag{2.19}$$

and the correlations of a_1 and a_2 depending on K_t, S_0 and $sin(h_0)$ are obtained respectively:

$$a_1 = 0.41341K_t + 0.61197{K_t}^2 - 0.01886K_tS_0 + 0.00759S_0 \ , \tag{2.20}$$

$$\begin{aligned} a_2 = \max\big(&0.054, 0.28116 + 2.2475K_t - 1.76118{K_t}^2 \\ &-1.84535\sin(h_o) + 1.6811\sin^3(h_o)\big) \end{aligned} \ . \tag{2.21}$$

Finally, functions of r_o and $B(W_s)$ are defined in terms of W and W_s as follows:

$$r_o = \frac{(\cos W - \cos W_s)}{\frac{24}{\pi}A(W_s)} \ , \tag{2.22}$$

$$B(W_s) = \frac{\pi W_s}{180}\left(0.5 + \cos^2 W_s\right) - 0.75\sin 2W_s \ . \tag{2.23}$$

After combination of the obtained parameters, the ratio of hourly to daily global solar radiation on horizontal surface is defined as:

$$\frac{I}{H} = r_o\frac{1 + q\left(\frac{a_2}{a_1}\right)\left(\frac{24}{\pi}\right)A(W_s)\,r_o}{1 + q\left(\frac{a_2}{a_1}\right)\frac{B(W_s)}{A(W_s)}} \ . \tag{2.24}$$

2.1.7. Jain Model 1

Eleven-year mean values that point out the ratio of hourly to daily global solar radiation are plotted for each month depending on solar time in [17]. The mean of the normal distribution is taken at the solar noon, and σ values are obtained for each month by matching the experimental and theoretical values at solar noon. The obtained σ values have good linear correlation with S_0. The σ values are obtained depending on S_0:

$$\sigma = 0.192S_0 + 0.461 \tag{2.25}$$

where S_0 is defined as in (2.19). As stated in [74], a Gaussian function is proposed to fit the recorded data in the model. This provides a simple technique to estimate hourly global solar radiation from the daily values. The technique enables the estimation of global solar radiation for any smaller interval of time as well. The model proposes the following relationship for hourly global solar radiation estimation:

$$\frac{I}{H} = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(t_s - 12)^2}{2\sigma^2}\right) . \tag{2.26}$$

2.1.8. Jain Model 2

The model developed in [17] is slightly modified to estimate hourly radiation values on horizontal surface in [18]. A different σ value is defined to be included in (2.26) as:

$$\sigma = 0.2S_0 + 0.378 . \tag{2.27}$$

2.1.9. Baig et al. Model

With the modification of Jain model, a model is developed in [19] to better fit the recorded data during the start and end periods of a day. The model in [19] based on the modified version of Gaussian distribution function is proposed to calculate the distribution of the broad-band global solar radiation on any clear day of the year. The proposed model provides the relationship for the ratio of hourly to daily global solar radiation as defined:

$$\frac{I}{H} = \frac{1}{2\sigma\sqrt{2\pi}} \left[\exp\left(-\frac{(t_s - 12)^2}{2\sigma^2}\right) + \cos\left(\frac{\pi\,(t_s - 12)}{S_0 - 1}\right)\right] \tag{2.28}$$

where σ values are calculated depending on S_0 as follows:

$$\sigma = 0.21S_0 + 0.26 \; . \tag{2.29}$$

2.1.10. Shazly Model

In [20], the performance of Jain and Baig et al. models, which are based on the Gaussian distribution function, are considered to estimate hourly global solar radiation from the daily values. Therein, distribution through hours of any clear day from sunrise to sunset is evaluated with the measured data. According to the analysis in [20], since the accuracy of the considered models, in particular Jain model, is not good enough for the region, a model is obtained by adding a correction factor to Jain model. The ratio of hourly to daily global solar radiation on horizontal surface is defined in [20] as follows:

$$\frac{I}{H} = \frac{1}{2.2\sigma\sqrt{2\pi}}\left[\exp\left(-\frac{(t_s-12)^2}{2\sigma^2}\right) + 1.2\cos\left(\frac{\pi\,(t_s-12)}{S_0-0.65}\right)\right] \tag{2.30}$$

where σ is calculated as:

$$\sigma = 0.174S_0 + 0.768 \; . \tag{2.31}$$

This proposed model results in higher performance than Jain model 1 and Baig et al. model for the considered region. In addition, the validity of this approach is verified with new measurements in some clear days.

2.1.11. Newell Model

CPR model is simplified and a different approach is performed in [21]. The proposed model is different than the first and second group daily global solar radiation decomposition models due to including any unique characteristic as only varying tendency of hourly radiation or randomness of weather conditions [9]. The developed model is described as;

$$\frac{I}{H} = \frac{1.5}{S_0}\left(1 - \frac{4(t_s-12)^2}{(S_0)^2}\right) \; . \tag{2.32}$$

2.2. Global Solar Radiation Estimation on Inclined Surface

Most measurement devices provide global solar radiations on horizontal surface. However, to increase the accuracy of solar energy analysis and studies, it is also necessary to estimate global solar radiation on solar panels which have a specific angle. This situation emphasizes the importance of global solar radiation estimation on inclined surface.

Since the diffuse radiation values have recently been available in our system, Olmo et al. model is used in this thesis. The estimated hourly global solar radiation values on horizontal surface which are the results of the model of highest accuracy are used to find the global solar radiation on inclined surface of solar panels. In the next subsection, Olmo et al. model is described in detail.

2.2.1. Olmo et al. Model

Olmo et al. model is developed in [23] to determine global solar radiation on inclined surfaces by using data obtained at Granada, Spain. Although only clear sky data are used, the model is intended for all sky conditions. The authors emphasize the general applicability of their model, which can be used with instantaneous values as well as averaged measurements.

Unlike many other methods, the model does not decomposite global solar radiation into its components as diffuse and direct radiations. Obviously, if such a model works properly allowing for accurate estimation of global radiation on inclined planes, its availability may imply a significant advancement in this field of research. Within the scope of this model, hourly extraterrestrial global solar radiation on horizontal surface (I_0) is needed and obtained as:

$$I_0 = I_{sol}\left(1 + 0.033\cos\left(\frac{360d}{365}\right)\right)(\cos\phi\cos\delta\cos W + \sin\phi\sin\delta)\ . \tag{2.33}$$

In addition, solar incidence angle (θ) and solar zenith angle (θ_z) are calculated respectively as follows:

$$\theta = \arccos\left(\sin\delta\sin\left(\phi-\gamma\right) + \cos\delta\cos\left(\phi-\gamma\right)\cos W\right)\ , \tag{2.34}$$

$$\theta_z = \arccos\left(\sin\delta\sin\phi + \cos\delta\cos\phi\cos W\right) \tag{2.35}$$

where γ represents the surface inclination angle. After dividing hourly global solar radiation to extraterrestrial global solar radiation on horizontal surface, hourly clearness index (k_t) is found by the following relationship:

$$k_t = I/I_0\ . \tag{2.36}$$

The multiplying factor (F_c) is defined depending on albedo of the underlying surface (ρ), which is commonly used as the radiation reflected from the ground, and θ as:

$$F_c = 1 + \rho \sin^2 (\theta/2) \tag{2.37}$$

where ρ is chosen as 0.25 as in [23]. Finally, the function that converts horizontal global solar radiation to the corresponding radiation on tilted surface (ψ_o) is defined as:

$$\psi_o = \exp\left(-k_t\left(\left(\frac{\pi\theta}{180}\right)^2 - \left(\frac{\pi\theta_z}{180}\right)^2\right)\right) \ . \tag{2.38}$$

As a result of obtaining all parameters, hourly global solar radiation on inclined surface (I_γ) is calculated from the hourly global solar radiation on horizontal surface as:

$$I_\gamma = I\psi_o F_c \ . \tag{2.39}$$

2.3. PV Cell Temperature Estimation

Cell temperature of solar panels is a fundamental parameter for power output prediction because this temperature directly affects the basic electrical quantities such as current and voltage. Since measurement of cell temperature is not possible in many cases, studies about estimation of cell temperature have received wide attention in recent years. The developed correlations in literature express cell temperature (T_c) as a function of outdoor parameters such as ambient temperature, wind speed and global solar radiation on solar panels. Generally, cell temperature is extremely sensitive to wind speed, less so to wind direction and practically insensitive to the atmospheric temperature [76]. On the other hand, it significantly depends on global solar radiation on the surface of solar panels.

