ECOMOMIC ANALYSIS OF HYBRID PHOTOVOLTAIC/THERMAL SOLAR SYSTEMS AND COMPARISON WITH STANDARD PV MODULES

S. Tselepis[1] and Y. Tripanagnostopoulos[2]
[1]Centre for Renewable Energy Sources, 19th km Marathonos Av., 190 09 Pikermi, Athens, Greece
Tel: +30 10 6603369, Fax: +30 10 6603301, e-mail: stselep@cres.gr
[2]Physics Department, University of Patras, Patra 26500 Greece
Tel/Fax: +30 610 997472, e-mail: yiantrip@physics.upatras.gr

ABSTRACT: Most of the absorbed solar radiation by solar cells is not converted into electricity it increases their temperature, reducing their electrical efficiency. The PV temperature can be lowered by heat extraction with a proper natural or forced fluid circulation. An interesting alternative to plain PV modules is to use Hybrid Photovoltaic/Thermal (PV/T) systems, which consist of PV modules coupled to heat extraction devices, providing electricity and heat simultaneously. Hybrid PV/T systems are of higher cost than standard PV modules because of the addition of the thermal unit and therefore a cost/benefit analysis is needed to find out the limits of practical use of these. A couple of typical applications are selected in order to assess the benefits for the users of hybrid PV/T systems comparing the payback time with PV systems and Solar thermal ones, under the current support schemes and conditions in Greece. A spreadsheet was developed that calculates on an hourly basis the annual energy output of the different systems. Furthermore, the energy output and the estimated system costs per surface area are introduced in an economic analysis spreadsheet, where the payback time for each system is calculated.

Keywords: Hybrid, Economic Analysis, Building Integration.

1 INTRODUCTION

The solar radiation increases the temperature of PV modules and natural cooling by radiation and wind convection is not enough to reduce their temperature sufficiently, resulting in a drop of their electrical efficiency. This undesirable effect can be partially avoided by heat extraction with a proper fluid circulation and the reduction of PV module temperature can be combined with a useful fluid heating. Hybrid Photovoltaic/Thermal (PV/T) solar systems can simultaneously give electrical and thermal output, achieving a higher energy conversion rate of the absorbed solar radiation. PV/T systems consist of PV modules coupled to heat extraction devices, by which air or water of lower temperature than that of PV modules is heated by cooling them.

In PV/T system applications, considering that the electricity is of priority, then the operation of the PV modules at lower temperatures is necessary in order to keep PV cell electrical efficiency at a sufficiently higher level. This demand limits the operation range of PV/T system thermal unit in lower temperatures and the extracted heat can be mainly used for low temperature thermal needs (space heating and natural ventilation of buildings, air or water preheating, etc). Hybrid PV/T systems with air heat extraction are more extensively studied because of their easier construction and operation. Water heat extraction is more expensive, but water from mains is usually under 20 ºC and therefore in most applications water heating is useful during all seasons. PV/T systems with air or water heat extraction could be cost effective if the additional cost of the thermal unit is low and the extracted heat is effectively used.

Main concepts on hybrid PV/T systems have been presented in the works of Kern and Russel [1], Hendrie [2], Florschuetz [3] and Raghuraman [4]. Bergene and Lovvik present results for liquid type PV/T systems [5] and Huang et al for an integrated PV/T system with hot water storage [6]. Regarding recent papers on PV/T systems, the works of Leeders et al on PV/T concepts [7] and Zondag et al on liquid type PV/T systems [8] can be suggested. The electrical and thermal output of hybrid PV/T systems can be increased by using reflectors of low concentration, of flat type, as presented by Al-Baali [9] and Garg et al [10].

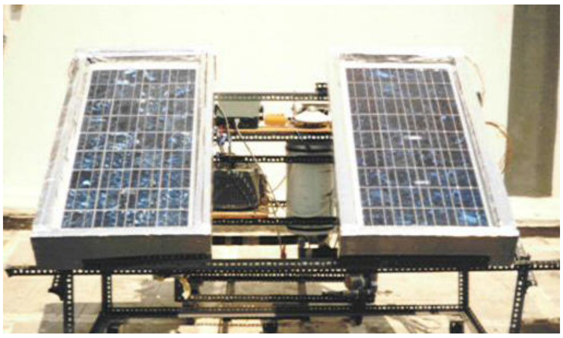

Figure 1: PV/T Water systems tested in the laboratory.

