Power Output Forecasting of a Solar House by Considering Different Cell Temperature Methods

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Abstract

Forecasting of power generation is needed for accurate design and performance evaluation of solar energy systems to associate demand and source side dynamics efficiently. Since the power output values of solar energy systems are significantly affected by the cell temperature, estimation of cell temperature has gathered wide interest in recent years. In this study, cell temperature values of the on-grid photovoltaic panels of a solar house placed in Anadolu University İki Eylül Campus are estimated by using six different models. In addition, power output values of the system are forecasted with three different models by using the estimated cell temperature values, measured outdoor parameters and panel specifications. Therefore, the most accurate models for cell temperature estimation and power forecasting are determined according to the results of statistical test analysis methods.

1. Introduction

With increasing concern about dependence on fossil fuels and environmental issues, alternative energy solutions have come into prominence in recent years [1]. Since energy is one of the basic factors of economic and social developments, it is crucial to meet required energy demand efficiently to contribute to the development of the countries. At that point, fossil fuels are not sufficient due to their environmental disadvantages and limited lifetime [2]. In place of fossil fuels, solar energy is mostly recommended to be used in electricity generation with its durability, abundance and cleanliness. Associated with the use of the solar energy in power system applications, photovoltaic systems (PV) are placed in appropriate regions to benefit from the sun in the most efficient ways.

PV cell temperature is an important parameter that directly affects the performance of solar cells. This temperature depends on many parameters such as outdoor conditions, climatic location of PV modules, type of PV cells and properties of materials used for PV systems. Increase in PV cell temperature causes open-circuit voltage to decrease significantly and short-circuit current to increase slightly [3]. It is known that PV cell temperature is the same with PV module temperature [4]. Therefore, PV cell temperature can be used as an efficient input to forecast power output value of a PV module on the basis of a single PV cell.

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Undoubtedly, it is assumed that solar panels operate under ideal conditions during the manufacturing process of PV panels. However, this situation is not valid when dynamic change of the outdoor parameters are considered. In addition, measurement of the PV cell temperature is not accessible in many systems. Due to these reasons, in literature, cell temperature estimation methods are presented to forecast power output values of the solar energy systems. Standard model which considers only global solar radiation and ambient temperature is developed in [5]. In [4], Mattei models are presented to obtain cell temperature with defining two different parametrizations of heat exchange coefficient. Skoplaki models are obtained in [6] by integrating wind data in standard model on the basis of two different descriptions of wind convection coefficient. In [7], Kurtz model is defined, which does not consider PV specifications. The model only considers outdoor parameters as global solar radiation, ambient temperature and wind speed. A simple emprical model proposed in [8] is used and some constants are described depending on PV technologies with Koehl model in [9]. In [10], Muzathik model is developed as a function of wind speed, global solar radiation and ambient temperature.

Accurate information on power generation of a PV system is essential for planning and projecting of a solar system in different environmental conditions. With the help of forecasting power generation, an efficient energy analysis can be achieved to meet the required energy demand. Hence, power generation forecasting methods have gathered wide interest in literature. These methods are divided into three main groups as physical, statistical and hybrid methods [11]. In physical models, output power values are defined as a function of global solar radiation, ambient temperature and some other outdoor parameters. In addition to the meteorological parameters, solar cell properties such as cell temperature plays an important role on the performance evaluation of a PV system by using physical models. As a second group, statistical models are based on the concept of persistence or stochastic time series. Within the scope of these models, artificial neural network (ANN) have been used. In these methods, historical data about weather estimation and environmental conditions are needed to train ANN and predict power generation values of solar energy systems [12]. Finally, hybrid models are described which combine two or more models to prevent disadvantages of a single model [13].

Among power generation forecasting models, physical models are commonly used with the increasing technological developments in measurement of outdoor parameters and analysis of solar panel specifications. Therefore, outdoor conditions and solar cell properties should be defined clearly to forecast power generation values. This detailed solar energy analysis helps us

