Energy Sources, Part A: Recovery, Utilization, and Environmental Effects

ISSN: 1556-7036 (Print) 1556-7230 (Online) Journal homepage: http://www.tandfonline.com/loi/ueso20

Photovoltaic thermal hybrid solar system for residential applications

L. Rekha, M. M. Vijayalakshmi & E. Natarajan

To cite this article: L. Rekha, M. M. Vijayalakshmi & E. Natarajan (2016) Photovoltaic thermal hybrid solar system for residential applications, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 38:7, 951-959, DOI: 10.1080/15567036.2011.651560

To link to this article: http://dx.doi.org/10.1080/15567036.2011.651560

Published online: 18 Apr 2016.

ENERGY SOURCES, PART A: RECOVERY, UTILIZATION, AND ENVIRONMENTAL EFFECTS
2016, VOL. 38, NO. 7, 951–959
http://dx.doi.org/10.1080/15567036.2011.651560

Photovoltaic thermal hybrid solar system for residential applications

L. Rekha[a], M. M. Vijayalakshmi[b], and E. Natarajan[c]

[a]Government Engineering College, Thrissur, Kerala, India; [b]Department of Civil Engineering, Sathyabama University, Chennai, India; [c]Department of Mechanical Engineering, Anna University, Chennai, India

ABSTRACT

Electrical and thermal energy have wide applications for the future of mankind. A solar photovoltaic thermal system is a hybrid system, which can produce both thermal and electrical energy. Chennai has an appropriate climate and is highly suitable for using photovoltaic thermal hybrid systems. This article presents the mathematical analyses of the thermal, electrical, and exergetic performance of a photovoltaic thermal system augmented by a flat plate collector for a typical domestic application. The system is found to have 11% average electrical efficiency, 15% overall exergy efficiency, and 56% overall energy efficiency.

KEYWORDS

Energy; exergy; flat plate collector; hybrid; photovoltaic; solar water heater

1. Introduction

Energy is essential for economic and social development. An energy shortage is a big impediment to the economic growth of a country and renewable energy can play a vital role for a clean and renewable nature. Using solar energy for electricity generation helps save the earth and reduces the emission of greenhouse gases. In residential buildings, energy performance has been one of the major target areas of emission reduction schemes and regulations. Photovoltaic thermal (PVT) hybrid technology can contribute to the significant reduction of fossil fuel consumption and reduce carbon emission (Zhang et al., 2011). Gang et al. (2011) designed a novel model for a heat-pipe PVT system and the results indicated that the daily electrical and thermal efficiencies of the heat-pipe photovoltaic/thermal system were 9.4 and 41.9%, respectively. Kalogirou and Tripanagnostopoulos (2006) reported that, for mono-crystalline and polycrystalline silicon solar cells, the efficiency decreases by about 0.45% for every degree rise in temperature. Ji et al. (2007) reported that about 80% of the solar radiation falling on photovoltaic cells could not be converted to electricity due to poor efficiency of solar cells, and most of this energy can be converted to a usable form of thermal energy in a hybrid PVT system. As reported by different authors in their recent reviews (Zondag, 2008; Chow, 2010; Ibrahim et al., 2011), many configurations of flat plate PVT collectors have been developed. Dubey and Tiwari (2010) analyzed overall annual energy and exergy provided in the form of heat and electricity from a hybrid PV/T solar water heating system by considering the five different cases with and without withdrawal from the tank. Kumar and Rosen (2010) determined the thermal performance of the rectangular collector/storage solar water heater that depends significantly on the heat transfer rate between the absorber surface and the water, and the amount of solar radiation incident on the absorber surface. Hasan and Sumathy (2010) recently conducted a review based on module aspects of different PVT collectors and their performances in terms of electrical as well as thermal output. Tiwari et al. (2009) have performed the exergy analysis of an integrated photovoltaic thermal solar water heater under constant flow rate and constant collection temperature modes. Joshi and Tiwari (2007) presented a detailed report of the applications of PV and

CONTACT L. Rekha rekhadinesh05@gmail.com Department of Mechanical Engineering, Anna University, Chennai 600025, India.

