

IMPROVEMENT OF THE PERFORMANCE OF PVT COLLECTORS

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Abstract

In a photovoltaic-thermal (PVT) collector one tries to collect heat from solar cells not used in the photovoltaic conversion process, as good as possible e.g. for heating of tap water. The thermal efficiency of the current PVT collector designs is on the one hand limited because of the limited absorption factor (around 85% compared to 95% for a black absorber) and on the other hand by the relatively high emissivity (85% compared to 12% for a spectrally selective coated absorber) of encapsulated solar cells.

This paper deals with the investigation of the possibilities to improve the annual electrical and thermal yield of systems with PVT collectors by the application of anti-reflective (AR) coatings and low-emissivity (low-e) coatings. The investigation was carried out using an advanced optical model for the absorption factor of solar cells together with a system simulation program. Both a system for Solar Domestic Hot Water (SDHW) heating and for combined SDHW and Room Heating (RH) were considered.

It turns out that application of AR coatings in the case of covered PVT collectors is quite favorable for both the annual thermal efficiency and the annual electrical efficiency. The gain in the annual thermal efficiency can be up to 5% relative, whereas the gain in annual electrical efficiency can be up to 10% relative. The application of a low-e coating is favorable for the annual thermal efficiency but reduces the annual electrical efficiency. Though this reduction can be limited by application of an AR coating on top of the low-e coating, the remaining reduction (up to 10%) is too large to justify application of a low-e coating in many cases.

1 Introduction

Solar cells convert solar energy into electricity at a typical conversion efficiency of about 15%. This implies that about 85% of the energy is available in the form of heat, in principle. In a photovoltaic-thermal (PVT) collector (van Helden, 2004) one tries to collect this heat as good as possible, e.g. for heating of tap water. An example of a PVT collector is presented in figure 1. In this case, the heat is collected by means of a sheet-and-tube configuration and is transferred to water, like in a conventional thermal collector. Alternatively, the heat can be transferred to air by an air channel running below the absorber consisting of the photovoltaic solar cells. As with conventional thermal collectors, also with PVT collectors one can distinguish covered and uncovered PVT collectors.

In comparison with a thermal collector, the thermal efficiency of the current PVT collector designs is limited because the absorption factor of the encapsulated solar cells (around 85%) is lower than the absorption factor of the black absorber (around 95%) in a conventional thermal collector. In addition, the emissivity of encapsulated solar cells (about 85%) is much higher than of the spectrally selective coated absorber in a conventional collector (about 12%). Moreover, the electrical energy withdrawn from the solar cells is not available as thermal energy anymore. This last fact is inherent to the concept of a PVT collector.

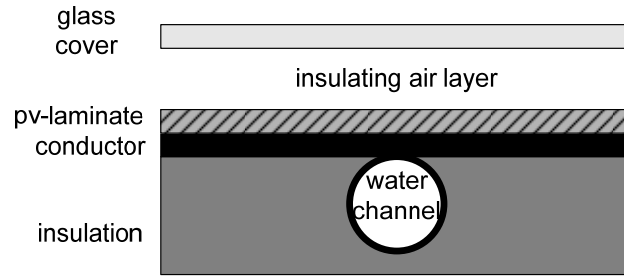


Figure 1: *Cross section of a covered sheet-and-tube PVT collector. The PV laminate contains the solar cells.*

The absorption factor of the solar cells and therewith the absorption factor of the whole PVT collector, can be increased either by adaptation of the solar cell design or by the use of anti-reflective (AR) coatings on top of the encapsulant and/or the cover plate in a PVT collector. A way to reduce the emissivity of encapsulated solar cells is to use a low-emissivity (low-e) coating on top of the encapsulated solar cells. Low-e coatings reduce the photovoltaic efficiency somewhat because these coatings absorb some light in the visible part of the spectrum where solar cells have their maximum sensitivity and because of some additional reflection.

