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Design and development of experimental setup of Hybrid PV/Thermal collector

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ABSTRACT: A portable Hybrid Photovoltaic/Thermal (PV/T) solar collector experimental apparatus was designed and developed. The purpose of this instructional experimental apparatus is to demonstrate solar energy applications. In this article, the authors present an experimental apparatus that will help undergraduate mechanical engineering students in understanding the basic heat transfer processes, and thermodynamics concepts and principles. This is achieved by utilising real life applications, such as using Hybrid Photovoltaic/Thermal solar collector to convert solar energy to both electrical and thermal energy. The article presents the details of the design and construction of the experimental apparatus, as well as testing procedures and sample results.

Keywords: Solar collector, Hybrid Photovoltaic/Thermal (PV/T), laboratory, design

INTRODUCTION

Heat transfer and thermodynamics are basic and very important topics that deal with energy, and have long been an essential part of mechanical engineering curricula all over the world. Heat transfer processes are encountered in a large number of engineering applications, such as solar energy systems. It is essential for thermal engineers to understand the principles of heat transfer, and be able to employ the right equations that govern the amount of energy being transferred. However, the majority of students perceive these topics as difficult.

A portable experimental apparatus for demonstrating heat recovery concepts and thermodynamics principles was developed by Abu-Mulaweh [1-3]. Similarly, it was decided that an experimental apparatus designed to demonstrate solar energy applications was needed, such as photovoltaic thermal hybrid solar collectors (Hybrid PV/T) system. The apparatus designed by companies specialising in education equipment may not exactly reflect the educational objectives intended by the faculty. These obstacles forced different venues to be searched in order to acquire instructional experimental laboratory apparatus to demonstrate solar energy applications. It was concluded that such an apparatus could be designed, developed and constructed *in house* within a manageable budget.

Photovoltaic thermal hybrid solar collectors (Hybrid PV/T) are systems that convert solar radiation into both electrical and thermal energy. These types of systems combine a photovoltaic panel, which converts solar energy into electricity, with a solar thermal collector, which captures the remaining energy and removes waste heat from the Photovoltaic (PV) module. The PV cells suffer from a drop in efficiency with the rise in temperature due to increased in PV electrical resistance. The Hybrid PV/T systems can be engineered to carry heat away from the PV cells, thereby cooling the cells and thus improving their efficiency by lowering PV electrical resistance.

Tests under different weather conditions showed an increase of system output in the range of 4-10% when a cooling technique was applied to a PV system [4]. Different types of PV/T system design have been introduced in the literature based on its application or type of cooling medium used [5]. Air cooling PV/T techniques are mainly used in building integrated systems, such as PV facade and PV thermal hybrid systems. Application of PV in buildings can be used for the production of electricity and space heating [6]. Another type of PV facade cooling is by using water or heat pipe network at the back of PV modules, which was used in this study [7][8].

THEORY AND MATHEMATICAL MODEL

A Hybrid Photovoltaic/Thermal (PV/T) collector is a combined system of a photovoltaic (PV) solar module for power generation and a flat plate solar collector for water heating. Such a type of hybrid system technique can improve the PV system efficiency significantly due to two main factors: the reduction of PV surface temperature by water cooling and the combined system output effect (electrical and thermal).

The performance evaluation of a PV panel is based on the voltage-current characteristics under various solar irradiations and various PV surface temperatures. In general, a PV panel manufacturer provides specifications of panel capacity (power, voltage and current) under standard conditions, which are irradiation of 1,000 W/m^2, and panel temperature of 25°C. A deviation from standard conditions by having lower irradiation and/or higher PV panel temperature will reduce PV panel power output.

Odeh and Behnia showed experimentally that if irradiation is reduced from 1,000 to 600 W/m^2, PV panel maximum power drops by 40 % [4]. Alternatively, when PV temperature is increased by 10°C, a 5% drop in PV panel maximum power was reported. Therefore, adopting the PV/T technique can reduce panel temperature by using a cooling fluid, which can provide a trade-off between PV efficiency and thermal output.

Solar irradiation level and ambient temperature are the major factors affecting PV panel temperature (T_p), which can be expressed by the following linearity [4]:

$$T_p = T_a + \left(\frac{T_p - T_a}{G_t}\right)_{st} \times G_t \tag{1}$$

The value of the bracket depends on the cell type of the PV panel. However, in this study, the PV panel temperature was measured experimentally using type K thermocouples.

