Detailed analysis of the energy yield of systems with covered sheet-and-tube PVT collectors

R. Santbergen, C.C.M. Rindt, H.A. Zondag, R.J.Ch. van Zolingen

Eindhoven University of Technology, Department of Mechanical Engineering, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
Energy research Centre of the Netherlands (ECN), P.O. Box 1, 1755 ZG Petten, The Netherlands

Abstract

Solar cells have a typical efficiency in the range of 5–20%, implying that 80% or more of the incident solar energy can be harvested in the form of heat and applied for low-temperature heating. In a PVT collector one tries to collect this heat. In this work, the electrical and thermal yield of solar domestic hot water systems with one-cover sheet-and-tube PVT collectors were considered. Objectives of the work were to understand the mechanisms determining these yields, to investigate measures to improve these yields and to investigate the yield consequences if various solar cell technologies are being used. The work was carried out using numerical simulations.

A detailed quantitative understanding of all loss mechanisms was obtained, especially of those being inherent to the use of PVT collectors instead of PV modules and conventional thermal collectors. The annual electrical efficiencies of the PVT systems investigated were up to 14% (relative) lower compared to pure PV systems and the annual thermal efficiencies up to 19% (relative) lower compared to pure thermal collector systems. The loss of electrical efficiency is mainly caused by the relatively high fluid temperature. The loss of thermal efficiency is caused both by the high emissivity of the absorber and the withdrawal of electrical energy. However, both the loss of electrical and thermal efficiency can be reduced further by the application of anti-reflective coatings. The thermal efficiency can be improved by the application of a low-emissivity coating on the absorber, however at the cost of a reduced electrical efficiency.

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Keywords: PVT collectors; PVT systems; PVT system yield; Solar thermal collector

1. Introduction

Solar cells have a typical efficiency in the range of 5–20%, depending on the type of solar cell. This implies that 80% or more of the incoming solar energy can be harvested in the form of heat. In a PVT collector one tries to collect this low-temperature heat. This heat can be used in a range of applications, for example tap-water heating and space heating. A wide variety of PVT collector designs exists. A comprehensive overview of flat-plate PVT collectors and systems was given by Zondag (2008). Examples of PVT collectors based on the concentration of sunlight were described by Coventry (2005) and Smeltink and Blakers (2007).

Flat-plate collectors can be either glazed or unglazed and either air or liquid can be used as heat transporting fluid. Either a sheet-and-tube plate (Saitoh et al., 2003) or a channel plate (Chow et al., 2006) can be used to transfer the heat from the cells towards the fluid. The yield of a system with flat-plate PVT collectors and water as a transporting fluid was investigated numerically by de Vries (1998) and Zondag et al. (2003). Several PVT collector designs were considered for Dutch climatic conditions. The unglazed PVT collector gives the highest electrical efficiency, but its thermal performance is very poor. Zondag concluded that the one-cover glazed sheet-and-tube design represents a good compromise between electrical and...
thermal yield and manufacturability. Also in the European PVT Roadmap (PVT Roadmap, 2005) it was concluded that the one-cover PVT collector with a liquid as heat transporting fluid, is the main market product for PVT collectors, with both tap-water heating and space heating being the main applications. Also in the work presented here, the focus was on solar domestic hot water systems with one-cover sheet-and-tube PVT collectors.

The design considered here is shown schematically in Fig. 1. At the heart there is the PV laminate with the solar cells, generating electricity. The heat generated in the laminate is extracted by a copper sheet at the back. Connected to this sheet is a serpentine shaped tube through which water flows collecting the heat. In order to reduce heat loss to the ambient, the backside is thermally insulated and at the front there is a cover glass. The stagnant air layer provides thermal insulation. This design is similar to the design of a glazed solar thermal collector with the spectrally selective absorber being replaced by a PV laminate.

The electrical efficiency of a glazed PVT collector is somewhat lower than the electrical efficiency of a PV module, because of the presence of an extra cover. In addition, the cell temperature will be influenced by the amount of heat collected by the fluid. A lower cell temperature is favorable for a higher electrical yield because of the negative temperature coefficient of the electrical cell efficiency. The cell temperature, however, will be influenced by the system sizing i.e. the ratio between the PVT collector area and the storage size and by the application dependent thermal load. Therefore it is impossible to conclude beforehand whether there will be an electrical energy gain or loss. So far, the influence of the system sizing and the resulting fluid temperature on the electrical efficiency was not studied in a systematic way.

The thermal efficiency of a PVT collector is lower than the efficiency of a thermal collector as well. This is caused by a higher emissivity of the PV laminate on the one hand and a lower (effective) absorption factor on the other hand. The total absorption factor is lower than that of a black absorber, because solar cells do not fully behave as a black absorber. Moreover, the total absorption factor \( A \) is reduced to an effective absorption factor \( A_{\text{eff}} \) because of the extraction of electrical energy

\[
A_{\text{eff}} = A - \eta_e
\]

with \( \eta_e \) being the electrical efficiency.