In this thesis, cell temperature values for solar panels of the considered system are estimated by using seven different models based on the estimated global solar radiation values on tilted surface, measured ambient temperature and wind speed values.

2.3.1. Standard Approach

The method in [51] does not consider the wind effect as in other used approaches in this thesis and proposes cell temperature as:

$$T_c = T_a + \frac{I}{I_{NOCT}} \left(T_{NOCT} - T_{a,NOCT}\right) \ . \tag{2.40}$$

In (2.40), T_{NOCT} depends on the PV manufacturer, so this temperature is the nominal operating cell temperature considered under nominal operating conditions of I_{NOCT}=800 W/m^2, $T_{a,NOCT}$=20°C and wind speed of 1 m/s.

2.3.2. Skoplaki Model 1

Within the developed model, wind speed is integrated to the standard approach in [52]. Besides global solar radiation and ambient temperature, the model takes into account wind speed and solar cell properties such as efficiency, temperature coefficient of maximal power, transmittance of the cover system and absorption coefficient of the cells. Cell temperature is defined as;

$$T_c = T_a + \frac{I}{I_{NOCT}} \left(T_{NOCT} - T_{a,NOCT}\right) \frac{h_{w,NOCT}}{h_w(v)} \cdot \left(1 - \frac{\eta_{STC}}{\tau.\alpha} \left(1 - \beta_{STC} T_{STC}\right)\right) \tag{2.41}$$

where η_{STC} and β_{STC} are efficiency and temperature coefficient of maximal power under standard test conditions of I_{STC}=1000 W/m^2, T_{STC}=25°C and AM=1.5. Also, $h_{w,NOCT}$ is the wind convection coefficient of wind speed under normal operating conditions. η_{STC} and β_{STC} values are obtained from the datasheet of the panel. The parameter $\tau.\alpha$ in (2.41) is chosen as 0.9 as in [52]. The wind convection coefficient (h_w) is defined with a parametrization;

$$h_w = 8.91 + 2.00 v_f \tag{2.42}$$

where v_f is the wind speed measured 10 meters above the ground.

2.3.3. Skoplaki Model 2

In addition to the parametrization defined in (2.42), another parametrization is defined for h_w to be used in (2.41) as [52];

$$h_w = 5.7 + 2.8 v_w \tag{2.43}$$

where v_w is the local wind speed close to the module. The relationship between v_w and v_f is defined as;

$$v_w = 0.68 v_f - 0.5 \ . \tag{2.44}$$

2.3.4. Koehl Model

The model which is proposed from the energy balance for a solar thermal collector by [54], is used in [55] to calculate cell temperature as a function of ambient temperature, global radiation and wind speed. The corresponding cell temperature estimation model is defined as:

$$T_c = T_a + \frac{I}{u_0 + u_1 v_w} \tag{2.45}$$

where the constants of u_0 and u_1 in (2.45) are defined as the coefficients describing the global radiation on module temperature and cooling by the wind respectively. These parameters are selected according to the specifications defined in [55] depending on PV technologies.

The model neglects the influence of the infrared radiation exchange with the cold sky and the natural convection which is noticeable at low wind-speed and low radiation.

2.3.5. Mattei Model 1

The model in [49] is developed by realizing an energy balance on PV module. According to that balance, the differences of temperature between PV cells and the cover are neglected. The temperature is confirmed as constant through the panel. Also, the radiative exchanges are neglected.

Temperature has different effects on efficiency (η) of PV cells, and the most known model about the effect of temperature on η is defined as:

$$\eta = \eta_{STC}\big(1 - \beta\left(T_c - T_{STC}\right)\big) \ . \tag{2.46}$$

In (2.46), solar radiance coefficient for the PV module is considered as 0 by assuming η_{STC} is the reference module efficiency and β is the temperature coefficient for the PV module. Also, the energy balance is:

$$\alpha \cdot \tau \cdot I = \eta \cdot I + u_{PV}\left(T_c - T_a\right) \ . \tag{2.47}$$

If (2.46) is placed in (2.47), the model that is based on energy balance is obtained as [49];

$$T_c = \frac{u_{PV}\left(v_w\right) T_a + I \cdot \left(\tau.\alpha - \eta_{STC}\left(1 - \beta_{STC} \cdot T_{STC}\right)\right)}{u_{PV}\left(v_w\right) + \beta_{STC} \cdot \eta_{STC} \cdot I} \tag{2.48}$$

where the expression of the heat exchange coefficient for the total surface of module (u_{PV}) is defined as:

$$u_{PV}\left(v_w\right) = 26.6 + 2.3v_w \ . \tag{2.49}$$

The input parameters of η_{STC}, β_{STC} and T_{STC} have the same values as in (2.41). The parameter $\tau.\alpha$ in (2.48) is chosen as 0.81 as in [49].

2.3.6. Mattei Model 2

In [49], the same expression defined in (2.48) is used with a different parameterization of u_{PV}, given as;

$$u_{PV}\left(v_w\right) = 24.1 + 2.9v_w \tag{2.50}$$

where, for v_w=1 m/s, u_{PV} is calculated as u_{PV}=27 $W^oC^{-1}m^{-2}$ instead of u_{PV}=28.9 $W^oC^{-1}m^{-2}$ which can be found by using (2.49).

2.3.7. Kurtz Model

In [53], polymeric-material degradation during PV-module operation at high ambient temperatures, high solar radiance and low wind speed is focused on. The thermal exposure of PV modules is explored in the field as a technical basis for this debate. The relationship is defined that is independent from PV technology of the considered solar panels as;

$$T_c = T_a + I \cdot \exp\left(-3.473 - 0.0594v_w\right) \ . \tag{2.51}$$

2.4. Power Generation of Solar Panels

In general, solar panel manufacturers provide maximum power, open circuit voltage and short circuit current under ideal test conditions [?]. However, these ideal conditions are not valid in real life because temperature and solar radiation values are dynamically changing and this changable behaviour affects the output power generation of solar panels directly. The short circuit current (I_{sc}) and open circuit voltage (V_{oc}) are calculated as;

$$I_{sc} = \frac{I_{sc}^*}{I^*} I \left(1 + \left(T_c - T_c^*\right) \frac{dI_{sc}}{dT_c}\right) \ , \tag{2.52}$$

$$V_{oc} = V_{oc}^{*} + (T_c - T_c^{*})\frac{dV_{oc}}{dT_c} + V_t \ln\left(\frac{I}{I^{*}}\right) \tag{2.53}$$

where "*" points out the reference value of the corresponding parameter. I^{*} and T_c^{*} are the reference global solar radiation and reference cell temperature which are defined as 1000 W/m^2 and 25^oC by solar panel manufacturers.