Maximum power of a PV module operating at conditions other than standard test condition (given by manufacturer) is estimated by:

$$\frac{P_{max}}{I_{sc} \times V_{oc}}\Big]_{st} = \frac{P_{max}}{I_{sc} \times V_{oc}}\Big]_{i} \tag{2}$$

where index (st) stands for standard conditions and (*i*) stands for the operating conditions other than standard.

In this study, P_{max} at conditions other than the standard can be evaluated experimentally. The performance of the different units introduced by this experimental setup was evaluated by using the following equations:

Efficiency of PV unit:

$$\eta 1 = \frac{(I \times V)}{G_t . A_1} \tag{3}$$

Efficiency of thermal unit:

$$\eta 2 = \frac{m^{\cdot} . C_W \, (T_o - T_i)}{G_t . A_2} \tag{4}$$

Efficiency of PV/T unit:

$$\eta 3 = \frac{[m^{\cdot} . C_W \, (T_o - T_i)] + (I \times V)}{G_t . A_3} \tag{5}$$

Where, $A_3 = A_2$ = aperture area of the unit.

Efficiency of PV/T unit can be evaluated also from:

$$\eta 3 = \eta 1 + \eta 2 \tag{6}$$

DESIGN AND BUILD

The PV/T experimental setup, which uses water as the cooling medium for the PV module that was designed and developed, is shown in Figure 1. The experimental rig consists of three test units: the PV unit, the PV/T unit, and the Thermal unit. The following is a brief description of each unit:

- PV unit: a thin film amorphous silicon PV panel (Battery Saver Plus) of an area of 30 cm^2 and total rated power of 1.8 W. This unit was used to conduct typical test of current-voltage (I-V) characteristics curves.
- PV/T unit: an in house developed hybrid system of collector integrated PV was used to investigate the effect of water cooling on the PV panel efficiency. This unit consists of two PV panels of thin film amorphous silicon same as in PV unit (Battery Saver Plus) connected in series to form a PV area of 60 cm^2. The PV panel is covered by a cooling water film enclosed by transparent glass cover (thickness 3 mm) as shown by the cross section view in Figure 2. Cooling water enters the unit on the lower side and leaves from the upper side.
- Thermal unit: a flat plate collector of similar dimensions to the PV/T unit to investigate its thermal performance individually. The difference between this unit and the PV/T unit is that the PV panel has been replaced by a black surface metal sheet to enclose the lower side of the water film space (see Figure 2).

In both the PV/T and thermal units, a water hose was used to connect each one to the water mains through a flow control valve. The enclosure frames of both units, were made of timber and mounted on an adjustable tilt platform board (timber) to change the tilt angle from 0 to 90 by using the protractor shown in Figure 3. The tilt angle can simulate PV/T system mounted on building roofs or building façades. The platform board was fixed on a metal stand with free rotation wheels to form two axis solar tracking mechanism. The free rotation stand accommodates normal solar radiation during some tests and/or to simulate real system orientation (north/south or east/west) in building integrated PV/T.

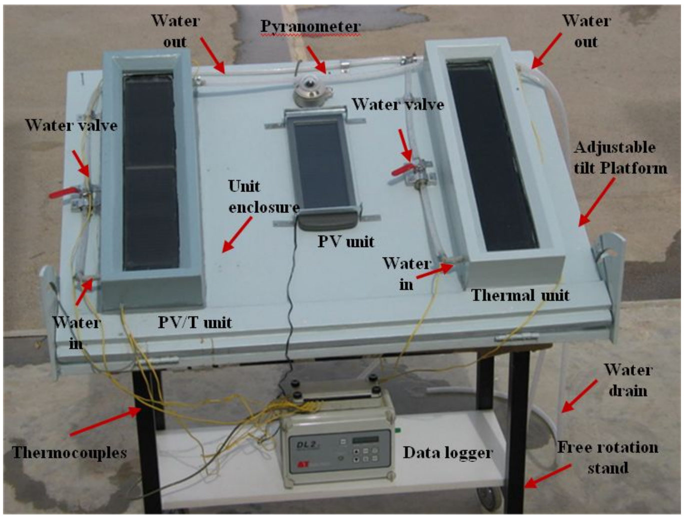

Figure 1: Experimental setup.