Both the total and the effective absorption factor of various types of solar cells were studied in detail by Santbergen et al. (2007), Santbergen and van Zolingen (2008), Santbergen (2008), both by modelling and by measurements on test structures. For the various types of solar cells, total absorption factors turned out to be in the range of 85–93\%, whereas effective absorption factors were in the range of 70–82\%.

In order to optimise the electrical and thermal yield of PVT collectors and systems, detailed knowledge of the factors that determine these yields is required. So far a detailed analysis of these factors has not been reported in literature, though the basic models to do so are available, as described above. Therefore the first objective of the work described here was to study these factors and to understand the mechanisms that limit the yields compared to systems with only PV modules or thermal collectors. The second objective was to analyse whether the yield could be improved by the use of anti-reflective coatings and what would be the effect of a low-emissivity coating on the encapsulated solar cells. The third objective was to gain insight in the differences in both the electrical and thermal yield if different types of solar cells are used.

The work was carried out with a system simulation model, enabling to simulate the annual electrical and thermal yield of PVT systems for several combinations of PV laminate and optical coatings. The PVT collector model developed by Zondag et al. (2002) is part of this simulation.
model. Effective absorption factors obtained by the optical model of Santbergen and van Zolingen (2008), Santbergen (2008) were used as input for the PVT collector model.

First, a description of the PVT system considered is given. Next, the models used for the simulation are introduced. Subsequently, the results of energy yield simulations are presented together with an analysis of the loss mechanisms and measures to improve the yields. Finally the results are discussed.

2. System description

The PVT system considered here is a system for domestic hot water heating and has a layout similar to the layout of a conventional system for solar domestic hot water heating (see Fig. 2). The PVT system consists of a number of sheet-and-tube PVT collectors of the type described in the introduction. The typical dimensions and some other parameters of the PVT system are given in Table 1. The PVT collectors are connected to a storage tank. In the study presented here, the tank volume was kept fixed (200 l) and the PVT collector area was varied.

The PV sub-system is a grid-connected PV system. The PV laminates are connected to a PV inverter, converting the DC current into AC current. Crystalline silicon (c-Si) PUM cells (Bultman et al., 1994; Weeber et al., 2006) were selected as representatives for the c-Si solar cell technology. Because PUM cells have their main current collection pattern at the back of the solar cell, only current collection fingers are present at the front side resulting in a front side

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Table 1

<table>
<thead>
<tr>
<th>Parameters of the PVT system.</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of cover glass</td>
<td>3.2 nm</td>
</tr>
<tr>
<td>Emissivity of glass</td>
<td>0.9</td>
</tr>
<tr>
<td>Heat conduction through glass</td>
<td>0.9 W/mK</td>
</tr>
<tr>
<td>Width of air layer</td>
<td>0.02 m</td>
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<tr>
<td>Heat conduction through air</td>
<td>0.025 W/mK</td>
</tr>
<tr>
<td>Thickness of PV glass</td>
<td>3.0 mm</td>
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<tr>
<td>Emissivity of PV laminate</td>
<td>0.9</td>
</tr>
<tr>
<td>Heat transfer PV laminate to sheet</td>
<td>120 W/m²K</td>
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<tr>
<td>Copper sheet thickness</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Tube diameter</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Tube spacing</td>
<td>0.095 m</td>
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<tr>
<td>Specific flow rate</td>
<td>10 kg/m²h</td>
</tr>
<tr>
<td>Heat capacity of water</td>
<td>4200 J/kg K</td>
</tr>
<tr>
<td>Heat transfer through back of col.</td>
<td>1 W/K</td>
</tr>
<tr>
<td>Collector surface area</td>
<td>3, 6 or 12 m²</td>
</tr>
<tr>
<td>Heat storage tank volume</td>
<td>200 l</td>
</tr>
<tr>
<td>Heat storage tank heat loss</td>
<td>1 W/K</td>
</tr>
</tbody>
</table>

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Fig. 1. A one-cover flat-plate sheet-and-tube PVT collector, converting incident solar irradiance into both electricity and heat. (Left) The complete collector. (Right) A detailed cross-section.

