DEVELOPMENT AND APPLICATIONS FOR PV THERMAL

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ABSTRACT: PV thermal collectors produce both electricity and heat simultaneously. The efficiency curves of three different collector concepts have been calculated. These curves have been used in a numerical systems study in which these collectors were used for hot tap water or domestic heating, either with or without a heat pump. It was found that the systems with uncovered PVT collectors had a relatively low yield. Further optimisation for this class of systems is necessary.
Keywords: PV thermal –1: PV systems – 2: c-Si – 3

1 INTRODUCTION

PV that is insulated at the rear side can get as hot as 85 °C if exposed to an irradiance of 1000 W/m^2. In a conventional PV laminate this heat is not used, and the generation of it is undesirable since the PV efficiency decreases with increasing temperature. Therefore it seems to be an attractive idea to extract this heat by means of active cooling of the PV and to use this heat. In this way, the PV is not only producing electricity but heat as well. This idea is worked out in the PV-thermal collector.
Potential Advantages of this integration are:
- a higher yield per unit area
- reduced BOS and labour costs
- an increased electrical yield by cooling of the PV

Research is presently going on at ECN and the Eindhoven University of Technology (EUT) in order to find out what are the possibilities and the problems of this integrated design. In order to obtain a clearer picture, several module concepts have been built, among which a single cover PV thermal sheet-and-tube collector and recently a 2 absorber channel collector. The sheet-and-tube prototypes have been tested with respect to thermal and electrical efficiency in the outdoor test facilities of ECN and EUT, as well as with respect to mechanical characteristics by means of thermal cycling and thermal shock tests in the climate chamber at ECN. In addition, numerical models were built and verified with data obtained from the single cover sheet-and-tube collector. It was found that the measured data corresponded fairly well with the model predictions (De Vries, 1998; Zondag et al., 1999). The numerical models were used to generate efficiency curves for various PV thermal collector concepts and the results were used in the systems study that is presented here. The systems focus on the residential market since this is the largest market for solar collector systems. Calculations have been made for a domestic hot water system and various domestic heating systems, either with or without heat pump and aquifer.

2 COLLECTOR CONCEPTS

2.1 Introduction

Several PV thermal collector module concepts are possible:
1. a different amount of top covers (zero, one or two covers)
2. channel constructions versus sheet-and-tube constructions
3. the possible addition of a secondary absorber located underneath the PV.

This basic set of design choices can be extended with material choices to be made:
1. what type of PV (monocrystalline silicon, multicrystalline silicon, amorphous silicon, CIS or other)
2. what cover materials (a secondary cover might be made of teflon instead of glass)
3. what collector medium (air, water or other)
4. what absorber material (copper, plastic)

In the present study, the effect of the basic design choices is examined. The choice of the materials is the same for all examined concepts, and is set to a multicrystalline PV laminate, a glass cover, copper tubing and a copper absorber. A sheet-and-tube concept is calculated with one or zero covers. In addition, a 2 absorber channel concept is examined.

2.2 Sheet-and-tube PV-thermal

Two types of sheet-and-tube PV thermal collectors have been studied: with zero and one top cover. The top cover was made from low-iron glass with a transmission of 92%. The PV laminate is a standard Shell Solar PV laminate with a tedlar rear side foil and a 9.7% laminate efficiency at STC. The presence of the top cover increases the thermal performance but reduces the electrical performance due to additional reflection losses.

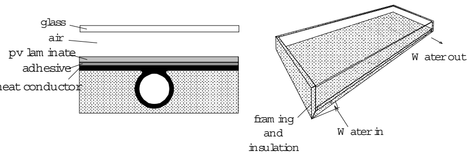

Figure 1: Sheet-and-tube PV thermal

2.3 Two absorber PVT collector

In addition, a 2 absorber channel PV thermal collector has been studied, as shown in Figure 2. In this concept, the PV-laminate is the primary absorber. The secondary absorber is a black copper absorber that is located underneath the PV and absorbs the radiation that is transmitted through the PV laminate. For this concept, the PV laminate should be as transparent as possible. This implies a glass rear of the laminate and a back grid at the rearside of the PV. The 2 absorber PV thermal collector is again covered by a glass cover.