The experimental setup includes the following measuring instruments and devices:

1. A Pyranometer (Kipp and Zonen): it is used to measure the total solar radiation in mV. The pyranometer is mounted on the adjustable platform and has a conversion factor of 157 mV per 1 kW/m^2 of solar irradiation.
2. A data logger (DL2e): registers mV readings received by the Pyranometer and thermocouples and convert them to irradiation in (W/m^2) and temperature in °C.
3. A variable resistance circuit (1,000 Ω): used to change PV panel unit load during the I-V characteristics curve test. The circuit layout is shown in Figure 4.
4. Millimetres: to measure voltage and current during I-V characteristics curve test and they are connected to the circuit as shown in Figure 4.
5. Temperature measurements: different temperature measurements for water in, water out, PV upper surface, PV lower surface and ambient temperature are logged in by type K thermocouples connected to the data logger.
6. A compass: to indicate system orientation. This is required only when performance simulation of a system at fixed orientation is required.

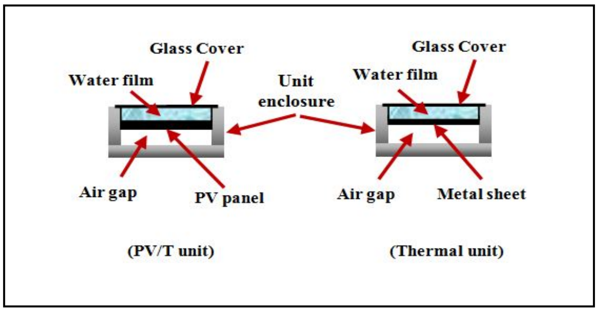

Figure 2: Cross section configuration of PV/T and thermal units.

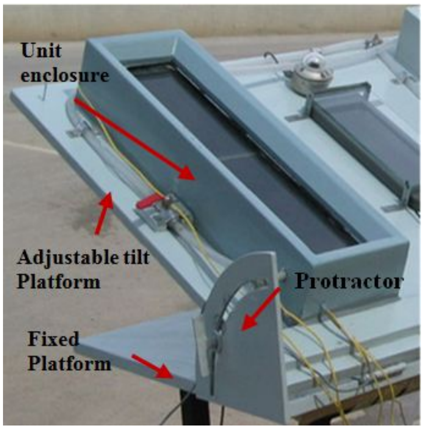

Figure 3: Test setup side view.

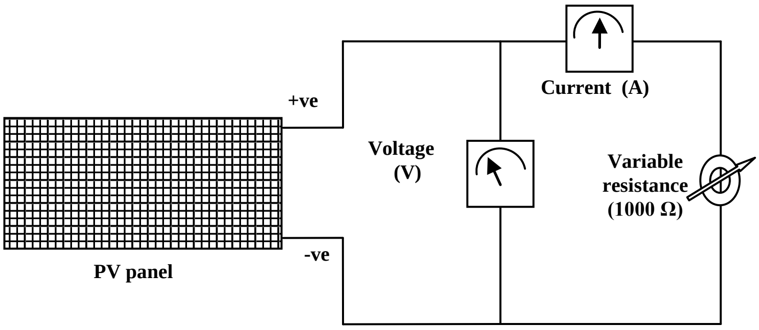

Figure 4: Variable resistance circuit.

TESTING AND SAMPLE RESULTS

I-V Characteristics Curve Test

The I-V characteristics curve of a PV panel at standard conditions (1,000 W/m^2 irradiation and ambient temperature 25°C) is provided with the manufacturer specification sheet. However, these I-V curves at conditions other than standard conditions can be measured following the procedure developed in an experimental test. The test procedure for these units is as follows:

1. Connect the PV panel unit with the variable resistance circuit as shown in Figure 4.
2. Connect the ammeter in series with the variable resistance and PV panel.
3. Connect the voltmeter in parallel with the variable resistance and PV panel.
4. Adjust the tilt platform and/or rotating stand to achieve the required irradiation, while PV surface temperature is at steady state.
5. Measure the incident solar irradiation, PV panel surface temperature and ambient temperature (using the data).
6. Find a PV panel short circuit current I_{sc} (minimum resistance, maximum current and minimum voltage) and an open circuit voltage V_{oc} (maximum resistance, minimum current and maximum voltage).
7. Change the resistance slightly from the variable resistance knob and take the reading of current and voltage.
8. Change irradiation and measurements by repeating steps 4 to 7.
9. Find the power generated at each load from Ohm's law (V x I). Maximum power point (MPP) is found from the peak point of the power voltage curve at V_{mp} and I_{mp}.
10. Find the optimum operation load resistance (R) in (Ω) from Ohm's law, where R = V/I.