PVT systems in detail. They reported that the thermal efficiency of a PVT water collector is more than that of a PVT air collector due to higher heat removal capacity. Thus, it is obvious that the flat plate PVT solar collector is a promising alternative system for low-temperature residential application, which requires electrical energy, power, and heat.

This study focuses on the analysis of a PVT thermal hybrid solar system for a typical residential application with an electrical energy demand of 3 kWhr/day and hot water demand of 100 LPD. In the present work, thermal, electrical, and exergetic performance of a PVT system augmented by a flat plate collector (FPC) is analyzed for a typical domestic application.

2. Methodology

Both thermal and electrical energy are required for the residential applications. A typical simple house requires about 2 to 4 kWh of electrical energy per day. A PV system of about 4 m^2 module area can produce about 3 kWh per day. A flat plate solar collector of 2 m^2 area can deliver about 100 LPD of hot water at about 80°C. A combination of a PVT system of 4 square meters area and solar flat plate collector of 2 square meters area, arranged as shown in Figure 1, can meet the thermal and electrical requirements of a typical house. For this analysis, a PVT module in combination with water heat extraction units made from copper sheet and pipes is used. The module is also assumed to have glazing covers of 4 mm thickness to achieve satisfactory thermal output.

3. Hybrid PVT water collector

The energy balance equation for each component of a PVT water collector can be obtained based on the assumptions: (i) the system is in quasi-steady-state condition, (ii) the transmissivity of ethyl vinyl acetate (EVA) is approximately 100%, and (iii) the temperature variation along the thickness is negligible.

From the basic energy balance for different components of PVT, the solar cell temperature and back surface temperature are obtained (Sarhaddi et al., 2010). The typical system parameters used in the analysis are summarized in Table 1. An expression for water outlet temperature from the

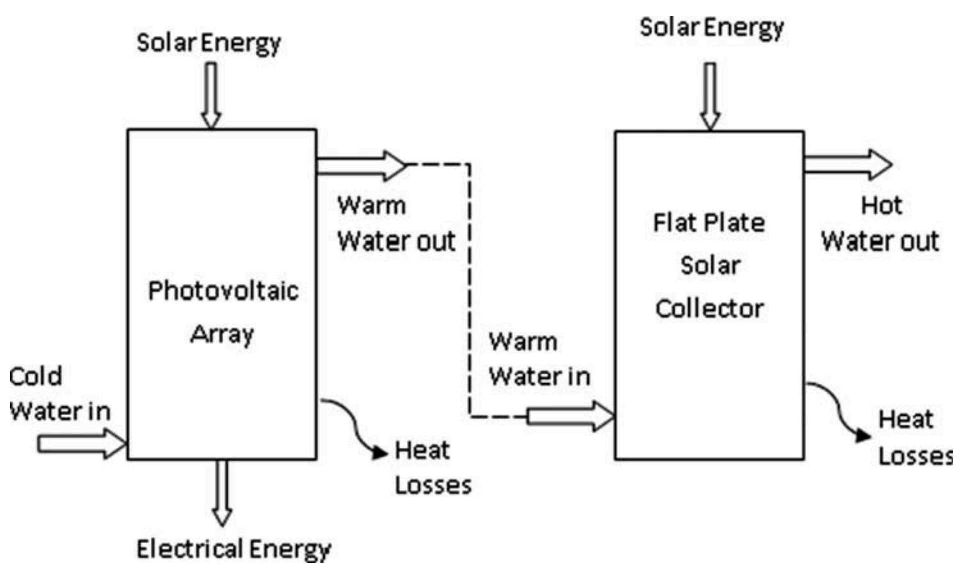

Figure 1. Schematic diagram of PVT and FPC connected in series.

Table 1. Typical values of the system used for the analysis.