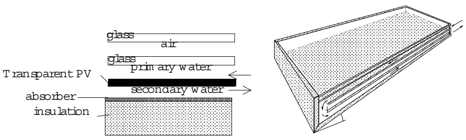

Figure 2: Two absorber channel PV thermal

3 EFFICIENCY CURVES

The efficiency curves of the three collectors were calculated with the numerical model at a fixed set of ambient conditions: a wind velocity of 1 m/s, ambient temperature of 20°C, irradiance of 800 W/m^2 and a water flowrate of 75 litres/hour/m^2. In the figures, the efficiency is plotted against the reduced temperature, which is defined here as

$$T_{red} = (T_{in} - T_a)/I$$

in which T_{in} is the inflow- and T_a the ambient temperature in °C, while I is the irradiance in W/m^2. In the calculations, the reduced temperature was varied by varying the inflow temperature from 20 °C to 60 °C.

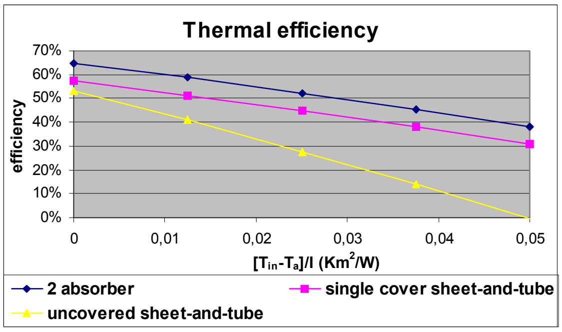

Figure 3: Thermal efficiency curves

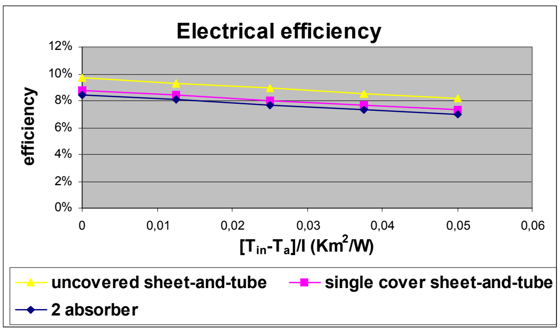

Figure 4: Electrical efficiency curves

These collector concepts differ in their thermal efficiency, as depicted in Figure 3. In particular, the uncovered PV-thermal collector has a lower thermal efficiency and a much larger slope than the covered concepts, while the 2 absorber collector shows the highest thermal efficiency. At the other hand, for the electrical efficiency, the ranking is reversed, as depicted in Figure 4; the uncovered concept performs best while the 2 absorber is worst.

The sensitivity of the generated efficiency curves for the applied set of ambient conditions was tested. It was found that the wind speed had a substantial effect on the thermal efficiency for the case in which no cover was applied, whereas the effect was small for the covered collectors. Therefore, different efficiency curves were calculated for different wind speeds. The results are presented in Figure 5 and Figure 6. The effect of wind speed for the 2 absorber case is not shown, but it closely follows the covered sheet-and-tube case. These figures also show the electrical efficiency. It is clear that the latter is not affected by the change in wind speed. At the other hand, the effects of irradiance and ambient temperature were found to be of less importance.

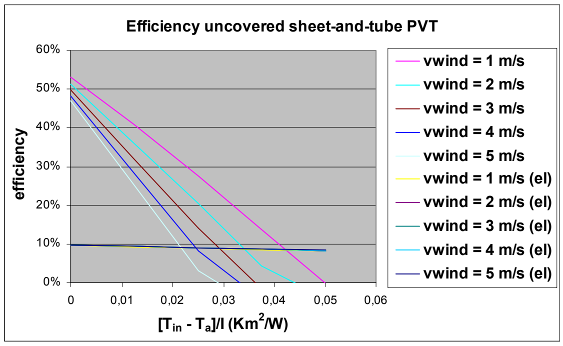

Figure 5: Thermal and electrical efficiency for the uncovered sheet-and-tube collector.

