*Available online at www.elixirpublishers.com (Elixir International Journal)*

**Agriculture**

*Elixir Agriculture 47 (2012) 8999-9004*

ISSN: 2229-712X

# A Technical study on hybrid photovoltaic/thermal solar collectors

Mohammad Jafar Dalvand*, Seyed Saeid Mohtasebi and Shahin Rafiee
Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology, University of Tehran, Karaj, Iran.

**ARTICLE INFO**

**Article history:**
Received: 15 June 2012;
Received in revised form:
16 June 2012;
Accepted: 19 June 2012;

**Keywords**
Efficiency,
Photovoltaic/thermal technology,
Water,
Air,
Electricity.

**ABSTRACT**

Significant amounts of research and development work on Photovoltaic solar cells generate electricity by receiving sun light or solar irradiance. But solar cell received heat from solar irradiance as well and this will reduced the efficiency of the solar cell so the solution for this was by adding a cooling system (air or water) to the photovoltaic panel. Photovoltaic/thermal technology has been done. Many innovative systems and products have been introduced while evaluated product's quality by academics and professionals. Some theoretical models also offered that experimental data have been validated their appropriateness. Important parameters in designing have known. Purpose of this paper is give review of trend to development photovoltaic/ thermal technology.

## 1. Introduction

Of all the renewable sources of energy available, solar thermal energy is the most abundant one and is available in both direct as well as indirect forms. The thermal energy has wider applications in the human's life. It can be generally utilized in the form of either low grade (low temperature) or high grade (high temperature) (Thirugnanasambandam et al., 2010).

The temperature profiles of the photovoltaic (PV) module in a non-steady state condition with respect to time have studied (Jones and Underwood, 2001). The overall electrical efficiency of the PV module can be increased by increasing the packing factor (PF) and reducing the temperature of the PV module by using the thermal energy associated with the PV module (Chow, 2003). Efficiency of solar cell will drop when the temperature of it increases. The efficiency of the system will lose about 0.3% when cells temperature increased by 1°C (Kemmoku et al, 2004). A photovoltaic/thermal hybrid solar system (or PVT system for simplicity) is a combination of photovoltaic (PV) and solar thermal components/systems which produce both electricity and heat from one integrated component or system. In other words, PV is used as (part of) the thermal absorber (Anonymous, 2006). The carrier of thermal energy associated with the PV module may be either air or water. Once thermal energy withdrawal is integrated with the photovoltaic (PV) module, it is referred as hybrid PV/T system so Photovoltaic–thermal (PV/T) technology refers to the integration of a PV module and conventional solar thermal collector in a single piece of equipment. The rationale behind the hybrid concept is that a solar cell converts solar radiation to electrical energy with peak efficiency in the range of 9–12%, depending on specific solar-cell type and thermal energy through water heating. More than 80% of the solar radiation falling on photovoltaic (PV) cells is not converted to electricity, but either reflected or converted to thermal energy (Chow, 2010). In view of this, hybrid photovoltaic and thermal (PV/T) collectors are introduced to simultaneously generate electricity and thermal power (Ji, 2007).

## 2. Basic concepts

A solar cell has its threshold photon energy corresponding to the particular energy band gap below which electricity conversion does not take place. Photons of longer wavelength do not generate electron–hole pairs but only dissipate their energy as heat in the cell. This may lead to extreme cell working temperature as much as 50 °C above the ambient environment. There can be two undesirable consequences (Chow, 2010):

a) A drop in cell efficiency (typically 0.4% per °C rise for c-Si cells)

b) A permanent structural damage of the module if the thermal stress remains for prolonged period.

Numerous correlations expressing cell temperature and efficiency as functions of the pertinent weather variables and cell working conditions are summarized by Skoplaki and Palyvos (Skoplaki and Palyvos, 2009a). By cooling the solar cells with a fluid stream like air or water, the electricity yield can be improved. But conceptually the better design is to re-use the heat energy extracted by the coolant. These are the incentives leading to the evolvement of PVT hybrid solar technology.