A_{fpc}	2	m^2
A_{pvt}	4	m^2
c_w	4,190	J/kg K
F_{R1}	0.57	
F_{R2}	0.71	
h_i	5.8	W/m^2K
h_o	9.5	W/m^2K
h_f	500	W/m^2K
p_1	0.87	
p_2 0.98		
k	385	W/m K
k_c	0.039	W/m K
k_g	1.00	W/m K
k_{ins}	0.035	W/m K
k_T	0.033	W/m K
L	1.31	m
L_c	0.0003	m
L_g	0.003	m
L_{ins}	0.05	m
L_T	0.0005	m
$\dot{m}$	0.005	kg/s
U_{L1}	8.60	W/m^2 K
U_{L2}	6.00	W/m^2 K
U_b	0.62	W/m^2 K
U_T	66.00	W/m^2 K
U_t	9.24	W/m^2 K
U_{tT}	8.10	W/m^2 K
U_{tf}	7.97	W/m^2 K
$(UA)_{tk}$	2.27	W/K
α_T	0.5	
β_c	0.83	
$(\alpha\tau)_{fpc}$	0.88	
$(\alpha\tau)_{pvt}$	0.69	
τ_g	0.95	

absorber of a PVT module can be calculated with the boundary condition $[T_f]_{x=0}$, $T_f = T_{fi}$ and at $[T_f]_{x=L}$, $T_f = T_{f'}$:

$$T_{f'} = \left(T_a + \left(p_1 p_2 (\alpha\tau)_{pvt} G \big/ U_{L_1}\right)\right)\left(1 - \exp\left(-F' A_{pvt} U_{L_1} / \dot{m} c_w\right)\right) + T_{fi}\left(\exp\left(-F' A_{pvt} U_{L_1} / \dot{m} c_w\right)\right). \tag{1}$$

The rate of useful thermal energy from a PVT collector is given as:

$$\dot{Q}_{u1} = \dot{m} c_w (T_{f'} - T_{fi}) = A_{pvt} F_{R_1} \left(p_1 p_2 (\alpha\tau)_{pvt}\right) G - U_{L_1}\left(T_{fi} - T_a\right). \tag{2}$$

Similarly, an expression of outlet water temperature at the end of a flat plate collector can be written as a function of the inlet water temperature, $T_{f'}$:

$$T_{fo} = \left(T_a + (\alpha\tau)_{fpc} G \big/ U_{L_2}\right)\left(1 - \exp\left(-F' A_{fpc} U_{L_2} / \dot{m} c_w\right)\right) + T_{f'} \exp\left(-F' A_{fpc} U_{L_2} / \dot{m} c_w\right). \tag{3}$$

The rate of useful thermal energy obtained from a FPC system is given as:

$$\dot{Q}_{u2} = \dot{m} c_w (T_{fo} - T_{f'}) = A_{fpc} F_{R_2} (\alpha\tau)_{fpc} G - U_{L_2}\left(T_{f'} - T_a\right). \tag{4}$$

The useful heat output of the combination of PVT and FPC is:

$$\dot{Q}_u = \dot{Q}_{u1} + \dot{Q}_{u2} = \left[A_{pvt}F_{R_1}\left(p_1p_2(\alpha\tau)_{pvt}\right)\left(1-\frac{A_{fpc}F_{R_2}U_{L_2}}{\dot{m}c_w}\right) + A_{fpc}F_{R_2}(\alpha\tau)_{fpc}\right]G - \left[A_{pvt}F_{R_1}U_{L_1}\left(1-\frac{A_{fpc}F_{R_2}U_{L_2}}{\dot{m}c_w}\right) + A_{fpc}F_{R_2}U_{L_2}\right](T_{fi}-T_a) \quad (5)$$

An instantaneous thermal efficiency can be obtained from the above equation as:

$$\eta_{thermal} = (\alpha\tau)_{eff} - (UA)_{eff}\frac{(T_{fi}-T_a)}{G}. \quad (6)$$

Here,

$$(\alpha\tau)_{eff} = \left[A_{pvt}F_{R_1}\left(p_1p_2(\alpha\tau)_{pvt}\right)C + A_{fpc}F_{R_2}(\alpha\tau)_{fpc}\right]\Big/A_{pvt}+A_{fpc};$$
$$(UA)_{eff} = \left[A_{pvt}F_{R_1}U_{L_1}C + A_{fpc}F_{R_2}U_{L_2}\right]/A_{pvt}+A_{fpc};\ C = \left(1-\frac{A_{fpc}F_{R_2}U_{L_2}}{\dot{m}c_w}\right)$$

.

