PHOTOVOLTAIC/THERMAL COLLECTORS IN LARGE SOLAR THERMAL SYSTEMS

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This paper has been presented at the "19th European PV Solar Energy Conference and Exhibition", 7-11 June 2004, Paris, France

ABSTRACT: Photovoltaic/Thermal (PVT) collectors in large solar thermal systems are the solution for the scarce roof space on high rise buildings. A technical and economical feasibility study showed that a system with PVT collectors generates more sustainable energy per square meter in comparison with system of PV modules and thermal collectors. A PVT collector system needs approximately 38% less roof space than a combined system of PV modules and thermal collectors with the same efficiency yield. The financial data of PVT collectors are still unreliable due to the lack of a learning curve. The used data are based on the costs for a batch production in stead of mass production. An indicative cost price for a PVT collector of €720/m^2 to become competitive with a combined system could be distilled from the results.
Keywords: hybrid, system, rooftop.

1 INTRODUCTION

On high-rise buildings, the available roof surface per dwelling is relatively small compared to that of low-rise buildings. This means that per dwelling less area is available for the harvesting of solar energy. Available solar roof technologies for high rise buildings are PV-modules and large solar thermal collectors. A choice has to be made between these two technologies to use the scarce roof surface and combinations of these systems are rarely applied. The introduction of PhotoVoltaic/Thermal collectors 'simplifies' this choice. Photovoltaic/thermal collectors or PVT-collectors generate more solar energy per unit surface area than a combination of separate photovoltaic panels and solar thermal collectors. Moreover, PVT collectors share the aesthetic advantage of PV. The higher annual energy efficiency is reached due to the integration of PV cells with a solar thermal absorber, forming one PVT-laminate that converts solar radiation into electricity and heat simultaneously. The PVT laminate is placed in an insulated glass covered aluminum box, which forms the PVT-collector.

Figure 1: Front and back of a PVT laminate

The potential of PVT-systems has already been proven but only a few demonstrations are applied in practice [1].

This paper presents the results of a technical and economical feasibility study [2]. Three case studies were carried out to determine the energetic, technical and financial differences for the application of PVT-collectors in large solar thermal systems in relation with three reference systems: 1) a solar thermal collector system only 2) a combined system of PV-modules and thermal collectors and 3) PV modules only. The selected cases were three high rise buildings in The Netherlands for which solar collectors already have been planned. Figure 2 shows an artist impression of the high rise buildings. The solar systems provide the houses with hot water and space heating. The available roof areas for solar components are 136 m^2; 163 m^2 and 184 m^2 respectively.

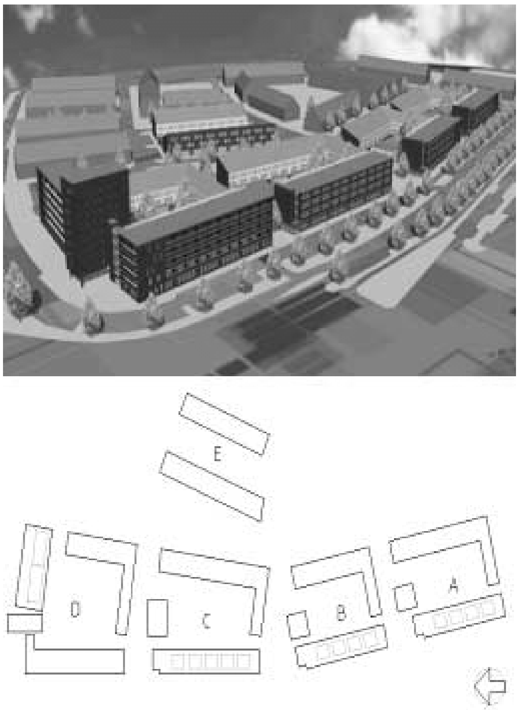

Figure 2: Artist impression of the project (above). Location of the solar components (below).

2 ENERGY COMPARISON

The comparison of a PVT collector can be approached from two perspectives, namely from a thermal perspective and from an electrical perceptive. The approach from these two perspectives has common aspects as the shading issues and the suitable amount of roof space. The annual thermal efficiency of a solar thermal component depends on the heating installation configuration in which it is installed. Therefore, the determination of the added value from a thermal point of view requires extra knowledge of the heat demand pattern of the building and the heating installation. For the present energy performance comparison it was chosen to keep the configuration and tilt angle constant and only vary the collector and PV module lay out as presented in table I.