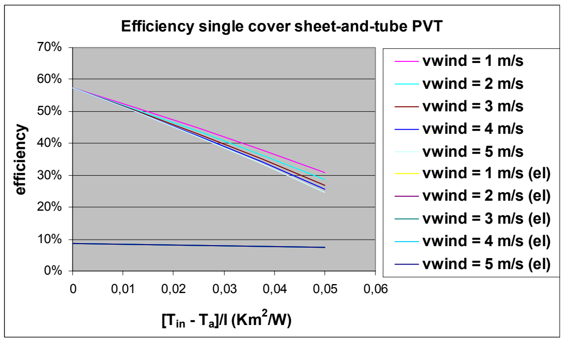

Figure 6: Thermal and electrical efficiency for the covered sheet-and-tube PV thermal concept.

4 ANNUAL YIELD CORRECTIONS

4.1 Introduction

In order to obtain annual efficiencies from the efficiency curves for thermal and electrical efficiency, several corrections have to be made. These corrections are related to efficiencies of system components other than the collector itself, such as power loss in the inverter or heat loss from the storage tank. In addition, the collector itself will show a change in performance when operated at conditions that differ from STC.

4.2 Thermal corrections

As indicated above, by interpolation between the efficiency curves calculated for different wind speeds, the effect of wind could be taken into account. In addition, the thermal efficiency decreases because of increased reflection losses at if the angle of the irradiance differs from the normal to the collector surface more than 60 degrees. For the calculation of the annual efficiency, η_0 is multiplied with the correction factor shown in Figure 7.

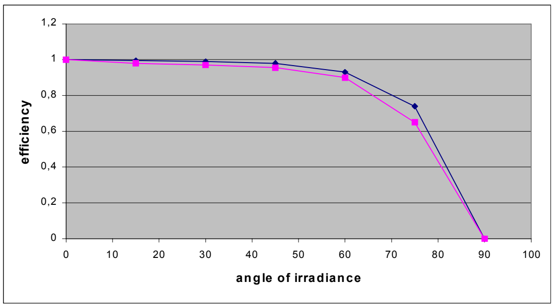

Figure 7: Effect of angle on transmission of irradiance.

4.3 Electrical corrections

The electrical efficiency is reduced by increased reflection losses at large irradiance angles, similar to the thermal efficiency. The same correction is applied to account for the effect. Furthermore, the PV efficiency is also affected by temperature and low irradiance. The effect of temperature on multicrystalline silicon can be modelled by the expression

$$\eta_{el} = \eta_{el,STC}\left(1 - 0.0045\left[T_{PV} - 25^{o}C\right]\right)$$

The effect of low irradiance is calculated with the correction factor shown in Figure 8.

Finally, the inverter losses should be taken into account. The inverter efficiency is also presented by Figure 8 while the MPP tracking efficiency was taken to be a constant 98%.

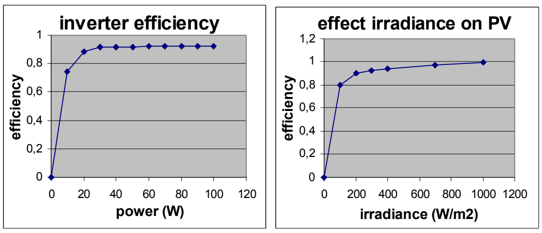

Figure 8: Left: Effect of low power on inverter efficiency. Right: Effect of low irradiance on PV efficiency.

5 SYSTEM CONCEPTS

5.1 introduction

All system configurations simulated here are aiming at an average family house, which is well insulated. For the ambient conditions (irradiance, wind speed, ambient temperature) the KNMI De Bilt test reference year is used. Several system concepts have been evaluated. These system configurations have been chosen to illustrate effects, but do not claim to be the optimal systems for practical applications.

The systems presently examined are

1. Domestic hot water
2. Domestic heating with a storage tank
3. Domestic heating with a storage tank and a heat pump
4. Domestic heating with heat pump and aquifer