Fig. 2. Schematic overview of the PVT system for domestic hot water. Besides the PVT collector, the electrical sub-system consists of an inverter, the thermal sub-system consists of a pump, heat exchanger, heat storage and auxiliary heater.
metallisation coverage of only 4.5% as compared with 8.0% for conventional c-Si solar cells, having also bus bars at the front. Reduced front metallisation coverage is favorable for both the cell efficiency and the absorption factor (Santbergen and van Zolingen, 2008). Two types of solar cells were selected as representatives of the thin-film solar cell technology. One being the single-junction amorphous silicon (a-Si) solar cell characterised by a relatively low electrical cell efficiency (7%) and a relatively low absorption factor (81%) (Santbergen et al., 2007; Santbergen, 2008). The other being the copper indium gallium diselenide \((\text{Cu(In,Ga})_{1-x}\text{Se}_2)\) solar cell with \(x=0.2\) being a typical composition for industrially produced solar cells and abbreviated here as CIGS solar cell (Santbergen, 2008). This cell has both a relatively high cell efficiency (11%) and high absorption factor (93%).

3. Modelling

The electrical yield and the thermal yield of a PVT system are the total amounts of solar energy supplied to the grid as electrical energy or extracted from the storage tank as thermal energy, respectively. Annual yields, i.e. the summed total yields of one year, are considered. In order to determine these yields, the performance of the PVT systems was simulated over an entire year. The year is divided into time steps of one hour. For each time step the flow of energy through the PVT system is calculated. This makes the simulation model very flexible and the model can therefore be used under a wide range of conditions. The sub-models used for these calculations will be discussed below.

3.1. Optical model

The optical model is used to determine the AM1.5 absorption factor \(A\) of the PVT collector, i.e. the fraction of incident solar irradiance absorbed in the PVT collector, as opposed to being reflected. The PVT collector is treated as an optical multilayer system (Santbergen, 2008). In this model, the extended net-radiation method is used to take into account the effect of light-trapping in the solar cells and in the PV laminate.

Because in the optical model layers can be added easily, it is possible to study the effect on \(A\) of the addition of optical coatings. In this work, anti-reflective and/or low-emissivity coatings on the cover glass or on the PV laminate itself are considered. Note that \(A\) is one of the input parameters of the PVT collector model that will be described in the next section.

Using the optical model the effects of spectrum and angle of incidence on the absorption factor were investigated first. It turned out that the absorption factor of c-Si solar cells changes less than 1% if the air mass number is changed from 1.5 to 5.6. Detailed analysis showed that the absorption factor hardly changes in case the angle of incidence remains between 0° and 60°. This indicates that the absorption factor of a PV laminate is more or less constant over a wide range of irradiation conditions.

3.2. PVT collector model

The thermal model for the PVT collector is a modified version of a widely used solar thermal collector model developed by Hottel and Whillier (Duffie and Beckman, 1991). de Vries (1998) incorporated electricity production in this steady-state one-dimensional model, making it suitable for PVT collectors as well. Zondag (Zondag et al., 2002, 2003) refined this model further and used it to analyse the performance of several flat-plate PVT collector designs. For the work presented here, this refined model was used. The working principles of this model are now summarised briefly.

The objective of the model is to determine the thermal efficiency of a solar thermal PVT collector \(\eta_{\text{th}}\). The task of the model therefore is to simulate the heat flows inside the collector in order to determine the amount of heat being transferred to the water flowing through the tube and the amount lost to the ambient. The problem is simplified by ‘stretching’ the serpentine geometry of the tube to a straight tube as indicated in the left panel of Fig. 3. This stretched out collector is then divided into a number of segments and the heat flow in each segment is analysed.

The cross-section of a single segment and the temperature nodes used in the model are indicated in the right panel of Fig. 3. The heat resistance between the nodes is determined, taking into account heat transport by convection, radiation and conduction (indicated by the arrows). Nusselt relations are used to describe heat transport by natural and forced convection. Weather conditions, like solar irradiance, ambient temperature, sky temperature (for radiation) and wind speed and the temperature of the water flowing into the tube are used as boundary conditions.

3.3. Heat storage tank model

The PVT system contains a form of heat storage. Here sensible heat storage is considered in a storage tank filled with water. As indicated in Fig. 4, the energy content of the storage tank is affected by two flows. At one side there is the collector loop, taking water from the bottom of the tank and returning it at an elevated temperature. At the other side there is the demand loop, taking water from the top of the tank and replenishing it at a temperature of 10 °C. Note that it is compulsory, in practice, to separate the water of both loops by means of a heat exchanger. Here it is assumed that this heat exchanger is located outside the tank on the collector side and is perfect in terms of effectiveness.

A pump control strategy is implemented to ensure that no water is pumped through the collector during unfavorable weather conditions (i.e. low irradiance) that would lead to a loss of heat. Note that in case the heat supply exceeds the heat demand, the temperature in the storage...
tank could eventually reach the boiling temperature. To prevent this dangerous situation, no water is pumped through the collector as long as the temperature in the storage tank exceeds 95 °C. Under this condition, known as stagnation, no heat is extracted from the absorber and its temperature could exceed 150 °C. The effect of stagnation on the solar cell temperature and therefore on the electrical yield is taken into account by the model.