The I-V characteristics curves presented in Figure 5 show that the I_{sc} current was affected by the solar irradiation incident on the PV panel. As can be seen from the figure, the current increases with increasing the irradiation. On the other hand, the voltage V_{oc} does not change with irradiation. It should be noted that the trend of I_{sc} and V_{oc} with solar irradiation is similar for the different types of PV panels [9]. The surface temperature of the panel has a significant effect on V_{oc}, which decreases as the temperature increases. Therefore, thermal equilibrium of PV surface is required to be achieved during the I-V test for results to be accurate. The effect of PV cooling on PV panel surface temperature is shown in Figure 6 during 60 minutes of exposing the PV/T unit to an irradiation of the 950 W/m^2. The linearity relationship between PV panel temperature and ambient temperature is clearly shown. The drop in PV surface temperature due to cooling technique used in this setup increases significantly at higher temperature and reaches up to 25°C. The effect of this cooling technique on PV/T unit output is shown in Figure 7. The effect of PV panel cooling on the increase in PV panel output is more significant at higher PV panel temperature and reaches up to 19%.

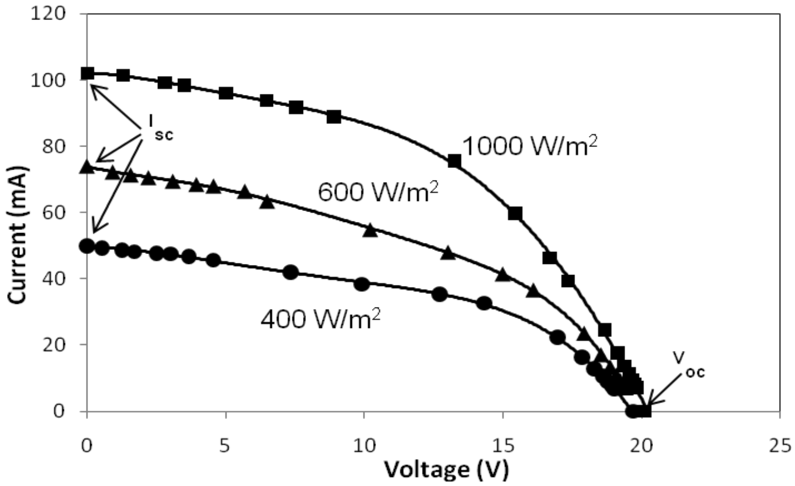

Figure 5: I-V curve for thin film amorphous silicon module at different solar irradiation and PV surface temperature 45°C.

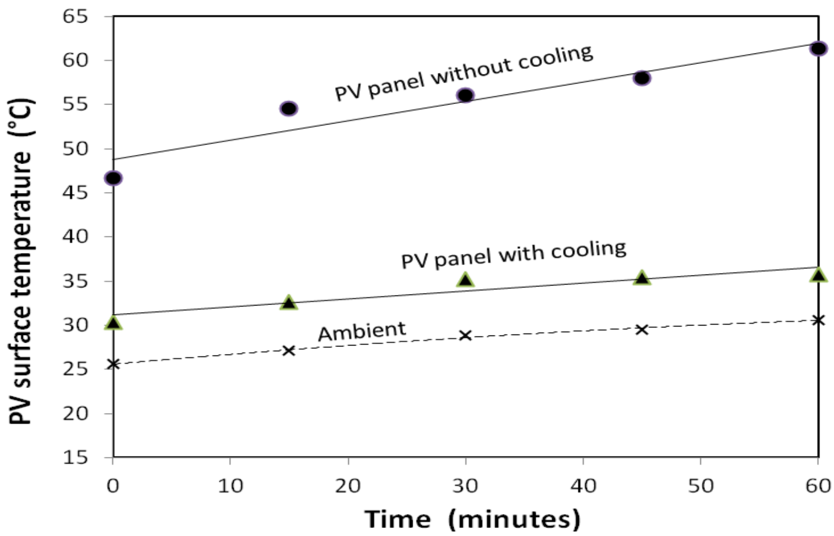

Figure 6: The effect of PV cooling and ambient temperature on PV panel surface temperature at an irradiation 950 W/m^2.