Table I: Overview of the solar energy system configurations analysed.

Configuration	Results energetically (GJp/yr)
Reference without solar system	Basic heat demand load
A m^2 Thermal collector*	$Q_{th}1$
A m^2 PVT*	$Q_{th}2 + Q_{el}1$
A m^2 PV-modules*	$Q_{el}2$
B m^2 Thermal collector + C m^2 PV-module	$Q_{th}2 + Q_{el}1$

** The A represents the amount of maximum suitable roof space for the solar components which does not vary per building; Q = heat and E = Electricity. B and C represents the area needed to produce as much energy as the PVT collector.*

In this study the dynamic simulation software program 'TRNSYS 15' was applied to determine the added value from a thermal perspective and the heat and electricity demand of the buildings. Table II shows the characteristics of the buildings.

Table II: Overview of the solar energy system configurations analysed.

Buildings	A	B	C
Roof area (m^2)	408	216	488
Max. available roof area for solar components	136	163	184
# households	32	61	72
Heat demand (GJ_p/yr)	686	1009	1434
Building related electricity demand (GJ_p/yr)	321	561	751
Hot water storage tank (l)	800	800	1400
Collector storage tank (l)	4000	5000	6000
Tilt angle	17°	10°	17°
Shading height angle solar collector	20°	20°	20°
Shading height angle PV modules	12°	12°	12°
Shading height angle PVT collectors	12°	12°	12°

* Ventilation, lights and pumps

In table III the thermal efficiency parameters of a solar thermal collector and a PVT collector are presented. These parameters are defined in the following equation.

$$\eta_{th} = \eta_{th,0} - a_1\left(\frac{T_{in} - T_a}{I}\right)$$

Table III: Thermal efficiency parameters Thermal collector and PVT collector [3][4]

Parameter	Solar collector	PVT-collector
Intercept efficiency ($\eta_{th,0}$)	0.76	0.58
First order coefficient (a_1)	3.47 m^2 /W K	5.30 m^2 /W K

Finally, the heating installation (see figure 1) determines the total annual thermal efficiency. The heating installation for all three buildings is the same with exception of the storage vessel (see table II). The heating installation consists of solar collectors; storage tank for solar collector; storage tank for hot water; heat exchangers; gas absorption heat pump; auxiliary heaters and distribution pipes for central heating and hot water. Detailed information of the thermal simulation process can be found in the work 'Simulating PV Thermal collectors in large solar systems in TRNSYS' [5].

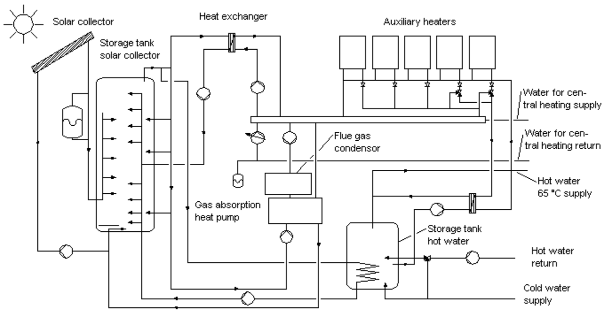

Figure 3: Diagram of heating installation

The electrical efficiency (η_{el}) of a PVT collector is calculated as shown in the formula below [6].

$$\eta_{el} = 0.092 - 0.00045(T_{PV} - 25)$$

T_{pv} is the temperature of the PV cell. For calculating T_{pv} two different cases are distinguished: The situation that water is running through the PVT collector and the situation that no water is flowing through the collector. In the first situation, T_{pv} is given by:

$$T_{PV} = T_{fluid} + \Delta T_{PV \rightarrow fluid} = \frac{T_{in} + T_{out}}{2} + \frac{\dot{m} C_p (T_{out} - T_{in})}{h_{ca}}$$

In which h_{ca} = heat transfer coefficient between PV cells and fluid (~150 W/m^2K).

