ENERGY EFFICIENCIES OF A PHOTOVOLTAIC/THERMAL SOLAR HYBRID SYSTEM

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***Abstract* – The paper presents a comparative analysis from the point of view of the energetic efficiency for different types of hybrid photovoltaic/ thermal systems. There are presented the adopted constructive solutions and their energetic performances. It is showed the possibility to obtain some superior efficiencies of conversion of the solar energy.**

Keywords: *PV/thermal hybrid system, Solar energy, Efficiency, Concentrator.*

1. INTRODUCTION

The electric power obtained from solar radiation conversion is again much more expensive than conventional power, and it is used only where high government subsides are available.
Hybrid systems for solar energy conversion have attracted considerable attention from scientists and engineers during the last decade, because of their higher efficiency and stability of performances in comparison to solar devices based on a single type of energy conversion. Hybrid PV/T systems are able to reduce the necessary space, but also first costs, as compared to the separate PV systems and to produce thermal energy, by the fact that they use a common box.
Heat cannot be transported over large distances; therefore only small systems that are installed closet to the consumer can use co-generation. Hybrid PV/T converters, combine the advantage of maintenance of an optimal photovoltaic cell's working temperature, using the thermal energy extracted from them, through its transfer to a cooling agent, used after for domestic or industrial applications.

2. THE HYBRID PHOTOVOLTAIC/TERMAL AIR COLLECTOR

Hybrid PV/T converters can use different substances as cooling agent. Most frequently used is air or water. Such a converter was realized in India and its scheme is presented in Fig.1. It uses two PV modules, having the effective area of 0,61 m^2 each, serially connected and cooled through a air forced ventilation system. When evaluating the results it has been used a classification of days on four categories, based on meteorological conditions, classification based on meteorological tests realized 1991-2001 by the Meteorological Department from India. The results of such a system were not spectacular, being presented a growth with about 2-3% of the energetic efficiency, and compared with the 12% of the photovoltaic converter itself [1].

3. THE HYBRID PHOTOVOLTAIC/TERMAL WATER-HEATING SYSTEM

Much more interesting for specialists are PV/T converters which use water as agent of thermal processing. One of the essential requirements that must be taken into account when projecting such a

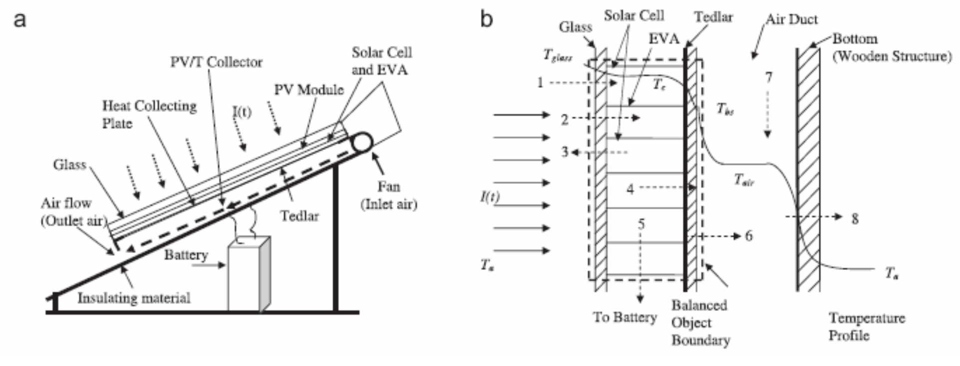

Figure 1. (a) Schematic diagram of integrated PV/T system when air is used as the medium to collect thermal energy (b) Cross-sectional view of hybrid PV/T air collector with temperature profile

device, is the assurance of a good thermal conduction and a good electrical insulation between the photovoltaic cells and the plate with role of thermal radiator, through which the heat is absorbed.

For example, the researchers from University of Science and Technology of China together with those from City University of Hong Kong, being financially supported by some organizations from the two countries, have created a system in which the collecting plate is fabricated from a variable number of extruded battens of Al-alloy which, can be easily assembled and interconnected (Fig.2).