These systems are indicated schematically in Figure 9

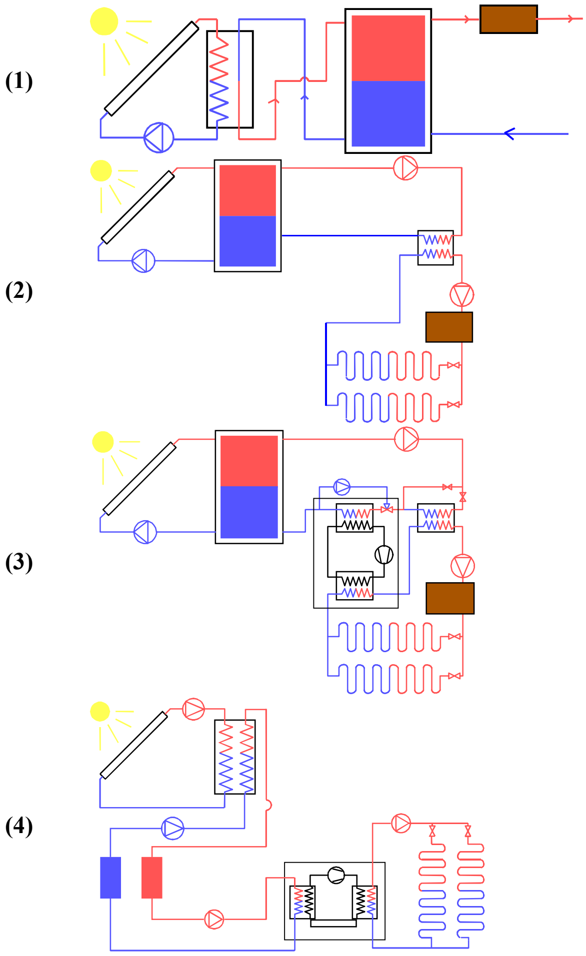

Figure 9: System concepts. Top to bottom: (1) domestic hot water, (2) domestic heating, (3) domestic heating with heat pump, (4) domestic heating with heat pump and aquifer.

For the system performance, the sizing of the various system components is very important. In particular, the size of the storage tank to the PV-thermal area, as well as the amount of the thermal demand to the tank size, are important for the temperatures obtained in the tank and therefore for the thermal system performance.

5.2 Hot water demand

For the tapping pattern a fixed tapping schedule is assumed that is the same for each day of the year. It is shown in Figure 10.

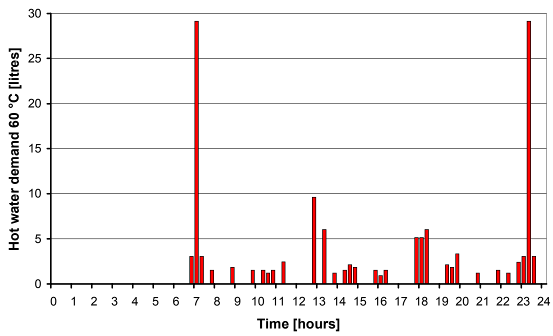

Figure 10: Tapping schedule

The schedule assumes a total daily tapping demand of 175 litres of heated water of temperatures between 45 and 55 °C. This implies a total demand 119 litres of water of 60 °C unmixed with cold water, corresponding to an annual demand of 9.2 GJ. However, piping losses have to be taken into account as well. The amount of hot water left in the piping after a tap, increases the total daily amount of hot water to 139 litres, corresponding to an annual energy demand of 10.6 GJ for hot water. This implies a piping loss of 1.4 GJ annually.

5.3 Tapping system characteristics

The tapping vessel contains 200 litres of water and has an insulation of 10 cm of mineral wool ($U = 0.35$ W/m^{2}K). The heat exchanger in the tapping vessel has an efficiency of 75%. The incoming water is assumed to have the same temperature as the ground. A heater is used to heat the water that is withdrawn from the tapping vessel to a temperature of 60 °C (because of legionella regulations).

5.4 Heating demand

For domestic heating, a load pattern was established for a well insulated house, using the TRNSYS package. The house was assumed to have a heat resistance Rc of 6 m^{2}K/W (the minimal insulation for new buildings in Holland is Rc = 2.5 m^{2}K/W) and windows with a heat loss coefficient U of 0.7 W/m^{2}K. The temperature control is based on a minimum temperature at the ground floor of 21 °C and a at the first floor of 16 °C throughout the day. For the systems without heat pump, the minimum temperature of the ground floor is reduced to 16 °C at night. The ventilation is 75% of the volume of the house per hour, which is applied at the ground floor during the day and at the first floor during the night. A balanced ventilation system is applied having 90% heat recovery. The resulting annual heating demand was found to be 5.6 GJ for the case with 16 °C at night and 5.8 GJ for the case with 21 °C.

