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Performance investigation of low – Concentration photovoltaic systems under hot and arid conditions: Experimental and numerical results

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ABSTRACT

In this study, a comparative performance analysis was performed between a conventional photovoltaic system and a low-concentration photovoltaic system. Two typical photovoltaic modules and two compound parabolic concentrating photovoltaic systems were examined. A Cooling system was employed to lower the temperature of the solar cells in each of the two configurations. Experimental and numerical investigations of the performance of the two arrangements with and without cooling were presented. Experiments were conducted outdoors at the Egypt-Japan University of Science and Technology, subjected to the hot climate conditions of New Borg El-Arab City, Alexandria, Egypt (Longitude/Latitude: E 029°42′/N 30°55′). A comprehensive system model was established, which comprises an optical model, coupled with thermal and electrical models. The coupled model was developed analytically and solved numerically, using MATLAB software, to assess the overall performance of the two configurations, considering the concentration ratio of the concentrated photovoltaic system to be 2.4X. The results indicated that cooling the solar panels considerably improved the electrical power yield of the photovoltaic systems. By employing cooling, the temperatures of the conventional photovoltaic system and the concentrated photovoltaic system were effectively lowered by approximately 25% and 30%, respectively, resulting in a significant enhancement in the electrical power output of the photovoltaic system by 11% and that of the concentrated photovoltaic system by 15%. Furthermore, the results revealed that the concentrated photovoltaic system outperformed the non-concentrated photovoltaic system, for both non-cooling and cooling cases, by 33% and 52%, respectively. Finally, experimental verification of the numerical results revealed a good agreement for both configurations, with an average error of 4% and 5% for the photovoltaic systems and the concentrated photovoltaic systems, respectively.

1. Introduction

In Egypt, solar energy is currently considered to have the highest potential, among all the available renewable energy sources, to solve the problems of fossil fuel depletion, the associated threats to the environment resulting from carbon emissions from fossil fuel consumption, and the dramatically increasing demand for electricity. Therefore, efficient utilization of solar energy for electricity generation has been recognized as an urgent technical issue. Electricity from solar energy can be generated either by using photovoltaic (PV) technology for the direct conversion of solar radiation to electrical power, or by first converting it into thermal energy and then to electrical power. Although direct conversion by a PV system is regarded as superior and more efficient, compared to first converting it into thermal energy and then to electrical power, the widespread use of PV technology is still relatively restricted due to the need for a large land area, and its prohibitively high initial cost. Thus, discovering new methods to minimize the cost of PV arrangements is essential; such cost reductions may be achieved in two ways: by using concentration photovoltaic technology (CPV) or by increasing the solar cell's efficiency. Recently, CPV systems are being considered to be an effective solution for reducing the initial cost of PV cells by using less expensive mirrors or a cheaper lens for solar radiation concentration, which would eventually lead to a smaller area usage. This strategy strives to lower the cost of the PV panels by minimizing the amount of

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Nomenclature

A	area (m^2)
a	modified ideality factor
b	CPC-PV collector width (m)
C	concentration ratio of CPC-PV collector
C_f	specific heat capacity of water (J/kg K)
D_h	diameter of heat exchangers tubes (m)
F	Control function
F'	Water collector efficiency factor
F_R	heat removal factor control function
G_{CPC}	radiation that PV cells received from the CPC (W/m^2)
G_{bn}	normal beam radiation component (W/m^2)
$G_{CPC,b}$	beam radiation component (W/m^2)
$G_{CPC,d}$	diffuse radiation component (W/m^2)
$G_{CPC,g}$	ground radiation component (W/m^2)
G_{ref}	solar radiation at reference conditions (W/m^2)
$h_{conv,g\text{-}amb}$	coefficient of heat transfer from glass to ambient by convection (W/m^2 K)
$h_{rad,g\text{-}amb,}$	coefficient of heat transfer from glass to ambient by radiation (W/m^2 K)
h_f	convective heat transfer coefficient of water (W/m^2 K)
h_{p1}	glass, EVA and solar cell materials penalty factor
h_{p2}	penalty factor because of the existence of boundary between working fluid and tedlar
I	circuit current (A)
I_L	light generated current (A)
I_{mp}	maximum power current (A)
I_o	dark saturation current (A)
K	glass extinction coefficient
$K\tau\alpha$	incidence angle modifier
k	coefficient of conductive heat transfer (W/m K)
L	glazing thickness, layers thickness (m)
M	air mass modifier
m	water mass flow rate (kg/s)
N	experiments number
n	number of reflections
P	power output (w)
Q	heat transfer rate (W)
R_b	view factor for beam radiation
r	correlation coefficient
T	temperature (K)
U_b	coefficient of heat loss from CPC-PV system to the atmosphere (W/m^2 K)
U_L	coefficient of total heat loss from CPC-PV collector to the atmosphere (W/m^2 K)
U_T	coefficient of heat transfer from solar cell to tedlar (W/m^2 K)
U_t	coefficient of heat transfer from solar cell to glass (W/m^2 K)
U_{tT}	coefficient of total heat transfer from solar cell- glass to tedlar (W/m^2 K)
V	volt (V)
V_w	wind speed (m/s)
X	simulated or experimental value parameter

Greek symbols

α	absorptivity
$(\alpha\tau)_{eff}$	product of transmissivity and effective absorptivity
β	packing factor, tilt angle
η_e	Efficiency (%)
μ_{isc}	short circuit current temperature coefficient
θ	angle of incidence
θ_S	acceptance half-angle
θ_z	zenith angle
ρ	reflectivity
ε	the semiconductor band gap energy
σ	Stefan Boltzmann constant
τ	transmissivity

subscripts

a	aperture
amb	ambient
avg	average
b	beam
bs	tedlar back surface
c	cell
d	diffuse
exp	experimental
g	ground
mp	maximum power
num	numerical
r	refraction
rad	radiation
ref	reference
s	series resistance, sky
sc	short-circuit current
sh	shunt resistance
si	silicon
T	tedlar

Abbreviations

EVA	ethyl vinyl acetate
PV	photovoltaic
CPC	compound parabolic concentrator
RMSE	root mean square percentage deviation

semiconductor materials consumed, which are the most expensive parts of a PV arrangement [1].

It is possible to create a cost-effective CPV system that features the same power output while having fewer cells than a conventional PV system. However, due to the increased solar intensity onto the concentrated panel, the PV cells' surface temperature and loss of the generated heat increases; consequently, the efficiency of the PV panel drops significantly if a proper cooling unit is not integrated. Increasing PV cells' surface temperature results in a reduction in the open circuit voltage and consequently a decline in cell performance. Therefore, a proper cooling system must be incorporated into the (CPV) system for it to provide the maximum benefit and operate efficiently; otherwise, its technical life will decline, and the performance will start getting worse in the long run [2]. The cooling unit maintains the cell temperature at nominal levels, which in turn enhances the electrical conversion efficiency, while simultaneously producing thermal energy that can be utilized for domestic applications. Several types of solar concentrators have been examined in concentrating PV systems. Nevertheless, the Compound Parabolic Concentrator (CPC) is considered one of the best concentrators that is commonly employed in low concentration PV (LCPV) systems. The CPC solar concentrators are non-imaging concentrators that are currently considered the most suitable and efficient for a cost saving on electricity production by PV systems. The most encouraging advantage, particularly for low-concentration systems, is the capability of the CPC to