Heat storage tanks are designed to avoid mixing of water of different temperatures in order to maintain good thermal stratification. Having a stratified tank instead of a tank of uniform temperature has two advantages. Firstly, the water extracted at the demand side (top) has a relatively high temperature, so less auxiliary heating is required. Secondly, the water extracted at the collector side (bottom) has a relatively low-temperature, which is beneficial for the efficiency of the collector. Therefore the degree of the stratification is an important system parameter.

Storage tank models have been developed, of which the multinode model is frequently used (Kleinbach et al., 1993). In this model the storage tank is divided into N segments, each segment being characterised by a uniform temperature. The choice of the number of segments N in the model determines the degree of stratification. The simplest case with only one tank segment N = 1 corresponds to a fully mixed tank of uniform temperature and the limiting case of N → ∞ corresponds to a perfectly stratified tank. According to Duffie and Beekman (1991), the case with N = 3 represents a reasonable compromise between the two extreme cases and this value was used for the simulations presented here.

3.4. Electrical model

The electrical collector efficiency $\eta_{e}^{col}$ can be approximated by

$$\eta_{e}^{col} = \eta_{e}^{col,STC} F_I F_T$$

(2)

where $\eta_{e}^{col,STC}$ is the collector's efficiency at STC (Standard Test Conditions, 1000 W/m² irradiance, AM1.5 spectrum and 25 °C cell temperature) and $F_I$ and $F_T$ describe the dependence of the electrical efficiency on irradiance $I_{sun}$ and cell temperature $T_{cell}$. $F_I$ is shown versus $I_{sun}$ in Fig. 5. This is an empirical curve that depends on the precise technology considered.

Within the practical temperature range $F_T$ can be considered linear,

$$F_T = 1 + \beta(T_{cell} - 25 \degree C)$$

(3)

where $\beta$ is the temperature coefficient of the electrical efficiency. For c-Si cells and CIGS cells $\beta = -0.0045/\degree C$ and for single-junction amorphous silicon cells $\beta = -0.002/\degree C$ (PVT Roadmap, 2005) indicating that the electrical efficiency of the amorphous solar cells is less sensitive to temperature variation.

An inverter has a maximum input power $P_{inv,max}$ for converting direct current into alternating current. The inverter efficiency used in the model is given in Fig. 6 as a function of the relative input power. Current dependent resistive cable losses were taken into account. The cable resistance
was chosen such that the resistive loss is 2% of the DC input power at an irradiance of 1000 W/m².

3.5. Input data

The meteorological data of the Dutch test reference year for de Bilt were used as input for the model. This data contains the hourly values of the ambient temperature, solar irradiation and wind speed for a full year. The irradiation defined by the test reference year for the south facing plane with a tilt of 45° considered here, is 1100 kWh/m²y.

The AM1.5 absorption factor was used throughout the whole year, implying that deviations from the AM1.5 spectrum were not taken into account. In addition, it was assumed that the absorption factor is not angle dependent, but equal to the absorption factor for normal incidence (see also Section 3.1).

For the domestic hot water demand, a standard withdrawal pattern was used. After correction for the heat loss in the pipes between storage tank and water tap, the effective hot water withdrawal is 139 l water per day at 60 °C (Zondag et al., 2001). This daily pattern is repeated for every day of the year, amounting to an annual thermal energy demand of 2960 kWh (10.6 GJ).

4. Results

The results presented in this section are calculated using the model described in Section 3, assuming Dutch climatic conditions. In Sections 4.1–4.5 systems with PVT collectors with c-Si solar cells are considered.

4.1. The energy yields of a reference PVT system

Table 2 shows the annual electrical and thermal system yield of a 6 m² PVT collector with crystalline silicon (c-Si) PUM solar cells and a 200 l storage tank. In this case no additional coatings are applied. Because of the finite packing density ρ of 90% of the solar cells in the laminate and because of the presence of the cover glass with a transmittance τcover = 92.5%, the electrical cell efficiency ηcell,STC of 15.52% is reduced to an electrical collector efficiency ηcol,STC of 12.97%. The presence of the cover glass also reduces the cell's absorption factor Acell,STC of 87.4% to a collector absorption factor Acol,STC of 81.0%, where also the absorption of light in the narrow spacing between the cells is taken into account. The annual electrical system efficiency ηsys,e of 9.96% is lower than ηcol,STC because of the various electrical system losses (i.e., low irradiance loss, cell temperature loss, cable loss and inverter loss). The annual thermal efficiency ηsys,th of 24.3% is not only determined by the absorption factor Acol,STC, but also by heat losses to the ambient by radiation and convection.