Nomenclature

I	Global solar radiation on PV module (W/m^2)	h_w	Wind convection coefficient $(W/(m^2K))$
T_c	Cell/module temperature $(^\circ C)$	V_t	Thermal voltage (V)
T_a	Ambient temperature $(^\circ C)$	V_{oc}	Open circuit voltage (V)
v_w	Local wind speed close to the module (m/s)	I_{sc}	Short circuit current (A)
u_{PV}	Heat exchange coefficient for the total surface of module *(*$W\,^\circ C^{-1}m^{-2}$*)*	u_0	Coefficient describing the effect of the radiation on the module temperature ($W\,^\circ C^{-1}m^{-2}$)
dV_{oc}/dT_c	Voltage temperature coefficient ($^\circ C^{-1}$)	dI_{sc}/dT_c	Current temperature coefficient ($^\circ C^{-1}$)
β	Temperature coefficient of maximal power of the solar cells ($^\circ C^{-1}$)	P_m	Maximum power of a PV module (W)
η	Efficiency of the solar cells *(unitless)*	$P_{m,cell}$	Maximum power of a PV cell (W)
u_1	Cooling by the wind *(*$Ws\,^\circ C^{-1}m^{-3}$*)*	V_m	Maximum voltage(V)
I_m	Maximum current (A)	α	Absorption coefficient of the solar cells *(unitless)*
τ	Transmittance of the cover system *(unitless)*	r_s	Normalized resistance *(unitless)*
R_s	Series resistance (Ω)	v_{oc}	Normalized voltage *(unitless)*
		γ	Cell maximum power temperature coefficient ($^\circ C^{-1}$)

to optimize system size and dynamics of a house. Along with the estimation of cell temperature and forecasting of power generation may improve the accurate application of the PV systems in future's world.

2. Cell Temperature Estimation

There are many correlations that describe cell temperature as a function of outdoor parameters as well as solar cell characteristics defined by the manufacturers [14]. Cell temperature significantly depends on global solar radiation on the surface of solar panels. In addition, it is affected by many outdoor parameters such as wind speed, wind direction and ambient temperature [15]. In this part of the study, cell temperature values of the on-grid PV system of a solar house placed in Anadolu University İki Eylül Campus are estimated for five months by using selected six different methods. The solar house built on campus is shown in Fig. 1.

Fig. 1. Solar house placed in Anadolu University İki Eylül Campus

2.1. Standard Model

The model only considers global solar radiation and ambient temperature. In this model, wind speed is not included unlike the other considered models. The proposed model is:

$$T_c = T_a + \frac{I}{I_{NOCT}} \left(T_{NOCT} - T_{a,NOCT}\right) \quad (1)$$

where T_{NOCT} is the nominal operating cell temperature considered under nominal operating conditions of $I_{NOCT} = 800$ W/m^2, $T_{a,NOCT} = 20^\circ C$ and wind speed of 1 m/s [16]. The value of T_{NOCT} is accepted as $45^\circ C$ depending on our PV module's datasheet.

2.2. Koehl Model

The model is developed by considering the energy balance of a solar thermal collector defined in [8]. The cell temperature estimation model is given as [9]:

$$T_c = T_a + \frac{I}{u_0 + u_1 v_w} \quad (2)$$

where the constants of u_0 and u_1 are the coefficients describing, respectively, the effect of global solar radiation on module temperature and cooling by the wind. These parameters are selected according to the specifications defined in [9] depending on PV technologies.

2.3. Mattei Model

The model is developed by confirming an energy balance on PV module, which neglects the temperature difference between PV cells and the cover.

The effect of temperature on PV cell efficiency (η) can be described in many ways. One of the most important models that shows the effect of temperature on η is defined as:

$$\eta = \eta_{STC}\big(1 - \beta\left(T_c - T_{STC}\right)\big) \quad (3)$$

where η_{STC} is the reference module efficiency and β is the temperature coefficient of maximal power for the PV module. In addition, the energy balance can be described as:

$$\alpha \cdot \tau \cdot I = \eta \cdot I + u_{PV}\left(T_c - T_a\right) \ . \quad (4)$$

If the expression in (3) is included in (4), the proposed model is obtained as:

$$T_c = \frac{u_{PV}\left(v_w\right) T_a + I \cdot \left(\tau \cdot \alpha - \eta_{STC}\left(1 + \beta_{STC} \cdot T_{STC}\right)\right)}{u_{PV}\left(v_w\right) - \beta_{STC} \cdot \eta_{STC} \cdot I} \quad (5)$$

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

$$u_{PV}\left(v_w\right) = 24.1 + 2.9\, v_w \ . \quad (6)$$

In (5), β_{STC} is defined as temperature coefficient of maximal power under standard test conditions of $I_{STC} = 1000\ W/m^2$,

$T_{STC} = 25°C$ and $AM = 1.5$. The values fo η_{STC} and β_{STC} are obtained from the panel's datasheet. In addition, $\tau \cdot \alpha$ is accepted as 0.81 as in [9].