5.5 Heating system characteristics

The seasonal storage tank was assumed to be 20 m^3 and to have an insulation of 50 cm of mineral wool ($U = 0.07$ W/m^{2}K). The heating is assumed to take place through a low temperature floor heating system, that requires a temperature of 35 °C. The floor heating system consists of two subsystems for the ground floor and the first floor, which can be operated independently. The heat is transferred from the storage through a heat exchanger with an efficiency of 90%, which functions as long as the storage temperature is over 35 °C.

In addition, some systems also use a heat pump, that is switched on if the storage temperature gets below 35 °C. It was assumed that the maximum source temperature of the heat pump is 25 °C. To be able to use the heat pump in the temperature range between 35 °C and 25 °C, the incoming fluid from the vessel is mixed with the chilled outlet fluid of the heat pump to reduce the temperature to 25 °C. The COP of this heat pump was assumed to depend on the temperature difference between the source and the load according to Figure 11, while the electrical power consumed by the heat pump was assumed to be fixed at 0.31 kW.

Finally, one of the systems uses an aquifer for ground storage of thermal energy. This aquifer is modelled by assuming a cold source temperature of 9 °C and a hot source temperature of 16 °C. During the summer, fluid from the cold source is heated and stored in the hot source. During the winter, energy is extracted from the hot source and the chilled fluid is stored in the cold source again. It is assumed that 60% of the energy supplied to the aquifer can be recovered.

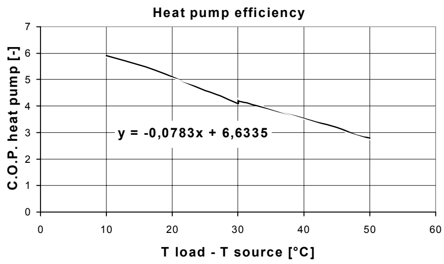

Figure 11: Heat pump performance

5.6 Collector control algorithm

The tapping vessel temperature and the irradiance are measured, and whenever the reduced temperature is such that a positive yield is to be expected (efficiency larger than zero, using an extrapolation of Figure 3), the pump is switched on.

In case of the aquifer, water of a fixed temperature has to be supplied to the hot source. The outflow temperature is kept at a constant value by continuously adapting the flow rate. It is assumed that the collector pump can be controlled over the range from 70 litres/hour to 400 litres/hour.

5.7 PVT area sizing

No straightforward procedure exists to determine the optimal PVT area. For each system, a slightly different approach is used.

For the domestic hot water system with the covered PVT concepts, the sizing is based on conventional thermal hot water collector systems; 6 m^2 of PVT area was chosen for a tank of 200 litres. Also for the uncovered PVT concept 6 m^2 is chosen, because simulations show that a larger area does not lead to a larger system yield.

For the domestic heating system without heat pump and a storage vessel of 20 m^3, calculations show that the thermal performance increases significantly up to an area of 10 m^2. The same value was used for the 2 absorber concept.

This approach was also used for the domestic heating system with heat pump. Here, smaller PVT areas were found: 9 m^2 for the uncovered system and 5 m^2 for the two covered systems. An overview of the effect of PVT size on system performance for this case is shown in Figure 12. Note that since the heat pump is consuming electricity, the electrical system efficiency becomes negative for small PVT-areas.

For the aquifer system with heat pump, it is decided to do the domestic heating entirely with the heat pump. Therefore, the PVT area is sized in such a way that it produces sufficient thermal energy to meet the heating demand, given the 60% aquifer efficiency. In this way, the higher the collector efficiency, the smaller the collector area required.

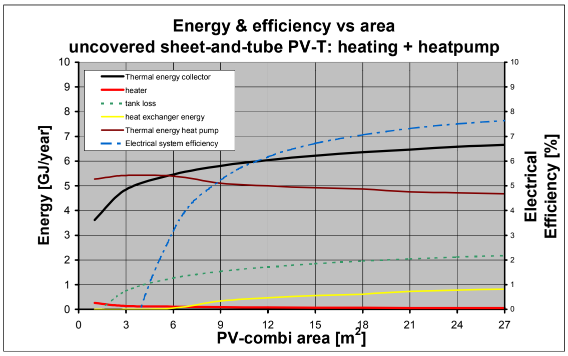

Figure 12: The size optimisation for domestic heating system with heat pump in combination with the uncovered sheet-and-tube PVT concept.