An extensive study regarding performance improvement of hybrid PV/T systems has been done by Tripanagnostopoulos et al in Physics Department of University of Patras [11,12,13]. In these papers new designs of PV/T systems are presented and experimental results are given. The suggested models include a number of modifications that contribute to the increase of thermal efficiency, to the decrease of PV module temperature and therefore to the improvement of the total energy output of the PV/T system. The studied hybrid systems can be used for space heating and for water heating in residential buildings, hotels, hospitals, etc. Aiming to the additional improvement of electrical and thermal output of PV/T systems, the combination of these systems with a diffuse reflector is suggested and experimentally studied [13].

2 PV/T WATER SYSTEM DESIGN CONCEPTS

This work concentrates on PV/T Water systems (PV/T W) with water heat extraction (Figure 1). The fluid is not circulated in direct thermal contact with the PV rear surface because of potential problems with the electrical conductivity of the PV module. To avoid these problems the water must circulate through pipes of reasonable diameter in contact with a flat sheet, which is placed in thermal contact with the PV module rear surface. 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 brings it to the final use. The cost of the thermal unit is the same either the PV module is c-Si, pc-Si or a-Si, but the ratio of the additional cost of the mounted thermal unit per PV module area cost is different and is almost double in using a-Si than c-Si or pc-Si PV modules. In addition to the lower cost of a-Si PV modules, they 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.

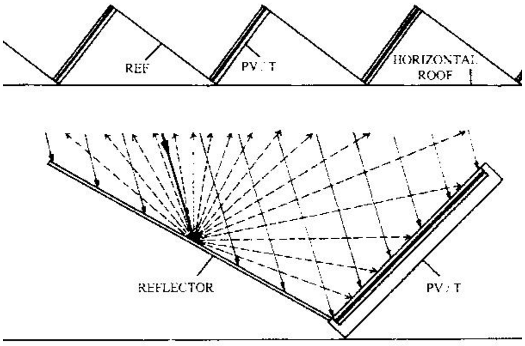

Figure 2: PV/T systems with diffuse reflectors installed between collector rows [13].

Considering solar energy systems installed on horizontal building roof they are usually placed in parallel rows, keeping a proper distance from one row to the other in order to avoid PV module shading. We suggest to place stationary flat diffuse reflectors from the higher part of PV modules of one row to the lower part of PV modules of next row (Figure 2). This installation increases solar input on PV modules almost all year resulting to an increase of electrical and thermal output of PV/T systems. The suggested diffuse reflectors don't contribute to electrical efficiency drop, as they provide an almost uniform distribution of reflected solar radiation on PV module surface.

3 PV/T SYSTEM PERFORMANCE

The experimental study of the hybrid PV/T Water systems includes tests for the determination of the steady state thermal efficiency η_{th} and electrical efficiency η_{el} . The PV/T systems of this study were constructed in University of Patras and the experimental models consisted of a-Si and pc-Si PV modules in combination with water heat extraction. The heat exchanger for the water heating was consisted of 10 mm in diameter copper pipes in thermal contact with a copper sheet, which was mounted on PV rear surface. The thermal unit of all models was thermally protected by 5 cm thermal insulation. The models are distinguished in pc-PV/WATER and a-PV/WATER, considering the use of pc-Si and a-Si PV modules correspondingly. The thermal efficiency of the experimental PV/T models is determined as function of the incoming 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 two PV module types as function of the operating temperature (T_{PV}) of them.

During tests 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 the relation $\eta_{th} = \dot{m} C_p(T_o-T_i)/GA_a$, 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 temperature and A_a the PV/T model aperture area. The thermal efficiency η_{th} is calculated as function of the ratio $\Delta T/G$ where $\Delta T= T_i-T_a$, and T_a the ambient temperature. The electrical efficiency η_{el} depends mainly on the incoming solar radiation and the PV temperature (T_{PV}) and is calculated by the relation $\eta_{el}=I_mV_m/GA_a$, where I_m and V_m the current and the voltage of PV module operating at maximum power. 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 included 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.