For the situation no water is flowing, the formula as shown below is used.

$$T_{PV} = \frac{T_a + \frac{I}{a_1}\left[\eta_{th,0} - \eta_{el,0}\left(1 + \beta T_{ref}\right)\right]}{1 - \frac{I}{a_1}\beta \eta_{el,0}} \quad [7]$$

$\eta_{el,0}$ = the PV-efficiency at standard test conditions[1] ($\eta_{el,0}$ = 9,2%) [4]

β = the temperature coefficient (β = 0,45 %/K) [4].

The formula written below is used for the calculation of the electrical efficiency of the PV modules. This efficiency is 8% higher than the electrical efficiency of a PVT collector. The additional glass layer of a PVT collector compared with a PV panel causes this difference.

$$\eta_{el} = 0.100 - 0.00045(T_{PV} - 25)$$

with

$$T_{PV} = \frac{T_a + \frac{I}{a_1}\left[\eta_{th,0} - \eta_{el,0}\left(1 + \beta T_{ref}\right)\right]}{1 - \frac{I}{a_1}\beta \eta_{el,0}}$$

The simulations results showed that T_{pv} in the PVT collectors reach higher temperatures than T_{pv} in the PV modules, expressed in figure 4. The higher temperatures result in a lower electrical performance.

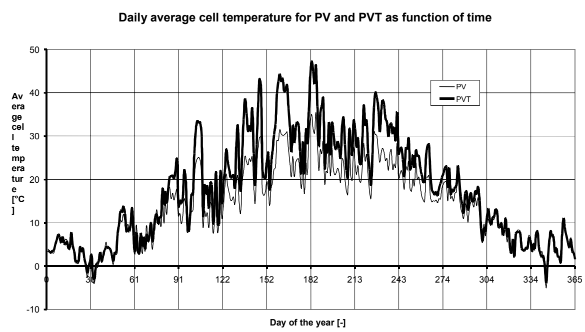

Figure 4: PV cell temperature of a PV module and PVT collector

[1] STC: radiation $I = 1000$ W/m^2, reference temperature $T_{ref} = 25$°C.

The energy performance simulation results are presented in table IV. It can be concluded that the annual energy performance per square meter of PVT-collectors is higher than the thermal collector system, the PV modules system and the combined thermal collector and PV module system.

Table IV: Average energy performance of solar systems

	Q_{th} (GJ_p/yr) /m^2	Q_{el} (kWh/yr) / m^2)	Q_{tot} (GJ_p/yr) /m^2 *
Thermal collector	1.17	-	1.17
PVT collector	0.87	82**	1.63
PV modules	-	93	0.86
Combi Thermal collector & PV modules	1.72	94	1.29***

** $Q_{tot} = Q_{th} + Q_{el}$ **1 kWh = 3.6 MJ. Electricity plant efficiency in The Netherlands is 0.39.*
**** $Q_{tot} = (Q_{th} + Q_{el})/2$. The PVT -collector produces the energy in one square meter in relation to this combination.*

3 TECHNICAL COMPARISON

The shading height angle, the tilt angle in relation to the distance between two arrays, and the available roof surface including the regulatory, safety and aesthetical aspects are important parameters in the determination of the maximum available area for solar components. During the design of the system roof configuration (saw tooth) it was found that the influences of the shading height angle or mutual shading has a big influence on the possible number of the integrated PV-components applied. The regulatory maximum shading height angle for solar thermal components is 20° but for PV-components 12°. In the table below the results of technical feasibility analysis are presented. The table shows the desired and physically possible amount of roof space per solar component on the buildings. It can be concluded from this table that the technical feasibility analysis that a the combined system of thermal collectors and PV modules requires ca. 38% more roof space in comparison with a PVT collector system which produces the same amount of energy (see table V). In all cases it was not possible to install the combined thermal collector and PV module system on the roof of the buildings.

Table V: Results of the technical feasibility analysis

	A		B		C	
	Desired # of m^2	Result	Desired # of m^2	Result	Desired # of m^2	Result
Thermal collector	136	+	163	+	184	+
PVT collector	136	-	163	+	184	+
PV modules	136	+	163	+	184	-
Thermal collector	68	-	80	-	98	-
PV modules	117	-	142	-	161	-

4 ECONOMICAL COMPARISON

The economical feasibility study only included the extra costs for the roof part of the solar components namely, the component costs, the BOS_{th} and BOS_{el} costs. This type of comparison (only roof part) between the thermal related solar components and the PV-modules is not totally valid because PV modules do not need the whole heating installation to function. In fact a 'whole' system compared with a reference would be better. The used data for the cost estimation of PVT collectors contain an uncertainty due to the lack of a learning curve in relation to the learning curves of thermal collectors and PV modules. The PVT collector costs are based on prototype batch productions costs. However, the results in the table can be used indicatively.

