

DESIGN AND PERFORMANCE OF HYBRID PV/T SOLAR WATER HEATERS

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ABSTRACT

The hybrid Photovoltaic/Thermal (PV/T) solar systems can simultaneously provide electricity and heat, achieving a higher conversion rate of the absorbed solar radiation than standard PV modules. When properly designed PV/T systems can extract heat from PV modules, heating water or air, aiming to reduce the operating temperature of PV modules and to keep the electrical efficiency at a sufficient level. In this paper we present design considerations for the hybrid PV/T solar systems that are investigated at the University of Patras. The systems are analyzed with respect to their design, electrical and thermal energy output for the pc-Si and a-Si PV module types under the climatic conditions of Patras. In addition, the results from TRNSYS simulation carried out on similar PV/T type systems at the Higher Technical Institute in Nicosia are presented, giving guidelines for their application. The optimum water flow rate is found to be 25 lt/hr, which is low enough to enable the system to work in thermosyphon mode and the solar contribution is 49%.

INTRODUCTION

The temperature of PV modules increases by the absorbed solar radiation that is not converted into electricity causing a decrease in their efficiency. This undesirable effect can

be partially avoided by a proper heat extraction with a fluid circulation. In hybrid Photovoltaic/Thermal (PV/T) solar systems the reduction of PV module temperature can be combined with a useful fluid heating.

Therefore, hybrid PV/T systems can simultaneously provide electrical and thermal energy, achieving a higher energy conversion rate of the absorbed solar radiation. These systems consist of PV modules coupled to heat extraction devices, in which air or water of lower temperature than that of PV modules is heated whilst at the same time the PV module temperature is reduced.

PV cooling is considered necessary to keep electrical efficiency at a satisfactory level. Natural or forced air circulation are simple and low cost methods to remove heat from PV modules, but they are less effective if ambient air temperature is over 20°C. To overcome this effect the heat can be extracted by circulating water through a heat exchanger that is mounted at the rear surface of the PV module.

PV/T systems provide a higher energy output than standard PV modules and could be cost effective if the additional cost of the thermal unit is low. Air type PV/T systems are recently applied in buildings, usually integrated on their inclined roof or façade. By using these systems the electrical output of the PV is increased, while avoiding building overheating during summer and covering part of the building space heating needs during winter. The water type PV/T systems can be

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practical devices for water heating (mainly domestic hot water), but they are not improved enough yet for commercial applications.

The main concepts on hybrid PV/T systems have been presented in the works of Kern and Russel (1978), Hendrie (1979), Florschuetz (1979), Raghuraman (1981) and Cox and Raghuraman (1985). Lalovic *et al.* (1986) propose a low cost PV/T system with transparent type a-Si cells. Loferski *et al.* give results from building integrated PV/T systems (1988) and Bergene and Lovvik give a detailed analysis on liquid type PV/T systems (1995). Recently, Hausler and Rogash (2000) presented a latent heat storage PV/T system and Huang *et al.* (2001) presented an integrated PV/T system with hot water storage. Finally, Zondag *et al.* (2002) give results on dynamic 3D and steady state 3D, 2D and 1D models for PV/T prototypes with water heat extraction whereas Zondag *et al.* (2003) presented PV/T systems with alternative water circulation modes.

Design and performance improvements of hybrid PV/T systems with water or air as heat removal fluid, have been carried out at the Physics Department of the University of Patras, Greece. The investigated models include a number of modifications that contribute to the increase of thermal efficiency, to the decrease of PV module temperature and to the improvement of the total energy output of the PV/T system. Design concepts, prototype construction and test results for water and air cooled PV/T systems are included in Tripanagnostopoulos *et al.* (2002a), where PV/T systems with and without additional glass cover are presented. The study of the dual type PV/T system, operating either with water or air heat extraction is presented in (Tripanagnostopoulos *et al.*, 2001). Also, in Tripanagnostopoulos *et al.* (2003), the results from a life cycle analysis are presented where water cooled PV/T systems are compared with standard PV modules and give an idea about the environmental impact of the studied systems.