## 3. Flat-Plate PV/T collector

Since the first hybrid collector being studied, variety of studies about the PV/T system has been carried out throughout the world. The studied mostly focusing on the air and water based as the medium to the heat transfer (Skoplaki and Palyvos, 2009b; Tripanagnostopoulos et al., 2002; Ibrahim et al., 2009). Amongst the PV/T solar collectors that being studied, the most popular is the air type solar collector with photovoltaic module, even though it is most popular, this type of collector has less in usage compared to the water collectors (Niccolo and Giancarlo, 2007).Theoretical and experimental studies of PVT were documented as early as in mid 1970s. Florschuetz (1975), Kern and Russell (1978) and Wolf (1976) on different occasions presented the key concept and the data with the use of either water or air as the coolant (i.e. the PVT/a and PVT/w systems in

**Tele:**
**E-mail addresses: Dalvand@ut.ac.ir**

abbreviation). The technical validity was soon concluded. The research works that followed were mainly on flat-plate collectors Lalovic (1986). The work Hamdy et al. (1988) included performance analysis on light concentrating PVT systems. Garg and Adhikari carried out detailed analytical and experimental studies on hybrid PVT air and liquid heating systems from late 1990s for about 10 years (Garg and Adhikari, 1997, 1998, 1999a, 1999b).

### 3.1. Analytic and numerical studies

Sopian et al. developed a steady–state model for comparing the performance of single- and double-pass PVT/a collectors; the better performance of the double-pass design was found attributed to the productive cooling of the solar cells and the reduction in front cover temperature. An experimental unit was introduced accordingly (Sopian et al., 2000). A numerical model of a wall-mounted hybrid photovoltaic/water-heating collector system was developed, and the simulation results indicated that the system operation at the optimum mass flow rate not only can improve the thermal performance of the system, but also can meet the PV cooling requirement so that a better electrical performance can also be achieved (Ji et al., 2006).

Zondag et al. developed a range of steady–state and dynamic simulation models for PVT/w energy performance analysis. These included 1-D, 2-D and 3-D models of a serpentine PVT/w collector and their accuracy was verified by experimental data. It was found that all these computational models are agreeable to the experimental results of the Eindhoven University of Technology within 5%, but the use of 2-D and 3-D models is possible to generate detailed performance data for design improvement (Zondag et al., 2002). Sandnes and Rekstad investigated the energy performance of a PVT/w collector with c-Si solar cells (either with or without front cover) pasted on polymer thermal absorber. The opposite surface was in black color (absorption coefficient = 0.94 for normal incidence) which allows its serving as a solar thermal collector when turned up-side-down. Square-shape box-type absorber channels were filled with ceramic granulates. This improves heat transfer to flowing water. The analysis showed that the presence of solar cells reduces the heat absorption by about 10% of the incident radiation, and the glass cover (if exists) reduces the optical efficiency by around 5%. Its application to low-temperature water-heating system is promising (Sandnes and Rekstad, 2002). Chow developed an explicit dynamic model, based on control volume finite difference approach for a single glazed PV/T collector. The model can generate results for hourly performance analysis, including instantaneous thermal / electrical gains and efficiencies. It was found that the maximum combined efficiency of a perfect collector can be over 70% and can decrease to less than 60% for a low quality collector (Chow, 2003).

### 3.2. Simulation and modeling studies

Using the TRNSYS program, Kalogirou modeled a pump operated domestic PVT/w system complete with water tank, power storage and conversion, and temperature differential control (Kalogirou, 2001). Later on, Kalogirou and Tripanagnostopoulos further examined domestic PVT/w applications working with either thermosyphon or pump circulation modes (Kalogirou and Tripanagnostopoulos, 2006) . Rockendorf et al. constructed prototypes of thermoelectric collector (first generating heat and subsequently electricity) and PVT/w collector (with solar cells on aluminum-absorber and copper-tubing combination); the TRNSYS simulation results showed that the electrical output of the PVT/w collector is significantly higher than that of the thermoelectric collector (Rockendorf et al., 1999). Hegazy performed an extensive investigation of the thermal, electrical, hydraulic and overall performance of four types of flat-plate PVT/a collectors. These included: channel above PV as Mode 1, channel-below PV as Mode 2, PV between single- pass channels as Mode 3 and finally the double-pass design as Mode 4. The numerical analysis showed that while Mode 1 has the lowest performance, the other three have comparable energy yields. In addition, Mode 3 consumes the least fan power (Hegazy, 2000).

