# PERFORMANCE OF A HYBRID PV/T THERMOSYPHON SYSTEM

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## ABSTRACT

Hybrid Photovoltaic/Thermal (PV/T) units are systems capable of producing both electrical and thermal energy in a single unit. Thermosyphon units are solar systems employing flat-plate collectors which are suitable for low temperature applications, like domestic hot water production. In this paper a hybrid PV/T thermosyphon system is modeled and simulated with TRNSYS program. The system's hybrid collectors are glazed, $4m^2$ in area and the hot water storage tank is 160 liters. Both polycrystalline and amorphous silicon solar cells are considered. The system is simulated on an annual basis at three different locations, Nicosia, Cyprus; Athens, Greece and Madison, Wisconsin. The results show that the electrical production of the system, employing polycrystalline solar cells, is 532 kWh, 515 kWh and 499 kWh and the solar thermal contribution is 0.686, 0.564 and 0.293 for the three locations respectively. The respective results for the system employing amorphous silicon cells are 260 kWh, 251 kWh, 224 kWh and 0.726, 0.601 and 0.341 for the three locations respectively. A non hybrid PV system produces about 30% more electrical energy but the present system covers also, depending on the location, a large percentage of the hot water needs of a house.

## 1. INTRODUCTION

Hybrid Photovoltaic/Thermal (PV/T) units are systems that produce both electrical and thermal energy in a single unit. Thermosyphon units are solar systems employing flat-plate collectors which are suitable for low temperature applications, like domestic hot water production [1]. The objective of this paper is to present the simulated performance of a hybrid PV/T thermosyphon unit. This is a system which looks like a standard thermosyphon unit whose absorbing surface is a PV module. Such system increases the total energy conversion of solar radiation by providing both electrical and thermal energy output, which results to cost effectiveness and low environmental impact of solar energy systems. In countries with good penetration of solar water heaters, like Cyprus and Greece, it is very difficult to convince customers to install a PV system, whereas a hybrid system producing both electricity and hot water has better chances of success [2, 3].

## 2. THERMOSYPHON SYSTEMS

Thermosyphon systems, shown in Fig. 1, heat potable water or a heat transfer fluid. These systems need no pumps and controls to transfer the water heated by solar energy, but they use natural convection to transport it from the collector to storage. The water in the collector expands becoming less dense as the sun heats it and rises through the collector into the top of the storage tank [1]. There it is replaced by the cooler water that has sunk to the bottom of the tank, from which it flows down the collector and circulation continuous as long as there is sunshine. The usual type of collector employed in thermosyphon units is the flat-plate. A typical flat-plate solar collector is shown in the detail of Fig. 1.

  

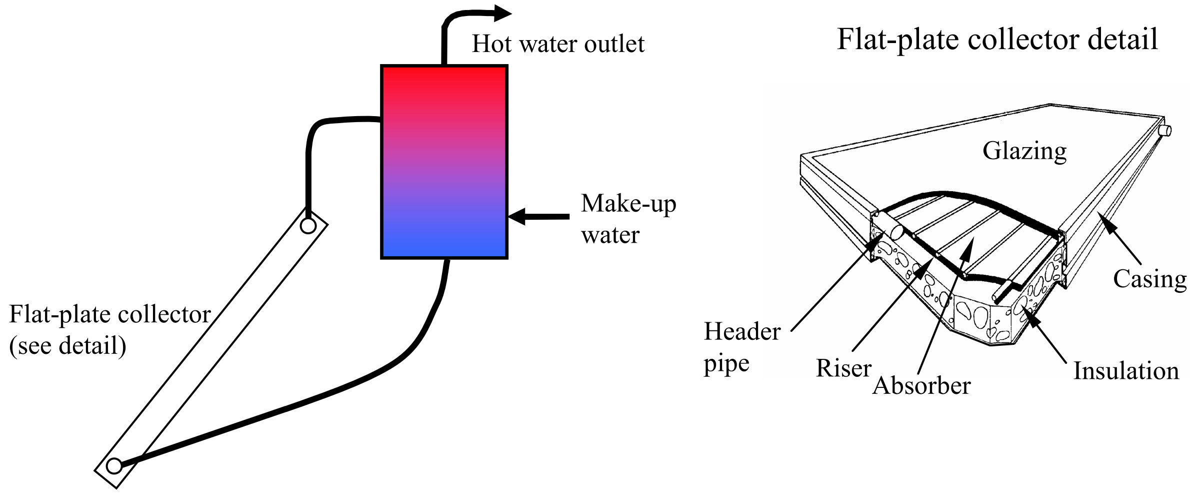


Fig. 1 Schematic of a thermosyphon solar water heater and flat-plate collector detail

When solar radiation passes through a transparent cover (used to reduce thermal losses) and impinges on the blackened absorber surface of high absorptivity, a large portion of this energy is absorbed by the plate and then transferred to the transport medium (water) in the fluid tubes to be carried away for storage or use. The underside of the absorber plate and the side of casing are well insulated to reduce conduction losses. The characteristics of the solar collector considered in this study are shown in Table 1.