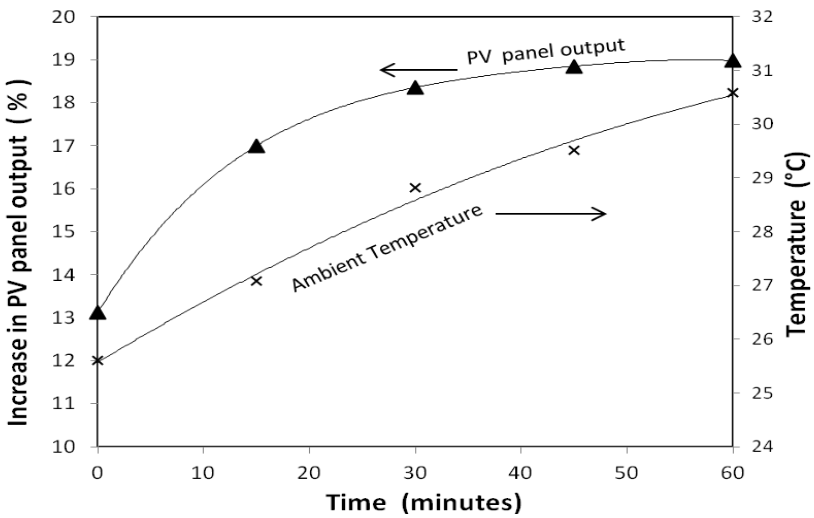

Figure 7: The effect of PV cooling on panel output at an irradiation of 950 W/m^2.

Theoretically, a PV panel operates at the maximum power point (MPP) of a current I_{mp} and a voltage V_{mp} , but practically the panel operates at a point on the I-V curve that matches the I-V characteristics of the load [9]. Therefore, to achieve maximum output from a PV system, a maximum power point tracker (MPPT) can be used to adjust the MPP with change in irradiation. In this study, the MPP of the PV unit at a certain irradiation was estimated by plotting the power-voltage curve with the I-V curve and, then, by locating the peak point as shown in Figure 8. From this figure, the I_{mp} and V_{mp} (or optimum load) can be found for irradiation of 1,000 W/m^2 and PV surface temperature 45°C.

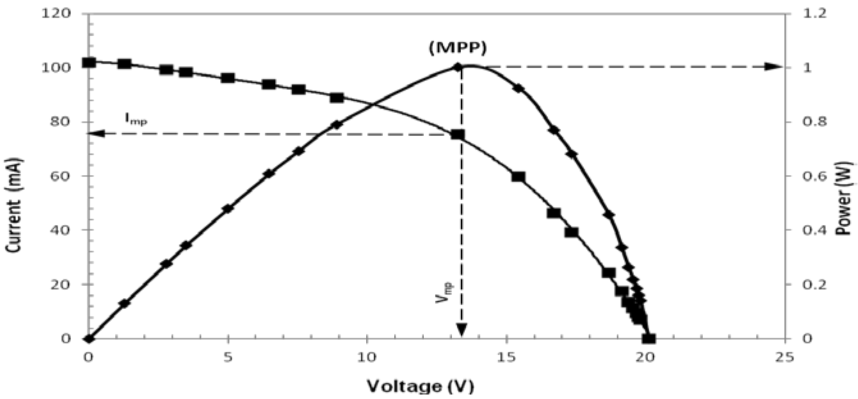

Figure 8: Maximum power point voltage and current at irradiation 1,000 W/m^2 and surface temperature 45°C.

Hybrid System Efficiency Test

The experimental setup that was designed and developed can be used to demonstrate the efficiency of a PV/T system, which has dual outputs: DC power and thermal heat deduced by cooling water. In order to pinpoint the value of each output experimentally, three units were used in the test: a PV unit, a PV/T unit, and a thermal unit. The test procedure for these units is as follows:

1. Adjust the tilt platform and stand to achieve the required irradiation reading on the data logger.
2. Open the water valves of PV/T and thermal units to a value where a significant difference between the inlet and exit can be reported. In this test, water flow rate is taken 0.17 ml/s to achieve temperature difference around 10°C.
3. In steady state conditions, take the readings of each the three units: irradiation, water flow rate, ambient temperature, water inlet and outlet temperatures.
4. Repeat step 1 for different irradiation while fixing the flow rate.
5. Repeat step 2 and 3.