### 3.3. Experimental studies

Tripanagnostopoulos et al. conducted outdoors tests on PVT/a and PVT/w collectors of different design configurations for wall-mounted applications. They found that PVT/a collectors are around 5% higher in production costs than the PV modules. This would be around 8% for PVT/w collectors with pc-Si cells, and around 10% when the entire system costs were considered (Tripanagnostopoulos et al., 2002). Experimental tests on PVT/w systems in Riyadh (at 24.6°N), Saudi Arabia showed that the high ambient temperature in summer could lead to 30% drop in PV efficiency, though the thermal efficiency remains good. In winter time the PV modules show improved performance yet the thermal side performance deteriorates (Harbi et al., 1998). Dubey and Tiwari examined the performance of a self-sustained single-glazed PVT/w collector system with a partial coverage of PV module (packing factor = 0.25) in New Delhi (Dubey and Tiwari, 2008). The electricity generated from the PV module positioned at the water inlet end was used to drive a DC circulation pump. The application in the industry of PV/T systems with water heat extraction was presented. The system consisted of 300 $m^2$ of hybrid PV/T collectors producing both electricity and thermal energy and a 10 $m^3$ water storage tank, and the results indicated that the electrical production of the system was more than the amorphous ones but the solar thermal contribution was slightly lower (Kalogirou and Tripanagnostopoulos, 2007). An experimental study of a centralized photovoltaic and hot water collector wall system was carried out, and different operating modes were performed with measurements in different seasons. The results showed that natural water circulation was more preferable than forced circulation in this hybrid solar collector system, and the thermal efficiency was 38.9% at zero reduced temperature and the corresponding electricity conversion efficiency was 8.56% during the late summer of Hong Kong (Chow et al., 2007a). The experimental model of a PV/thermal hybrid system with bifacial PV module was constructed and studied, and the overall solar energy utilization efficiency for the system was about 60% with an electric efficiency of 16.4% (Robles-Ocampo et al., 2007).

## 4. Building integration installation PVT (BiPVT)

Compared to the development of BiPVT/a systems, the research works on BiPVT/w systems have been less popular (Charalambous et al., 2004). Chow et al. studied a BiPVT/w system applicable to multistory apartment building in Hong Kong for water pre-heating purpose. The a-Si PVT collector arrays covered two-third of the west- and south-facing external facades, giving a solar fraction of 34%. A portion of the electricity generation was used to support the two independent sets of circulating pumps which are operating at optimized flow rate. The net thermal efficiency was found around 30% and cell efficiency around 5.4% (Chow et al, 2005). Later on, Chow et al. constructed an experimental BiPVT/w system at a roof-top environmental chamber. The modular box-structure PVT/w collectors were mounted on a SW-facing facade. The energy efficiencies of thermosyphon and pump circulation modes were compared across the subtropical summer and winter periods. The results show the better energy performance of the thermosyphon operation, with thermal efficiency reaches 39% at zero reduced temperature and the corresponding cell efficiency 8.6%. Compared with the bare facade, the interior surface temperature of the PVT/w wall fluctuates with much smaller amplitude. The space cooling load is reduced by 50% in peak summer (Chow et al., 2007b). The performance of a novel building integrated photovoltaic/thermal (BiPVT) solar collector was theoretically and experimentally studied, and the results showed that key design parameters such as the fin efficiency, the thermal conductivity between the PV cells and their supporting structure, and the lamination method had a significant influence on both the electrical and thermal efficiency of the BIPVT (Anderson et al., 2009).