In the Mechanical Engineering Department of the Higher Technical Institute in Nicosia, Cyprus, an extensive study of solar energy applications, by using advanced simulation tools, has been performed. A part of this work refers to hybrid PV/T water heaters and is based on the use of TRNSYS program (Kalogirou, 2001). In this work a hybrid PV/T system was modeled and simulated for the environmental conditions of Cyprus, which are very similar to those of Patras. The system can satisfy the thermal and electrical requirements of a family of four persons. From the results presented it was shown that the mean annual electrical of the PV was increased considerably and the system can satisfy 50% of the thermal needs of the family.

In this paper we present basic design considerations for hybrid PV/T systems that were investigated at the University of Patras and can be applied in houses, multiflat residential buildings, hotels, etc, aiming to provide both electricity and hot water. The electrical and thermal efficiency of designed, constructed and tested prototype PV/T panels of polycrystalline silicon (pc-Si) and amorphous silicon (a-Si) PV modules are presented and performance results are given considering the weather conditions of Patras. Analysis of similar systems with TRNSYS simulation tools are also presented for applications in the weather conditions of Nicosia, giving some typical performance figures of the PV/T systems.

STUDY OF PV/T SOLAR SYSTEMS

Experimental PV/T models

Water heat extraction is more expensive than air, but water from mains usually remains under 20°C throughout the year in low latitude countries, which have high air temperatures during summer. Therefore, water heating is useful during all seasons for most applications. PV/T systems could be cost effective if the additional cost of the thermal unit is low and the extracted heat is effectively used. Regarding practical water

heat extraction, the water can circulate through pipes in contact with a flat sheet, placed in thermal contact with the rear surface of the PV module.

The increase of the electrical output of PV/T systems is of priority, as the cost of PV modules is much higher than that of the thermal unit. The different performance of the two subsystems regarding operation at high temperature, affects system life cycle cost benefits and thus optimised modifications for both electrical and thermal efficient operation are necessary.

In PV/T systems the thermal unit for water heat extraction, the necessary pump and the external pipes for fluid circulation constitute the complete system that extracts the heat from PV module and transfer it to the final use. Practical considerations in PV/T system design include the evaluation of the thermal and electrical efficiency improvement with respect to the system cost. It should be noted that the cost of the thermal unit remains the same irrespective of whether the PV module is made from c-Si, pc-Si or a-Si, but the ratio of the additional cost of the thermal unit per PV module cost is almost double in the case where a-Si modules are used rather than the crystalline silicon (c-Si) or pc-Si PV ones. In addition, a-Si PV modules present lower electrical efficiency, although the total energy output (electrical plus thermal) is almost equal to that of c-Si or pc-Si PV modules.

The hybrid PV/T systems consisting of PV modules without thermal protection of their illuminated surface to ambient, have high top thermal losses and therefore the operating temperature is not high. To increase the system operating temperature, an additional transparent cover is necessary (like the glazing of the typical solar thermal collectors), but this has as a result the decrease of the PV module electrical output from the additional absorption and reflection of the solar radiation.

In Fig.1 we show the cross section of the two basic PV/T module designs, one without glazing, PV/T UNGLAZED (or PV/T-

UNGL) and a second with the additional glazing PV/T GLAZED (or PV/T-GL). These systems use flat heat exchanger with pipes for the circulation of water and thermal insulation to avoid thermal losses from the non-illuminated system surfaces. We consider that these systems can be installed on the horizontal roof, on the inclined roof or on the façade of a building. The horizontal and the inclined roof installation is of more interest for low latitude countries, while the building façade installation is more effective for medium and high latitude applications because of the low sun altitude angles.

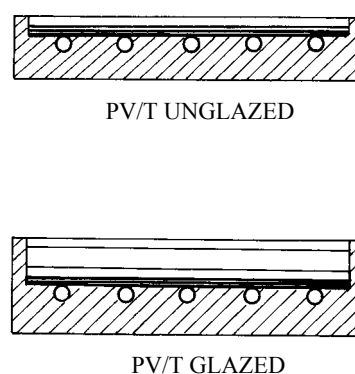


Figure 1 Cross section of the PV/T experimental models

The PV/T systems were constructed at the University of Patras and the experimental models consisted of pc-Si and a-Si PV modules in combination with water heat extraction units made by copper sheet and pipes, thermally protected with 5 cm polyurethane thermal insulation. The two PV/T model types that were considered for installation in parallel rows on horizontal building roof are the PV/T-UNGL(HOR) and the PV/T-GL(HOR) and were tested with slope equal to the latitude of Patras (38.25°). The experimental models that simulated the systems for the inclined roof installation, with same building roof slope (38.25°), consisted of the same basic system units (PV/T-UNGL and PV/T-GL) with additional external thermal insulation of 5 cm on their rear system surface (total thermal insulation 10 cm), named PV/T-UNGL(INCL) and PV/T-GL(INCL).

