



Performance analysis of a multi crystalline Si photovoltaic module under Mugla climatic conditions in Turkey

Rustu Eke^{a,b,*}, Huseyin Demircan^c

^a Photovoltaic Materials and Device Laboratory, Department of Physics, Faculty of Sciences, Mugla Sıtkı Kocman University, 48120 Mugla, Turkey

^b Clean Energy Research & Development Centre, Mugla Sıtkı Kocman University, 48120 Mugla, Turkey

^c Graduate School of Natural and Applied Sciences, Mugla Sıtkı Kocman University, 48100 Mugla, Turkey

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ABSTRACT

Commercially available, a multi crystalline silicon (mc-Si) photovoltaic (PV) module has been monitored outdoors under Mugla climatic conditions in Turkey. Electricity yield of this module is calculated from the uninterrupted measured current–voltage curves from sunrise to sunset during a year. Calculated electricity yield from the measured plane of array or in-plane (POA) irradiation is compared with the calculated electricity from the manufacturer's electrical values of the module and the measured electricity from the photovoltaic system consisting 26 mc-Si PV modules from the same manufacturer. Calculated annual energy rating for the PV system is 1415.79 kW h/kW p and 1414.18 kW h/kW p from the manufacturer data and tested module respectively. The measured energy rating value is 1412.78 kW h/kW p. Comparison of results from this study with those obtained from the measurements show that the average difference in monthly electricity values varies between $\pm 12\%$ with an annual average value less than 1% and a performance ratio (PR) of 0.72.

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1. Introduction

Manufacturers of photovoltaic modules typically provide electrical parameters at only one operating condition. PV modules operate over a large range of conditions so the manufacturer's information is not sufficient to determine their overall performance. Designers need a reliable tool to predict energy production from a PV module under all conditions in order to make a sound decision on whether or not to incorporate this technology. PV modules are currently rated by power rating given by an output power under the standard test condition (STC), i.e., incident solar irradiance: 1 kW/m²; solar spectrum distribution: AM1.5G; and module temperature: 25 °C. The performances of PV modules depend on these three environmental factors; thus the condition to measure the PV performance is important [1,2]. Theoretical models for PV modules have been widely validated at a laboratory level, but little has been done in the application. There are various empirical models to simulate the DC output current–voltage characteristics of a PV module under different radiation levels and temperatures [3–9]. The models were based on three basic parameters, which are generally available by the manufacturer. But actual outdoor conditions change from hour to hour. Electricity consumers and suppli-

ers buy and sell energy in units. Thus, energy rating given by an actual electrical energy generated by PV modules is appropriate for the rating of PV modules. However, energy rating is more complicated than power rating because energy rating needs actual operation data for PV modules and environmental factors where the PV modules are installed.

In this study, commercially available, a multi crystalline silicon (mc-Si) photovoltaic module has been monitored outdoors under Mugla climatic conditions in Turkey [10–12]. Energy yield of this module is calculated from the uninterrupted measured current–voltage curves from sunrise to sunset during a year. At Mugla Sıtkı Kocman University PV outdoor test centre, the actual field performances of several PV modules/systems of various technologies. The facility also includes a mc-Si PV module and a PV system including 26 modules from the same manufacturer.

Measured POA radiation is used to calculate the electricity output and the manufacturer's electrical values of the module and photovoltaic system and calculated electricity yield is compared with the measured electricity.

2. Materials and methods

The electrical power output from a photovoltaic module/array depends on the incident solar radiation, the cell temperature, the solar incidence angle and the load resistance. Manufacturers typically provide only limited operational data for photovoltaic

* Corresponding author at: Department of Physics, Faculty of Sciences, Mugla Sıtkı Kocman University, 48120 Mugla, Turkey. Tel.: +90 2522111601; fax: +90 2522111472.

E-mail address: erustu@mu.edu.tr (R. Eke).