The results from the performed tests regarding thermal efficiency are the following:

pc-PV/WATER: $\eta_{th} = 0.55 - 11.99\ (\Delta T/G)$
a-PV/WATER: $\eta_{th} = 0.60 - 12.02\ (\Delta T/G)$

The results regarding the electrical efficiency for the two PV module types are the following:

$\eta_{el}\,(\text{pc-Si}) = 0.1659 - 0.00094\, T_{PV}$
$\eta_{el}\,(\text{a-Si}) = 0.0601 - 0.00011\, T_{PV}$

The results for thermal and electrical efficiencies from the addition of the diffuse reflector to the pc-PV/WATER hybrid system achieve a concentration ratio from C=1.00 in December up to C=1.30 in June, where for C=1.30 the efficiencies are:

$\eta_{th} = 0.640 - 11.53\ (\Delta T/G)$,
and $\eta_{el} = 0.1860 - 0.00107\, T_{PV}$.

4 ENERGY PRODUCTION CALCULATION

In order to estimate the economic benefits from the use of PV/T and compare with PV systems as well as Solar thermal systems, we have to estimate first the electricity and heat production of all the considered systems.

For that matter we have considered the meteorological conditions of Athens, Greece and assumed that the systems are oriented due South at an inclination of 40°. All the calculations presented are on the basis of the active collector area (m^2).

The energy production calculation is made for a representative year on an hourly basis. The formulae of the steady state efficiencies determined by the

experimental study above, for each technology, were used to calculate the hourly energy output. The temperature for the PV cells, acting as solar energy collector, is calculated from the formula: T_{PV}= 30.0006+0.0175(G-300)+1.14(T_a-25) [14], where G is the irradiance in W/m^2 and T_a is the ambient temperature in ºC. Regarding the component of the thermal energy coming from the PV/T systems, we presume that when the incoming fluid temperature is low but still higher than the ambient temperature, then it contributes as useable energy for preheating. Therefore, it is considered that the energy received from the PV/T systems is the maximum potentially available under the circumstances.
In Tables I and II, a summary of the monthly energy production for each different system is presented.

TABLE I: Monthly energy output in kWh per m^2

Month	Solar Insolation incl. 40º kWh/m^2	PV sys pc-Si kWh/m^2	PV sys a-Si kWh/m^2	Solar Thermal kWh/m^2
Jan	84.70	10.22	4.14	37.52
Feb	101.31	12.78	5.23	49.56
March	127.99	15.69	6.52	64.60
Apr	147.92	18.48	7.73	77.75
May	172.83	21.32	9.15	92.53
June	175.98	21.08	9.33	89.58
July	191.40	22.56	10.21	95.43
Aug	197.43	23.32	10.54	101.27
Sept	168.84	20.27	8.93	88.39
Oct	131.33	16.14	6.88	69.74
Nov	102.49	12.63	5.26	53.97
Dec	84.66	10.36	4.21	40.21
Total	**1686.87**	**204.85**	**88.12**	**860.55**

The hourly data are summed and displayed on a monthly basis for one representative year in Athens, Greece. For the Hybrid systems, electric and thermal energy are presented separately.

TABLE II: Monthly energy output in kWh per m^2

Month	PV/T pc-Si kWh/m^2		PV/T a-Si kWh/m^2		PV/T-Refl. pc-Si, kWh/m^2	
	Thermal	Electric	Thermal	Electric	Thermal	Electric
Jan	29.64	10.22	33.12	4.14	30.74	10.37
Feb	37.16	12.81	41.63	5.23	40.00	13.19
March	45.69	15.84	51.28	6.53	51.01	16.65
Apr	54.45	18.72	61.17	7.76	62.99	20.11
May	63.15	21.93	71.21	9.21	76.08	24.12
June	62.51	22.36	70.80	9.47	78.70	24.98
July	67.01	24.57	76.14	10.42	81.82	27.03
Aug	69.32	25.38	78.74	10.76	81.47	27.28
Sept	59.93	21.38	67.85	9.05	67.54	22.50
Oct	47.84	16.46	53.89	6.92	51.70	16.96
Nov	37.49	12.68	42.07	5.26	38.95	12.87
Dec	30.22	10.36	33.80	4.21	30.22	10.36
Total	**604.41**	**212.73**	**681.71**	**88.96**	**691.22**	**226.41**

In our calculations, the energy consumption due to the circulator pump has been neglected, as the electric power requirements of 1 to 2 W per m^2 of collector over the estimated operation of 2000 hours per year, is a small percentage of the produced electricity (1 to 4%).