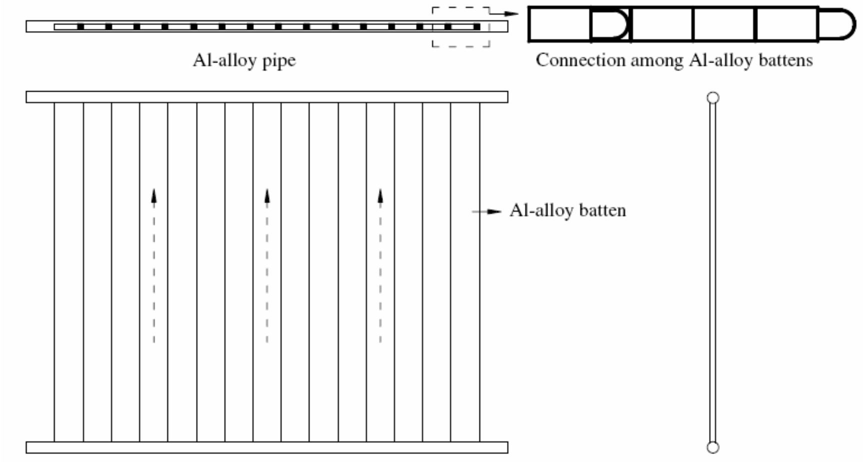

Figure 2. Construction of flat-box Al-alloy absorber plate

Each batten has the dimension of 1380×85×12 mm and has 3 built-in channels, each of cross-sections 10×20 mm. In this way, it is achieved a large contact area between the absorber plate and the coolant, doubled by a top surface of the plate, facilitating the lamination of photovoltaic cells [3].

The PV/T converter is presented in Fig.3. The surface formed from photovoltaic single-crystalline silicon cells was covered both sides with a layer of EVA (Ethyl Vinyl Acetat) of 0.4-0.6 mm thick, and externally with a transparent layer of TPT (Tedlar-Poliester-Tedlar) of about 0.2 mm thick. The two layers provide a good electrical insulation and a very good thermal conduction, the transmissivities exceeding 0.9. They were laminated to the PV cells and then, through a silica gel, on the absorber surface. The whole assembly is protected on the surface with photovoltaic cells by a window (at almost 25 mm) and on the back of the absorber plate, it is protected by a thermal insulator 30 mm thick. The absorber plate of the prototype was constructed from 15 battens of aluminum with a total heat-collecting area of 1.76 m2 and whole was housed in a Al-alloy frame, giving the overall dimension 1.33×1.5 m.

The water heating system consists of one collector, one water tank and the associated valves and pipes. The water tank was provided with 30 mm thick polyurethane foam, and fixed horizontally to an Al-alloy bracket, having three openings at the top of the tank which serve as an air vent and for thermocouple insertion.

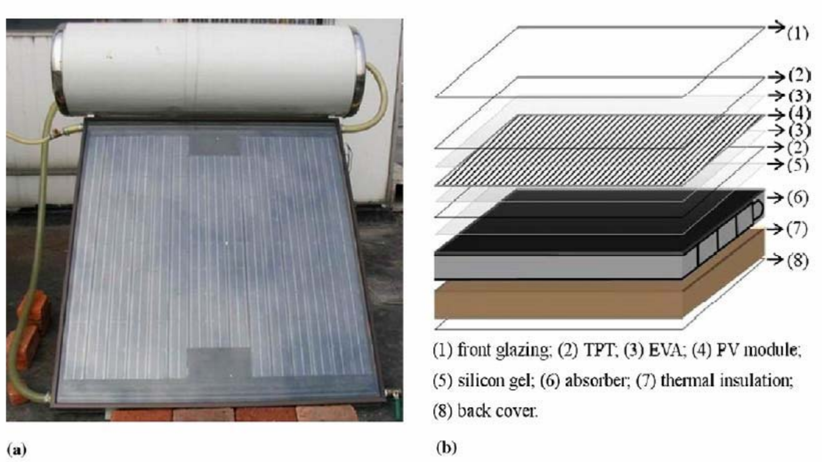

Figure 3. Physical configuration of the PV/T collector: (a) front view (b) the constituent layers