4.2. The effect of system sizing

For the standard configuration just described, the influence of system sizing on the annual electrical and thermal...
system efficiency was investigated. In order to do so, the collector area was varied, see Table 3, keeping all other parameters constant, including the storage tank volume (200 l) and the thermal load. With increasing collector area the thermal solar fraction (SF) increases, as one would expect. However, both the annual electrical and thermal system efficiency decrease with increasing collector area. The electrical efficiency decreases because the storage tank temperatures and therewith the solar cell temperatures reach higher values with increasing collector area. The thermal efficiency drops because higher fluid temperatures result also in higher thermal losses.

4.3. The effect of optical coatings

In order to investigate the possibilities to increase the electrical and thermal yield of PVT collectors, the effect of the application of anti-reflective coatings and of low-emissivity (low-e) coatings was considered. Four PVT collector configurations were used, see Fig. 7. Configuration A is the standard configuration without additional coatings. Configuration B has a low-e coating on the PV laminate. Configuration C has an anti-reflective coating on the cover glass (both sides) and on the PV laminate. In configuration D, the low-e coating of configuration B and the anti-reflective coatings of configuration C are combined.

The anti-reflective coating considered here is a single layer SiO$_2$ coating, deposited by a dip coating technique (Hammarberg and Roos, 2003). For the low-emissivity coating, SnO$_2$:F was used, which is widely used as a low-e coating (Hammarberg and Roos, 2003; Granqvist, 2007). Note that very thin metal films could be used as low-e coating as well. However, because of their relatively low transmittance in the near infrared (where c-Si solar cells have a high spectral response), these metal coatings are less suitable for application in PVT collectors. Applying a 300 nm SnO$_2$:F coating with a fluorine doping concentration of $3 \times 10^{20}$ cm$^{-3}$ will reduce the emissivity of the PV laminate from 80% to about 20% (Haitjema, 1989). In Table 4 the electrical efficiency and the absorption factor at STC are given together with the emissivity, for the various configurations. These parameters are calculated using the optical model and are used as input for the annual yield simulations.

The annual electrical and thermal system efficiencies are considered for solar domestic hot water systems with a 200 l storage tank with collector type A, B, C and D. PVT collector areas of 3, 6 and 12 m$^2$ were selected respectively. In practice, typical collector areas are in the range of 3–6 m$^2$ for solar domestic hot water heating, 12 m$^2$ was selected as an extreme case. The results are presented in Fig. 8. The annual thermal system efficiency is plotted versus the annual electrical efficiency.

It can be seen that the addition of a low-e coating to the PV laminate (compare configuration A and B), increases

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\eta_{\text{col,STC}}$ (%)</th>
<th>$A_{\text{col,STC}}$ (%)</th>
<th>$\varepsilon$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12.97</td>
<td>81.0</td>
<td>85</td>
</tr>
<tr>
<td>B</td>
<td>11.84</td>
<td>76.9</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>14.19</td>
<td>87.9</td>
<td>85</td>
</tr>
<tr>
<td>D</td>
<td>13.67</td>
<td>86.7</td>
<td>20</td>
</tr>
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</table>

Table 4

The annual electrical and thermal system efficiencies for a PVT collector system with a 2001 storage tank for various PVT collector areas.

<table>
<thead>
<tr>
<th>PVT collector area</th>
<th>$\eta_{\text{sys,STC}}$ (%)</th>
<th>$\eta_{\text{systh,STC}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 m$^2$</td>
<td>10.34</td>
<td>34.5</td>
</tr>
<tr>
<td>6 m$^2$</td>
<td>9.96</td>
<td>24.3</td>
</tr>
<tr>
<td>12 m$^2$</td>
<td>9.53</td>
<td>14.6</td>
</tr>
</tbody>
</table>

Fig. 7. Four PVT collector configurations (drawing not to scale). (A) Without coatings. (B) Low-emissivity coating on the laminate. (C) AR coatings on both sides of the cover glass and on the PV laminate. (D) AR coatings on both sides of the cover glass and a sandwich of low-emissivity coating and AR coating on the PV laminate.

Fig. 8. The annual electrical system efficiency versus the annual thermal efficiency for hot water heating systems with PVT collectors with c-Si PUM cells and coating configurations A, B, C and D, for various collector areas.
the annual thermal efficiency somewhat, but reduces the annual electrical efficiency by more than 1% absolute. However, adding anti-reflective coatings (compare configuration A and C) is beneficial for both the annual electrical efficiency, increasing by almost 1% absolute, and the thermal efficiency. Having both a low-e coating and anti-reflective coatings (configuration D) results in the highest thermal efficiency. The electrical efficiency, however, is not as high as in the case with only anti-reflection coatings (configuration C) and is in the 6 and the 12 m² cases even lower than in the case without any coatings (configuration A).