T_c is estimated by using the methods described in the previous section to be used in (2.52) and (2.53). Also, the series resistance (R_s) is obtained as 0.0069 according to the values that solar panel manufacturers defined under test conditions. The obtained value is assumed as constant for all ambient temperature and global radiation conditions.

In real PV systems, a maximum power point tracking (MPPT) is used to maximize the obtained energy from available solar energy values [77]. The maximum power (P_m) is defined as;

$$P_m = V_m I_m \tag{2.54}$$

where maximum voltage (V_m) and maximum current (I_m) values are found;

$$V_m = V_{oc}\left(1 - \frac{b}{\nu_{oc}}\ln a - r_s\left(1 - a^{-b}\right)\right) \ , \tag{2.55}$$

$$I_m = I_{sc}\left(1 - a^{-b}\right) \ . \tag{2.56}$$

In (2.55) and (2.56), a and b coefficients are described by the following relationships:

$$a = \nu_{oc} + 1 - 2v_{oc}r_s \ , \tag{2.57}$$

$$b = \frac{a}{1+a} \tag{2.58}$$

where normalized voltage (v_{oc}) and normalized resistance (r_s) are defined respectively as:

$$v_{oc} = V_{oc}/V_t \ , \tag{2.59}$$

$$r_s = R_s/\left(V_{oc}/I_{sc}\right) \ . \tag{2.60}$$

3. APPLICATION AND RESULTS

In this chapter, simulations and results are discussed along with the considered system description. In Section 3.1, hybrid system model of RERH, which is developed under the Scientific Research Projects, is clearly described by emphasizing in particular on-grid PV system, off-grid PV system and measurement system of outdoor parameters. In Section 3.2, accuracy of the considered models to estimate hourly global solar radiation on horizontal surface is discussed in detail with related figures and tables. Finally, evaluation of predicted power output values depending on estimated cell temperature values is shown in Section 3.3.

3.1. RERH System Development

PV systems are placed in two ways as on-grid and off-grid, and depending on the position of solar panels, they are either ground-mounted or mounted on the roof. Also, they are designed as static or solar tracker systems. The system placed in RERH has a PV system that is modelled by combining both on-grid and off-grid solar panels and consists of ground-mounted panels, rooftop panels and solar tracker system. The PV system has 39 solar panels. Among these panels, 24 of solar panels are used for 6 kW on-grid system and the rest 15 of solar panels are used for 4 kW off-grid system. Half of on-grid panels are static and the other half are used with solar tracker. In the system considered in this thesis, 1 kW wind turbine is added to the PV system to develop a hybrid system model as shown in Figure 3.1.

Figure 3.1. *Hybrid system model.*

Parameters of 260 W AXITEC solar panels used in the PV system of RERH are given in Table 3.1.

Table 3.1. *Datasheet values of AXITEC solar panel*

Open circuit voltage (V_{oc})	38.17 V
Short circuit current (I_{sc})	8.99 A
Maximum voltage (V_{mp})	30.56 V
Maximum current (I_{mp})	8.51 A
Maximum power of module (P_m)	260 W
Voltage temperature coefficient	-0.30 %/K
Current temperature coefficient	0.04 %/K
Number of cells	60

The PV system contains multiple PV modules that convert the radiation coming from the sun into direct current (DC) electrical energy, solar inverters that convert DC to alternative current (AC) and synchronize it with the grid, charge regulators that provide to store electrical energy in batteries, constructions to be used for solar module placements and switching equipments. The PV system scheme that consists of both on-grid and off-grid solar panels is shown in Figure 3.2.

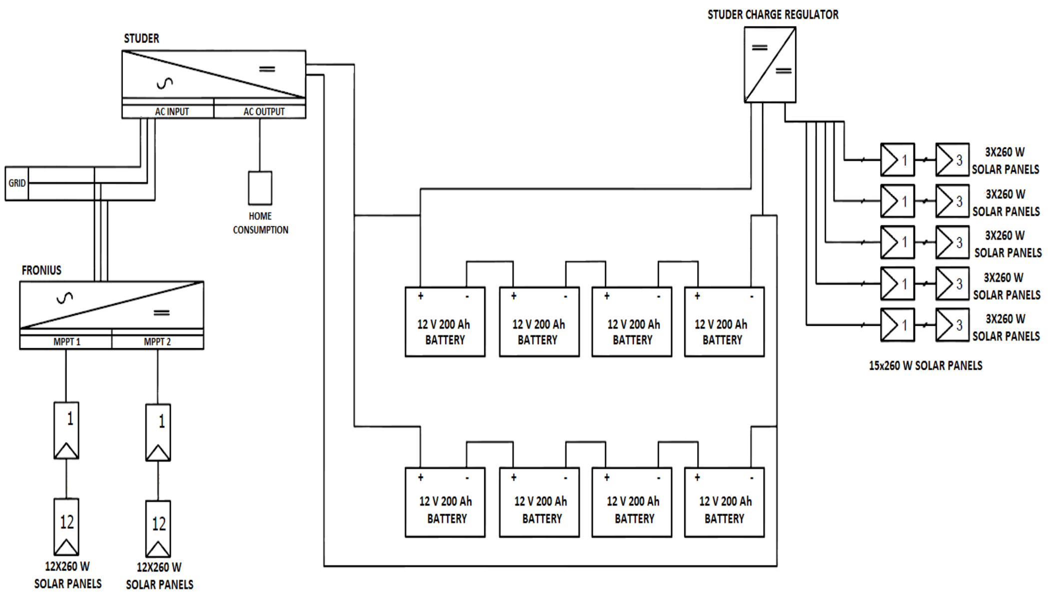
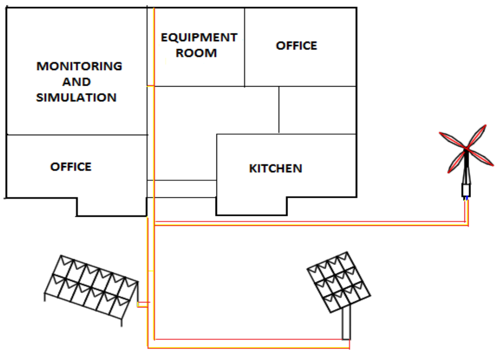
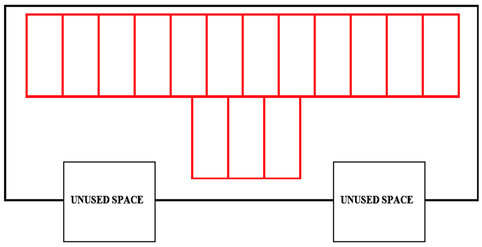


Figure 3.2. *PV system scheme.*

One of the most important advantage of this system is the installation of a hybrid system that includes both solar and wind energy. The recent studies indicate that the realiability of the systems that consist of only one renewable energy resource is low, so using two or more renewable energy resources that have the characteristic of completing each other increases the system's efficiency. These systems are called hybrid energy systems and generally composed of solar-wind, biomass-wind-fuel cell and solar-wind-biomass-hydrogen resources [78]. Although solar-wind hybrid energy systems are a good alternative option for small sized systems, hybrid systems that include other renewable energy resources are generally preferred for medium-sized systems. The considered system in RERH uses solar and wind energy together which results in a hybrid system. Hence, the current system is able to meet the energy requirement of the home efficiently for different weather conditions. The placement of on-grid solar panels, off-grid solar panels and wind turbine are shown in Figure 3.3.