An expression for temperature-dependent electrical efficiency of a PV module (Zondag, 2008) is given as:

$$\eta_{electrical} = \eta_{e0}\left[1-0.0045(T_c-T_{a0})\right], \quad (7)$$

where η_{e0} is the reference efficiency of the PV module (12%) and T_{a0} is the reference temperature (25°C) under standard test conditions.

4. Energy balance for the water heating system

The thermal energy available at the outlet of FPC is fed into an insulated tank for storage, and then by the energy balance of whole system, the following is obtained:

$$\dot{Q}_u = M_wc_w\frac{dT_w}{dt} + (UA)_{tk}(T_w-T_a). \quad (8)$$

The above equation can be solved by assuming $T_{fi} = T_w$ due to perfectly insulating connecting pipes:

$$(\alpha\tau)_{overall}G - (UA)_{overall}(T_w-T_a) = M_wc_w\frac{dT_w}{dt} + (UA)_{tk}(T_w-T_a), \quad (9)$$

$$\frac{dT_w}{dt} + aT_w = f(t). \quad (10)$$

In order to obtain an approximate solution for Eq. (10), it is assumed that (i) the time interval Δt ($0 < t < \Delta t$) is small, (ii) the function $f(t)$ is constant, and (iii) a is constant during the time interval Δt:

$$a = \left[(UA)_{eff} + (UA)_{tk}\right]\Big/M_wc_w;\ f(t) = \frac{(\alpha\tau)_{eff}G + \left\{(UA)_{eff} + (UA)_{tk}\right\}T_a}{M_wc_w}$$

.

The water temperature in the storage tank can be obtained as:

$$T_w = \frac{\overline{f(t)}}{a}\left(1-e^{-at}\right) + T_{w0}e^{-at}, \quad (11)$$

where T_{w0} is the temperature of storage tank water at $t = 0$ and $\overline{f(t)}$ is the average value of $f(t)$ for the time interval between 0 and t.

5. Overall thermal and exergy efficiency

An expression for thermal efficiency of a system can be obtained as:

$$\eta_{\text{thermal}} = \frac{\dot{Q}}{A.G} \; where \, (A = A_{pvt} + A_{fpc}). \tag{12}$$

For the thermal analysis, an overall thermal efficiency of the system has been calculated:

$$\eta_{overall\text{thermal}} = \eta_{thermal} + \frac{\eta_{electrical}}{C_f}. \tag{13}$$

In this equation, electrical efficiency has been converted to the equivalent of thermal efficiency using electric power generation efficiency for a conventional power plant. The value of conversion factor C_f varies between 0.20 and 0.40. Conversion factor of the thermal plant in this study is taken as 0.38.

Then the overall exergy efficiency can be given as:

$$\eta_{overallexergy} = \eta_{electrical} + \eta_{thermal}\left[1 - \frac{T_a}{T_{fo}}\right]. \tag{14}$$

6. Economic analysis

The overall cost of the present system is around 114,000 INR, based on the local market values for four numbers of 150 Wp SPV modules, FPC of 2 square meters area, tank, and balance of system. Taking unit cost of electricity as 5 INR/kWh, the simple payback period works out to be about 5 years. It is in reasonable agreement with the findings of others under Indian climatic conditions (Prakash and Bansal, 1995).

