DESIGN ASPECTS OF HYBRID PVT/WATER SOLAR SYSTEMS

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ABSTRACT: Hybrid photovoltaic thermal (PVT) systems consist of PV modules and heat extraction units mounted together. They convert the absorbed solar radiation into electricity and circulating water or air which are heated by cooling the PV modules. The PVT systems using water (PVT/WATER) for heat extraction are more expensive than air type PVT systems and can be used all seasons, mainly in low latitude applications, as water from mains is usually under 20°C. In this paper we present design aspects for the hybrid PVT/WATER systems that can be applied in residential buildings, hotels, etc, aiming to provide electricity and hot water. The suggested systems are analyzed regarding the design concepts and the electrical and thermal conversion effect for different PV module configurations. The study is focused to small size PVT/WATER systems that can be applied to one family houses, multiflat residential buildings, small hotels, etc and can be used alternatively to the widespread thermosiphonic solar systems, in stand-alone and mini-grid application of photovoltaics. Additionally, we study the application of a booster diffuse reflector, which increases the solar radiation on PVT panel aperture surface and overcomes in a way the reduction of the electrical output due to the optical losses from the additional glazing.

Keywords: Building integration-1: Thermal performance-2: Cost reduction-3

1 INTRODUCTION

The photovoltaics convert only a small part of the absorbed solar radiation into electricity, with the greater part converted into heat, increasing their temperature and decreasing their electrical efficiency. The combined or hybrid Photovoltaic/Thermal (PV/T) solar systems are new solar devices, which can simultaneously provide electricity and heat, achieving therefore a higher energy conversion rate of the absorbed solar radiation. PV/T 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

Among the main works of last ten years on the liquid type hybrid systems are the presentation of the design and the results of a commercial type PV/T system [1], the study of a system with cylindrical water storage tank [2], the PV/T collectors with polymer absorber [3] and the performance analysis of PV/T solar systems [4]. The investigations on 1D, 2D and 3D models for PV/T prototypes with water heat extraction [5], the systems with water circulation in channels attached to PV modules [6] and the developed systems for domestic applications [7], are the most important recent works on water cooled PV/T systems. Aspects and cost analysis results on PV/T systems [8,9] give an idea for the practical use of them and the application of Life Cycle Assessment (LCA) methodology [10] considers their environmental impact.

Design concepts, prototype construction and test results for water and air-cooled PV/T systems have been presented by the University of Patras [11], where PV/T systems with and without additional glass cover are experimentally analysed. In the same work the concept of using stationary diffuse reflector to increase the total energy output, instead of specular reflector, is also suggested. The dual type PV/T system, operating either with water or air heat extraction [12], the economic analysis that compares water cooled PV/T systems with standard PV and thermal systems [13] and the LCA study [14], are some additional works on water cooled PV/T solar systems.

In this paper we present design aspects for hybrid Photovoltaic/Thermal systems that use water as heat extraction fluid (PVT/WATER), providing electricity and hot water. The suggested systems are analyzed regarding the design concepts, the electrical and thermal conversion effect for different PV module technologies and alternative heat extraction modes, the size of the hot water storage tank and the circulation modes, the necessary electronic devices and other components as well. The study is focused to small size PVT/WATER systems that can be applied to one family houses, multiflat residential buildings, small hotels, etc, and can be used alternatively to the widespread flat plate thermosiphonic solar systems, in stand-alone and mini-grid application of photovoltaics.

2 THE PVT/WATER SYSTEM CONCEPT

The water type PVT systems (PVT/WATER) are more expensive than air type PVT systems and can be effectively used all seasons, mainly in low latitude applications, as water from mains is usually under 20°C. On the other hand, the ambient air temperature during the day is over than 20°C for almost half a year, limiting therefore the application of air type PVT systems in terms of effective electricity production to a shorter period. The PVT/WATER systems can contribute to the electrical consumption of buildings and can be divided in low, medium and high temperature applications. The low temperature applications up to about 45°C are associated with water preheating, heating of swimming pools and heat pump applications. The medium temperature systems may produce water of temperatures between 45°C and 65°C for domestic water heating, space heating and other thermal needs. Systems that produce water above 65°C can be used for space cooling and industrial processes, but so far there is no such known application.

Most of the investigated PVT models consist of silicon PV modules and the heat extraction unit is a metallic sheet with pipes for the water circulation, to avoid the direct contact of water with the PV rear surface. The heat exchanger is in thermal contact with the PV module rear surface and is thermally insulated to the ambient from the rear side of the heat exchanger element and the panel edges.

The additional thermal output that is provided from the PVT systems makes them cost effective compared to separate PV and thermal units of same total used aperture surface area. 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 thermal unit in low temperatures, thus, the extracted heat can be used mainly for water preheating. In case of using PV modules without additional glazing (UNGLAZED type), they provide satisfactory electrical output, depending on the operating conditions, but the thermal efficiency is reduced for higher operating temperatures due to the increased thermal losses from the PV module front surface.