4.4. The inherent losses in PVT collectors and systems

In order to study the inherent losses in PVT collectors and systems, both their electrical and thermal yield were compared with the corresponding yields of a pure PV and a pure thermal system. In this part of the study the glass cover of the PVT collectors has an anti-reflective coating on both sides and PV absorbers with and without a low-e coating are considered (configuration D and C respectively). The results of this study are displayed by presenting the relative annual electrical and thermal system efficiencies in comparison with the corresponding annual efficiencies of the pure systems, see Fig. 9. The causes of the reduced thermal efficiencies are displayed as well. Note that in order to make a fair comparison, the efficiency of the PVT systems is presented relative to the efficiency of pure systems having anti-reflective coatings as well.

In all cases displayed, 3.5% of the relative electrical efficiency is lost because of the presence of the glass cover. In case no low-e coating is applied (configuration C), the additional temperature loss introduced by the presence of the cover is 4.2–12.2% depending on the system sizing. In case a low-e coating is applied on the absorber an additional temperature loss ranging from 1.8% to 7.1% is introduced. Moreover, the low-e coating introduces an extra reflection (2.8%) and absorption (0.9%) loss. The extra reflection is caused by the high refractive index \( n \) low-e coatings have compared to glass \( n \approx 2 \).

In the systems without a low-e coating the two main mechanisms that cause the reduction of the relative annual thermal efficiency are the high emissivity and the fact that
electrical energy is withdrawn from the collector. In case a low-e coating is applied (configuration D), the withdrawal of electrical energy is the main mechanism for the reduction of the relative annual thermal efficiency.

Typical PVT collector areas for solar domestic hot water applications are in the range of 3–6 m². If a collector area of 6 m² is considered, then in case C (with only anti-reflective coatings) 88.6% of the annual electrical efficiency of a pure PV system is obtained, whereas at the same time only 83.1% of the annual thermal efficiency. Application of a low-e coating (case D) enhances the relative thermal efficiency up to 91.2%, but reduces the relative electrical efficiency to only 80.4% at the same time. It can be concluded that both the electrical and thermal efficiency of a typical PVT collector are inherently about 10–20% lower compared to separate conventional PV and thermal collector systems.

Note that though the thermal efficiency of the PVT system decreases with increasing collector area, it increases relative to the efficiency of the thermal reference system. This is caused by the fact that the amount of heat produced by a thermal system with a large collector surface area exceeds the heat demand, especially in the summer season. This implies that, under those conditions, the system efficiency is much less affected by the efficiency of the collector used. Therefore, in case of larger collector areas, the thermal yield of a PVT system will approach the yield of the thermal reference system.

4.5. The trade-off between electrical and thermal efficiency

The increase of the thermal efficiency by means of the low-e coating is realised, at the cost of a significant reduction of the electrical efficiency. This implies that a trade-off exists between electrical and thermal system efficiency. In order to investigate this trade-off in more detail, the thickness of the low-e coating was varied in order to vary the emissivity. The relation between the emissivity and the thickness of the SnO₂:F low-e coating was derived from data from Haitjema (1989). The resulting electrical and thermal system efficiencies are presented in Fig. 10. The thermal efficiency increases with increasing low-e coating thickness as one would expect. Because the emissivity increases hardly any more above a thickness of 300 nm, the thermal system efficiency tends to saturate. The electrical efficiency decreases with increasing low-e coating thickness because of increasing cell temperatures and a slight increase of the absorption in the low-e coating.

4.6. The influence of the solar cell technology

The influence of the use of various solar cell technologies on the electrical and thermal yield of PVT systems was investigated as well. Yield differences are expected because of differences in the effective absorption factor (resulting from both differences in the absorption factor and in the cell efficiencies) and because of differences in the temperature coefficient of the cell efficiency of the various technologies.

The standard system described above has a c-Si PUM solar cell laminate as the absorber in the PVT collector. The energy yield of systems with PVT collectors having configuration A with an a-Si thin-film laminate and a CIGS thin-film laminate were investigated as well. An overview of the cell efficiencies of the various solar cell technologies is given in Table 5. Cell efficiency, laminate efficiency and collector efficiency at STC are distinguished, taking into account cell packing density and optical losses caused by the glass cover. Both the annual electrical efficiency and the performance ratio (PR) are presented. The PR is the ratio between the annual electrical collector efficiency and the PV laminate efficiency at STC. The PR takes into account all the losses that occur on the system level. The concept of the PR makes it possible to compare the electrical performance of systems with different cell efficiencies at STC and in this case to compare pure PV systems and PVT systems with various solar cell technologies. The PV system with the a-Si solar cell laminate has the highest PR because the a-Si solar cell has the lowest temperature coefficient of the cell efficiency and the most favorable low light intensity behaviour. Both the PV systems with the c-Si solar cells and with the CIGS solar cells have a similar PR, because of the same temperature coefficient and because of the same low light intensity behaviour. In the case of a transition from a PV system to a system with PVT collectors the PR is best preserved in the case of a-Si, as can be concluded from the ratio PR_{PVT}/PR_{PV} in Table 5. This turns out to be the case because of the lower temperature coefficient.