Ibrahim et al. have conducted some experiment to investigate effect of water and air mass flow rate on electrical, thermal and combined photovoltaic thermal efficiencies in BiPVT. They have been structured collector in to configuration:

a) spiral flow absorber collector(Fig. 1)

b) Single pass rectangular tunnel absorber collector (Fig. 2)

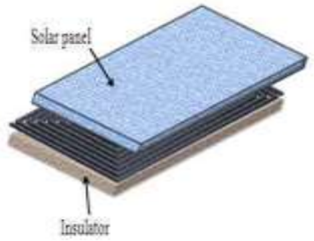

**Fig. 1**: The perspective view of Spiral flow rectangular absorber tunnel Col

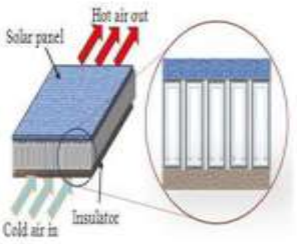

**Fig. 2**: The design of Single pass absorber

The experiment results showed that the single flow absorber collector generates combined PV/T efficiency of 64%, electrical efficiency of 11% and power maximum achieved at 25.35 W (Ibrahim et al., 2009). Single pass rectangular tunnel absorber collector generated combined PV/T efficiency of 55%, electrical efficiency of 10% and maximum power of 22.45 W. The best mass flow rate achieved for spiral flow absorber collector is 0.011 kg sec-1 at surface temperature of 55% and 0.0754 kg sec-1 at surface temperature of 39°C for single pass rectangular collector absorber (Jin et al., 2010).

In Australia, the design of a roof-mounted BiPVT/w system was theoretically analyzed by Anderson et al. (Anderson et al., 2009). Their prototype BiPVT/w collector was integrated to the standing seam or toughed sheet roof, on which passageways were added to the trough for liquid coolant flow. Their modified Hottel–Whillier model was validated by a steady–state outdoor thermal test rig. The results showed that the key design parameters like fin efficiency, lamination requirements, as well as thermal conductivity between the PV module and the supporting structure, affect significantly the electrical and thermal efficiencies.

## 5. PVT integrated heat pump (PVT/heat pump)

Fang et al. have been done an experimental study on operation performance of photovoltaic–thermal solar heat pump air-conditioning system. The experimental results show that the mean photovoltaic efficiency of photovoltaic–thermal (PV/T) solar heat pump air-conditioning system reaches 10.4%, and can improve 23.8% in comparison with that of the conventional photovoltaic module, the mean COP of heat pump air-conditioning system may attain 2.88 and the water temperature in water heater can increase to 42 °C. Except the PV/T collectors with air or water as the working fluid, the PV/T collector with refrigerant as the working fluid can be coupled with a solar assisted heat pump. The cooling effect of the refrigerant allows the PV modules to work at lower temperature and so its photovoltaic efficiency may be improved (Fang et al., 2010). The performance of photovoltaic solar assisted heat pump system was experimentally studied, and the results showed that this system had a superior coefficient of performance than the conventional heat pump system and the photovoltaic efficiency was also higher (Ji et al., 2008). The photovoltaic solar assisted heat pump (PV-SAHP) with variable-frequency compressor was presented and the mathematical models were developed to evaluate the energy performance of the combined system. The results indicated that the average COP could reach 6.01, and the average electricity efficiency, thermal efficiency and overall efficiency were 0.135, 0.479 and 0.625 respectively (Liu et al., 2009).

In the above studies of flat-plate collectors, the calculated thermal efficiency of PVT/liquid systems are generally in the range of 45–70% for unglazed to glazed panel designs. For PVT/a systems, the thermal efficiencies can be up to 55% for optimized collector design (Liu et al., 2009).