2.4. Skoplaki Model

In addition to global solar radiation and ambient temperature, the proposed model considers 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 [6]. The developed model is defined as:

$$T_c = \frac{T_a + \frac{I}{I_{NOCT}}\left(T_{NOCT} - T_{a,NOCT}\right)\frac{h_{w,NOCT}}{h_w(v)} \cdot \left(1 - \frac{\eta_{STC}}{\tau \cdot \alpha}\left(1 + \beta_{STC} \cdot T_{STC}\right)\right)}{1 - \frac{\beta_{STC} \cdot \eta_{STC}}{\tau \cdot \alpha}\left(\frac{I}{I_{NOCT}}\right)\left(\frac{h_{w,NOCT}}{h_w(v)}\right)\left(T_{NOCT} - T_{a,NOCT}\right)} \tag{7}$$

where η_{STC} and β_{STC} are defined as in Mattei model. Also, $h_{w,NOCT}$ is the wind convection coefficient of wind speed under normal operating conditions. The $\tau \cdot \alpha$ value in (7) accepted as 0.9 as in [6]. The wind convection coefficient (h_w) is defined as:

$$h_w = 5.7 + 3.8\, v_w \tag{8}$$

where v_w is the local wind speed close to the module.

2.5. Muzathik Model

The proposed model derives PV cell temperature as a function of global solar radiation, ambient temperature and wind speed. However, the model does not consider the PV technology of the considered solar panels. Hence, cell temperature is defined as [10]:

$$T_c = 0.943 \cdot T_a + 0.0195 \cdot I - 1.528 \cdot v_w + 0.3529\,. \tag{9}$$

2.6. Kurtz Model

Similar to (9), the proposed model does not include material characteristics of the PV panels. Instead, it is a parametrization of global solar radiation, ambient temperature and wind speed, which is defined as [7]:

$$T_c = T_a + I \cdot \exp\left(-3.473 - 0.0594\, v_w\right)\,. \tag{10}$$

3. Power Output Forecasting

Solar panel manufacturers provide maximum power values of solar panels in datasheets by considering ideal conditions. However, these conditions are not stable in real time applications. Therefore, solar panel specifications should be defined depending on unsteady outdoor parameters and, actual power generation values must be analyzed in detail. In this part of the study, three different power output forecasting models are performed by using the estimated cell temperature values. These values are gathered from the model that has the highest accuracy according to the measured values.

3.1. Model 1

Since panel datasheets show theoretical short-circuit current and open-circuit voltage parameters, these values are found as [17]:

$$I_{sc} = \frac{I_{sc}^*}{I^*} I \left(1 + \left(T_c - T_c^*\right)\frac{dI_{sc}}{dT_c}\right)\,, \tag{11}$$

$$V_{oc} = V_{oc}^* + \left(T_c - T_c^*\right)\frac{dV_{oc}}{dT_c} + V_t \ln\left(\frac{I}{I^*}\right) \tag{12}$$

where I^* and T_c^* are, respectively, the reference global solar radiation on solar panels and cell temperature values. T_c is estimated by using considered methods. The series resistance, R_s is found as $0.0069\,\Omega$ according to the panel specifications given by solar manufacturers. The maximum power point is defined as:

$$P_{m,cell} = V_m I_m \tag{13}$$

where V_m and I_m values are found:

$$V_m = V_{oc}\left(1 - \frac{b}{\nu_{oc}}\ln a - r_s\left(1 - a^{-b}\right)\right)\,, \tag{14}$$

$$I_m = I_{sc}\left(1 - a^{-b}\right)\,. \tag{15}$$

In (14) and (15), a and b coefficients are defined by the following relationships:

$$a = \nu_{oc} + 1 - 2v_{oc}r_s\,, \quad b = \frac{a}{1+a} \tag{16}$$

where $v_{oc} = V_{oc}/V_t$ and $r_s = R_s/\left(V_{oc}/I_{sc}\right)$. After finding $P_{m,cell}$, P_m of a single PV module is found by considering cell number of the PV module, which is 60.

3.2. Model 2

The model in [18] is performed by considering PV-Trombe wall (PV-TW) assisted with DC fan. The proposed power forecasting model is defined as:

$$P_m = \eta_{STC} \cdot A \cdot I\big(1 - 0.0045\left(T_c - 25\right)\big) \tag{17}$$

where A is the surface area of the PV module exposed to the interlayer and η_{STC} is the reference module efficiency. The value of η_{STC} is accepted as 0.1598 according to the panel's datasheet.