Test results of the PV/T models

The study of the hybrid PV/T water systems includes outdoor tests for the determination of the steady state thermal efficiency η_{th} and the electrical efficiency η_{el} . Two experimental models are produced a pc-Si/T and a a-Si/T, corresponding to the use of pc-Si and a-Si PV modules respectively. The thermal efficiency of the experimental PV/T models is determined as a function of the global solar radiation (G), the input fluid temperature (T_{in}) and the ambient temperature (T_a). The electrical efficiency of the PV/T systems is determined for all PV module types as a function of the operating temperature $T_{PV/T}$.

During the testing for the determination of system thermal efficiency, the PV modules were connected with load to simulate real system operation and to avoid PV module overheating by the solar radiation that is converted into heat instead of electricity. The steady state efficiency is calculated by:

$$\eta_{th} = \dot{m} C_p (T_o - T_i) / G A_a, \quad (1)$$

where \dot{m} is the fluid mass flow rate, C_p the fluid specific heat, T_i and T_o the input and output fluid temperatures and A_a the aperture area of the PV/T model. The thermal efficiency η_{th} of PV/T systems is calculated as a function of the ratio $\Delta T/G$ where $\Delta T = T_i - T_a$, with T_a being the ambient temperature. The electrical efficiency η_{el} depends mainly on the incoming solar radiation and the PV module temperature (T_{PV}) and is calculated by:

$$\eta_{el} = I_m V_m / G A_a \quad (2)$$

where I_m and V_m the current and the voltage of PV module operating at maximum power.

The electrical efficiency of the PV cells depends on the incoming solar radiation and their operating temperature. The formula that can be used for the calculation of PV module temperature is a function of the ambient temperature T_a and the incoming solar radiation G and is given by (Lasnier and Ang, 1990):

$$T_{PV} = 30 + 0.0175(G - 300) + 1.14(T_a - 25) \quad (3)$$

This relation is used for standard pc-Si PV modules. In PV/T systems the PV temperature depends also on the system operating conditions, such as the heat extraction fluid mean temperature. In PV/T systems, the PV electrical efficiency η_{el} can be function of a parameter $(T_{PV})_{eff}$, which corresponds to the PV temperature for the operating conditions of the PV/T systems. Thus, for the PV/T systems that were considered for horizontal roof installation (HOR) we used the effective value $(T_{PV})_{eff}$ calculated by the formula:

$$(T_{PV})_{eff} = T_{PV} + (T_{PV/T} - T_a) \quad (4)$$

The operating temperature $T_{PV/T}$ of the PV/T system corresponds to the PV module and to the thermal unit temperatures and can be determined approximately by the mean fluid temperature. We can consider several operating temperature levels, but in this work we present the results for the most useful operating temperature: $T_{PV/T} = 45^\circ\text{C}$. For the inclined building roof pc-Si PV/T system installation (INCL), the calculation of the $(T_{PV})_{eff}$ can be done again by eq (4), by using the value of T_{PV} derived from:

$$T_{PV} = 30 + 0.0175(G - 150) + 1.14(T_a - 15) \quad (5)$$

This modified formula was experimentally validated and corresponds to the increase of PV operating temperature due to the reduced heat losses to the ambient from the PV/T system. For the a-Si PV modules, their lower electrical efficiency results to slightly higher PV module temperature as compared to pc-Si PV modules. For this purpose the following formulas, also validated by experiments were used:

Horizontal roof installation (HOR):

$$T_{PV} = 30 + 0.0175(G - 150) + 1.14(T_a - 25) \quad (6)$$

Inclined roof installation (INCL):

$$T_{PV} = 30 + 0.0175(G - 100) + 1.14(T_a - 15) \quad (7)$$

In this study we also compare the PV/T models with standard pc-Si and a-Si PV modules. The experimentally determined steady state electrical efficiency for these PV modules is:

$$\text{pc-Si/PV: } \eta_{el} = 0.1659 - 0.00094 T_{PV} \quad (8)$$

$$\text{a-Si/PV: } \eta_{el} = 0.0601 - 0.00011 T_{PV} \quad (9)$$

In equations (8) and (9) the parameter T_{PV} is calculated from eqs (3) and (5) for pc-Si and from eqs (6) and (7) for a-Si PV modules, for the two installation modes respectively. The results from the tests performed on all PV/T systems regarding their thermal and electrical efficiency are the following:

pc-Si/T-UNGL(HOR):

$$\begin{aligned} \eta_{th} &= 0.55 - 11.99 (\Delta T/G) \\ \eta_{el} &= 0.1659 - 0.00094 (T_{PV})_{eff} \end{aligned}$$

a-Si/T-UNGL(HOR):

$$\begin{aligned} \eta_{th} &= 0.60 - 12.02 (\Delta T/G) \\ \eta_{el} &= 0.0601 - 0.00011 (T_{PV})_{eff} \end{aligned}$$

pc-Si/T-GL(HOR):

$$\begin{aligned} \eta_{th} &= 0.71 - 09.04 (\Delta T/G) \\ \eta_{el} &= 0.1457 - 0.00094 (T_{PV})_{eff} \end{aligned}$$

a-Si/T-GL(HOR):

$$\begin{aligned} \eta_{th} &= 0.75 - 08.83 (\Delta T/G) \\ \eta_{el} &= 0.0485 - 0.00011 (T_{PV})_{eff} \end{aligned}$$

pc-Si/T-UNGL(INCL):

$$\begin{aligned} \eta_{th} &= 0.54 - 10.77 (\Delta T/G) \\ \eta_{el} &= 0.1659 - 0.00094 (T_{PV})_{eff} \end{aligned}$$

a-Si/T-UNGL(INCL):

$$\begin{aligned} \eta_{th} &= 0.58 - 10.58 (\Delta T/G) \\ \eta_{el} &= 0.0601 - 0.00011 (T_{PV})_{eff} \end{aligned}$$

pc-Si/T-GL(INCL):

$$\begin{aligned} \eta_{th} &= 0.70 - 08.35 (\Delta T/G) \\ \eta_{el} &= 0.1457 - 0.00094 (T_{PV})_{eff} \end{aligned}$$

a-Si/T-GL(INCL):

$$\begin{aligned} \eta_{th} &= 0.73 - 08.24 (\Delta T/G) \\ \eta_{el} &= 0.0485 - 0.00011 (T_{PV})_{eff} \end{aligned}$$

For the pc-Si type PV/T systems the $(T_{PV})_{eff}$ is calculated from eqs (3) and (4) for HOR type and from eqs (4) and (5) for INCL type systems. For the calculation of $(T_{PV})_{eff}$ of a-Si type PV/T systems, the eqs used are (4) and (6) and (4) and (7) for HOR and INCL installation mode respectively. The thermal efficiency in INCL type PV/T systems is higher than that of HOR type systems because the back surface of the PV/T modules is thermally protected from low

ambient temperatures and high values of wind speed.

PV/T system annual energy output

The experimentally derived steady state thermal and electrical efficiencies of the above mentioned PV/T systems were used to calculate the annual energy output. In the calculations we used the weather conditions of Patras (annual solar input 5.92 GJ/m²y), considering only the positive thermal energy output of systems. The annual energy output for the studied PV module types (pc-Si and a-Si) and for all considered PV/T systems is shown in Table 1.

The use of inverters, heat exchangers, etc reduces the final energy output of all systems by about 15%, as electrical and thermal losses make the efficiency of the above equipment not to exceed 85%. The PV/T systems achieve an increase of the total energy output, but their electrical energy output is somewhat lower than that of standard PV modules due to the operation of PV modules at high temperature (45°C). The additional glazing increases the thermal output, but the higher optical losses reduce the electrical output of the panel.

The pc-Si PV modules give higher total energy output compared to a-Si PV modules, while for UNGL type PV/T systems the a-Si PV modules present higher thermal output. In real applications however, the lower cost of a-Si PV modules, which is almost half that of pc-Si, must be taken into consideration to achieve cost effective PV/T installations.