## 6. Concentrator-type PVT (c-PVT)

The use of concentrator-type PVT (or c-PVT) instead of flat-plate type is able to increase the radiation intensity on the solar cells. This approach is promising due to the significantly lower cost of the reflectors relative to the solar cells. Higher efficiency solar cells that handle higher current can be used though they are more expensive than the flat-plate module cells. Additional costs may also go to the complex sun tracking driving mechanism (Segal et al., 2004). Cell efficiency decreases when non-uniform temperature across the cell exists. Series connections of cells increase the output voltage and decrease the current at a given power output, thus reducing the ohmic losses. Concentrators with the use of lenses or reflectors can be generally grouped into three categories: single cells, linear geometry, and densely packed modules. For highly concentrating systems, more concentrator material per unit cell/absorber area is needed. The use of lenses is then more appropriate than reflectors owing to their lower weight and material costs. However, concentrator systems that utilize lenses are unable to focus scattered light, and this limits their usage at places largely with clear weather. On the other hand, using ‘‘liquid” as the coolant is more effective than using ‘‘air” to obtain better electrical output. For these reasons, reflector-type c-PVT systems are common for medium- to high-temperature hot water systems applicable for cooling, desalination, or other industrial processes. At lower operating temperatures, a flat-plate solar collector may give a higher efficiency than the concentrator-type collector when both are directly facing the sun (Kribus et al., 2006). They developed a miniature concentrating PV system that can be installed on any rooftop. By concentrating sunlight about 500 times, the solar cell area is greatly reduced. The design is based on a small parabolic dish which is similar to a satellite dish and is relatively easy to deliver and handle without the use of special tools (Kribus et al., 2006).

## 7. Parameters (factors) affecting PV/T performance

A number of parameters have been identified to affect PV/T performance. These include mass flow rate, inlet temperature of working fluid, number of covers, absorber to fluid thermal conductance and absorber plate design parameters such as tube spacing, tube diameter and fin thickness (Charalambous et al., 2004). An analysis of these parameters follows:

### 7.1. Covered and uncovered PV/T collector

Sandnes and Rekstad explained that the effect of adding a glass cover to the PV/T collector is to reduce the heat losses to the surroundings. However, the energy absorptance is also reduced by reflection (around 10%) from the glass. They found that the simulated total electrical energy output over a day for the plain PV module was 306.9 Wh, for the PV/T without glass cover was 339.3 Wh and for the PV/T with glass cover was 296.2 Wh (Sandnes and Rekstad, 2002).

The exergy analysis performed by Fujisawa and Tani indicated that the exergy output density of the uncovered design is slightly higher than the single-covered design, taking the fact that the thermal energy contains much unavailable energy (Fujisawa and Tani, 1997).

### 7.2. Mass flow rate

Chow showed that as mass flow rate in the tube increases from 0.002 to 0.016 kg/s, for a 2 $m^2$ PV/T collector area (i.e. 0.001 to 0.008 $kg/sm^2$), the thermal and electrical efficiencies also increase (Chow, 2003). Garg and Agarwal carried out simulations for different solar cell areas, mass flow rates and different water masses by solving the governing equations using an iterative finite difference method. The system was composed of a PV/T collector, storage tank, pump and differential control. The optimum flow rate was found to be 0.03 kg/s, for a 2 $m^2$ PV/T collector area (i.e. 0.015 $kg/sm^2$), for maximum thermal collector efficiency. However, electrical efficiency was found to decrease at 0.03 kg/s and was minimum when solar insolation was maximum (which is expected as at this time absorber temperature is maximum) (Garg and Adhikari, 1997). Morita et al. determined that maximum exergetic efficiencies for single cover (of 13.36%) and coverless (of 11.92%) PV/T collectors occur at optimum flow rates of 0.0014 and 0.0049 kg/s, respectively, for a PV/T collector area of 0.61 $m^2$ (i.e. 0.002 and 0.008 $kg/sm^2$, respectively) (Morita et al., 2000).

### 7.3. Absorber plate parameters

Bergene and Lovvik elaborated on the effect of tube spacing to tube diameter ratio (*W/D*). It was found that:

a) The thermal efficiency is approximately halved when *W/D* increases from 1 to 10, by keeping *W* constant. It was also emphasized that different results are expected when increasing *W* whilst keeping *D* constant.

b) The fact that the speed of cooling liquid increases when tube diameter is decreased does not compensate for losses from the fin.

c) Increasing *W/D* from 1 to 10, decreases outlet fluid temperature.

d) Even though electrical efficiency is not heavily affected by fin size, combined efficiency is largely dependent on fin size.

e) If thermal efficiency is of any importance, its dependence on the relative tube diameter should be weighed against the cost of the tubes (Bergene and Lovvik, 1995).