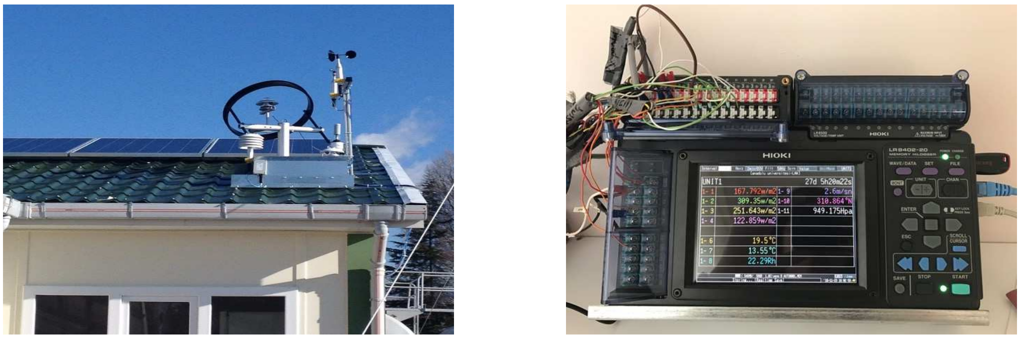
(a) *Ground-mounted solar panels, solar tracker system and wind turbine.*



(b) *Rooftop solar panels.*

Figure 3.3. *Placement of solar panels and wind turbine in the system.*

In future's grid systems, observing and analyzing outdoor parameters in the systems will play an important role to help us use of renewable energy resources efficiently. Hourly average meteorological values do not consider dynamic change of outdoor parameters. Also, some data loss occurs while obtaining data from meteorology and data is not sufficiently often provided. Hence, models that are developed depending on these data may not give accurate results. This results in decrease in the reliability of solar systems that are strongly dependent on the outdoor parameters. Therefore, real time outdoor parameters are measured and recorded with high resolution to improve renewable energy developments and studies. Using the data that is recorded sensitively in models and analysis help studies involving renewable energy resources to have accurate results. The system placed in RERH includes a data monitoring system that measures and records global radiation, direct radiation, diffuse radiation, sunshine duration, ambient temperature, panel temperature, ambient air humidity, wind speed, wind direction and weather pressure. In the system, measurement sensors are placed appropriately as shown in Figure 3.4 (a). The data that are obtained from sensors are collected and recorded in 60-channelled data collecting unit called HIOKI LR-8402-20 as shown in Fig. 3.4 (b). Hence, outdoor parameters are observed and recorded up to 20 ms time interval efficiently.



(a) *Placement of measuring sensors.* (b) *Data recording unit.*

Figure 3.4. *Data measurement system.*

Parameters of MS-410 pyranometer used in the PV system to measure global solar radiation values are given in Table 3.2.

Table 3.2. *Datasheet values of MS-410 pyranometer*

ISO 9060 classification	First Class
Response time 95 % (sec)	18
Sensitivity $(\mu V/W \cdot m^{-2})$	Approx. 7 $\sim$ 14
Impedance (Ω)	Approx. 20 $\sim$ 140
Operating temperature range (^oC)	-40 to $+80$
Irradiance range (W/m^2)	0 $-$ 4000 W/m^2
Wavelength range	285 to 3000 nm

Data that are obtained by using the off-grid inverter called Studer XTH 6000-48 Inverter and Charger and on-grid inverter called Fronius Primo 6.0 Monofaze are observed via Local Area Network (LAN). On-grid inverter has the capability to connect LAN directly, but there are some external sensors needed such as remote control and programming center and XCOM-LAN communication set for LAN connection of off-grid inverter to observe all system parameters, record the values instantaneously and control the system remotely. Off-grid inverter and on-grid inverter connections are shown in Figure 3.5 and Figure 3.6 respectively.

Figure 3.5. *Off-grid inverter, sensors and batteries.*

Figure 3.6. *On-grid inverter with Solar-log.*

On-grid inverter includes two MPPTs. The first MPPT is connected to solar tracker system and the other one is connected to ground-mounted solar panels. Total power generation of on-grid system can be monitored and recorded from the inverter's web portal in 5 minutes interval, but it is needed to see the power generation values of each system separately to compare the power output values of solar systems individually. Therefore, Solar-Log 300 Data Logger is implemented to the system as shown in Figure 3.6. With this data logger, it is possible to monitor the systems that are connected to on-grid are monitored on the basis of MPPT in 5 minutes interval through interface of the module, which provides to analyze the different type of solar systems for the same time interval in detail.

3.2. Global Solar Radiation Estimation on Horizontal Surface

Both measured and estimated hourly global solar radiation values on horizontal surface are averaged over the months by calculating arithmetic mean of individual hourly radiation values for the considered months. By using the statistical analysis methods, calculated and measured hourly global solar radiation values are compared, so accuracy of the existing models is evaluated to determine the best model for the considered region. Since the system does not operate during the installation of new subsystems, some data are lost. Hence, missing global solar radiation data are interpolated accurately during this analysis. Root mean square error (RMSE), mean absolute bias error (MABE), mean bias error (MBE) and t-statistical analysis methods are used to validate these models, which are described by:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(c_i - m_i\right)^2}\ , \tag{3.1}$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(c_i - m_i\right)\ , \tag{3.2}$$

$$MABE = \frac{1}{n}\sum_{i=1}^{n}\left(\left|c_i - m_i\right|\right)\ , \tag{3.3}$$

$$t - statistic = \sqrt{\frac{(n-1)\,MBE^2}{RMSE^2 - MBE^2}} \tag{3.4}$$

where c_i is the i^{th} calculated global solar radiation data, m_i is the i^{th} measured global solar radiation data and n is the number of data. In these statistical analysis methods, the results should be closer to zero to result in better performance of the considered models used for global solar radiation estimation [79]. The accuracy of the considered models is shown in Table 3.3.

Table 3.3 indicates that CPRG model is the most accurate model among the considered models. CPRG model has minimum MBE, RMSE and t-statistical values in March and August, and in the other months, the model has minimum statistical values or smaller relatively. RMSE values of the CPRG model differ from almost 20 to 50. The model has the maximum RMSE value in July as 50.469 and gives the minimum RMSE value in February as 19.257. After CPRG model, CPR model gives the minimum RMSE values in general. Unlike these two models,