Table 1. Electrical and Thermal energy output of all systems considered

SYSTEM	Electrical MJ/m ² y	Thermal MJ/m ² y
pc-Si PV (HOR)	731.34	-
a-Si PV (HOR)	296.32	-
pc-Si PV(INCL)	662.58	-
a-Si PV (INCL)	289.26	-
pc-Si/T-UNGL(HOR)	644.76	143.14
a-Si/T-UNGL(HOR)	282.78	239.54
pc-Si/T-GL(HOR)	501.01	881.53
a-Si/T-GL(HOR)	218.23	1070.21

pc-Si/T-UNGL(INCL)	546.88	219.96
a-Si/T-UNGL(INCL)	275.72	326.12
pc-Si/T-GL(INCL)	433.51	976.46
a-Si/T-GL(INCL)	211.32	953.03

TRNSYS MODELLING RESULTS

The system that was modelled with TRNSYS, for Nicosia weather conditions, consists of a series of PV panels a battery bank and an inverter whereas the thermal system consists of a hot water storage cylinder, a pump and a differential thermostat. A heat exchanger is installed at the back of the photovoltaic panel and the whole system is enclosed in a casing with insulation installed at the back and sides and a single low-iron glass is installed at the front to reduce the thermal losses. Each “new” panel thus created (PV/T unit) consists of four (4) monocrystalline PV panels 1.2x0.53m. The new panel dimensions are 2.12x1.2m. Two such panels are employed in the system under investigation. A copper heat exchanger is used consisting of pipes with fins in contact with the backside of the PV modules and headers. Water is used as a heat transfer medium. The system employs also eight batteries connected in a 4x2 mode, i.e., 4 battery cells in parallel and 2 in series.

The primary component used in the TRNSYS model of the system is Type 49. This includes a combined collector (having both thermal and electrical output), power conditioning equipment (primarily a regulator and an inverter) and storage batteries. This type uses a numerical integration scheme to determine the battery state of charge. The use of this simple subroutine can reduce the computation required in some simulations and also simplify the set-up of the deck file. Type 49 has two modes of operation one for power peak operation of the solar collector and one for clamped voltage operation, when the collector voltage equals the battery voltage. The latter is applied in the present work.

The present model considers that the system is applied to a house of four persons. For this application, both electricity and hot water consumption (load) profiles are required. Both of these loads are subject to a high

degree of variation from day to day and from consumer to consumer, however, it is impractical to use anything but a repetitive load profile. This is not quite correct, for the case of the hot water load, during the summer period, where the consumption pattern is somewhat higher due to frequent bathing. However, during this period, the temperature requirement for hot water is not as high as during winter. Consequently, the total thermal energy requirement is reasonably constant throughout the year. For the present study, the electricity and hot water consumption profiles, illustrated in Figs. 2 and 3 respectively, are used. These assume a daily electrical consumption of 25700 kJ and a daily hot water consumption of 120 litres at 50°C for a family of four (30 litres/person).

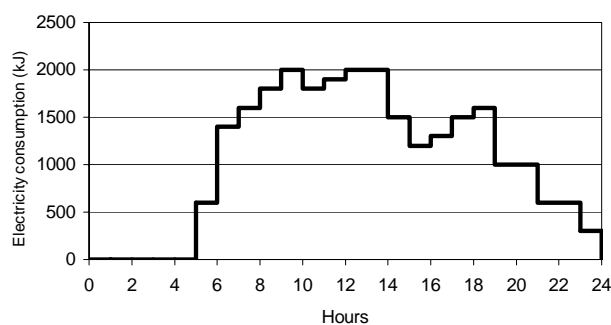


Figure 2 Electricity daily consumption profile

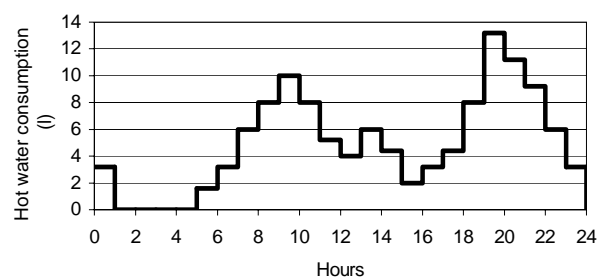


Figure 3 Hot Water daily consumption profile

Optimum system flow rate

By performing a number of simulations with TRNSYS it was found that the electrical energy output from the PV panel increases as the flow rate increases. This is due to the fact that the panel is working at a lower temperature. The thermal energy output increases and then drops. The optimum value of flow rate can be found by adding the total system output energy ($Q_{\text{output}} =$

electrical + thermal) and the required extra energy ($Q_{required} = \text{electricity from utility} + \text{auxiliary thermal energy}$) and plotting the values against the water flow rate (see Fig. 4). The optimum value corresponds to 25 lt/hr. This low value of flow rate suggests that the system can be used in a thermosyphon mode, i.e., without a pump and a differential thermostat which will enhance the economic viability of the system.