### 7.4. Absorber to fluid thermal conductance

Design approaches must be undertaken carefully since they may increase the pressure drop to unacceptably high values or increase costs for what may only be marginal improvements in performance (Charalambous, 2004). Chow refers to the two manufacturing defects found in PV/T collectors (imperfect adhesion between PV plate and absorber plate, imperfect bonding between absorber plate and tubes) and for a range of thermal conductances 10000 W/mK to 25 W/mK (perfect to defective), found that the maximum combined efficiency of a perfect collector can be over 70% and for a low quality collector, may decrease to less than 60% (Chow, 2003).

### 7.5. Design types

Zontag et al. compared the efficiency of seven different design types of PV/T collectors. They observed that:

a) All channel concepts have a substantially higher efficiency than sheet and tube due to the better heat transfer characteristics of channels.

b) In the case of free flow panel, evaporation strongly reduces the thermal efficiency and condensate on top of the glass causes additional reflection.

c) Since the sheet and tube design is the easiest to manufacture (and is only 2% less in efficiency), it is the most promising of the different design concepts examined (Zontag et al., 2003).

## 8. Summary

The performance of various PVT collector types had been studied theoretically, numerically and experimentally. In this article generally expressed that in the early work, the research efforts were on the fundamental theories, the consolidation of the conceptual ideas and the feasibility study on basic PVT collector design configurations.

The ideas of building-integrated design began to emerge and the demonstration projects made available for documentation. In the last decade however, the focus has been generally shifting towards the development of complimentary products, innovative systems, testing procedures, and design optimization. The numerical analyses become more comprehensive with the use of powerful analytical tools. There have been increased uses of explicit dynamic modeling approach. The evaluation has been extended to geographical comparison of year round performance based on typical weather data on one hand, and the second-law thermodynamic assessment on the other. There have been attentions on monitoring product robustness, system reliability, and environmental implications. After all, there exist no perfect rules in the correct use of PVT collector and/or system; all depend on the geographical location and actual application case by case. At locations with low levels of solar radiation and ambient temperatures, space heating is almost required all the year and PVT/a can be useful and cost effective. At locations with high solar input as well as ambient temperature, PVT/w can be useful for providing year round water pre-heating services, and on top with intermittent air heat extraction to provide space heating in winter and natural ventilation in summer. There are good opportunities for extension to solar cooling and heat pump integrations. Concentrator type can be used for elevating fluid service temperature from medium to high level. At this stage, the research and development work should be carried on, including thermal absorber design and fabrication, material and coating selection, energy conversion and effectiveness, performance testing, system optimization, control and reliability.

## References

Al Harbi Y, Eugenio NN, Al Zahrani S. Photovoltaic-thermal solar energy experiment in Saudi Arabia. Renewable Energy, 1998; 15: 483–6.

Anderson TN, Duke M, Morrison GL, Carson JK. Performance of a building integrated photovoltaic/thermal (BIPVT) solar collector. Solar Energy, 2009; 83: 445–455.

Anonymous. PVT Roadmap – a European guide for the development and market introduction of PV-thermal technology; 2006. Available from: <http://www.pvtforum.org/index.html>.

Bergene T, Lovvik OM. Model calculations on a flat plate solar heat collector with integrated solar cells. Solar Energy, 1995; 55: 453-462.

Charalambous PG, Kalogirou SA, Maidment G, Karayiannis TG, 3rd International Conference on Heat Powered Cycles; 2004; Cyprus, Greek.

Chow TT. Performance analysis of photovoltaic-thermal collector by explicit dynamic model. Solar Energy, 2003; 75: 143-152.

Chow TT. A review on photovoltaic/thermal hybrid solar technology. Applied Energy, 2010; 87: 365–379.