The thermal system efficiencies are given in Table 6 together with both the absorption factor, the electrical
Table 5
The annual electrical system efficiency $\eta_{\text{sys}}^{e}$ and the performance ratio $\text{PR}_{\text{PVT}}$ for PVT systems of 6 m\(^2\) with PVT collectors with various solar cell types.

<table>
<thead>
<tr>
<th>Solar Cell Type</th>
<th>$\eta_{\text{cell,STC}}$ (%)</th>
<th>$\eta_{\text{lum,STC}}$ (%)</th>
<th>$\eta_{\text{col,STC}}$ (%)</th>
<th>$\eta_{\text{sys}}^{e}$ (%)</th>
<th>$\text{PR}_{\text{PVT}}$ (%)</th>
<th>$\text{PR}_{\text{PV}}$ (%)</th>
<th>$\text{PR}_{\text{PVT/PV}}$</th>
<th>$\beta$ (%/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si PUM</td>
<td>15.52</td>
<td>13.97</td>
<td>12.97</td>
<td>9.96</td>
<td>0.708</td>
<td>0.825</td>
<td>0.859</td>
<td>−0.45</td>
</tr>
<tr>
<td>a-Si</td>
<td>7.00</td>
<td>6.30</td>
<td>5.80</td>
<td>4.88</td>
<td>0.775</td>
<td>0.860</td>
<td>0.901</td>
<td>−0.20</td>
</tr>
<tr>
<td>CIGS</td>
<td>11.00</td>
<td>9.90</td>
<td>9.11</td>
<td>6.84</td>
<td>0.691</td>
<td>0.82</td>
<td>0.843</td>
<td>−0.45</td>
</tr>
</tbody>
</table>

Table 6
The annual thermal system efficiency $\eta_{\text{sys}}^{\text{th}}$ for PVT systems with PVT collectors with various solar cell types.

<table>
<thead>
<tr>
<th>Solar Cell Type</th>
<th>$\Delta\eta_{\text{cell,STC}}$ (%)</th>
<th>$\Delta\eta_{\text{col,STC}}$ (%)</th>
<th>$\eta_{\text{col,STC}}^{\text{eff}}$ (%)</th>
<th>$\eta_{\text{sys}}^{\text{th}}$ (%)</th>
<th>$\text{PR}_{\text{PVT/PV}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si PUM</td>
<td>87.4</td>
<td>81.0</td>
<td>12.97</td>
<td>68.0</td>
<td>19.4</td>
</tr>
<tr>
<td>a-Si</td>
<td>81.4</td>
<td>74.9</td>
<td>5.80</td>
<td>69.1</td>
<td>19.3</td>
</tr>
<tr>
<td>CIGS</td>
<td>93.5</td>
<td>86.0</td>
<td>9.11</td>
<td>76.9</td>
<td>22.0</td>
</tr>
</tbody>
</table>

5. Discussion

5.1. Electrical yield

In systems with single-glazed sheet-and-tube PVT collectors, the fluid temperatures can become quite high, especially in systems used for tap-water heating. The occurring temperatures are also influenced by the sizing of the system i.e. the ratio between the (PVT) collector area and the thermal load. The storage tank size will play a role as well. The presence of a low-e coating will increase the fluid temperature further at a given system sizing.

The inherent electrical loss (called additional temperature loss) caused by the higher cell temperatures imposed by the heat collecting fluid in the PVT systems investigated, turns out to be significant (see Fig. 9) especially in case of a relatively large collector area compared to the storage tank size. The effect is even more pronounced if a low-emissivity coating is being used (see Fig. 9). The application of solar cells with a low-temperature coefficient of the efficiency $\beta$, like amorphous silicon based thin-film solar cells ($\beta = -0.20\%$/°C) and HIT crystalline silicon solar cells ($\beta = -0.30\%$/°C), is therefore favorable if conservation of electrical yield is important.

5.2. Thermal yield

As shown in Fig. 9, the reduction of the thermal efficiency of a PVT system with respect to a system with conventional thermal collectors is caused for a large part by the high emissivity of the absorber and the fact that the total absorption factor is reduced by the withdrawal of electrical energy to a lower effective absorption factor. This

Fig. 11. An overview of the performance ratio of a PV and a PVT system, both with c-Si and a-Si laminates. The loss mechanisms are indicated as well. A PVT system for domestic hot water with a collector surface area of 6 m\(^2\) without additional coatings is considered. The PV module area is 6 m\(^2\) as well.
work shows, that if a low-e coating is applied on the absorber, the thermal efficiency is increased substantially whereas the electrical efficiency is reduced substantially at the same time. This implies that there exists an inherent trade-off between electrical and thermal efficiency.