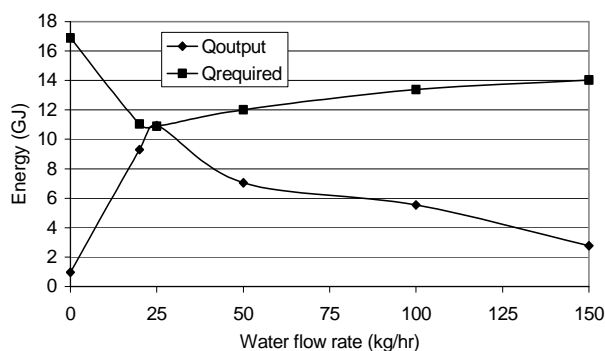


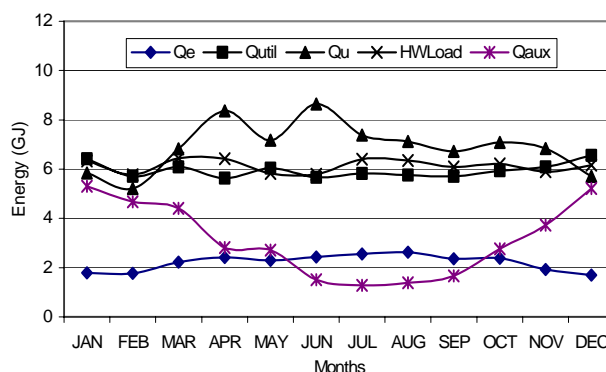
Figure 4 Optimum flow rate selection

Monthly performance of the system

The monthly variation of the various energy flows of the system is shown in Fig. 5. These include the total electrical output from the system (Q_e), the energy required from utility to cover the electricity consumption (Q_{util}), the useful thermal energy supplied to the tank (Q_u), the hot water energy requirements (HWLoad), and the thermal auxiliary energy demand (Q_{aux}). As it can be seen the maximum value of the useful thermal energy (Q_u), occurs in the month of June (8.6 GJ). The electrical energy supplied from the collector (Q_e) is almost constant throughout the year and is maximised in the month of August (2.6 GJ).

It can also be seen from Fig. 5 that the thermal auxiliary energy required is considerably reduced during the summer months. Another important point is the drop of the useful energy collected during the month of May. This is due to the reduced solar radiation available during that month; it is a characteristic of the climatic conditions of Nicosia and is due to the development of clouds as a result of excessive heating of the ground and thus excessive convection, especially in the afternoon hours.

Considering that the total aperture area of



PV/T systems is 5.1 m^2 and the annually solar input is 34.47 GJ, the PV/T system gives 2.65 GJ (7.7%) electricity and 8.29 GJ (24%) heat for the optimum water flow rate of 25 kg/hr. Figure 5 Energy flows of the PV/T system

The solar fraction, f , of the system is also investigated. This is defined as the ratio of the useful solar thermal energy supplied to the system divided by the energy needed to heat the water when no solar energy is used. Therefore, f is a measure of the fractional energy savings relative to that used for a conventional system. The annual solar fraction of the system is determined to be 0.49, i.e., 49% of the thermal needs for hot water production is covered from the present system.

CONCLUSIONS

Several hybrid Photovoltaic/Thermal solar systems developed by University of Patras and based on water heat extraction are suggested for practical use. The energy output of all PV/T systems is calculated for system operation at 45°C and the results showed that the PV/T systems with additional glazing are of lower electricity output, but of sufficiently higher thermal energy output.

Regarding the use of a-Si or pc-Si PV modules, the higher electrical efficiency of pc-Si PV modules makes them more effective in electricity generation, considering the available area for their installation. In practical applications a cost analysis is

necessary to find the cost effectiveness of the two types of the PV modules.