5 ECONOMIC ANALYSIS

The economic analysis considers two cases, one for domestic systems with a solar collector area less than 10m^2 and a second for larger systems with an area more than 100m^2, usually suitable for heating applications in multi-flat residential buildings, hotels, the industry and other sectors. The economic analysis follows the principles worked out in a similar effort for PV systems [15]. Other efforts for economic analysis of PV/T systems where made by Leenders [7] and by P. Frankl and al. [16], were the great potential of PV/T systems is also pointed out. 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 the case of the larger systems, the equivalent energy used for heating by burning oil is considered as avoided cost. In addition, for PV and PV/T systems, the user avoids the consumption of electricity that it is produced by the system. The evaluation runs for several years, until the initial investment and the yearly sum of benefits or charges are nullified. The last year that the investment is negative is considered as the year that the total amount paid for the system is amortized. The starting cost for electricity and oil per kWh electric and thermal produced, for the first year in the analysis, is taken to be as: 0.0851 Euro/kWhe and 0.0587 Euro/kWhth, correspondingly. For the domestic users that buy a RES system a single time tax rebate is applied during the first year of the system operation. The tax rebate is taken as 26,25% of the initial investment (average case). For the companies, the investment cost is depreciated over a period of 10 years, by 10% every year. This is a benefit that for 10 years adds to the cash flow 3,5% of the investment cost as the avoided tax payment. 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.

TABLE III: System Cost installed, Euro per m^2 with VAT.

System Description	Domestic Systems	Larger Systems
	Euro/m2 with VAT	
PV sys only C-Si	880.4	792.4
PV sys only a-Si	462.2	416.0
PV/T W C-Si	1115.2	939.1
PV/T W a-Si	697.0	562.7
PV/T W-R C-Si	1137.5	957.9
Solar Thermal	352.2	264.1

The following list summarizes the assumptions:

1. Electricity prices and oil prices are increased by 3,5% every year.
2. The interest rate for personal saving accounts is assumed to be 4%.
3. The discount interest rate is taken as the savings account rate minus the inflation rate (0,5%).
4. The energy produced annually is taken from Tables I and II.
5. The cost of the system installed, is taken from Table III, which includes 18% VAT.

Taking into account the above assumption, we introduce in the economic analysis spreadsheet the data, where the payback time for each system is calculated. Then, we plot the results for the evaluated systems for the two cases, domestic and larger systems (Figure 3).

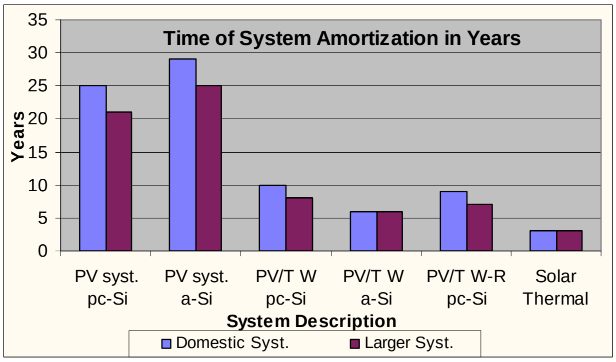

Figure 3: Time period for system payback in years.

The time of system amortization determined by the above analysis is considered to be the minimum possible under the conditions mentioned earlier. As a first observation one may notice that although the pc-Si PV system has a shorter payback time than the a-Si PV system, however the situation is reversed for the PV/T systems due to the higher thermal output of the a-Si PV/T system. The pc-Si PV/T system fitted with a reflector has a shorter payback time than pc-Si PV/T system but larger than the a-Si PV/T system. From another perspective, a PV system supporter or industrialist recognizes that there is a synergy that works in favour of the PV systems and a potential market window would open for the re-introduction of the PV technology, through a modified product, this time without the need for heavy subsidies, taking into account that the payback time is less than 10 years. It is considered that the 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.