6 RESULTS

The system calculations show the amount of energy produced by the various installations at each quarter of an hour time interval in the year. As an example, Figure 13 shows the cumulative performance over a year for the combination of a domestic hot water system with a covered sheet-and-tube collector.

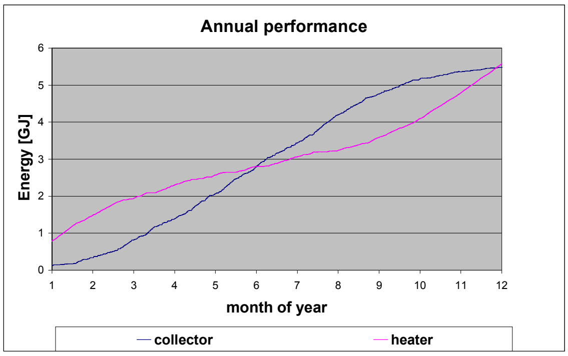

Figure 13: Annual performance of a hot water system

It is clear from this figure that the collector produces roughly half of the required heat, while the heater produces the remainder. However, the collector produces most during the summer (as seen from the steepness of the slope of the cumulative curve), while the heater produces most during the winter.

At the other hand, Figure 14 presents an overview of the annual performance for the combination of a covered sheet-and-tube collector with the domestic heating system with heat pump. This figure shows the cumulative energy yield over the year of the various installation components. It is shown that the heater only has a very small contribution, while the contribution of the collector is very large. The heat exchanger extracts heat from the storage tank only in November. At the end of this month, the heat storage temperature gets below 35 °C and the heat pump takes over, which continues its operation up to the first half of March. In addition, the figure shows a substantial heat loss from the storage tank in the period from May to December, which is larger than the contributions of the heat exchanger and the heater together.

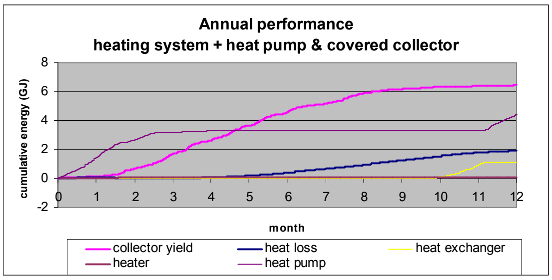

Figure 14: The annual system performance for a heating system

From these results, the annual thermal and electrical efficiencies are calculated for the different systems. These are presented in Table 1 and Table 2. In these tables, several quantities appear that have been defined as follows:

Electrical PVT efficiency: $$\eta_{PVT} = \frac{P_{el,PVT}}{IA}$$

Electrical system efficiency: $$\eta_{sys} = \frac{P_{el,PVT} - P_{el,heatpump}}{IA}$$

Thermal PVT efficiency: $$\eta_{PVT} = \frac{P_{th,PVT}}{IA}$$

Thermal system efficiency: $$\eta_{sys} = \frac{P_{th,total} - P_{th,heater}}{IA}$$

Solar Fraction: $$SF = \frac{P_{th,total} - P_{th,heater}}{P_{th,total}}$$

In these equations, I is the irradiance (W/m^2), A is the PVT area (m^2), P_{el} is electrical power, which is produced by the PVT and consumed by the heat pump, while $P_{th,total}$ is the total thermal power produced by the system (including the heater). Note that electrical power consumed by the heater or the circulation pump of the PVT is not included in the electrical system efficiency. Also note that depending on system configuration, SF may refer to the heating demand or the hot water demand.

Several conclusions can be drawn from these tables. First of all, the application of a heat pump strongly increases the thermal yield of the heating system. This was expected since the application of a heat pump leads to a lower average tank temperature. This is demonstrated in Figure 15. A lower tank temperature leads to a higher thermal efficiency due to two effects. First of all, the yield is higher if the inflow temperature in the collector is lower. Second, the amount of running hours of the collector is increased since the collector produces a positive yield over a larger range of climate conditions.