Table VI: Results of the economical feasibility analysis

	Q_{tot} (GJ_p/yr)/ m^2	Compo-nent (€/m^2)	BOS_{th} (€/m^2)	BOS_{el} (€/m^2)	Total (€/m^2)	(€/GJ_p) t = 20yr
Thermal collector	1.17	184	129	-	313	14.23
PVT collector	1.63	610*	162	131	903	27.70
PV modules	0.86	375	-	281	656	38.14
Combi Thermal collector	1.29	184	121	-	524**	20.31**
PV modules		375	-	240		

* The PVT component costs are based on a batch production.

** Total system cost divided by total solar system surface (Thermal + PV), which is 36% larger than the PVT collector surface. It is technically not possible to place a combined system that produces the same amount of energy as the PVT collector.

It can be concluded from the economical feasibility analysis between the thermal related components that thermal components are the cheapest for the three cases. Also it can be concluded that the price (€/m^2) of a PVT collector system must reduce to € 655/m^2 (20.31*1.63*20) to compete with the larger combined thermal collectors and PV module system. In the case that the total costs for the combined system are divided by the PVT collector surfaces applied the average maximum costs for a PVT collector system must reduce to € 720/m^2. Cost lowering of the PVT collector is expected due to better insight in costs when PVT collectors are produced in mass.

5 CONCLUSIONS

PVT collectors annually generate the highest quantity of primary energy per square meter in comparison with a thermal collector system, a PV module system or a combined system of thermal collectors and PV modules. Further a combined system requires 38% more roof space for the same yield as a combined system, which was physically not possible in the case analysed. The shading height angle, the tilt angle in relation to the distance between two arrays, and the available roof surface including the regulatory, safety and aesthetical aspects are important parameters in the determination of the maximum available surface for solar components.

A good comparison between PVT collectors and PV modules need to be executed on building/system level. The target price for a PVT collector is €720/m^2 in order to become competitive with a combined system.

6 ACKNOWLEDGEMENT

This work has been realised in part by support of the Renewable Energy in the Netherlands research program, implemented by the Dutch Organisation for Energy and Environment Novem, in commission of the Ministry of Economic Affairs.

6 LITERATURE

[1] Helden, W.G.J. van; Zondag, H.A." Photovoltaic thermal panels: on the brink of demonstration"; PV in Europe - From PV Technology to Energy Solutions Conference and Exhibition, Rome, Italy, October 7-11, 2002. ECN report: ECN-RX--02-048

[2] Elswijk, M.J.; Strootman, K.J.; Jong, M.J.M. (ECN, Petten (Netherlands)); Lange, E.T.N. de (Eneco Energie); Smit, W.F. (Eneco Energie), PVT in collectieve zonthermische systemen, ECN-report ECN-C--03-112, Petten, The Netherlands, December 2003.

[3] TNO; TNO-report 2002-DEG-R023, page 47, 12 november 2002

[4] Zondag, H.A.; M.J. Elswijk, 3e prototype combi-paneel fase 1, ECN-rapport ECN-C-01-0134, Petten, the Netherlands, 2001.

[5] Jong M.J.M; Elswijk M.J.; Strootman K.J., "Simulating PV Thermal collectors in large solar systems in TRNSYS", TRNSYS user day, Stuttgart, Germany, March 2004. ECN-report ECN-RX--04-028, May 2004.

[6] De Vries, D.W.; Design of a photovoltaic/thermal combi-panel, PhH Thesis Eindhoven University of Technology, Eindhoven, the Netherlands, 1998.

[7] Bakker M.; Strootman K.J.; Jong M.J.M.; Elswijk M.J.; 'PVT Bodemregeneratie - Haalbaarheidsstudie naar bodemregeneratie met behulp van een dakvullend PVT-systeem'; ECN-rapport ECN-C-03-103, Petten, December 2003.

[8] http://www.ecn.nl/dego/research/thermal_systems/
pvt.en.html