7. Results and discussion

The variation of global solar intensity and ambient temperature for a typical day in the month of May in Chennai was taken for the present study (Mani, 1981). Figure 2 shows the hourly variation of the water outlet temperature from the combination and back surface temperature of Tedlar. The final temperature of the water obtained from the combination is in the range of 42–102°C, the maximum occurring at 13.00 h as shown in Figure 2. Inlet water temperature entering the FPC is 36°C, which is obtained from the PVT at 7.00 h in May. The variation of cell temperature and electrical efficiency is shown in Figure 3, where it is seen that the solar cell temperature increases with solar intensity and it clearly shows that the increase in cell temperature decreases the electrical efficiency. Also, during local time of 11.00–15.00 h the

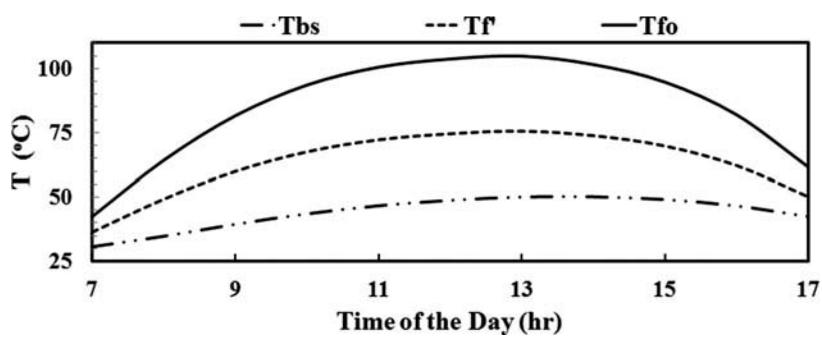

Figure 2. Hourly variations of water outlet temperature from FPC and PVT and back surface of the solar cell at $\dot{m} = 0.005 kg/s$.

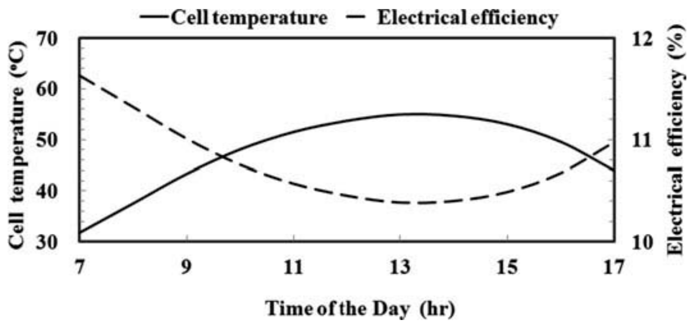

Figure 3. Hourly variations of cell temperature and electrical efficiency at $\dot{m} = 0.005kg/s$.

variation of electrical efficiency is significant because of the cell temperature variation. The average solar cell temperature is 47°C, while its maximum temperature is about 55°C. The electrical efficiency is found to vary from 10.4 to 11.6%, efficiency being low at high temperature. The temperature difference between the back surface of the cell and solar cell is about 1 to 5°C. The overall thermal and exergy efficiency variation is shown in Figure 4. The overall exergy efficiency is found to vary from 12.89 to 15.53%, while overall energy efficiency ranges from 51.74 to 60.61%. Calculations made for a typical winter day in December indicated the overall exergy efficiency and overall energy efficiency in the range of 12.97 to 16.07%, and 55.30 to 61.66%, respectively. Better efficiency is realized in winter, due to efficacious use of thermal energy, reduced losses, and lower atmospheric temperature. However, the maximum temperature of the water is considerably reduced to 36 to 28°C in December. The water from the PVT collector has an average and maximum temperature of 63 and 76°C, respectively. An additional FPC increases the maximum water temperature to about 100°C, with an average temperature to the level of 84°C. A simple analysis of FPC alone showed that it can deliver hot water at a maximum of 80°C, with an average temperature of 67°C. If the maximum temperature of the water can be low, then the PVT collector and the FPC can be used independently, and the water generated from both of them can be either used separately or mixed before use. Such systems are expected to operate with higher efficiency. Monthly electrical energy produced in kWh is shown in Figure 5. It is in the range of about 2–4 kWh per day. The monthly variation of electrical, overall energy, and exergy efficiency of the present system is analyzed and found to have 10–12, 53–58, and 14–16%, respectively, which is in close agreement with the outcome of other related analyses (Dubey and Tiwari, 2009).