3.3. Model 3

The model calculates the maximum power on the basis of a single cell and, it is described as [19]:

$$P_{m,cell} = P_{m,cell}^* \cdot \frac{I}{I^*} \cdot \left(1 + \gamma\left(T_c - 25\right)\right) \tag{18}$$

where $P_{m,cell}^*$ is the cell maximum reference power and γ is the cell maximum power temperature coefficient. The value of γ ranges from -0.005 to $0.003°C^{-1}$ in crystalline silicon. Since the parameter is not provided routinely by the AIL certificate of calibration of the module, the value of γ is accepted as $-0.0035°C^{-1}$ as in [20]. Similar to Model 1, $P_{m,cell}$ is multiplied by 60 to calculate P_m.

4. Simulation and Results

Cell temperature values which are estimated by using six different models are compared with the measured cell temperature values as shown in Fig. 2. In addition, statistical analysis methods of Root Mean Square Error (RMSE), Mean Bias Error (MBE) and Mean Absolute Bias Error (MABE) are used to evaluate the performance of the considered cell temperature estimation methods, which are described as:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(c_i - m_i\right)^2}\,, \tag{19}$$

$$\text{MBE} = \frac{1}{n}\sum_{i=1}^{n}\left(c_i - m_i\right)\,, \tag{20}$$

$$\text{MABE} = \frac{1}{n}\sum_{i=1}^{n}\left(\left|c_i - m_i\right|\right)\,, \tag{21}$$

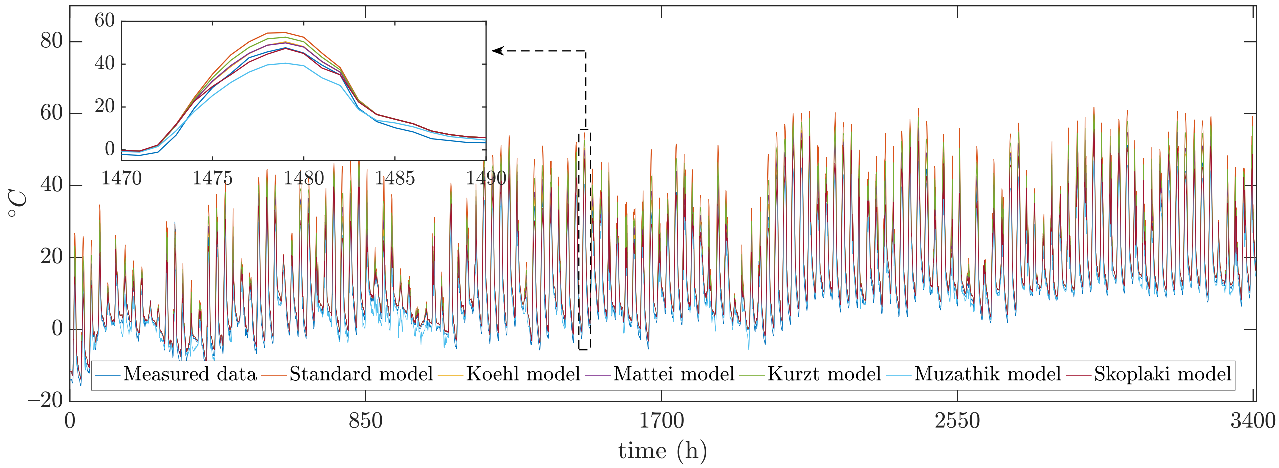

Fig. 2. Comparison of different cell temperature estimation models

where c_i is the i^{th} calculated cell temperature data, m_i is the i^{th} measured cell temperature data and n is the number of data. The accuracy of the cell temperature estimation methods is shown in Table 1. The results show that Skoplaki model has the highest accuracy with the lowest RMSE, MBE and MABE values. From the point of accuracy, it is analyzed that Skoplaki model is followed by Koehl model in terms of RMSE and MABE values. When MBE values are considered, Muzathik model is the second model that leads the highest accuracy after Skoplaki model. In addition, Muzathik model is the only model that gives underestimation with the result of negative MBE values among models. Finally, Table 1 indicates that Standard model, which is the only model that does not consider wind speed among the considered models, has the lowest accuracy.

Table 1. Accuracy of the cell temperature estimation methods

Model Name	RMSE	MBE	MABE
Standard Model	4.5730	3.4378	3.4448
Koehl Model	2.3829	1.9520	2.0086
Mattei Model	2.5647	2.1248	2.1616
Skoplaki Model	2.2349	1.0943	1.8188
Muzathik Model	3.0926	-1.4297	2.3718
Kurzt Model	3.3401	2.7028	2.7164

Since Skoplaki model has the highest accuracy among the considered cell temperature methods, the cell temperature values estimated by this model are used to forecast power output values. For this purpose, three different models are selected to perform for four months of 2017. These forecasted power output values are compared with the measured power output values of the PV system in Fig 3.