Chow TT, Chan ALS, Fong KF, Lo WC, Song CL. Energy performance of a solar hybrid collector system in multi-story apartment building. Power Energy, 2005; 219: 1–11.

Chow TT, He W, Ji J. An experimental study of facade-integrated photovoltaic/water-heating system. Applied Thermal Enegy, 2007a; 27: 37–45.

Chow TT, He W, Ji J. An experimental study of façade-integrated photovoltaic/water-heating system. Applied Thermal Energy, 2007b; 27: 37–45.

Dubey S, Tiwari GN. Thermal modeling of a combined system of photovoltaic thermal (PV/T) solar water heater. Solar Energy, 2008; 82: 602–12.

Fang G, Hu H, Liu X. Experimental investigation on the photovoltaic–thermal solar heat pump air-conditioning system on water-heating mode. Experimental Thermal and Fluid Science, 2010; 34: 736–743.

Florschuetz LW. On heat rejection from terrestrial solar cell arrays with sunlight concentration. In: Proceedings of the 11th IEEE PVSC conference; 1975; New York, USA.

Fujisawa T, Tani T. Annual exergy evaluation on photovoltaic-thermal hybrid Collector. Solar Energy Material and Solar Cells, 1997; 47: 135–48.

Garg HP, Adhikari RS. Conventional hybrid photovoltaic/thermal (PV/T) air heating collectors: steady-state simulation. Renewable Energy, 1997; 11: 363–85.

Garg HP, Adhikari RS. Transient simulation of conventional hybrid photovoltaic/ thermal (PV/T) air heating collectors. International Journal Energy Research, 1998; 22: 547–62.

Garg HP, Adhikari RS. Performance analysis of a hybrid photovoltaic/thermal (PV/T) collector with integrated CPC troughs. International Journal Energy Research, 1999a; 23: 1295–304.

Garg HP, Adhikari RS. System performance studies on a photovoltaic/ thermal (PV/T) air heating collector. Renewable Energy, 1999b; 16: 725–30.

Hamdy MA, Luttmann F, Osborn D. Model of a spectrally selective decoupled photovoltaic/thermal concentrating system. Applied Energy, 1988; 30: 209–25.

Hegazy AA. Comparative study of the performances of four photovoltaic/ thermal solar air collectors. Energy Conversation Manage, 2000; 41: 861–81.

Ibrahim A, Othman MY, Ruslan MH, Alghoul MA, Yahya M, Zaharim A, Sopian K. Performance of photovoltaic thermal collector (PVT) with different absorbers design. WSEAS Transactions on Environment & Development, 2009; 5: 321-330.

Ji J, Han J, Chow TT, Yi H, Lu JP, He W, Sun W. Effect of fluid flow and packing factor on energy performance of a wall-mounted hybrid photovoltaic/ water heating collector system. Energy and Buildings, 2006; 38: 1380–1387.

Ji J, Lu JP, Chow TT, He W, Pei G. A sensitivity study of a hybrid photovoltaic/thermal water-heating system with natural circulation. Applied Energy, 2007; 84: 222-237.

Ji J, Pei G, Chow TT, Liu KL, He HF, Lu JP, Han CW. Experimental study of photovoltaic solar assisted heat pump system, Solar Energy, 2008; 82: 43–52.

Jin GL, Ibrahim A, Chean YK, Daghigh R, Ruslan H, Mat S, Othman MY, Sopian K. Evaluation of Single-Pass Photovoltaic-Thermal Air Collector with Rectangle Tunnel Absorber. American Journal of Applied Sciences, 2010; 7: 277-282.

Jones AD, Underwood CP. A thermal model for photovoltaic systems. Solar Energy, 2001; 70: 349-359.

Kalogirou SA. Use of TRNSYS for modeling and simulation of a hybrid PV thermal solar system for Cyprus. Renewable Energy, 2001; 23: 247–60.

Kalogirou SA, Tripanagnostopoulos Y. Industrial application of PV/T solar energy systems. Applied Thermal Energy, 2007; 27: 1259–1270.