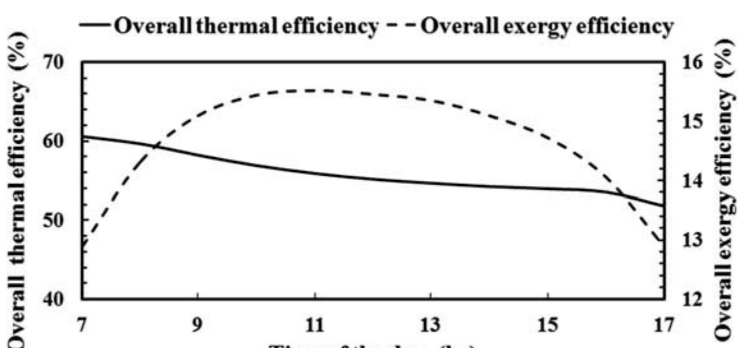

Figure 4. Hourly variations of overall thermal and overall exergy efficiency at $\dot{m} = 0.005kg/s$.

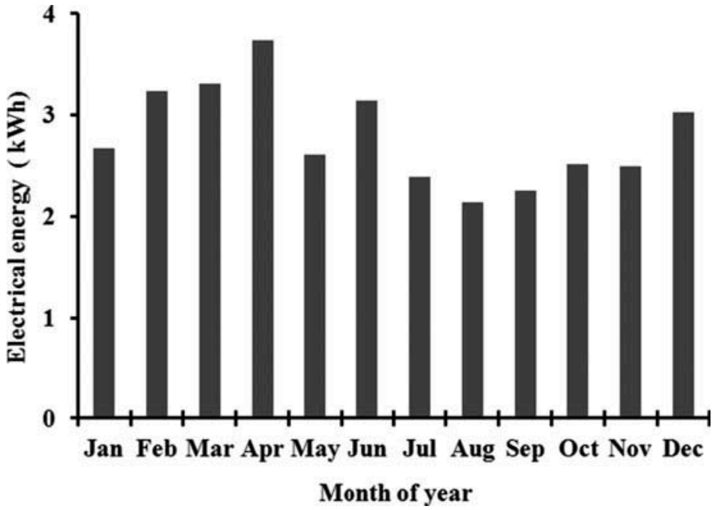

Figure 5. Month-wise electrical energy in kWh.

8. Conclusion

In this article, the analytical model of a photovoltaic thermal (PVT) solar water heating system has been formulated. The average value for overall electrical, thermal, and exergy efficiency of the proposed hybrid PVT system is 11, 63, and 15%, respectively. It has high reliability with an expected life span of 20 to 30 years and very low maintenance costs. The payback period obtained for the present system is about 5 years, depending on the unit cost of electricity. It can be easily integrated with the buildings to make it self-sustainable and such a system can be a preferable option for achieving goals of green buildings. The combined system of a photovoltaic thermal (PVT) solar water heater presented in this study is a self-sustainable system, suitable for standalone applications. This system can be installed at remote areas for fulfillment of hot water requirements and the electrical energy produced by this system can be utilized for other purposes. Moreover, it works noiselessly with no toxic residues or unwanted waste, such as radioactive materials.