Table 1 Characteristics of a the solar collector considered

| Parameter | Characteristics |
|---|---|
| Riser pipe diameter | 15mm |
| Header pipe diameter | 28mm |
| Absorber plate thickness | 0.5mm |
| Insulation material and thickness | Fiber wool, 40mm |
| Fixing of risers on the absorber plate | Embedded |
| Glazing | Low-iron glass |
| Collector area | 4m$^2$ |
| Storage tank volume | 160 lt |
| Collector slope | 40° |

## 3. HYBRID PV/T COLLECTOR

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 heat extraction with a fluid circulation. In hybrid PV/T solar systems the reduction of PV module temperature can be combined with a useful fluid heating [2, 3]. Therefore, hybrid PV/T systems can simultaneously provide electrical and thermal energy, thus 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.

In PV/T system applications the production of electricity is the main priority, therefore it is necessary to operate the PV modules at low temperature in order to keep PV cell electrical efficiency at a sufficient level. This requirement limits the effective operation range of the

  

PV/T unit for low temperatures, thus, the extracted heat can be used mainly for low temperature applications such as domestic water heating [2, 3].

Natural or forced air circulation is a simple and low cost method to remove heat from PV modules, but it is less effective at low latitudes where ambient air temperature is over $20^oC$ for many months of the year. Regarding water heat extraction, the water can circulate through pipes in contact with a flat sheet (heat exchanger), placed in thermal contact with the PV module rear surface as shown in Fig. 2. The additional thermal protection increases the thermal efficiency of the system, but the lower thermal losses keep the PV temperature at a higher level, therefore operating with reduced electrical efficiency. To increase the system operating temperature, an additional glazing is used, but this results in a decrease of the PV module electrical output because an amount of solar radiation is reflected away, depending on the angle of incidence [4].

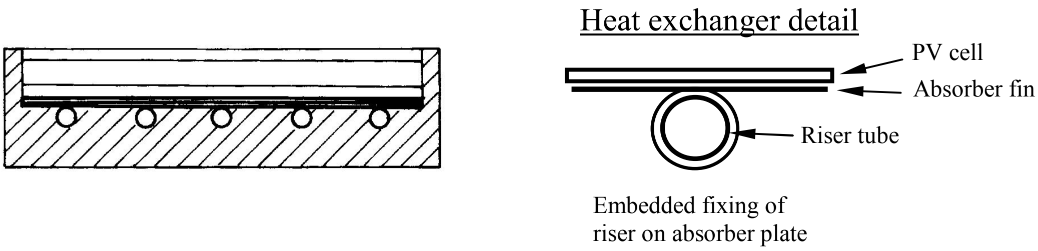


Fig. 2 Hybrid PV/T flat-plate collector and absorber detail

In PV/T systems the collector needs to be connected electrically to mains (for grid connected systems) and hydraulically to a hot water storage tank. Two types of PV cells have been considered in this work poly-crystalline silicon (pc-Si) and amorphous-silicon (a-Si). It should be noted that the complete PV/T systems include the necessary additional components called Balance of System, (BoS), including inverters and other power conditioning equipment and therefore the final energy output is reduced by about 15% [5].

The study of the hybrid PV/T water systems includes outdoor tests for the determination of the steady state thermal efficiency $\eta_{th}$ and the electrical efficiency $\eta_{el}$. Two experimental models were considered, a pc-Si/T and a a-Si/T, corresponding to the use of pc-Si and a-Si PV modules respectively [3]. 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 the PV module types as a function of the operating temperature [4, 5]. The steady state efficiency is obtained from:

$$\eta_{th} = \dot{m}\, C_p(T_o-T_i)/GA_a, \qquad (1)$$

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 $\eta_{th}$ 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 $\eta_{el}$ depends mainly on the incoming solar radiation and the PV module temperature ($T_{PV}$) and is calculated by:

$$\eta_{el}=I_mV_m/GA_a \qquad (2)$$

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

From the tests performed on both PV/T systems the following performance equations are obtained [4, 5]:

  

For pc-Si/T model: $\eta_{th} = 0.71 - 9.04\ (\Delta T/G)$ (3)

$\eta_{el} = 0.1457 - 0.00094\ (T_{PV})_{eff}$ (4)

For a-Si/T model: $\eta_{th} = 0.75 - 8.83\ (\Delta T/G)$ (5)

$\eta_{el} = 0.0485 - 0.00011\ (T_{PV})_{eff}$ (6)

The effective PV operating temperature $(T_{PV})_{eff}$ 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 [4, 5]. The use of inverters reduces the final energy output of all systems by about 15%, as electrical and thermal losses, thus the efficiency of the above equipment does not exceed 85%.

## 4. SYSTEM MODEL

The system is modelled with the well known TRNSYS program [6]. For the simulation of this system the TRNSYS model for thermosyphon (TYPE 45) is used. The thermal performance of the system is analyzed by dividing the thermosyphon loop into a number of segments normal to the flow direction and applying Bernoulli's equation for incompressible flow to each segment. The flow rate is obtained by numerical solution of the resulting set of equations. Flow in the loop is assumed to be steady-state.

The system is simulated on an annual basis at three different locations, Nicosia, Cyprus (35°); Athens, Greece (38°) and Madison, Wisconsin (43°). The first two locations represent locations with hot summer weather and mild winters, whereas the latter represents a location with mild summer and severe winter and was considered to find out the difference in system performance, for comparison purposes. For each of these three locations a Typical Meteorological Year (TMY) file, which is required in simulations, is available. A variable water consumption profile of a total of 120 liters of hot water per day is considered in simulations which is the consumption required for a four-person family (see Fig. 3).

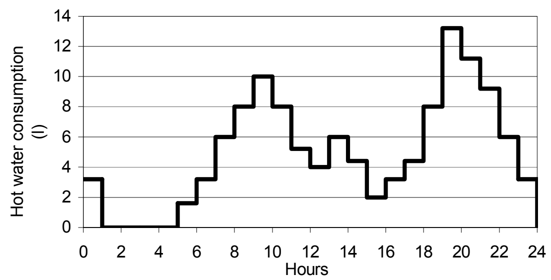


Fig. 3 Hot Water daily consumption profile

In a previous work in which an active PV/T system was modelled it was found that the optimum water flow rate value was 4.9 lt/hr-m$^2$ [2]. This low value of flow rate suggests that the system could be used in a thermosyphon mode. In the deck file required to run TRNSYS all the above equations are incorporated and whenever possible outputs from readymade modules were used directly. For example the mass flow rate and collector inlet and outlet temperatures are obtained in this way and used in the appropriate equations.

## 5. RESULTS

The annual results obtained are shown in Table 2. As can be seen the PV/T systems achieve an increase of the total energy output because hybrid systems utilise the thermal energy whereas in a standard PV system this is lost to ambient. However the electrical energy output of a hybrid system is somewhat lower than that of standard PV modules due to the operation of PV modules at higher temperatures. This is presented in the last column of Table 2 representing the percentage difference between the stand alone PV panel electrical energy output and the energy output of the PV/T units. The reduced electrical performance is also due to the additional glazing which increases the thermal output, but increases optical losses.

Table 2. Annual performance of a hybrid PV/T thermosyphon system

| Location | Cell type | $Q_u$ (MJ) | $Q_{aux}$ (MJ) | f (%) | PV/T electrical energy (kWh) | PV electrical energy (kWh) | Electrical energy % dif. |
|---|---|---|---|---|---|---|---|
| Nicosia | pc-Si | 5741 | 1736 | 68.6 | 532.1 | 843.2 | 63.1 |
| | a-Si | 6083 | 1516 | 72.6 | 257.6 | 353.6 | 72.9 |
| Athens | pc-Si | 5047 | 2410 | 56.4 | 515.1 | 827.1 | 62.3 |
| | a-Si | 5370 | 2208 | 60.1 | 249.1 | 343.4 | 72.5 |
| Madison | pc-Si | 3807 | 3910 | 29.3 | 499.0 | 774.4 | 64.4 |
| | a-Si | 4151 | 3643 | 34.1 | 222.7 | 305.2 | 72.9 |
| **Notes:** $Q_u$=useful thermal energy, $Q_{aux}$=auxiliary thermal energy required to cover hot water Load, f = solar contribution. Electrical energy is estimated by considering an 85% efficiency for the BoS. | | | | | | | |

The pc-Si PV modules give higher total energy output compared to a-Si PV modules however the a-Si gives more thermal energy and thus higher solar contribution in water heating. The solar contribution determines the percentage of the hot water load covered by solar energy. In cold climates and although the overall performance of the hybrid system is reduced due to the excessive cloudiness the comparative performance of the PV is better because of the operation at a lower temperature environment. It should be noted that although the model used cannot work with a heat exchanger in practice a mantle-type tank and a water with antifreeze liquid needs to be used in locations where freezing is a possibility, like in Madison, with a small reduction (about 15%) in the thermal performance of the unit.