Nomenclature

PR	performance ratio	I_0	diode reverse saturation current (A)
PV	photovoltaic	a	modified ideality factor
mc-Si	multi crystalline silicon	k_B	Boltzmann's constant (1.38×10^{-23} J/K)
STC	standard test conditions	q	electronic charge (1.6×10^{-19} C)
I	current (A)	n_1	usual ideality factor
V	voltage (V)	N_S	the number of cells in series
AM	air mass	T_C	the cell temperature (K)
G	global	E_{DC}	total DC energy generated by the PV module/system (kW h)
POA	plane of array or in-plane	Y_A	array yield
mpp	maximum power point	$E_{DC,t}$	instantaneous energy output of the PV module (kW h)
MPPT	maximum power point tracker	$t_{interval}$	time interval (h)
I_{SC}	short circuit current (A)	$E_{AC,d}$	daily total energy output of the PV module/array (kW h)
V_{oc}	open circuit voltage (V)	$E_{AC,m}$	monthly total energy output of the PV module/array (kW h)
I_{mpp}	current at mpp (A)	$Y_{A,d}$	daily array yield
V_{mpp}	voltage at mpp (V)	$Y_{A,m}$	monthly average daily array yield
P_{max} or P_{mpp}	power at mpp (W)	$P_{PV, rated}$	installed PV power (W)
NOCT	normal operating cell temperature ($^{\circ}$ C)	Y_F	final yield (kW h/kW p)
A	module area (m^2)	Y_R	reference yield ((kW h/m ²)/(kW/m ²))
μ_{isc}	temperature coefficient at short circuit current (mA/ $^{\circ}$ C)	H_t	plane of array irradiation (kW h/m ²)
μ_{voc}	temperature coefficient at open circuit voltage (mV/ $^{\circ}$ C)	η	efficiency (%)
R_S	series resistance (Ω)		
R_{SH}	shunt resistance (Ω)		
I_L	light generated current (A)		

modules, such as the open circuit voltage (V_{oc}), the short circuit current (I_{sc}), current at maximum power (I_{mpp}) and voltage at maximum power (V_{mpp}), the temperature coefficients at open circuit voltage and short circuit current (μ_{voc} and μ_{isc} , respectively), and the nominal operating cell temperature (NOCT) [7]. These data are available only at standard test or rating conditions (STC) (except for the NOCT which is determined at 800 W/m² POA radiation level and an ambient temperature of 20 $^{\circ}$ C). These conditions produce high power output, but are rarely encountered in actual operation.

The electrical power available from a photovoltaic (PV) device can be modeled with the well-known equivalent circuit shown in Fig. 1 [5,7]. This circuit includes a series resistance and a diode in parallel with a shunt resistance. This circuit can be used either for an individual cell, for a module consisting of several cells, or for an array consisting of several modules [5]. The current–voltage relationship at a fixed cell temperature and solar radiation for the circuit in Fig. 1 is expressed in (1). Five parameters must be known in order to determine the current and voltage, and thus the power delivered to the load. These are: the light current I_L , the diode reverse saturation current I_0 , the series resistance R_S , the shunt resistance R_{SH} , and the modified ideality factor have defined in equation:

$$I = I_L - I_0 \left[e^{-\frac{V+IR_S}{a}} - 1 \right] - \frac{V + IR_S}{R_{SH}} \quad (1)$$

where

$$q \equiv \frac{N_S n_1 k_B T_C}{q} \quad (2)$$

The electron charge q and Boltzmann's constant k_B are known, n_1 is the usual ideality factor, N_S is the number of cells in series and T_C is the cell temperature. The power produced by the PV device is the product of the current and voltage. Ideally, a PV module would always operate at a voltage that produces maximum power. Such operation is possible, approximately, by using a maximum power point tracker (MPPT). Without a MPPT the PV module operates at a point on the cell I – V curve that coincides with the current–voltage (I – V) characteristics of the load.

In order to analyze the energy related performance of a PV module/array, some important parameters are to be computed using data collected during its operation in a given location. These parameters include: the total energy generated by the PV module/system (E_{DC}) and reference yield (YR). These normalized performance indicators are relevant since they provide a basis under which PV systems can be compared under various operating conditions.

The instantaneous energy output of the mc-Si PV module was calculated by the maximum power obtained from the current–voltage curves taken for 2 min intervals as:

$$E_{DC,t} = P_{max} t_{interval} \quad (3)$$

The total daily ($E_{AC,d}$) and monthly ($E_{AC,m}$) electricity generated by the PV module/array are obtained as:

$$E_{DC,d} = \sum_{t=\text{sunrise}}^{t=\text{sunset}} E_{DC,t} \quad (4)$$

and

$$E_{DC,m} = \sum_{d=1}^N E_{DC,d} \quad (5)$$

where d is the number of days in a month. PV module/array yield is given as:

$$Y_A = \frac{E_{DC}}{P_{PV, rated}} \quad (6)$$

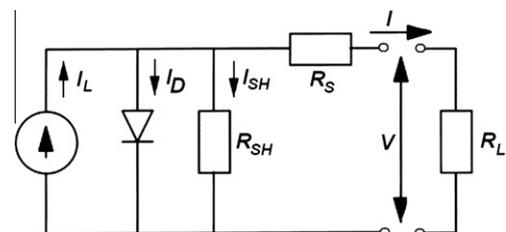


Fig. 1. Equivalent circuit of a solar cell or a photovoltaic module.

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