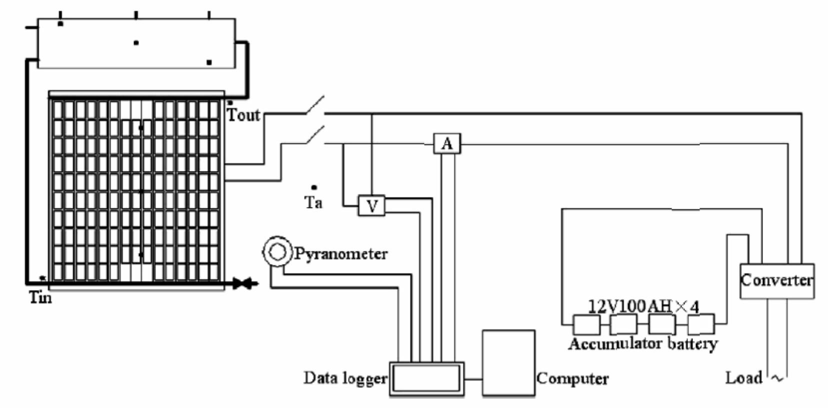

Figure 4. Electrical system of the PV/T test rig

The electrical system (Fig.4) is composed mainly of 144 photovoltaic cells connected in series, one converter, four accumulator batteries of 12 V-100Ah in series and the auxiliary measuring equipments, switches and command.

Each solar cell has a surface of 62.5×125 mm and ensures in standard testing conditions (incident lighting flux 1000W/m2, 25ºC) a theoretical efficiency of electric conversion of 14.5%.

The converter was equipped with protection systems at input over-voltage, no input voltage, output over-load and over-heat.

The results showed that about 30÷50% of the solar energy available at the converter surface is converted to thermal energy, and only about 10,15% to electrical energy. This electrical energy could be obtained maintaining the plate's temperature within the range of 30÷55ºC which means a water temperature at the output of 50ºC.

We have to remark the fact that for a PV/T converter of this type, it is essentially to ensure a good transmission of solar rays over the absorbent plane, this one being placed by construction behind the photovoltaic cells frame.

Also a PV/T plane converter, but with a very different conception is presented in [4]. In this case, to increase the efficiency of transforming solar energy into electrical energy, specialists form Mexico, have created a bifacial converter, having two active surfaces (where are disposed photovoltaic cells).

Calculations show a drop of the total cost price, because of the fact that the surface is basically half of the surface that should be covered with cells at mono-facial converter, and that should be cooled (Fig.5 and Fig.6).

The cooling is realized also with water, but the water is, in this case, between sun and photovoltaic cells. There are used in this way the optical properties of the water. Water absorbs light mainly in the infrared region, being compatible with photovoltaic cells using shorter wavelengths in the solar radiation spectra for its conversion to electricity.

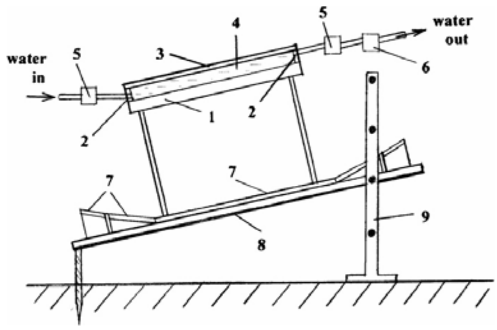

Figure 5. Schematic presentation of the hybrid system

Figure 6. Photos of the hybrid system

In Fig.7 it is presented in the curve 1 the optical transmission of a water layer of 1.5 mm thick and in the curve 2, the absorption of a silicon monocrystalline photovoltaic layer with a thickness of 50 µm.

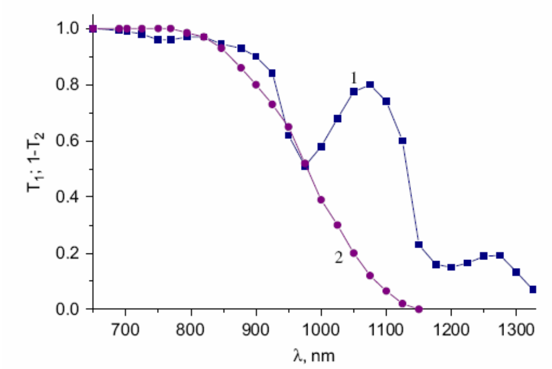

Figure 7. Optical spectra of water and Si parameters: (1) transmission of a water layer 1,5cm thick and (2) absorption of c-Si layer with thickness of 50µm

It is seen that the water absorption only slightly affects the working region of a Si PV cell around the waves of 950 nm long.