The monthly performance is shown in Fig. 4. As can be seen on monthly basis pc-Si cells produce more electrical energy ($P_{el}$) than the corresponding a-Si cells. This is due to the higher efficiency of pc-Si cells. The a-Si cells produce more thermal useful energy ($Q_u$) in all three locations considered. For Nicosia and Athens both types of cells cover all thermal energy required for hot water production in the summer months as represented by the zero or near zero auxiliary energy required ($Q_{aux}$). For Madison where the temperatures and available solar radiation are lower a substantial amount of thermal energy is covered in summertime but some thermal auxiliary is still required. All systems represent a substantial thermal energy collection and a good electrical performance throughout the year.

## 5. CONCLUSIONS

A hybrid Photovoltaic/Thermal (PV/T) thermosyphon unit is modeled and simulated with TRNSYS program. The results show that the electrical production of the system, employing polycrystalline solar cells, is more than the amorphous ones but the solar thermal contribution is slightly lower. A non hybrid PV system produces about 30% more electrical energy but the present system covers also, depending on the location, a large percentage of the hot water needs of a house.

  

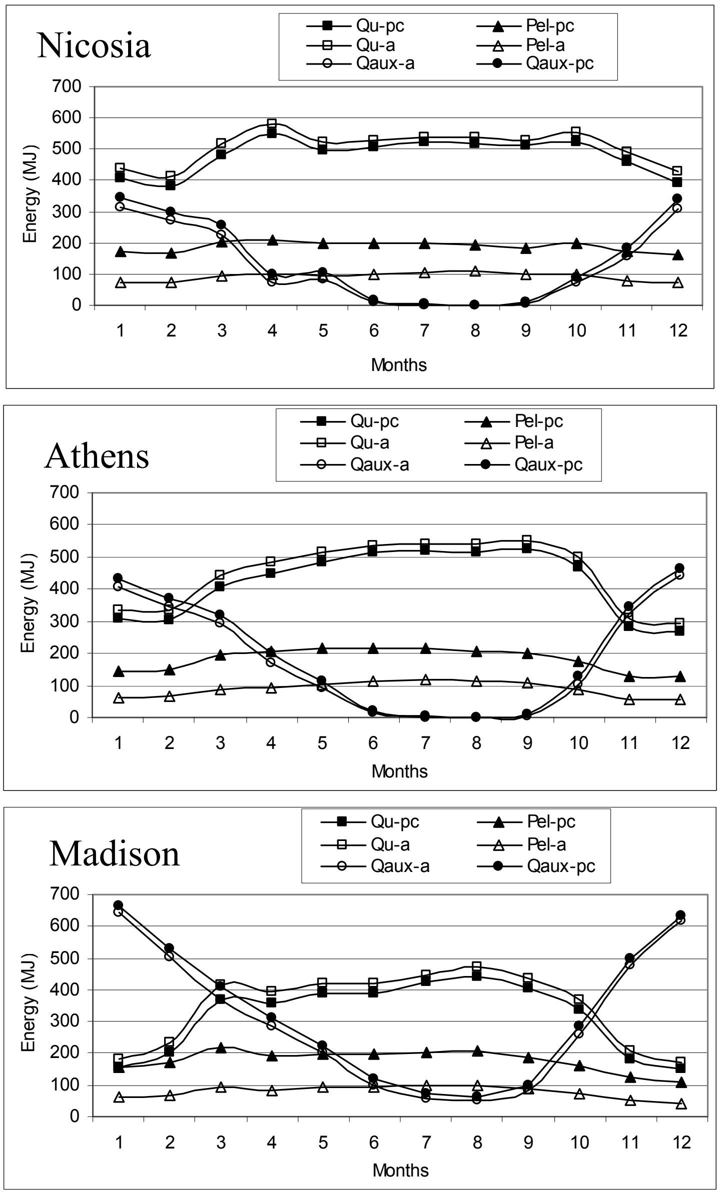


Fig. 4 Monthly performance of a hybrid PV/T thermosyphon system

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