The addition of a glazing increases significantly the thermal efficiency (GLAZED type) for a wider range of operating temperatures, but the additional optical losses from it reduce the electrical output of the PVT system. The electrical output of PV/T systems is of priority, as the cost of PV modules is several times higher than the thermal unit. The different performance of the two subsystems regarding temperature affects system cost and optimised modifications for both electrical and thermal efficient operation must be considered. Thus it is necessary to take into account the cost in relation to the increase of system electrical and thermal energy output. Monocrystalline or polycrystalline silicon (c-Si or pc-Si) PV modules are almost double the cost per system aperture area than amorphous silicon (a-Si) PV modules. Therefore, the addition of the thermal unit is of lower relative cost for PV/T system based on c-Si or pc-Si (about 8%-10%) than of a-Si PV modules (about 15%-20%) of same size. In addition, the thermal unit additional cost must be offset by the corresponding increase in electrical efficiency and thermal output in order to make the PV/T system cost effective.

3 THERMOSIPHONIC PVT/WATER SYSTEM

In Greece, in the last 30 years a large thermal market for domestic hot water systems was developed due to an initial generous subsidy scheme that was applied in the solar thermal single family systems. The basic solar thermosiphonic family system is composed of a 1.8 to 4.0 m^2 collector area and a hot water storage tank of 120 to 250 litres. On the other hand, the single family market for PV systems has not developed in Greece, despite the tax deduction scheme that was applied for about 10 years until 2003. The main reason was that the incentive was not sufficient to generate any interest.

The use of PVT./WATER hybrid systems creates a synergy that works in favour of the PV systems and a potential market window could open for the re-introduction of the PV technology, through a modified product, this time without the need for heavy subsidies. It is considered that the PV/T hybrid solar system is an opportunity to develop a series of new solutions for the electric and thermal energy needs of the consumers and enterprises. The current annual solar thermal market in Greece, which is represented by about 99% by domestic/small systems, fluctuates between 50000 and 70000 single family units (about 200000 m^2 per year) including also hotels studios, small commercial and industrial consumers. An initial penetration of 10% in this market would mean PV annual sales of 1.0 to 1.8 MWp depending to the PV technology used. Therefore a PVT/WATER system of slightly larger area has to be developed in order to offer the same hot water production as a solar thermal optimised system.

As most of the domestic solar thermal systems are installed on houses with electricity service, the electricity produced by the PV can be used locally or fed to the grid as it is done for PV grid-connected systems. Provided the installation is composed of approved products, then the framework for the domestic electricity transactions with the electricity system operator has to be simplified and the green electricity produced valorised accordingly. When PV is combined with a solar thermal collector for tap water heating a compromise operating temperature has to be reached. PV needs to have a low temperature to maintain a high efficiency, whereas a solar thermal collector requires a high temperature. With the current technologies, the PVT combination has a lower efficiency than two separate systems and, due to the initial development stage, the PVT combination is also more expensive. However, advantages are foreseen in aesthetics, future system cost reductions (production of PVT modules & installation) and market/consumer requirements.

A number of obvious advantages exist, and if the obstacles are overcome, there seems to be a large potential for PV/T systems in the future. However, much R&D work is still required, and knowledge transfer is needed in PV/T systems. The total area used to extract a given amount of electricity and heat may be smaller than for two (PV and Thermal Collector) separate systems. The materials used for a PV/T system, and thus the total energy and economy balance, may be better than for separate units. In PV/T building installations the roof or facade will have a more uniform look, providing the potential for pre-fabricated systems developed for various types of roofs. When using building integrated elements a potential saving in installation costs compared to separate systems can turn out to be an important factor for future development of the market for photovoltaics/thermal solar collectors. In addition, a suitable design for use in low temperature levels e.g. for swimming pools and in combination with heat pumps can be also considered.

4 PVT/WATER EXPERIMENTAL MODELS

The electrical and thermal efficiency of a laboratory-constructed and tested PVT/WATER solar systems shows satisfactory thermal performance regarding operation in low (PVT/UNGL) and medium (PVT/GL) temperatures. We used two PV module types (pc-Si and a-Si) in both forms (GLAZED and UNGLAZED) and we also tested them by applying a diffuse reflector [11,12]. The suggested diffuse reflector doesn't contribute to electrical efficiency drop, as it provides an almost uniform distribution of reflected solar radiation on PV module surface.