This paper deals with the improvement of the annual electrical and thermal yield of a number of systems with PVT collectors, in particular by means of the application of AR coatings and a low-e coating. Because the absorption factor plays such a crucial role, some information on the absorption factor will be provided first. Subsequently the effect of the application of AR coatings and low-e coatings on the electrical efficiency at Standard Test Conditions (STC, 25 °C cell temperature, 1000 W/m² irradiance, AM 1.5 spectrum) and on the absorption factor of the collector as a whole will be demonstrated, using an advanced optical model for the absorption factor developed by Santbergen (2007, 2008). Next the influence of the use of coatings on the annual electrical and thermal system yield is shown. A number of system configurations are considered for this purpose.

2 The absorption factor

For PVT applications solar cells with an absorption factor as high as possible, are desired. Therefore, the absorption factor of various types of solar cells was investigated in detail by Santbergen (2007, 2008). Both optical measurements and a dedicated simulation model were used. Because solar cells are semiconductor devices, one would expect that only photons with an energy larger than the band gap of the semiconductor ($h\nu > E_g$) would be absorbed and that photons with $h\nu < E_g$ would hardly be absorbed. It turned out, however, that both in the classical crystalline silicon solar cell and in thin-film solar cells free-carrier absorption takes place resulting in a significant absorption for $h\nu < E_g$ as well. It also appeared that the absorption factor strongly depends on the degree of optical confinement.

In crystalline silicon solar cells (Santbergen, 2008) the free-carrier absorption appeared to take place especially in the heavy doped emitter, in spite of the limited thickness of this emitter (about 0.2 μm). In addition absorption occurs in the back contact as well. The absorption factor of crystalline silicon solar cells depends on the metal coverage. There is a strong tendency to reduce this coverage because in this way the electrical efficiency can be improved. For multicrystalline silicon solar cells the absorption factor ranges from 85% for traditional cells (8% metal coverage), via 87% for PUM cells (4.5% metal coverage) to 90% for future EWT cells (0% metal coverage).

In thin-film solar cells (Santbergen, 2007) a Transparent Conducting Oxide (TCO) is commonly used as a front electrode to collect the photocurrent generated. The free-carrier absorption that takes place in the TCO is quite significant and turns out to be responsible for the absorption for $h\nu < E_g$ to a high degree. Thin-film solar cells have an absorption factor in the range of 87 to 90%.

3 The application of anti-reflective coatings

Anti-reflective coatings (ARC's) are used to reduce optical reflection losses. For PVT applications, such a coating should work preferably not only in the visible part of the spectrum but in the infrared part of the spectrum as well. The anti-reflective coating considered here, is a single layer porous SiO_2 coating, deposited by a dip-coating technique (see e.g. Hammarberg and Roos, 2003). This type of coating has the advantage that the reflection in the infrared part of the spectrum is lower than the reflection of an AR coating structure consisting of two or more layers.

The effect of the use of anti-reflective coatings on the total area electrical efficiency and absorption factor of PVT collectors was investigated by means of simulation, using the optical model for the absorption factor of crystalline silicon solar cells (Santbergen, 2008), combined with PC1D (Clugston, 1997), a standard program for the simulation of the electrical properties of solar cells. The laminate as a whole (see also figure 1) is the "absorber" in the PVT collector. The laminate is the sandwich containing the solar cells with glass as a front plate and a number of foils for the encapsulation of the solar cells and as back sheet. Due to the finite packing density of the solar cells in the laminate, both the efficiency and the absorption factor of the laminate will deviate from the ones of an individual solar cell. The simulations were carried out for PUM-type multicrystalline silicon solar cells (Weeber, 2006) with a cell efficiency of 15.62%. The results are presented in table 1. Both collectors without cover (the left two columns in table 1) and with cover (the right columns in table 1) were considered.

Application of an AR coating on the solar cell laminate increases the total area electrical efficiency by 4.8% (from 14.06% to 14.79%). The addition of an uncoated cover reduces the total area collector efficiency by 7.8% (from 14.06% to 12.97%). Application of both an AR coating on the laminate and on both sides of the cover plate (see figure 2) increases the efficiency to 14.42%.