Kalogirou SA, Tripanagnostopoulos Y. Hybrid PV/T solar systems for domestic hot water and electricity production. Energy Conversation Manage, 2006; 47: 3368–82.

Kemmoku Y, Egami T, Hiramatsu M, Miyazaki Y, Araki K. Modelling of module temperature of a concentrator PV system. 2004;

http://www.physics.usyd.edu.au/app/solar/research/Syracuse/pdf /19thEUPVSEC_5BV-2 40.pdf / .

Kern JEC, Russell MC. Combined photovoltaic and thermal hybrid collector systems. In: Proceedings of the 13th IEEE photovoltaic specialists; 1978; Washington DC, USA.

Kribus A, Kaftori D, Mittelman G, Hirshfeld A, Flitsanov Y, Dayan A. A miniature concentrating photovoltaic and thermal system. Journal Energy Conversation Manage, 2006; 47: 3582–90.

Lalovic B. A hybrid amorphous silicon photovoltaic and thermal solar collector. Solar Cells, 1987; 19: 131–8.

Liu KL, Ji J, Chow TT, Pei G, He HF, Jiang AG, Yang JC. Performance study of a photovoltaic solar assisted heat pump with variable-frequency compressor – a case study in Tibet. Renewable Energy, 2009; 34: 2680–2687.

Morita Y, Fujisawa T, Tani T. Moment performance of photovoltaic/thermal hybrid panel (Numerical analysis and exergetic evaluation). Electrical Engineering in Japan, 2000; 13: 381-87.

Niccolo A, Giancarlo C, Francesco V. Design, development and performance monitoring of a Photovoltaic-Thermal (PVT) air collector. Renewable Energy, 2007; 10: 6-22.

Robles-Ocampo B, Ruiz-Vasquez B, Canseco-Sanchez H, Cornejo-Meza RC, Trapaga-Martinez G, Garcia-Rodriguez FJ, Gonzalez-Hernandez J, Vorobiev YV. Photovoltaic/thermal solar hybrid system with bifacial PV module and transparent plane collector. Solar Energy Materials & Solar Cells, 2007; 91: 1966–1971.

Rockendorf G, Sillmann R, Podlowski L, Litzenburger B. PV-hybrid and thermoelectric collectors. Solar Energy, 1999; 67: 227–37.

Sandnes B, Rekstad J. A photovoltaic/thermal (PV/T) collector with a polymer absorber plate: experimental study and analytic model. Solar Energy, 2002; 72: 63–73.

Segal A, Epstein M, Yogev A. Hybrid concentrated photovoltaic and thermal power conversion at different spectral bands. Solar Energy, 2004; 76: 591–601.

Skoplaki E, Palyvos JA. On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. Solar Energy, 2009; 83: 614 24.

Skoplaki E, Palyvos JA. Operating temperature of photovoltaic modules: a survey of pertinent correlations. Renewable Energy, 2009; 34: 23–9.

Sopian K, Liu HY, Kakac S, Veziroglu TN. Performance of a double pass photovoltaic thermal solar collector suitable for solar drying systems. Energy Conversation Manage, 2000; 41: 353–65.

Thirugnanasambandam M, Iniyan S, Goic R. A review of solar thermal technologies. Renewable and Sustainable Energy Reviews, 2010; 14: 312–322.

Tripanagnostopoulos Y, Nousia T, Souliotis M, Yianoulis P. Hybrid photovoltaic/ thermal solar systems. Solar Energy, 2002; 72:217-234.

Wolf M. Performance analysis of combined heating and photovoltaic power systems for residences. Energy Conversation, 1976; 16: 79–90.

Zondag HA, De Vries DW, Van Helden WGJ, Van Zolingen RJC, Van Steenhoven AA. The yield of different combined PV-thermal collector designs. Solar Energy, 2003; 74: 253-269.

Zondag HA, De Vries DW, Van Helden WGJ, Van Zolingen RJC, Van Steenhoven AA. The thermal and electrical yield of a PV-thermal collector. Solar Energy, 2002; 72: 113–28.