Table 3.3. *Accuracy of the daily global solar radiation decomposition models*

Model Name	Analy. Method	Febr.	March	April	May	June	July	August	Sept.	Oct.
Whillier Model	MABE	12.345	18.545	27.935	17.259	39.489	40.767	39.192	25.975	17.004
	MBE	-0.125	-0.614	-0.251	-0.715	-0.088	-0.564	-0.599	-0.830	-0.211
	RMSE	21.872	30.926	46.456	29.409	61.392	62.623	60.198	45.204	30.919
	t-static	0.0274	0.0952	0.0259	0.1167	0.0068	0.0432	0.0478	0.0881	0.0327
Liu-Jordan Model	MABE	12.089	18.394	27.579	16.955	39.147	40.485	38.971	25.778	16.822
	MBE	0.292	-0.139	0.329	-0.288	0.433	0.015	-0.028	-0.211	0.363
	RMSE	21.779	30.753	46.242	29.183	61.044	62.296	59.944	44.923	30.728
	t-static	0.0643	0.0216	0.0341	0.0473	0.0340	0.0012	0.0023	0.0225	0.0566
CPR Model	MABE	12.011	14.186	26.993	16.690	30.464	34.788	32.321	19.516	13.622
	MBE	-0.782	-1.433	-1.169	-0.480	0.719	-0.005	-1.115	-1.920	-1.158
	RMSE	19.204	22.007	40.409	27.273	47.177	50.470	47.433	31.591	22.177
	t-static	0.1956	0.3129	0.1388	0.0845	0.0732	0.0005	0.1128	0.2921	0.2508
CPRG Model	MABE	12.163	14.379	27.531	16.640	30.413	34.787	32.177	19.265	13.406
	MBE	0.186	-0.086	0.222	-0.201	0.291	-0.002	-0.011	-0.145	0.239
	RMSE	19.257	21.860	40.468	27.323	47.226	50.469	47.311	31.205	21.979
	t-static	0.0462	0.0189	0.0263	0.0353	0.0296	0.0002	0.0012	0.0222	0.0522
Garg-Garg Model	MABE	11.644	17.998	28.229	17.849	40.225	38.901	37.875	26.371	17.094
	MBE	0.626	0.376	1.219	0.659	1.733	1.402	0.942	0.554	0.842
	RMSE	21.314	30.213	47.669	30.471	62.911	60.322	58.624	45.798	31.330
	t-static	0.1409	0.0597	0.1226	0.1038	0.1322	0.1115	0.0771	0.0580	0.1289
Gueymard Model	MABE	11.796	14.243	26.085	16.208	30.786	35.312	32.701	19.855	13.923
	MBE	0.213	-0.097	0.243	-0.216	0.312	0.00002	-0.013	-0.161	0.271
	RMSE	18.987	22.749	39.990	25.937	48.045	50.783	48.429	32.781	22.925
	t-static	0.0538	0.0205	0.0292	0.0399	0.0312	0.000002	0.0013	0.0235	0.0567
Jain Model 1	MABE	13.719	15.794	30.841	23.882	35.934	38.994	32.586	25.014	15.880
	MBE	-3.205	-6.824	-7.169	-9.675	-7.143	-6.873	-8.741	-4.533	-4.975
	RMSE	24.451	27.149	50.182	38.718	59.081	62.089	53.540	42.424	29.726
	t-static	0.6342	1.2455	0.6922	1.2377	0.5841	0.5341	0.7937	0.5153	0.8141
Jain Model 2	MABE	13.727	15.678	30.598	23.751	36.082	39.715	32.302	25.407	15.973
	MBE	-3.229	-6.967	-7.469	-10.144	-7.611	-7.315	-9.132	-4.685	-5.027
	RMSE	24.448	27.241	49.973	37.915	59.595	62.351	53.892	42.785	29.798
	t-static	0.6389	1.2687	0.7250	1.3317	0.6175	0.5665	0.8246	0.5283	0.8207
Baig et al. Model	MABE	12.430	14.697	27.556	16.775	30.439	34.860	32.147	19.136	13.249
	MBE	-3.350	-3.143	-1.909	-0.442	1.142	0.094	-1.313	-3.805	-4.395
	RMSE	20.901	22.215	41.154	27.223	48.069	50.408	47.449	31.513	23.042
	t-static	0.7788	0.6853	0.2227	0.0779	0.1140	0.0090	0.1327	0.5834	0.9318
Shazly Model	MABE	12.359	14.350	26.555	16.556	30.574	34.696	32.383	19.904	14.579
	MBE	-3.850	-2.826	1.344	4.441	8.922	7.891	2.662	-2.415	-4.984
	RMSE	20.258	23.283	40.620	26.955	49.879	51.744	48.930	33.479	24.719
	t-static	0.9285	0.5864	0.1588	0.8011	0.8719	0.7400	0.2613	0.3468	0.9873
Newell Model	MABE	13.874	23.003	34.432	27.308	56.789	52.381	48.054	32.090	20.759
	MBE	0.346	-0.175	0.411	-0.370	0.619	0.056	-0.064	-0.246	0.426
	RMSE	25.191	38.308	58.106	43.675	83.557	83.699	74.914	56.604	37.285
	t-static	0.0660	0.0219	0.0339	0.0406	0.0356	0.0032	0.0041	0.0208	0.0549

Newell model results in maximum RMSE values in all months. As in CPRG model, the model has maximum RMSE value in July as 83.699 and minimum RMSE value in February as 25.191. Comparison between the recorded and estimated hourly global solar radiation values from eleven different models of February and July are shown in Figure 3.7 and Figure 3.8 respectively.

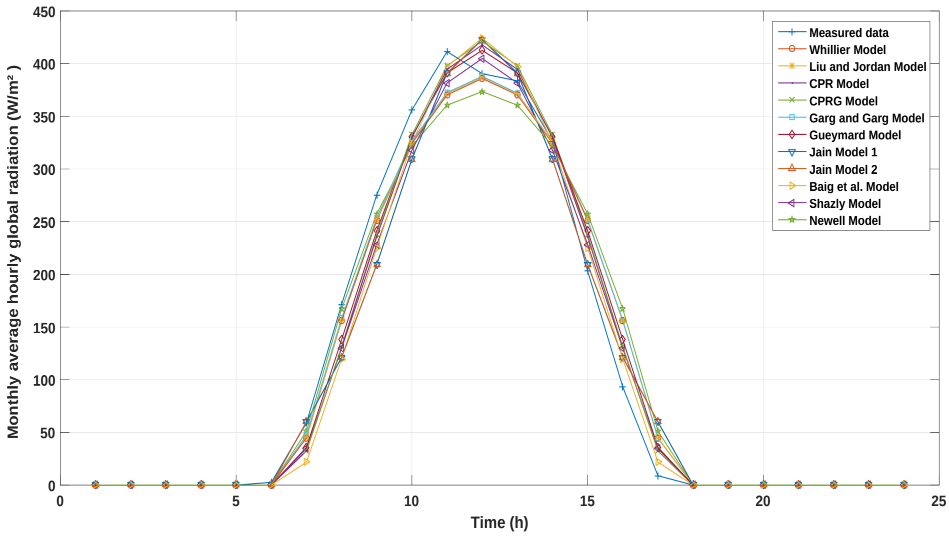


Figure 3.7. *Measured and estimated global solar radiation values of the models in February.*

MBE values are also significant to analyze the accuracy of the global solar radiation estimation models. It is seen that the hourly global solar radiation values obtained from Whillier model, Jain model 1 and Jain model 2 are always less than the measured values, which results in underestimation. In addition to these models, CPR model gives negative MBE values except in June. However, Garg and Garg model gives an overestimation in all months as a result of positive MBE values.

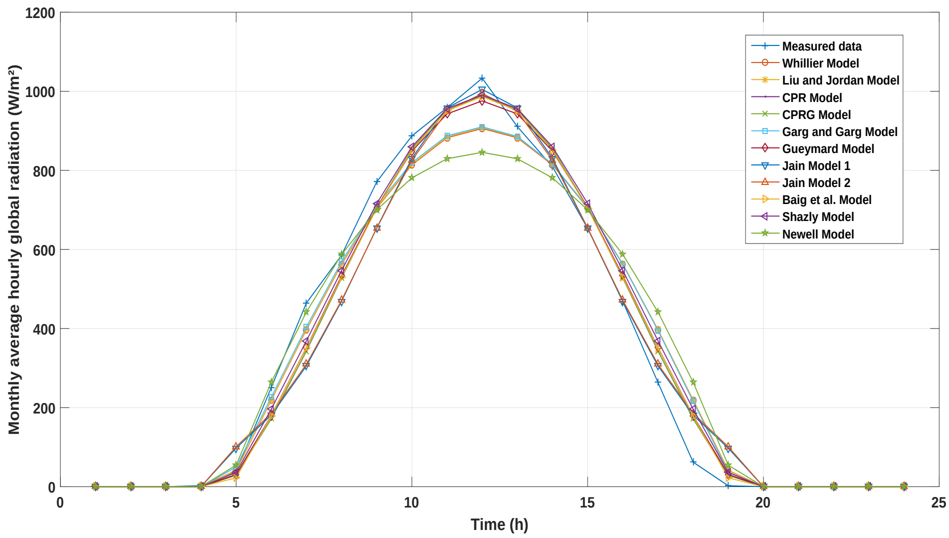


Figure 3.8. *Measured and estimated global solar radiation values of the models in July.*

The maximum MBE values belong to Jain model 2 followed by Shazly model. Jain model 2 has minimum MBE value of -3.229 and maximum MBE value of -10.144 in February and May respectively. Unlike Jain model 2, CPRG yields the lowest MBE results generally with the minimum value of -0.002 in July and maximum value of 0.291 in June. CPRG model is followed by Whillier and Gueymard models that mostly have minimum MBE values among the considered models.