Because one can apply an AR coating also directly onto the encapsulant of solar cells in a pure photovoltaic module, one needs to compare the efficiency of 14.42% with the 14.79% given above, implying a reduction of 2.5%, which is moderate. At the same time the total area collector absorption factor drops from 91.0% to 88.5%, implying a reduction of 2.8%.

Table 1: *The total collector area electrical efficiencies (at STC) and absorption factors for various collector configurations.*

Cover:	No cover		Cover without ARC	Cover with ARC on both sides
Laminate:	No coating	ARC	No coating	ARC
Electrical efficiency (%)	14.06	14.79	12.97	14.42
Absorption factor (%)	88.53	91.02	81.70	88.45

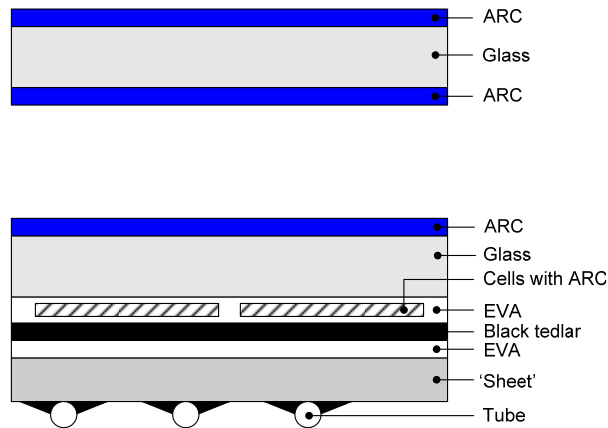


Figure 2: *Cross section of a covered sheet-and-tube PVT collector with both an AR coating on the laminate and on both sides of the cover glass.*

4 The application of a low-emissivity coating on the laminate

Today, low-emissivity (low-e) coatings are frequently used in double glazed windows in order to reduce the heat loss by radiation. As described by Granqvist (2007), both metals and doped semiconductor coatings can be used for this purpose.

Metal coatings can be used as a low-e coating because metals have a high reflectivity in the far infrared part of the spectrum, implying a low emissivity in this part of the spectrum. This high reflectivity is because of the high concentration of free carriers in metals and the related free-carrier absorption mechanism. By making the coatings thin enough a reasonable transmission in the visible part of the spectrum can be obtained for window applications, without affecting the low emissivity too much. A serious drawback for PVT applications of even thin metallic coatings is that their transmission in the near infrared region is already significantly reduced. This implies that the output of solar cells is reduced significantly as well, because of their high spectral sensitivity in this wavelength region.

The alternative is the use of a doped semiconductor coating. These coatings have a relatively good transmission in the visible and near infrared part of the spectrum and metallic properties in the far infrared part of the spectrum, provided that the doping concentration is high enough.

Both in the case of metals and in the case of a semiconductor coating the free-carrier absorption mechanism is responsible for the low emissivity in the far infrared. In case of a metal the free-carrier concentration is high by nature. In case of a semiconductor coating a rather heavy doping is required. Roughly speaking the free-carrier absorption increases with wavelength. The presence of the high doping in the semiconductor coating implies that a little bit of absorption will also occur in the near infrared part of the spectrum.

Application of a low-e coating implies that the electrical efficiency will be reduced in two ways. First, the efficiency at Standard Test Conditions (STC) will be reduced somewhat by the free-carrier absorption as just described above and by additional reflection, because of the high index of refraction semiconductor coatings have. This additional reflection can be reduced to a great extent by the use of an AR coating on top of the low-e coating, as shown by Hammarberg and Roos (2003). Secondly, the application of a low-e coating increases the operational cell temperatures, reducing the operational electrical efficiency of solar cells, having a negative temperature coefficient of the solar cell efficiency. The influence of the presence of a low-e coating on the electrical efficiency at STC was investigated using the optical simulation model of Santbergen (2007, 2008), combined with PC1D (Clugston, 1997). Also in this case a PUM-type multicrystalline silicon solar cell with a cell efficiency of 15.62% has been used.