Under the collector, it is a system of mirrors which provide illumination of the rear face of the bifacial PV module. The reflecting planes were made of stainless steel and were placed at a height of 0.77 m above the converter module. The system is formed from a plane mirror of 3×1.465 m on top of which, at a height of 77 cm, it is transversally disposed the PV/T converter with an area of 118×55 cm.

The left and right margins which overpass the PV/T converter have the role of reflecting solar radiations, when these are not perpendicular on the plane of the absorber. When the sun sends perpendicular waves on the absorber, this one will overshadow the mirror. Because of this, there have been created another two curved mirrors, being part of a cylindrical mirror with its focal plane of 0.77 m, this means, where the PV module is placed. Their dimensions (56.5×90 cm) and angles were calculated in a way to provide a uniform illumination to the rear face. Having this constructive system proposed by authors, was able to collect over 80% of reflection from the mirrors on the rear face, while 64% of the amount of solar energy is collected by the PV/T converter's front face.

The collector is made of an Al frame covered with glass. The necessary water volume is about 9l and it is overturned once every 30 min (300 ml/min).

The heating effect of the solar converter can be estimated using the following equation:

$$Q = I \cdot A \cdot (1-\beta) \cdot \alpha \cdot \Delta t = C_p \cdot m \cdot \Delta\theta \qquad (1)$$

where:

Q - total energy gained by the water

Δt - considered time interval

A - the collector surface area

I - the solar irradiance at the level of considered time interval

α - the relative increase of irradiance due to illumination from the rear face of the converter using mirrors

C_p - the water heat capacity (4,18 kJ/kg·K)

m - the mass of water in the converter

$\Delta\theta$ - the increase of temperature

The coefficient β takes into account all the thermal losses (by reflection, convection, radiation, and solar energy transformed to electricity in the PV cells).

It can be written as follows:

$$\beta = r + \eta + \frac{h \cdot \Delta\theta + \varepsilon \cdot c_n \cdot \left[(T_0 + \Delta\theta)^4 - T_0^4\right]}{\alpha \cdot I} \qquad (2)$$

where:

r - the average reflection coefficient of the system

η - the efficiency of the PV module (around 0,15)

h - the convection coefficient (for natural convection in air it ranges between 5 and 10 W/m^2·K)

c_n - the Stephan-Boltzmann constant for radiation of the black corpus (5,67·10^{-8}W/m^2·K^4)

T_0 = 300 K –the ambient temperature

ε - blackness degree

Considering a small growth of the temperature $\Delta\theta << T$ the expression can be expressed:

$$\beta = r + \eta + \frac{\left(h + 4 \cdot \varepsilon \cdot c_n \cdot T_0^3\right) \cdot \Delta\theta}{\alpha \cdot I} \qquad (3)$$

from (1) and (3) it will result:

$$\Delta\theta = \frac{\alpha \cdot I \cdot A \cdot (1-\eta-r) \cdot \Delta t}{m \cdot C_p + \left[h + 4 \cdot \varepsilon \cdot c_n \cdot T_0^3\right] \cdot A \cdot \Delta t} \qquad (4)$$

Taking into consideration that the front surface of the hybrid converter's system is glass or plastic with a reflectance of around 5% and the PV modules have an antireflection coating, it can be considered as being covering a value $r \approx 0{,}1$.

Mirrors placed on the back side ensure an illumination amount with reflected light of minimum 80%, in this way, for the multiplication factor α we can consider the value $\alpha = 1{,}8$.

The analyzed hybrid solar converter has the surface $A = 0{,}6$ m^2 and the mass of water is $m = 9$ Kg.

The collector is colored in black, so it can be considered $\varepsilon = 1$.

In these conditions, from equation (4) it will result:

$$\Delta\theta_{\mathbf{var}\,a} \approx 25\,\text{K} \ (I_{\mathbf{var}\,a} \cong 925\ \text{W/m}^2)$$

$$\Delta\theta_{iarna} \approx 19\,\text{K} \ (I_{iarna} \cong 785\ \text{W/m}^2)$$

The system gave practically a constant voltage during the daytime, and equal to 19,5V. This one was measured as open circuit voltage with an interval of 15 minutes, and the short-circuit current had an approximately sinusoidal variation during the daytime. The highest total value is 7,1A (from which 2A for the real face which works with reflected light). The total electrical energy produced in the mid-summer day is 617 Wh, and for a mid-winter day is 380 Wh. In the same time the system produced 2130Wh thermal energy during mid-summer day and 1675 Wh for a mid- winter day.