The optimum flow rate of such hybrid PV/T units was found to be equal to 25 lt/hr. In fact this value is low enough leading to the conclusion that the systems can be operated in thermosyphon mode without any pumps and controls. The solar fraction of a system modeled with TRNSYS at the environmental conditions of Cyprus was found to be 49%.

REFERENCES

- Bergene T. and Lovvik O.M., Model calculations on a flat-plate solar heat collector with integrated solar cells. *Solar Energy* Vol. 55, pp. 453-462, 1995.
- Cox C.H. III and Raghuraman P., Design considerations for flat - plate-photovoltaic/thermal collectors. *Solar Energy*, Vol. 35, pp. 227-241, 1985.
- Florschuetz L.W., Extension of the Hottel - Whillier model to the analysis of combined photovoltaic / thermal flat plate collectors. *Solar Energy*, Vol. 22, pp. 361-366, 1979.
- Garg H.P. and Agarwal P.K., Some aspects of a PV/T collector/forced circulation flat plate solar water heater with solar cells. *Energy Conv. Mgmt.*, Vol. 36, pp.87-99, 1995.
- Hausler T. and Rogash H., Latent heat storage of photovoltaics. *In Proc. 16th Europ. PV Solar Energy Conf.*, 1-5 May, Glasgow, U.K. Vol III, pp 2265-2267, 2000.
- Hendrie S.D., Evaluation of combined Photovoltaic/Thermal collectors. *Proc. of Int. Conf. ISES*, Atlanta, Georgia, USA, May 28 – June 1, Vol.3 pp. 1865- 1869, 1979.
- Huang B.J. Lin T.H. Hung W.C. and Sun F.S., Performance evaluation of solar photovoltaic/thermal systems. *Solar Energy*, Vol. 70, pp. 443-448, 2001.
- Kalogirou S.A., Use of TRNSYS for modelling and simulation of a hybrid PV-Thermal solar system for Cyprus. *Renewable Energy*, Vol. 23, pp 247-260, 2001.
- Kern E.C. Jr and Russel M.C., Combined photovoltaic and thermal hybrid collector systems. *Proc. of 13th IEEE Photovoltaic Specialists*, Washington DC, USA, pp. 1153 – 1157, 1978.
- Lalovic B., A hybrid amorphous silicon photovoltaic and thermal solar collector. *Solar Cells*, Vol. 19 pp. 131-138, 1986-87.
- Lasnier F. and Ang T.G., *Photovoltaic Engineering Handbook*, Adam Higler, p. 258, 1990.
- Loferski J.J., Ahmad J.M. and Pandey A., Performance of photovoltaic cells incorporated into unique hybrid photovoltaic / thermal panels of a 2.8 KW residential solar energy conversion system. *Proc. of the 1988 Annual Meeting*, American Solar Energy Society, Cambridge, Massachusetts, USA, pp. 427-432, 1988
- Raghuraman P., Analytical Predictions of liquid and air Photovoltaic / Thermal, flat – plate collector performance. *Journal of Solar Energy Engineering*, Vol 103, pp. 291-298, 1981.
- Tripanagnostopoulos Y., Tzavellas D., Zoulia I. and Chortatou M., Hybrid PV/T systems with dual heat extraction operation. *In Proc. 17th PV Solar Energy Conference*, Munich, 22-26 Oct pp 2515-2518, 2001.
- Tripanagnostopoulos Y., Nousia Th., Souliotis M. and Yianoulis P., Hybrid Photovoltaic/Thermal solar systems. *Solar Energy*, Vol. 72, 3, pp 217-234, 2002a.
- Tripanagnostopoulos Y. and Souliotis M., Battisti R. and Corrado A. Application aspects of hybrid PV/T solar systems. *In Proc. (CD-ROM) ISES Solar World Congress 2003*, Goteborg, Sweden, 4-19 June, 2003.
- Zondag, H. A., De Vries D.W., Van Helden W.G.J., Van Zolingen R.J.C. and Van Steenhoven A.A., The thermal and electrical yield of a PV-Thermal collector. *Solar Energy*, Vol. 72, pp 113-128, 2002.
- Zondag, H. A., De Vries D.W., Van Helden W.G.J., Van Zolingen R.J.C. and Van Steenhoven A.A., The yield of different combined PV-thermal collector designs. *Solar Energy*, Vol. 74, pp 253-269, 2003.