Table 2: *The application of various types of coatings on the laminate in a PVT collector. All configurations have a cover with an AR coating on both sides.*

Laminate:	No coating	ARC	Low-e	ARC/low-e	ARC/low-e /ARC
Electrical efficiency at STC (%)	13.79	14.42	12.77	13.73	13.84
Absorption factor (%)	86.04	88.45	82.07	87.26	87.83

The configuration used to study the effect of a low-e coating is a PVT collector with a cover with an AR coating on both sides, comparable with the configuration in figure 2. The coating on top of the laminate is varied, however. The following cases are considered: no coating, an anti-reflection coating, a low-e coating without and with AR coating on top and a low-e coating sandwiched between two AR coatings. A 300 nm thick fluorine-doped tin oxide coating was considered as the low-e coating. The optical properties of this type of coating were described in detail by Haitjema (1989).

From table 2 it can be seen that the application of a low-e coating reduces the electrical efficiency by 7.4% relative (from 13.79% to 12.77%). The drop is caused by the high index of refraction of the low-e coating (about 2.0 compared to 1.5 of glass) and some internal absorption in the low-e coating. Application of an ARC on top of the low-e coating increases the efficiency to 13.73%, which is almost equal to the efficiency in the uncoated case (13.79%) and about 4.8% lower than the case with an AR coating directly onto the laminate (14.42%). In this case about 2.8% is lost by additional reflection and 2.0% by absorption in the low-e coating. The application of an additional ARC between the glass and the low-e coating can increase the efficiency only slightly (from 13.73% to 13.84%). The gain of this additional anti-reflection coating is, however, too small to justify its application.

The reduction of the total area collector absorption factor in the case with a laminate with an AR coated low-e coating (87.26%) compared to a laminate with only an AR coating (88.45%) is only minor (1.3% relative).

5 The influence of coatings on the annual system efficiencies

The influence of coatings on the annual system efficiencies was studied for a Solar Domestic Hot Water (SDHW) system and for a combined Solar Domestic Hot Water and Room Heating (SDHW + RH) system. The SDHW system consists of 6 m² covered sheet-and-tube PVT collectors and a 200 liter storage tank. The SDHW + RH system consists of 25 m² PVT collectors and two storage tanks of 200 liter (for tap water) and 40.000 liter (for seasonal storage), respectively. The PV sub-systems contain an inverter coupled to the public grid implying that all electricity generated is delivered to the public grid.

The analysis was carried out using a system simulation program. In this program the PVT collectors were described by means of the model developed by Zondag et. al. (2003). The yields were calculated on a hourly basis using a Test Reference Year for de Bilt (the Netherlands), providing hourly data regarding irradiance, ambient temperature and wind speed. In addition, typical Dutch household patterns for hot water and heat demand were used. The results are presented as annual efficiencies being the ratio of the annual electrical and thermal energy yield respectively and the annual irradiation. Note that the annual thermal efficiency is also influenced by the hot tap water demand, the room heating demand and the ratio between the PVT collector area and the storage volume.

Table 3: *The annual electrical and thermal efficiencies of both a SDHW system and a combined SDHW and RH system with sheet-and-tube PVT collectors without and with coatings.*

Cover:	Cover without ARC	Cover with ARC	
Laminate:	No coating	ARC	ARC/low-e
Electrical efficiency at STC (%)	12.97	14.42	13.73
Absorption factor (%)	81.70	88.45	87.26
SDHW system			
Annual electrical efficiency (%)	10.02	11.00	9.84
Annual thermal efficiency (%)	24.6	25.7	28.2
Combined SDHW and RH system			
Annual electrical efficiency (%)	9.87	10.83	9.72
Annual thermal efficiency (%)	15.4	16.2	18.3

From table 3 it can be concluded that in case of the SDHW system, the annual thermal efficiency is increased by application of an AR coating on both the laminate and on both sides of the cover glass. The same applies to both the electrical efficiency at Standard Test Conditions and the annual electrical efficiency. From table 3 (compare the last two columns) it can also be concluded that the application of a low-e coating (with an emission coefficient of 0.20)

- enhances the annual thermal efficiency by 9.7% (from 25.7% to 28.2%),
- reduces the electrical collector efficiency at STC by 4.8% (from 14.42% to 13.73%) as mentioned earlier,
- reduces the annual electrical efficiency by 10.5% (from 11.00% to 9.84%), because of the higher cell temperatures due to the lower emission factor (0.20 versus 0.85).