Figure 9 presents the efficiency of the three units at different irradiations and constant water flow rates. It can be seen from the figure that the efficiency of the PV/T and thermal units is affected significantly by irradiation due to the increase of thermal losses with the increase of water temperature. However, the efficiency of the PV unit is almost constant with irradiation due to its steady surface temperature. At low irradiation, the dual efficiency of PV/T unit is almost 5 times the PV unit, mainly because of the heat reduced by cooling water. However, at higher irradiation the dual efficiency of the PV/T unit declines to twice that of the PV unit due to the increase in thermal loss. Comparing the results of dual efficiency of PV/T unit (as evaluated from Equation (5)) and by adding the two efficiencies of PV and thermal units individually (as evaluated from Equation (6)), an error of around 7% is reported. This can be seen in Figure 9, in which the efficiency values from curve fitting of PV and thermal unit tests are added and compared with PV/T test fitting at a certain irradiation.

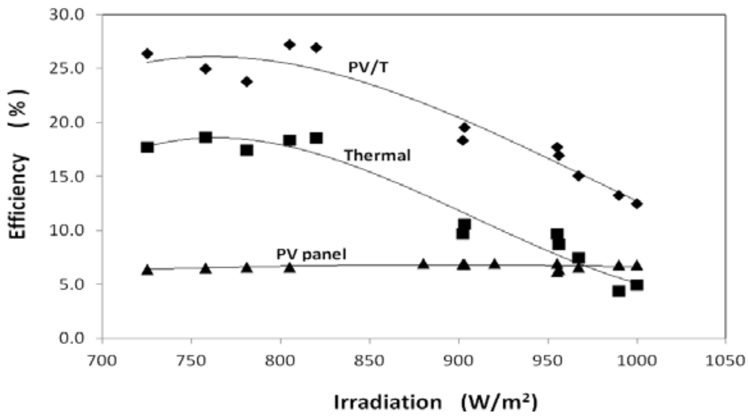

Figure 9: Efficiency of the PV, PV/T and Thermal units at different irradiation, and water flow rate 0.17 ml/s.

CONCLUSION

A prototype of a Hybrid Photovoltaic/Thermal (PV/T) solar collector experimental apparatus was designed and developed. The experimental apparatus described in this article is a valuable addition to the undergraduate mechanical engineering laboratory. The experimental apparatus is portable and it can be used as an instructional experimental apparatus for demonstrating basic heat transfer principles.

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Nomenclature

A_1 -	Aperture area of PV unit	[m^2]	PV -	Photovoltaic	
A_2 -	Aperture area of thermal unit	[m^2]	R -	Resistance	[Ω]
A_3 -	Aperture area of unit PV/T unit	[m^2]	T_i -	Water inlet temperature	[°C]
C_w -	Specific heat of water	[kJ/kg]	T_o -	Water outlet temperature	[°C]
G_t -	Global irradiation	[W/m^2]	T_p -	PV panel temperature	[°C]
I -	Current	[A]	V -	Voltage	[V]
I_{sc} -	Short circuit current	[A]	V_{oc} -	Open circuit voltage	[V]
I_{mp} -	Maximum power point current	[A]	V_{mp} -	Maximum power point voltage	[V]
$\dot{m}$ -	Water flow rate	[kg/s]	$\eta 1$ -	Efficiency of PV unit	
MPP -	Maximum power point		$\eta 2$ -	Efficiency of thermal unit	
P_{max} -	Maximum power	[W]	$\eta 3$ -	Efficiency of PV/T unit	

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BIOGRAPHIES

Saad Odeh is an Associate Professor in mechanical engineering. He received his PhD in mechanical engineering/solar thermal power generation from the University of New South Wales, Sydney, Australia. Saad has over 25 years experience in the field of sustainable energy, power and co-generation systems. His main research area is solar thermal and solar photovoltaic systems. He has had over 40 papers published in international journals and conference proceedings. He is a member of Association Building Sustainability Assessors, and Clean Energy Council - Australia.

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