The differences in the total absorption factor of the various solar cells are relatively small. Typical values for the total absorption factor of crystalline silicon solar cells are around 87% (Sanbergen and van Zolingen, 2008), whereas for most thin-film solar cells they are around 90% (Sanbergen et al., 2007; Sanbergen, 2008). In future, the total absorption factor of both crystalline and thin-film solar cells will grow to about 91% (Sanbergen, 2008). By the application of an anti-reflective coating on the glass encapsulating the cell, this can be enhanced further to about 94%, which is close to the absorption factor of the absorber in a conventional thermal collector (95%). More important, however, are the relatively large differences in the cell efficiencies of the various solar cell technologies, being about 16% for crystalline silicon and about 10% for thin-film solar cells, currently. Also in future this difference will continue to exist. Efficiencies of 20–25% are expected for crystalline silicon solar cells, whereas for thin-film solar cells efficiencies around 15% are expected (Photovoltaic Technology Platform, 2007). This implies that the effective absorption factor of thin-film solar cells will remain 5–10% higher than of crystalline silicon solar cells.

5.3. Avoided primary energy

The main reason for the reduced (effective) absorption factor is the withdrawal of electrical energy. This is an inherent loss mechanism, reducing the thermal efficiency. However, from an electrical point of view a high electrical efficiency is desirable. In order to compare the total yield (electrical and thermal) between various PVT systems, the avoided primary energy can be considered. This means that the electrical energy \( E_{e} \) and thermal energy \( E_{th} \) are converted into primary energy before they are added

\[
E_{\text{prim}} = \frac{E_{e}}{\eta_{\text{prim-e}}} + \frac{E_{th}}{\eta_{\text{prim-th}}},
\]

where \( \eta_{\text{prim-e}} \) and \( \eta_{\text{prim-th}} \) are the conversion efficiencies for converting primary energy into electrical and thermal energy, respectively, in the conventional way. For \( \eta_{\text{prim-e}} \) the power generation efficiency of a conventional power plant is used, which typically is 40% (Coventry, 2003). For \( \eta_{\text{prim-th}} \) the thermal efficiency of a conventional gas-fired domestic hot water system is used, which typically is 65% (Bosseelaar and Gerlagh, 2006). In Table 7 the annual yield of several PV systems is given in terms of avoided primary energy. It can be seen that the PVT system with the c-Si PUM laminate has the highest avoided primary energy of more than 600 kWh/m²y. The avoided primary energy caused by the higher electrical efficiency of the c-Si PUM laminate outweighs the loss in primary energy caused on the thermal side, resulting from the lower effective absorption factor of this laminate.

<table>
<thead>
<tr>
<th>Solar Cell Type</th>
<th>( E_{\text{col prim}} ) (kWh/m²y)</th>
<th>( E_{\text{th prim}} ) (kWh/m²y)</th>
<th>( E_{\text{tot prim}} ) (kWh/m²y)</th>
<th>( E_{\text{col prim}} ) (kWh/m²y)</th>
<th>( E_{\text{th prim}} ) (kWh/m²y)</th>
<th>( E_{\text{tot prim}} ) (kWh/m²y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>c-Si</td>
<td>109.6</td>
<td>273.9</td>
<td>383.5</td>
<td>109.6</td>
<td>273.9</td>
<td>383.5</td>
</tr>
<tr>
<td>a-Si</td>
<td>53.7</td>
<td>134.2</td>
<td>187.9</td>
<td>53.7</td>
<td>134.2</td>
<td>187.9</td>
</tr>
<tr>
<td>CIGS</td>
<td>71.28</td>
<td>178.2</td>
<td>250.7</td>
<td>71.28</td>
<td>178.2</td>
<td>250.7</td>
</tr>
</tbody>
</table>

6. Concluding remarks

Both the annual electrical and thermal efficiency of systems with covered sheet-and-tube PVT collectors are about 15% (relative) lower compared to separate conventional PV and conventional thermal collector systems. The loss of electrical efficiency is mainly caused by the relatively high fluid temperature. This temperature is influenced strongly by the system sizing. The loss of thermal efficiency is caused both by the high emissivity of the PV laminate and the withdrawal of electrical energy.

Both the electrical and the thermal efficiency can be improved by the application of anti-reflective coatings. To obtain a high electrical efficiency, not only a high cell efficiency at Standard Test Conditions, but also a low-temperature coefficient are required. The thermal efficiency can be improved by the application of a low-e coating, however, at the cost of a reduced electrical efficiency.

The model developed here is very suitable for PVT system design optimisation. For the further development of systems with PVT collectors the work should be extended to other PVT collector designs and other climate zones. In addition, the development of a yield cost function would be an important tool to optimise the PVT collector system as a whole and the PVT collector in particular.

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References