The experimental PVT/WATER models were tested outdoors in steady state conditions. The efficiency is calculated by the relation: $\eta_{th} = \dot{m}\, C_p(To\text{-}Ti)/GAa$, where $\dot{m}$ is the water mass flow rate, C_p the water specific heat, Ti the inlet and To the water output temperature, G the intensity of the incoming solar radiation and Aa the PVT module aperture area. The water was input into the systems at several temperatures from mains temperature up to stagnation (zero thermal efficiency) to get system efficiency at different operating temperatures. In Table 1 we give the test results for the thermal efficiency η_{th} of PVT/WATER systems as function of the ratio ΔT/G ($KW^{-1}m^2$), with ΔT=Ti-Ta (K), where Ta is the ambient temperature. During tests, the PV electrical output was connected to a load in order to avoid PV module additional heating.

Table 1 Electrical and thermal efficiency of tested PV, PVT/WATER and THERMAL models

SYSTEM	EFFICIENCY
(pc-Si) PV (a-Si) PV	$\eta_{el} = 0.1659 - 0.00094\, T_{PV}$ $\eta_{el} = 0.0601 - 0.00011\, T_{PV}$
(pc-Si) PVT/UNGL	$\eta_{el} = 0.1659 - 0.00094\, T_{PV,eff}$ $\eta_{th} = 0.55 - 11.99\, (\Delta T/G)$
(pc-Si) PVT/GL	$\eta_{el} = 0.1457 - 0.00094\, T_{PV,eff}$ $\eta_{th} = 0.71 - 9.04\, (\Delta T/G)$
(a-Si) PVT/UNGL	$\eta_{el} = 0.0601 - 0.00011\, T_{PV,eff}$ $\eta_{th} = 0.60 – 12.02\, (\Delta T/G)$
(a-Si) PVT/GL	$\eta_{el} = 0.0485 - 0.00011\, T_{PV,eff}$ $\eta_{th} = 0.73 – 8.24\, (\Delta T/G)$
THERMAL	$\eta_{th} = 0.78 – 7.5\, (\Delta T/G)$

Table 2 Electrical and thermal efficiency of tested PV, PVT/WATER and THERMAL models using reflector with 20% additional solar input

SYSTEM	EFFICIENCY
(pc-Si) PV+REF (a-Si) PV+REF	$\eta_{el} = 0.1773 - 0.00098\, T_{PV}$ $\eta_{el} = 0.0698 - 0.00014\, T_{PV}$
(pc-Si) PVT/UNGL+REF	$\eta_{el} = 0.1773 - 0.00098\, T_{PV,eff}$ $\eta_{th} = 0.61 - 11.74\, (\Delta T/G)$
(pc-Si) PVT/GL+REF	$\eta_{el} = 0.1560 - 0.00096\, T_{PV,eff}$ $\eta_{th} = 0.78 - 9.67\, (\Delta T/G)$
(a-Si) PVT/UNGL+REF	$\eta_{el} = 0.0698 - 0.00014\, T_{PV,eff}$ $\eta_{th} = 0.68 – 11.98\, (\Delta T/G)$
(a-Si) PVT/GL+REF	$\eta_{el} = 0.0565 - 0.00015\, T_{PV,eff}$ $\eta_{th} = 0.82 – 8.41\, (\Delta T/G)$
THERMAL+REF	$\eta_{th} = 0.92 – 8.18\, (\Delta T/G)$

The electrical efficiency η_{el} depends mainly on the incoming solar radiation and the PV temperature (T_{PV}) and is calculated by the relation η_{el}=ImVm/GAa, where Im, and Vm the current and the voltage of PV module operating at maximum power. Considering solar systems installed on horizontal building roof, they are usually placed in parallel rows, keeping a proper distance from one row to the other to avoid PV module shading.

We suggest to place a flat diffuse reflector in front of the PVT system, which can be properly adjusted to sun altitude a few times during the year, to increase the solar input on PV modules improving therefore the electrical and thermal output of it. In the case of using diffuse reflector, the calculation of thermal and electrical efficiency of the system is based on the net solar radiation on the PV module surface (not including the radiation from the reflector). This result could be considered as system performance rather than system efficiency and it is done in order to get a clear idea about the achieved effect from the additional solar input by the diffuse reflector. This solar input depends on the season and the slope of the reflector, but we consider a minimum 20% (CR=1.2) for all year round. The results from the performed tests for the electrical and thermal efficiency of all tested PVT/WATER models are included in Table 1. In the same Table we include the test results from the two standard PV module types and from a typical flat plate solar thermal collector. The results of the same solar systems but using reflector that increases the solar input by a minimum 20% are given in Table 2.

5 PVT/WATER SYSTEM ELECTRICAL AND THERMAL ENERGY CALCULATION

In order to estimate the economic benefits from the use of the thermosiphonic PVT/WATER systems and compare with standard PV and typical solar thermal systems, we have to estimate first the electricity and heat production of all the considered systems. We considered the meteorological conditions of Athens, Greece, assuming that the systems are oriented to South at an inclination of 40º (1686.87 Wm^{-2} total annual irradiance). All the calculations presented in Table 3 are on the basis of the active collector area, which is considered to be 4.0 m^2 and a corresponding water storage tank of 200 l.