Nomenclature

A area, m^2
c_w specific heat of water, J/kg K
F' collector efficiency factor
F_R collector heat removal factor
G solar insolation, W/m^2
h heat transfer coefficient, W/m^2 K
p penalty factor
K thermal conductivity, W/m K
L the length of PVT water collector, thickness, m
$\underline{m}$ mass flow rate of air, kg/s
Q rate of useful energy transfer, W
T temperature, K
U an overall loss coefficient, W/m^2 K

Subscripts

0 reference
1 due to the presence of solar cell material, glass, and EVA, from PVT
2 due to the presence of interface between Tedlar and working fluid, from FPC
b back loss coefficient from flowing water to ambient, W/m^2 K
bs back surface of Tedlar
c solar cell
f flat plate collector
pvt photovoltaic thermal
f ' fluid outlet from FPC/fluid inlet to PVT
i fluid in, inner
o fluid out, outer
L_1 from the FPC water collector to the environment
L_2 from the PVT water collector to the environment
t from solar cell to ambient through glass cover
tT from glass to Tedlar through solar cell
tf from glass to water through solar cell and Tedlar
tk water tank
T from solar cell to flowing water through Tedlar
u useful

Greek symbols

α absorptivity
(ατ) the product of effective absorptivity and transmittivity
β packing factor
η efficiency
τ transmittivity

References

Chow, T. T. 2010. A review on photovoltaic/thermal hybrid solar technology. *Appl. Energy* 87:365–379.
Dubey, S., and Tiwari, G. N. 2009. Analysis of PV/T flat plate water collectors connected in series. *Sol. Energy* 83:1485–1498.
Dubey, S., and Tiwari, G. N. 2010. Energy and exergy analysis of hybrid photovoltaic/thermal solar water heater considering with and without withdrawal from tank. *J. Renewable Sustainable Energy* 2:043106.
Gang, P., Fu, H., Zhang, T., and Ji, J. 2011. A numerical and experimental study on a heat pipe PV/T system. *Sol. Energy* 85:911–921.
Hasan, M. A., and Sumathy, K. 2010. Photovoltaic thermal module concepts and their performance analysis: A review. *Renewable Sustainable Energy Rev.* 14:1845–1859.
Ibrahim, A., Othman, M. Y., Ruslan, M. H., Mat, S., and Sopian, K. 2011. Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors. *Renewable Sustainable Energy Rev.* 15:352–365.
Ji, J., Lu, J. P., Chow, T. T., He, W., and Pei, G. 2007. A sensitivity study of a hybrid photovoltaic/thermal water-heating system with natural circulation. *Appl. Energy* 84:222–237.
Joshi, A. S., and Tiwari, A. 2007. Energy and exergy efficiencies of a hybrid photovoltaic–thermal (PV/T) air collector. *Renewable Energy* 32:2223–2241.
Kalogirou, S. A., and Tripanagnostopoulos, Y. 2006. Hybrid PV/T solar systems for domestic hot water and electricity production. *Energy Convers. Manage.* 47:3368–3382.
Kumar, R., and Rosen, M. A. 2010. Thermal performance of integrated collector storage solar water heater with corrugated absorber surface. *Appl. Therm. Eng.* 30:1764–1768.
Mani, A. 1981. *Handbook of Solar Radiation Data for India*. New Delhi, India: Allied Publishers.
Prakash, R., and Bansal, N. K. 1995. Energy analysis of solar photovoltaic module production in India. *Energy Sources* 17:605–613.

Sarhaddi, F., Farahat, S., Ajam, H., and Behzadmehr, A. 2010. Exergetic performance assessment of a solar photovoltaic thermal (PV/T) air collector. *Energy Build*. 42:2184–2199.

Tiwari, A., Dubey, S., Sandhu, G. S., Sodha, M. S., and Anwar, S. I. 2009. Exergy analysis of integrated photovoltaic thermal solar water heater under constant flow rate and constant collection temperature modes. *Appl. Energy* 86:2592–2597.

Zhang, X., Zhao, X., Smith, S., Xu, J., and Yu, X. 2011. Review of R&D progress and practical application of the solar photovoltaic/thermal (PV/T) technologies. *Renewable Sustainable Energy Rev*. 16:599–617.

Zondag, H. A. 2008. Flat-plate PV–thermal collectors and systems: A review. *Renewable Sustainable Energy Rev*. 12:891–959.