In addition, when MABE values are considered, although Baig et al. model gives the lowest MABE values in August, September and October, the model does not perform well in other months. The minimum and maximum MABE values of Baig et al. model are 12.430 and 34.860 in February and July respectively. In general, in summer months, Baig et al., CPRG and CPR models give low MABE values. However, in spring months, together with CPR model, Gueymard and Shazly models mostly give the minimum MABE values. Table 3.3 indicates that Newell model has the maximum MABE values in all considered months. The model gives the values that are almost between 15 and 55. Comparison between the recorded and estimated hourly global solar radiation values from eleven different models of May and September are shown in Figure 3.9 and Figure 3.10 respectively.

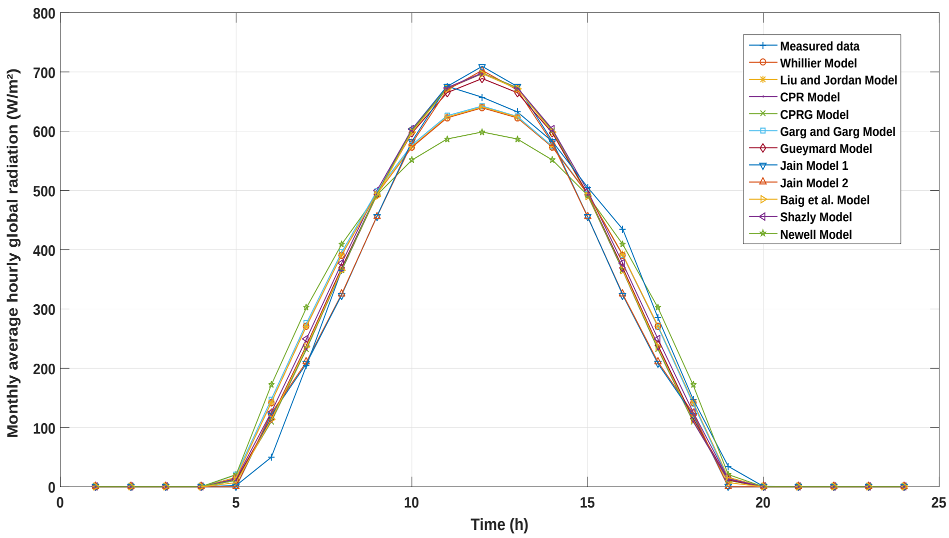


Figure 3.9. *Measured and estimated global solar radiation values of the models in May.*

Finally, t-statistical analysis is performed to validate the results of the considered models. As in RMSE and MBE analysis methods, CPRG model has

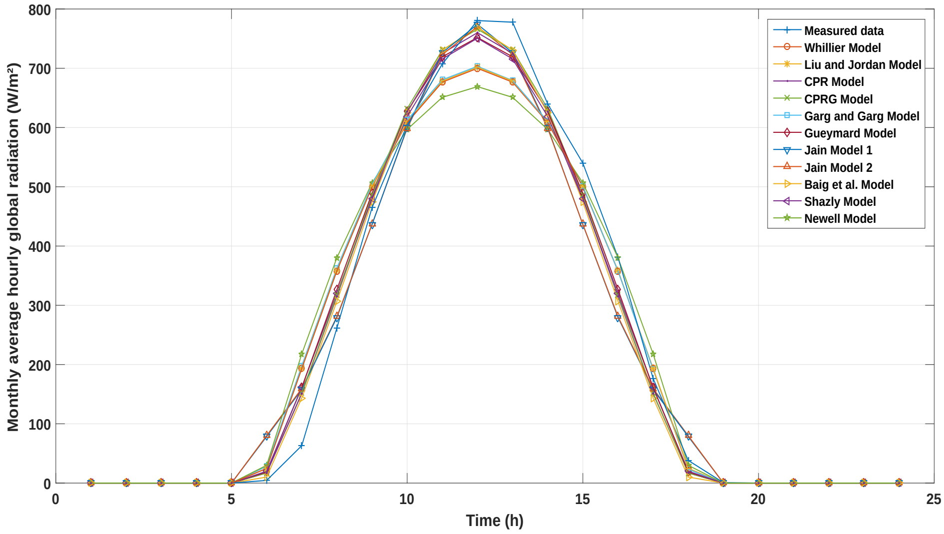


Figure 3.10. *Measured and estimated global solar radiation values of the models in September.*

minimum values generally. The model has minimum t-statistical value in July as 0.0002 and gives the maximum t-statistical value in October as 0.0522. In addition, Table 3.3 indicates that Jain model 2 and Shazly model mostly result in maximum t-statistical values with the highest values of 1.3317 in May and 0.9873 in October respectively.

As a result of the statistical comparison methods placed in Table 3.3, in fact, any of considered daily global solar radiation decomposition models gives the best accuracy in all outdoor conditions for İki Eylül Campus in Eskişehir. Hence, the specifications that belong to the region should be analyzed in detail to prefer the appropriate radiation model. In addition, it is noted that CPRG model has better accuracy than other considered global solar radiation estimation models generally. Therefore, CPRG model should be firstly recommended to be carried out to obtain monthly average hourly global solar radiation for this region.

3.3. Power Generation Prediction from Estimated Cell Temperature and Global Solar Radiation on Tilted Surface

In this section, theoretical power generation values of ground-mounted on-grid and rooftop off-grid solar panels are predicted and the results are compared with actual power generation values for specific time intervals. This analysis starts from 5^{th} of April for off-grid solar system and 9^{th} of August for on-grid solar system, and ends with 28^{th} of October for both systems. Up to 9^{th} of August, total power generation values of on-grid system that has both static solar panels and solar-tracker system have been monitored. However, after the installation of a data logger called Solar-log to on-grid system, the power generation value of each solar system connected to on-grid inverter has been started to be monitored separately. Since the analysis is based on only static solar panels, the time interval of on-grid system's power generation analysis is shorter as compared to off-grid system depending on the date of data-logger integration to the system.

Within the scope of this purpose, the estimated global solar radiation values on horizontal surface of CPRG model, which is generally more accurate than the other methods, are converted to global solar radiation values on tilted surface for both off-grid (4 kW) solar panels and on-grid (3 kW) solar panels with the inclination angles of 16^o and 30^o respectively. The comparison of global solar radiation estimation values on horizontal and inclined surfaces of off-grid and on-grid solar panels are shown in Figure 3.11 and 3.12 respectively.