However, the application of a heat pump demands a price in electrical energy. The simulations show that for most systems the PVT collector is able to supply more electrical power than is consumed by the heat pump, but nevertheless this presents a serious drain on the electrical system efficiency. However, for the aquifer system, more power is consumed by the heat pump than is produced by the PVT collector.

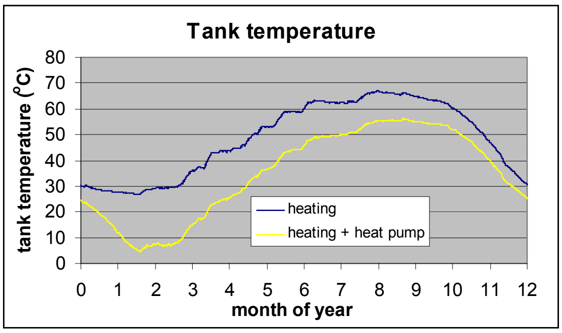

Figure 15: The temperature in the 20 m^3 storage tank for the case with and without heat pump (for the calculation with covered sheet-and-tube collector).

Furthermore,, it is clear that the uncovered PVT thermal efficiency becomes better the more the collector temperature is reduced. The uncovered PVT thermal efficiency is much lower than for the covered PVT collectors for the hot tap water system and the domestic heating system with storage tank, even if a heat pump is applied. However, for the aquifer system, the thermal efficiency of the uncovered PVT becomes higher than that of the covered sheet-and-tube PVT.
At the other hand, if the focus is on electrical system performance, the uncovered collector for domestic hot water performs best. However, the thermal system efficiency for this system is half of the thermal system efficiency for the other PVT concepts. As expected, the best PV efficiency is found for the uncovered collector in combination with a heat pump.

7 CONCLUSIONS

In this paper, a number of conclusions have been drawn.

- For the tap water system and the domestic heating systems with storage tank calculated here, the thermal efficiency of the uncovered PVT is clearly less than for the covered PVT concepts, even if a heat pump is applied. For an aquifer, however, the uncovered PVT performs roughly as well as the covered concepts.
- A heat pump consumes more power than the increase in power output from the PV-laminate due to low temperature.
- The application of a heat pump raises both thermal collector- and system efficiency dramatically.
- The best thermal system efficiency and the best thermal collector efficiency is for all systems given by the 2 absorber collector
- The best electrical system efficiency is obtained with the uncovered collector for domestic hot water. However, thermal system efficiency here is half of that for the other systems
- The best PV efficiency is obtained with the uncovered collector for the heating system with heat pump.

In drawing these conclusions, it should be kept in mind that only a limited set of non-optimised systems has been calculated. In addition, the systems presented are not optimised from a practical point of view. Therefore, further system optimisation should be carried out.

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Thermal efficiency	PVT uncovered			PVT 1 cover			2 absorber		
System- and collector efficiencies	System	PVT	SF	system	PVT	SF	system	PVT	SF
Domestic hot water	5.75% (6 m^2)	13.0%	15%	15.2% (6 m^2)	23.3%	39%	17.4% (6 m^2)	25.8%	45%
Domestic heating	-	-	-	6.7% (10 m^2)	15.5%	48%	8.0% (10 m^2)	17.9%	57%
Domestic heating + heatpump	16.2% (9 m^2)	17.3%	98%	29.5% (5 m^2)	34.5%	99%	29.5% (5 m^2)	37.1%	99%
Domestic heating + heatpump & aquifer	45.5% (3.3 m^2)	57.0%	100%	42.3% (3.5 m^2)	52.6%	100%	47.2% (3.2 m^2)	59.8%	100%

Table 1: Annual thermal system and module efficiencies

Electrical efficiency	PVT uncovered		PVT 1 cover		2 absorber	
System- and collector efficiencies	System	PVT	system	PVT	system	PVT
Domestic hot water	7.7%	7.7%	6.4%	6.4%	6.1%	6.1%
Domestic heating	-	-	6.6%	6.6%	6.3%	6.3%
Domestic heating + heat pump	5.2%	8.8%	2.1%	7.5%	2.4%	7.2%
Domestic heating + heat pump & aquifer	-1.1%	8.7%	-1.2%	7.9%	-2.6%	7.6%

Table 2: Annual electrical system and module efficiencies