The medium efficiencies calculated were of 16.4% for the electrical conversion and 50% for the thermal conversion [4].

4. THE CONCENTRATING PHOTOVOLTAIC AND THERMAL SYSTEM

The solar radiation's concentration before the energetic conversion is delivering a drop of the surface where are disposed the photovoltaic cells, so, a decrease of the cost price. Generally, this type of concentrators are big (100÷200 m^2) and use reflecting disks and Fresnel lentils, being not useful in big cities. Now, it is followed the conceiving of some devices with smaller dimensions, which, could be assembled close to the consumer and which can realize co-generation of heat, together with the transformation of solar radiation energy into electrical energy.

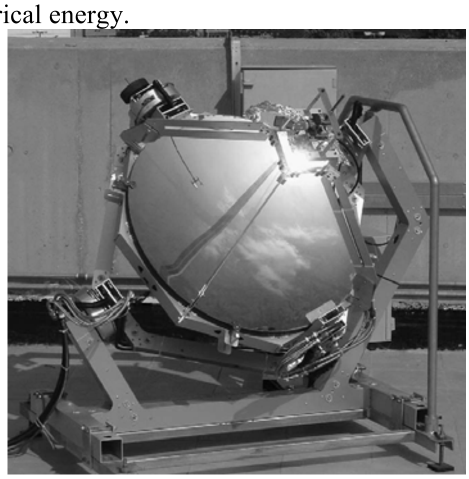

Figure 8. The MCPV unit

The device realized with the support of the National Ministry of Infrastructure and of Israel Ministry of Industry is based on a small parabolic disk, similar with a satellite antenna, very easy to transport and to install [2]. The conversion of the absorbed solar radiation is realized by using some photovoltaic cells with high efficiency. The solar radiation is concentrated for about 500 times, which would permit the use of PV receiver of small dimensions, placed at the focal point, and which cannot produce a shadow on the disk bigger than 1%. The parabolic reflector (Fig.8) was realized with silvered glass on the reflective surface (mirror) thermally treated. An external protective coating covers the silver layer. The mirror is assembled with the tracking support mechanism (similar with the satellite antenna).

The PV conversion module is based on triple-junction cells, with the conversion efficiency of 32%(data from Spectrolab Inc., Sylmar, California certificate). In the near future, it is possible to reach 40%. The cells are installed over a cooling plate, which removes the surplus heat to a coolant fluid (usually water in closed circuit). Water is cooled with the help of a heat exchanger which produce hot water for domestic or industrial applications, or the heating of air, or is used as an absorption cooling system.

The conversion efficiency realized by such a system can be determined if we analyze different losses during the conversion from radiated solar energy into electrical energy and thermal energy. The light-to-electricity conversion can be characterized by the equation:

$$\eta_{EL} = \eta_{OPT} \cdot \eta_{PV} \left(1 - \frac{\dot{Q}_{AUX}}{\dot{Q}_{TOT}}\right) \cdot \eta_{INV} \qquad (5)$$

where:

η_{OPT} - the efficiency of the optic system

η_{PV} - the efficiency of the photovoltaic cells' conversion

η_{INV} - the efficiency of the inverter system

$\dot{Q}_{AUX}$ - the power consumption for internal services

$\dot{Q}_{TOT}$ - the gross electrical power produced by the PV modules

Imperfect reflection at the disk causes losses of typically (6÷12%) depending on the type of mirror used and its state of cleanliness. A clean mirror made of low-iron glass with a silver back-coat provides a reflectivity of 90÷94%.

The photocells are covered with a protector transparent layer with low reflexivity, reducing this loss to about 2÷4%. On the other side, it can be considered a loss of 2÷3% because of the reflected radiations arriving outside the PV cells module aperture from the focal point. It can be considered the value of $\eta_{OPT} \approx 0{,}85$.