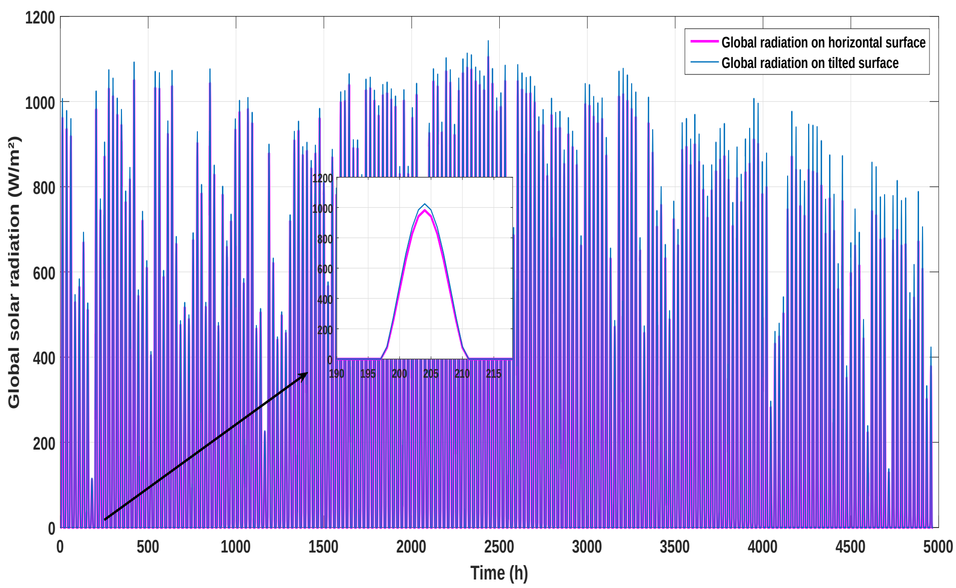


Figure 3.11. *Horizontal and inclined global solar radiation values of off-grid solar panels.*

Figure 3.11 shows that the estimated global solar radiation values on tilted surface are always higher than the global radiation values on horizontal surface as

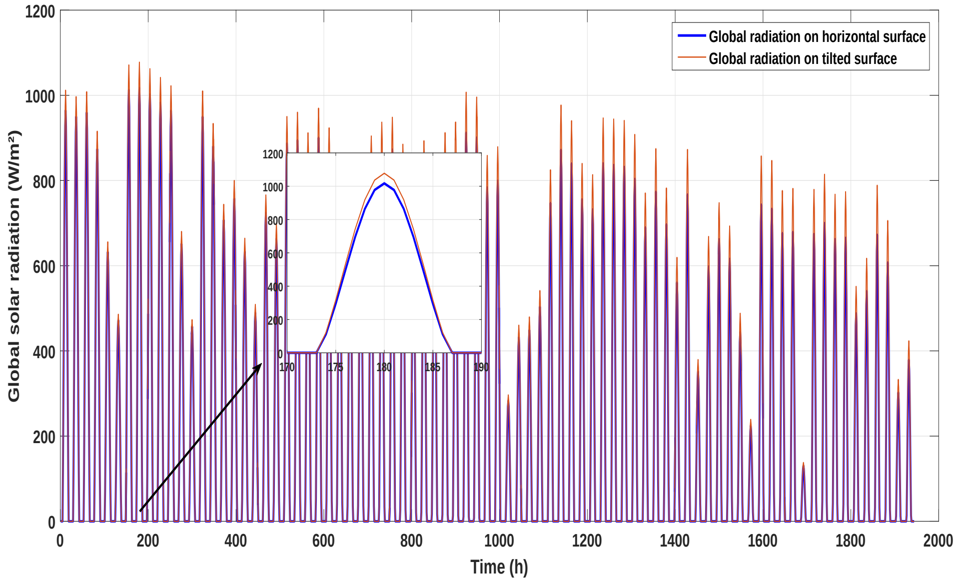


Figure 3.12. *Horizontal and inclined global solar radiation values of on-grid solar panels.*

almost between 2 and 15 % for off-grid solar system. Also, global solar radiation estimation on tilted surface of on-grid system results in higher values than horizontal global solar radiation values for all hours in the considered days as seen in Figure 3.12. The effect of inclination angle on horizontal global solar radiation changes approximately between 5 and 17 %. In addition, it is analyzed that the highest percentage effect is seen in October among the considered months for both off-grid and on-grid systems. Since the related sensors to measure tilted global solar radiation have recently been connected to on-grid and off-grid solar panels, the estimated global solar radiation values on inclined surface are not compared with the actual measured radiation values.

After obtaining global solar radiation values on tilted surfaces of solar panels, recorded outdoor parameters such as ambient temperature and wind speed are monitored. Ambient temperature and wind speed values that belong to the considered time interval are shown in Figure 3.13 and Figure 3.14 respectively.

Since RERH has been still in development, the wind speed values that belong to September and October are missing. Hence, the wind speed values of these two months are provided by Turkish State Meteorological Service to be used in the power prediction analysis.

Depending on the estimated global solar radiation values on solar panels,

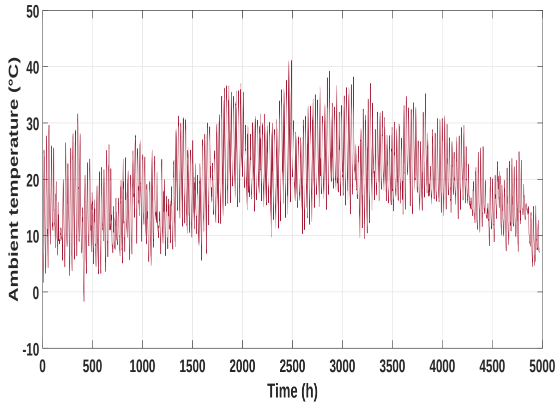


Figure 3.13. *Measured ambient temperature of the considered time interval.*

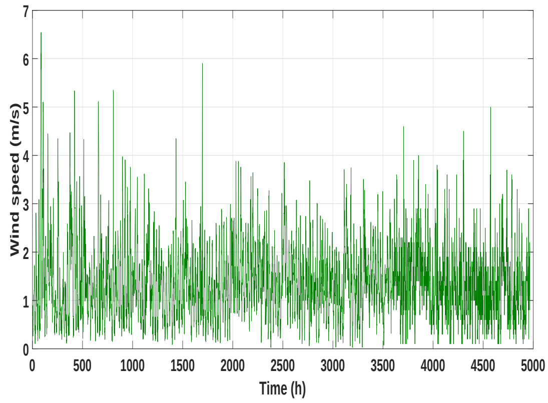


Figure 3.14. *Measured wind speed of the considered time interval.*

measured ambient temperature and wind speed values, different cell temperature methods are used to predict power output values of both on-grid and off-grid systems. Actual and predicted power output values of off-grid and on-grid solar systems based on the performed cell temperature methods are shown in Figure 3.15 and 3.16 respectively.

