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Thermal management of solar photovoltaics modules for enhanced power generation

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A R T I C L E I N F O

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A B S T R A C T

Industry and government interest in solar energy has increased in recent years in the Middle East. However, despite high levels of solar irradiance in the Arabian Gulf, harsh climatic conditions adversely affect the electrical performance of solar photovoltaics (PV). The objective of this study is to compare the annual performance characteristics of solar PV modules that utilize either sun-tracking or water cooling to increase electrical power generation relative to that of stationary, passively cooled modules in the Middle East climatic conditions. This is achieved using an electro-thermal model developed and validated against experimental data acquired in this study. The model is used to predict the annual electrical power output of a 140 W PV module in Abu Dhabi (24.43°N, 54.45°E) under four operating conditions: (i) stationary geographical south facing orientation with passive air cooling, (ii) sun-tracked orientation with passive air cooling, (iii) stationary geographical south facing orientation with water cooling at ambient air temperature, and (iv) stationary geographical south facing orientation with water refrigerated at either 10 °C or 20 °C below ambient air temperature. For water cooled modules, annual electrical power output increases by 22% for water at ambient air temperature, and by 28% and 31% for water refrigerated at 10 °C and 20 °C below ambient air temperature, respectively. 80% of the annual output enhancement obtained using water cooling occurs between the months of May and October. Finally, whereas the annual yield enhancement obtained with water cooling at ambient air temperature from May to October is of 18% relative to stationary passive cooling conditions, sun-tracking over the complete year produces an enhancement of only 15% relative to stationary passive cooling conditions.

1. Introduction

Abu Dhabi's government plans to facilitate 7% of all its energy demands through renewable resources, primarily solar, by 2020 [1]. In parallel, oil and gas production facilities have recently commenced utilizing solar photovoltaic (PV) modules for on-site power generation [2]. This choice is due to many facilities being isolated from electrical grids and having a necessity to conserve space (e.g., off-shore platforms). As a result of increased usage of photovoltaics, there is significant interest in efficiently utilizing PV solar modules in the United Arab Emirates (UAE). The typical environmental conditions in the Middle East, including limited cloud coverage, are overall beneficial to electrical power generation by PV modules, but there is also a significant negative effect caused by high solar irradiance. PV module electrical efficiency can degrade by 0.2%–0.5% per °C increase in module temperature [3]. Additionally, it is typical in the UAE to operate PV modules in stationary, geographical south facing conditions, which confines the time period of maximum electrical power generation to solar noon. In this study, means of increasing PV module electrical power output using sun-tracking and module cooling are evaluated numerically using an experimentally validated electro-thermal model.

A PV module tends to produce maximum electrical power output when receiving peak solar irradiation, which occurs when the module collecting face is positioned normal to the sun. Sun-tracking can be easily achieved by matching the module and sun's elevation angles from the horizon for a given day, and subsequently rotating the module from East to West about a North–South axis at the same angular velocity as that of the sun's relative to the earth. In order to maximize the incident yearly solar irradiance at the latitude of Abu Dhabi (24.43°N, 54.45°E), a module is angled at 24.5° above the horizon. Except when significant wind or cloud coverage exists, a solar module's surface can be considerably

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above the ambient air temperature due to the absorbed solar irradiance. Rodgers et al. [4] provide an overview of the thermal management of PV modules and the potential for water cooling to improve electrical power output by lowering module's operating temperature. Using an integrated water flow piping system, a PV module's collecting surface temperature can be convectively cooled down to water temperature. Even with cooling water at ambient air temperature, water cooling will provide a significant cooling enhancement to the module relative to air cooling, owing to the higher convective heat transfer coefficient, thus increasing the PV module's electrical efficiency.

The objective of this paper is to quantify the annual electrical power output enhancements obtained using sun-tracking and thermal management strategies, relative to a stationary, geographically south facing, passively air cooled PV module.

2. Model validation

The PV module electro-thermal modeling methodology employed is based on standard energy balance and thermal resistance and capacitance equations presented in Armstrong & Hurley [5], Sarhaddi et al. [6], Candanedo et al. [7] and Posharp [8]. The model is shown in Fig. 1, and takes as inputs measured solar irradiation, ambient air and water temperatures, wind speed, and module thermophysical properties to calculate module gross electrical power output and surface temperature. The thermophysical properties of the module layers are derived from Ref. [5]. Cell absorptivity and glass transmissivity values are taken from Ref. [6]. Details for the PV module design and its thermophysical properties are given in Tables 1 and 2, respectively.

The PV module is operated free-standing, with both its upper (i.e., active) and lower (i.e., non-active) surfaces exposed to free-air for passively-cooled conditions. For water-cooling conditions, cooling water is discharged on the module active surface through an outlet pipe positioned at the upper edge of the module [9]. Wind induced forced convection is generally the dominant cooling heat transfer mode for passively cooled modules, with natural convection and radiation heat transfer combined providing minimal

Table 1
PV module design.