Additional losses can be caused by some unavoidable spaces among between the cells, by front contacts that shade the cell active area, and by current mismatch due to differences in the output of cells connected in series. It can be considered a gross of losses of 10% from gross efficiency of 32%. The photovoltaic cells efficiency can also depend on the incident flux and on the cells temperature. For an incident standard flux of 1 kW/m^2 it can be considered:

$$\eta_{PV} = 0{,}9 \cdot \left[0{,}32 - 0{,}00062\left(T_c - 25^{\circ}C\right)\right] \qquad (6)$$

The sensitivity of photovoltaic cells to temperature becomes lower when the incident radiation flux increases. In this case, working with a concentrator, the incident flux can achieve 400kW/m^2, and using the temperature coefficient 0,00062 corresponding to a radiation of 1 kW/m^2, it covers completely. Generally, the sensitivity to incident radiation concentration is lower than the sensitivity to temperature.

For the gross electrical power produced by the module, it can use the relation:

$$\dot{Q}_{TOT} = \dot{Q}_{IN} \cdot \eta_{OPT} \cdot \eta_{PV} \quad (7)$$

The power consumption for auxiliary services can be interpreted as a parasitic power. It is useful to ensure tracking motors, the cooling pump, and the control electronics. Generally, the pumping power is small and it can be neglected. The consumption of the control electronics is also quite small. The tracking motors, as dominant contribution, operate intermittently, and therefore their average power consumption is much lower than their peak power. For example, if the axe is well arranged, tracking motors can move only once or twice per day.

The estimate for the average power consumption for a unit with a reflector of 0.95 m^2 aperture area is:

$$\dot{Q}_{AUX} = 0{,}02\dot{Q}_{IN} + \dot{Q}_{POMPA} \quad (8)$$

And the required pump power is:

$$\dot{Q}_{POMPA} = \frac{\dot{m} \cdot \Delta P}{\rho \cdot \eta_P} \quad (9)$$

where:

$\dot{m}$ - the coolant mass flow rate

ΔP - the pressure drop

ρ - the cooling fluid density

η_P - the pump efficiency

The inverter performs the conversion of the direct current into electrical energy of alternative current, synchronized with the system. The inverter efficiency has a typical value of $\eta_{INV} = 0{,}9$.

For thermal losses calculation it is used a simplified model based on steady state operations, presented in Fig.9. We consider that the metallic cooling plates have uniform temperature (due to their good thermal conductivity).

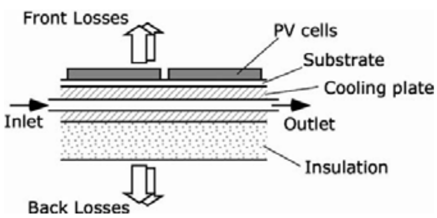

Figure 9. The thermal model of the PV module

The energetic equations are:

$$\dot{Q}_{Th} = \eta_{OPT}(1-\eta_{PV})\dot{Q}_{IN} = \dot{Q}_{COO} + \dot{Q}_F + \dot{Q}_B \quad (10)$$

$$\eta_{REC} = \frac{\dot{Q}_{COO}}{\dot{Q}_{Th}} \quad (11)$$

where:

η_{REC} - the recovery efficiency of thermal energy

Q_{Th} - the total thermal energy obtained based on solar radiation

Q_{COO} - the thermal energy transferred to the cooling agent

Q_F - the thermal energy lost on the module front surface

Q_B - the thermal energy lost on the module rear surface

Generally, evidences show that photovoltaic cells temperature is with 10 ºC bigger than the cooling fluid temperature.

At coolant outlet temperature of 58 ºC, the electrical power is 172 W and the thermal power is 530 W (for an irradiation of 900 W/m^2). This means that more than 60% of the captured incident radiation is transformed into thermal energy, and about 20% is transformed into electrical energy. The global energetic efficiency is, in this case, over 80%.

5. CONCLUSIONS

This paper shows clearly the possibility to grow the efficiency of the conversion of the solar energy by using hybrid converters, proportionally with simple PV systems. The electrical energy obtained from solar radiation is more expensive then conventional power and it can be used only where high government subsides are available. The simultaneous conversion of solar radiations into thermal energy, ensures the drop of the total cost price of the energy and the possibility to pay the initial investment.

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