6 DISCUSSION- CONCLUSION

The application of PV/T systems is effective in electrical output for lower PV module operating temperature, which corresponds to high thermal energy output, but to lower fluid temperature rise. These results determine the limits of the practical use of PV/T systems and regarding the use of a-Si or pc-Si PV modules, the higher electrical efficiency of pc-Si PV modules make them more effective considering the available area for their installation. The payback time under 10 years for PV/T hybrid systems is an opprotunity for a large potential market for the PV industry, as the industry environment needs products that can be marketed without or with lower subsidy support.

7 REFERENCES

[1] E.C. Kern Jr and M.C. Russel, Combined photovoltaics and thermal hybrid collector systems. Proc. of 13th IEEE Photovoltaic Specialists, Washington DC, USA, pp. 1153 – 1157 (1978)

[2] S.D. Hendrie, Evaluation of combined Photovoltaic/Thermal collectors. Proc. of Int. Conf. ISES, Atlanta, Georgia, USA, May 28 – June 1, Vol.3 pp. 1865- 1869 (1979)

[3] L.W. Florschuetz, Extention of the Hottel -Whillier model to the analysis of combined photovoltaic/thermal flat plate collectors. Solar Energy 22, pp. 361-366 (1979)

[4] P. Raghuraman, Analytical Predictions of liquid and air Photovoltaic / Thermal, flat – plate collector performance. Journal of Solar Energy Enginnering, Vol 103, pp. 291-298 (1981)

[5] T. Bergene and O.M. Lovvik, Model calculations on a flat-plate solar heat collector with integrated solar cells. Solar Energy 55, pp. 453-462 (1995)

[6] B.J. Huang, T.H. Lin, W.C. Hung and F.S. Sun, Performance evaluation of solar photovoltaic/thermal systems. Solar Energy 70, pp. 443-448 (2001)

[7] F. Leenders, A.B. Shaap, B.G.C. van der Helden, Technology review on PV/Thermal concepts. In Proc. 16th European PV Solar Energy Conference Glasgow 1-5 May pp1976-1980 (2000)

[8] H. A. Zondag, D.W. De Vries, W. G. J. Van Helden, R.J.C. Van Zolingen and A.A. Van Steenhoven, The thermal and electrical yield of a PV-Thermal collector. Solar Energy 72, pp 113-128 (2002)

[9] A.A.Al Baali, Improving the power of a solar panel by cooling and light concentrating. Solar & Wind Technology 3, pp. 241-245 (1986)

[10] H.P. Garg, P.K. Agarwal, A.K. Bhargava, The effect of plane booster reflectors on the performance of a solar air heater with solar cells suitable for a solar dryer. Energy Conv. Mgmt. 32, pp. 543-554 (1991)

[11]Y. Tripanagnostopoulos, D. Tzavellas, I. Zoulia and M. Chortatou, Hybrid PV/T systems with dual heat extraction operation. In Proc. 17th PV Solar Energy Conference Munich, 22-26 Oct pp 2515-2518 (2001)

[12]Y. Tripanagnostopoulos, Th Nousia and M. Souliotis, Test results of air cooled modified PV modules. In Proc. 17th PV Solar Energy Conference Munich, 22-26 Oct pp 2519-2522 (2001)

[13]Y. Tripanagnostopoulos, Th. Nousia, M. Souliotis and P. Yianoulis, Hybrid Photovoltaic/Thermal solar systems. Solar Energy Vol 72, 3, pp 217-234 (2002)

[14]F. Lasnier and T.G.Ang, Photovoltaic Enginnering Handbook, Adam Higler, p. 258 (1990)

[15] S.Tselepis, Financial analysis of grid connected photovoltaic systems in Greece, towards a national PV roof programme. Proc. 17th PV Solar Energy Conference Munich, 22-26 Oct pp 919-922 (2001)

[16]P. Frankl, M. Gamberale, R.Battisti, Proc. 16th European PV Solar Energy Conf., pp. 1910-1913, 1-5 May, Glasgow, U.K. (2000)