Table 3 Annual electrical and thermal energy of systems

SYSTEM	ANNUAL ELECTR. ENERGY kWh	ANNUAL THERMAL ENERGY kWh
(pc-Si) PV	819.44	--------
PV + REF	881.52	--------
(a-Si) PV	352.48	--------
PV + REF	404.52	--------
(pc-Si) PVT/UNGL	850.92	2175.87
PVT/UNGL +REF	881.52	2316.49
(pc-Si) PVT/GL	724.36	2729.41
PVT/GL +REF	773.64	2918.16
(a-Si) PVT/UNGL	355.84	2454.15
PVT/UNGL +REF	404.52	2688.12
(a-Si) PVT/GL	281.12	2905.92
PVT/GL +REF	321.52	3226.50
THERMAL	--------	2980.69
THERMAL + REF	--------	3631.75

The energy production calculation is made for a representative year on an hourly basis. The formulae of the steady state efficiency of each PVT model determined by the previous experimental study were used to calculate the hourly energy output. The PV temperature of pc-Si modules, is calculated from the formula [15]:

$$T_{PV}= 30.0006+0.0175(G-300)+1.14(Ta-25)$$

with G in W/m^2 and Ta in ºC. For the a-Si PV modules, their lower electrical efficiency results to slightly higher operating temperature, compared to that of the pc-Si PV modules. For this reason we used the following modified formula, which was also validated by experiments:

$$T_{PV}= 30.0006+0.0175(G-150)+1.14(T_a-25).$$

These values can be used to find the effective PV module temperature $T_{PV,eff}$ by the relation $T_{PV,eff}=T_{PV}+(T_{PVT}-Ta)$, where T_{PVT} is taken as the system operating temperature (approximately equal to the water input temperature). In the case of PVT systems that use diffuse reflector the corresponding validated equations for T_{PV} are:

$$T_{PV}= 30.0006+0.0175(G*CR-300)+1.14(T_a-25)$$

T_{PV}= 30.0006+0.0175(G*CR-150)+1.14(T_a-25)
for pc-Si and a-Si type PV modules correspondingly.

6 ECONOMIC ANALYSIS

The economic analysis considers domestic systems with a solar collector area of 4.0 m^2 and storage tank of 200 l, usually suitable for heating applications in one family houses, multi-flat residential buildings, and small hotels. We followed the principles worked out in a similar effort for PV systems [16] and the evaluation determines the system cost pay back time (CPBT). The cost and the CPBT of all systems are shown in Table 4. The great potential of PV/T systems was also pointed out by the economic analysis made by Leenders [7] and by P. Frankl and al [10]. In our work, the analysis is performed on an annual basis and it assumes that the domestic user avoids the use of equivalent amount of electric energy for water heating according to the system's output. In addition, for PV and PV/T systems, the user avoids the consumption of electricity that it is produced by the system. The starting cost for electricity per kWh electric produced, for the first year in the analysis, is taken to be 0.1 €/kWhe We assume a subsidy of 40% in the system cost, applied during in the first year of the system operation and assume that all electricity produced is consumed locally. The cost of money is also included in the cash flow, by subtracting the amount that the user would have made as a profit, if the money were gaining the discount interest rate. No subsidy is applied to the Solar Thermal systems studied.

Table 4 Economic analysis results for systems

SYSTEM 4 m^2 - 200 l water tank	COST €/system	CPBT years
(pc-Si) PV PV + REF	3600 3800	17 16
(a-Si) PV PV + REF	2400 2600	23 22
(pc-Si) PVT/UNGL PV + UNGL +REF	4400 4600	7 6
(pc-Si) PVT/GL PVT/GL +REF	4800 5000	6 6
(a-Si) PVT/UNGL PVT/UNGL +REF	3200 3400	5 5
(a-Si) PVT/GL PVT/GL +REF	3600 3800	5 5
THERMAL THERMAL + REF	1400 1600	4 3

CONCLUSIONS

The application of PVT/WATER systems is effective in electrical output, reducing CPBT by 2.5 and 4.5 times regarding that of the typical pc-Si and a-Si PV modules. The addition of the thermal unit for the water heating contributes to a satisfactory total energy output, which is more effective for the pc-Si PVT than for a-Si PVT type systems. The CPBT of all considered hybrid systems is considered encouraging as they are less than 8 years, with better results for the a-Si type systems (about 5 years). The diffuse reflector increases the electrical and thermal output, but without significant improvement of CPBT. These results show that PVT/WATER systems are of interest for application and wider use of photovoltaics.

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