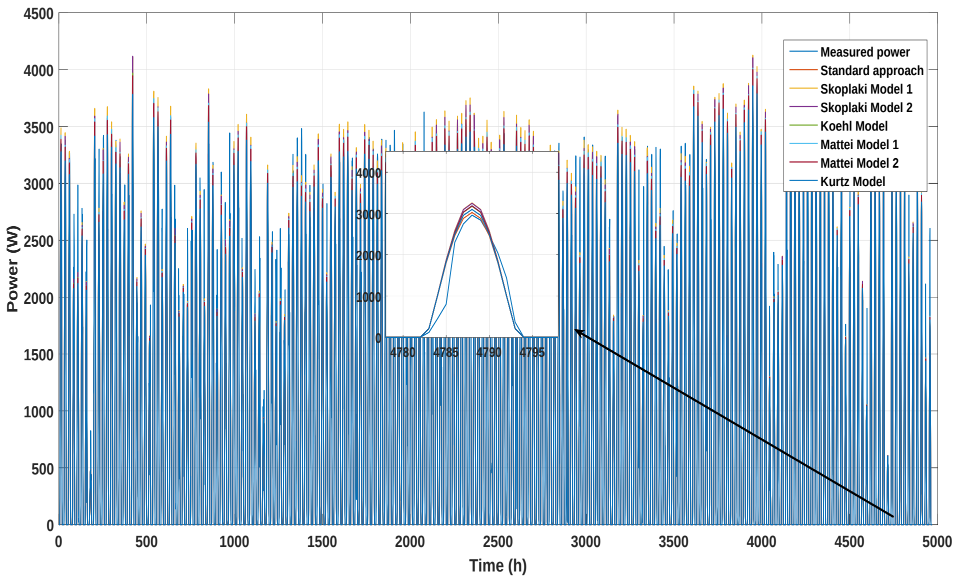


Figure 3.15. *Actual and predicted power values of off-grid solar panels for different cell temperature models.*

As Figure 3.15 and 3.16 show that the actual power output values are generally less than the predicted power output values for both on-grid and off-

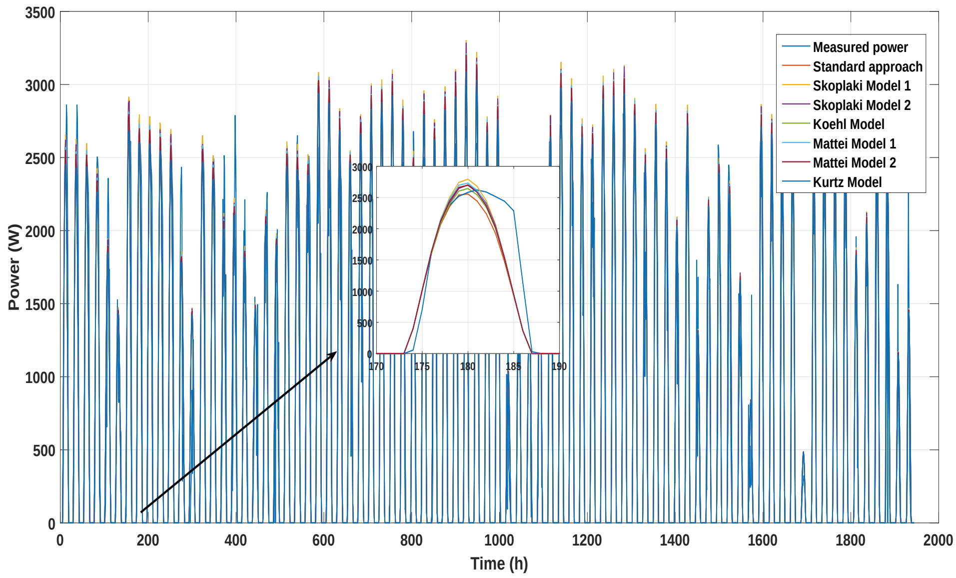


Figure 3.16. *Actual and predicted power values of on-grid solar panels for different cell temperature models.*

grid systems. Since the off-grid system is connected to batteries for storage, it is possible to generate low power if the batteries are even nearly full and there is low consumption in the loads. The power generation is regulated to avoid overloading the batteries, therefore, there may be low power generation even if the system has a potential for a huge amount of power generation in off-grid system. In addition, the reason of obtaining less power generation than expected for on-grid system may be due to the consideration of a short time interval as almost three months for the analysis. Hence, these constraints can decrease the power generation of considered PV systems.

The predicted power output values based on different cell temperature models are compared to the actual power generation values by using two statistical analysis methods as normalized mean absolute error (NMAE) and weighted mean absolute error (WMAE). These analysis methods are described:

$$NMAE_{\%} = \frac{1}{N} \sum_{h=1}^{N} \frac{|P_{m,h} - P_{p,h}|}{C_N} \cdot 100 \ , \tag{3.5}$$

$$WMAE_{\%} = \frac{\sum_{h=1}^{N} |P_{m,h} - P_{p,h}|}{\sum_{h=1}^{N} P_{m,h}} \tag{3.6}$$

where $P_{m,h}$ is the power measured in the hour, $P_{p,h}$ is the power predicted in the hour, C_N is the net capacity of the plant and N is the number of daylight hours. Table 3.4 shows the accuracy of the cell temperature methods on prediction of power output values of the solar systems.

Table 3.4. *Accuracy of the cell temperature methods on prediction of power values*

Model Name	**Analysis Method**	**Standard Approach**	**Skoplaki Model 1**	**Skoplaki Model 2**	**Koehl Model**	**Mattei Model 1**	**Mattei Model 2**	**Kurtz Model**
On-grid System	NMAE%	10.447	10.769	10.656	10.517	10.613	10.576	10.452
	WMAE%	22.834	23.539	23.291	22.986	23.196	23.116	22.843
Off-grid System	NMAE%	11.835	12.616	12.326	12.096	12.368	12.272	11.947
	WMAE%	28.205	30.065	29.374	28.828	29.476	29.245	28.472

According to Table 3.4, although standard approach is the only model that does not include wind speed values among the considered models, the model has minimum $NMAE_{\%}$ and $WMAE_{\%}$ values for both off-grid and on-grid systems. Standard approach is followed by Kurtz and Koehl models in terms of accuracy for both solar systems. In addition, Skoplaki model 1 gives the highest $NMAE_{\%}$ and $WMAE_{\%}$ values as shown in Table 3.4. Therefore, standard approach is recommended for the estimation of cell temperature to be used in power generation prediction for the considered region.

4. CONCLUSION

In this thesis, solar energy analysis of RERH placed in Anadolu University İki Eylül Campus is performed in detail. Within the scope of this aim, eleven daily global solar radiation decomposition models are used to estimate hourly global solar radiation on horizontal surface from the measured daily values. The estimated values are averaged over the months and the results of the considered models are compared with the measured values. The results show that there is not a unique model that performs with the highest efficiency in all conditions. However, it can be concluded that CPRG model is more accurate than the other methods in general. After the estimation of global solar radiation on horizontal surface, these values are converted to the values on inclined surfaces of both on-grid and off-grid PV systems by using Olmo et al. model, which does not need to decomposite global solar radiation into its components as direct and diffuse radiation. As a result of obtaining global solar radiation on tilted surfaces, these values are modeled with outdoor parameters such as measured wind speed and ambient temperature to predict ideal power generation values of PV systems. During this prediction analysis, seven different cell temperature models are performed. The output power prediction values depending on cell temperature estimated by different methods, ambient temperature, wind speed and characteristics special to the used solar panels are compared and visualised with related figures. The results indicate that the model that estimates cell temperature with standard approach gives the best power generation prediction.

Estimation of global solar radiation values play an important role along with prediction of power values for PV systems as described in Section 1.1. A detailed solar energy analysis can contribute to the system's efficiency, optimize the size and decrease the cost. Therefore, the models that have the highest accuracy in this study may be recommended depending on the considered time and outdoor parameters before applying real time applications in Eskişehir.

In future, the obtained results can be developed in many ways. The considered models will be applied to long-term data to observe the accuracy in more detail, and new power prediction methods will be discussed and performed to get the desired accuracy in different cases. Also, battery effect that causes solar panels not to produce high power even in the best conditions will be studied to minimize the occurrence of undesired situations. Finally, the topic of energy management may be studied with the help of the new system that has recently been installed in RERH.

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