Length (m)	Width (m)	Packing factor	Cell absorptivity	Glass transmissivity	Power temperature coefficient
1.485	0.655	90%	90%	95%	−0.48%/°C

Table 2
Thermophysical properties of PV module layers.

Layer	Thickness (m)	Thermal conductivity (W/m°C)	Density (kg/m^3)	Specific heat capacity (J/kg °C)
Glass	0.003	1.8	3000	500
ARC	100×10^{-9}	32	2400	691
PV cells	225×10^{-6}	148	2330	677
EVA	500×10^{-6}	0.35	960	2090
Rear contact	10×10^{-6}	237	2700	900
Tedlar	0.0001	0.2	1200	1250

Note: EVA refers to ethylene vinyl acetate.

contribution [10,11]. This was verified in this study for wind speeds of 1–10 m/s. Forced convective heat transfer was calculated for both the exposed upper and lower surfaces of the module. Many empirical formulae have been developed for the prediction of the air-side forced convective heat transfer coefficient covering a wide range of PV module and solar collector plate sizes and orientations. In this study, two correlations are selected, that were derived from both similar testing environments and module geometries, namely Sharples and Charlesworth [10], and Sartori [11]. Additionally, an analytically-derived flat plate forced convection heat transfer correlation for parallel flow over an isothermal flat plate [12] is also evaluated. The three correlations employed are listed in Table 3. Sharples and Charlesworth [10] presented a range of correlations for different wind incidence angles, but found from field measurements that there was only a slight variation in convective heat transfer coefficient between these correlations. This finding is in-line with Rowley and Eckley [13], who observed that the forced convection heat transfer coefficient from a flat plate only slightly

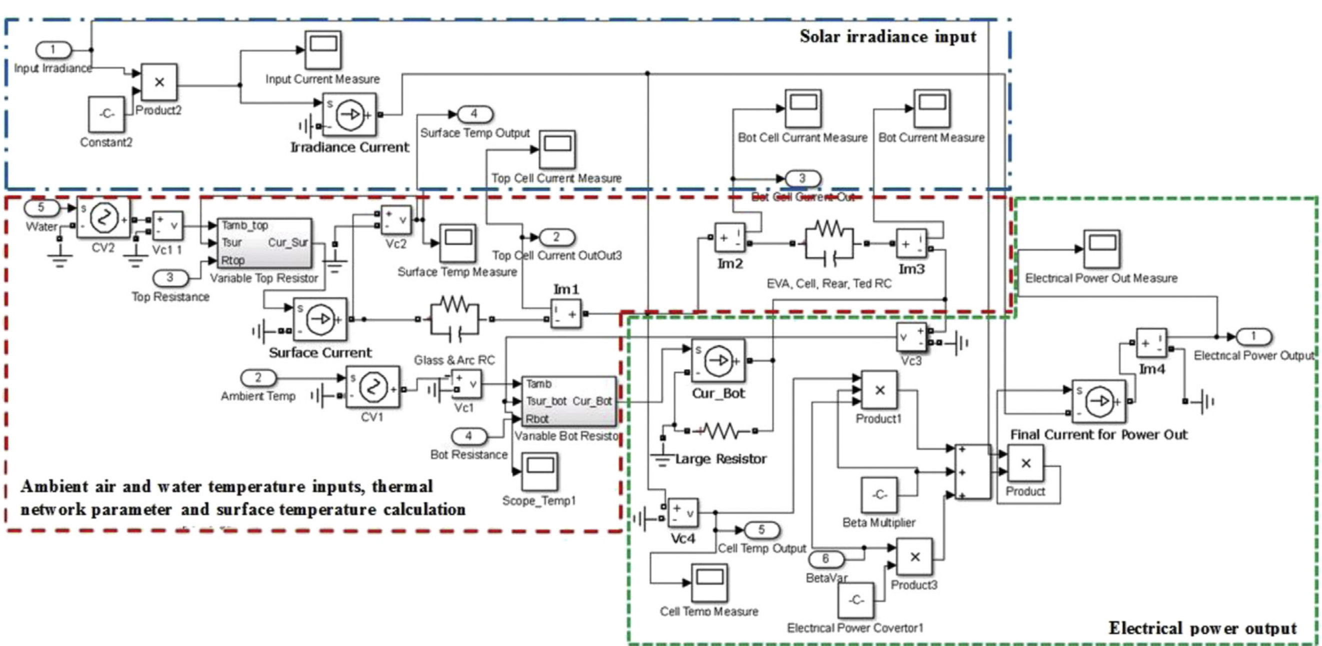

Fig. 1. Electro-thermal model for the prediction of solar PV module electrical power output and surface temperature.