The forecasted power output values based on the cell temperature, global solar radiation and the specifications of the PV modules are evaluated by using two statistical analysis methods as Normalized Mean Absolute Error ($\mathrm{WMAE}_{\%}$) and Weighted Mean Absolute Error ($\mathrm{WMAE}_{\%}$). These analysis methods are described as:

$$\mathrm{WMAE}_{\%} = \frac{\sum_{h=1}^{N} |P_{m,h} - P_{f,h}|}{\sum_{h=1}^{N} P_{m,h}} \cdot 100 \tag{22}$$

$$\mathrm{NMAE}_{\%} = \frac{1}{N} \sum_{h=1}^{N} \frac{|P_{m,h} - P_{f,h}|}{C_N} \cdot 100 \,, \tag{23}$$

where $P_{m,h}$ is the power measured in the hour, $P_{f,h}$ is the power forecasted in the hour, C_N is the net capacity of the plant and N is the number of daylight hours. Table 2 shows the accuracy of the power output forecasting methods. According to this table, Model 1 has the highest accuracy among the considered models because it has minimum $\mathrm{NMAE}_{\%}$ and $\mathrm{WMAE}_{\%}$ values. Unlike Model 1, Model 3 has the maximum $\mathrm{NMAE}_{\%}$ and $\mathrm{WMAE}_{\%}$ values, which results in the lowest accuracy.

Table 2. Accuracy of the power output forecasting methods

	$\mathrm{NMAE}_{\%}$	$\mathrm{WMAE}_{\%}$
Model 1	4.6394	12.3645
Model 2	4.7363	12.6229
Model 3	4.8816	13.0102

5. Conclusion

In this study, cell temperature values of a solar house placed in Anadolu University İki Eylül Campus are estimated by using selected methods. The results show that Skoplaki model has the highest accuracy. Estimated cell temperature values of Skoplaki model are used in three different power forecasting methods with global solar radiation, ambient temperature and panel specifications. The statistical analysis methods indicate that Model 1 gives the best results among the considered models. Therefore, it is concluded that these models are recommended to be performed in any location that has similar climatic conditions with the considered region.

6. Acknowledgement

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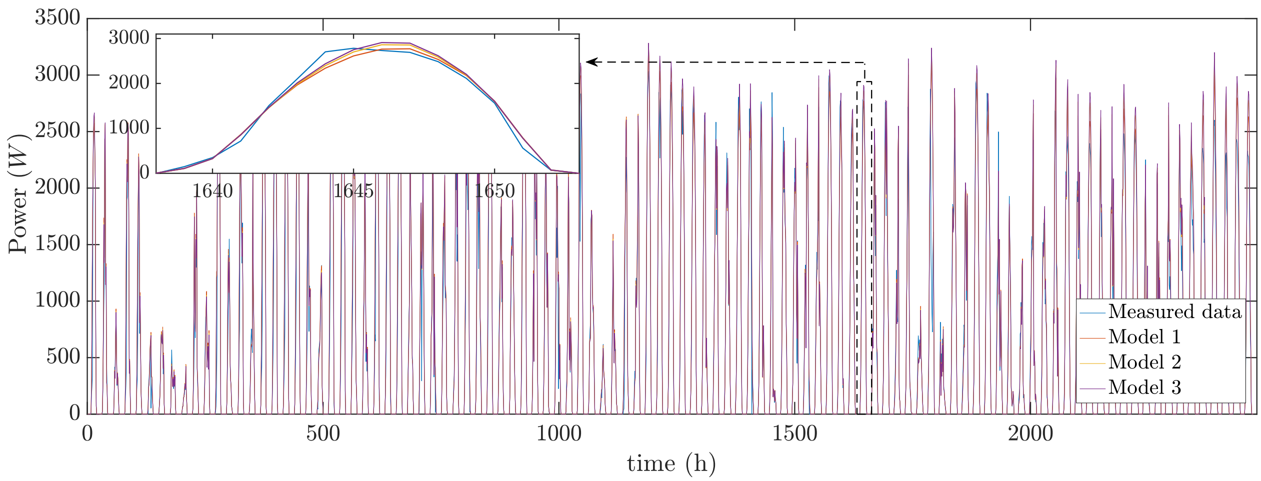

Fig. 3. Comparison of different power forecasting models

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