Also in the case of the combined SDHW + RH system (see bottom of table 3), the application of AR coatings increase both the annual thermal and electrical yield. The application of a low-e coating increases the annual thermal efficiency by 12.9% (from 16.2% to 18.3%), but reduces the annual electrical efficiency also in this case rather drastically by 10.2% (from 10.83% to 9.72%).

Both in the case of the SDHW and the combined SDHW and RH system, the application of a low-e coating increases the thermal system efficiency but reduces the electrical system efficiency. Therefore the trade-off between the annual electrical and thermal efficiency of the SDHW system was studied in more detail, by varying the thickness of the low-e coating and therewith the emissivity. In figure 3 these efficiencies are shown as a function of the thickness of the low-e coating. Note that the thickness of 50 nm corresponds with an emissivity of 0.57 whereas a thickness of 300 nm corresponds with an emissivity of 0.20. A further increase of the thickness hardly changes the emissivity any further. The avoided primary energy, taking into account an efficiency of 40% for a conventional power plant, is displayed as well. The avoided primary energy hardly changes when the thickness of the low-e coating is varied over a wide range. This implies that in the case of a SDHW system with standard sizes (6 m² collector area, 200 liter storage tank), a trade-off exists between thermal and electrical efficiency.

In table 4 results are given for PVT collectors with amorphous silicon solar cells (with an efficiency of 6.3% at STC) in stead of crystalline silicon solar cells. In case a low-e coating is used, the drop in annual electrical efficiency is only 6.7% (5.02% versus 5.38%), because of the lower temperature coefficient of the efficiency of single junction amorphous silicon solar cells (-0.18%/°C relative versus

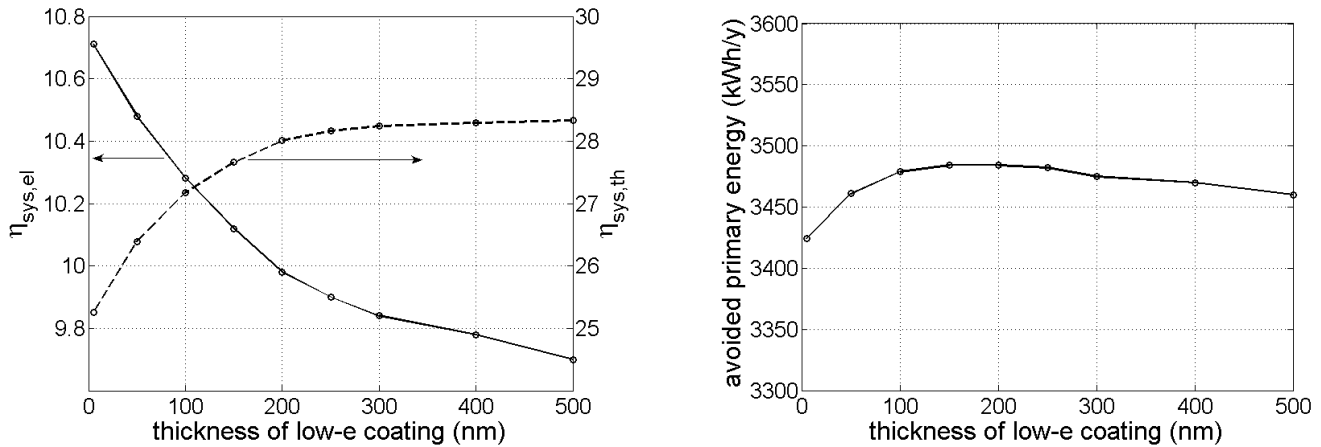


Figure 3: The annual electrical and thermal system efficiency (left) and the avoided primary energy (right) for a SDHW PVT system in case the thickness and therewith the emissivity of the low-e coating is varied.

-0.45%/ °C for crystalline silicon solar cells). Though the avoided primary energy increases from 2715 kWh/y to 2805 kWh/y, one needs to be aware that this level is much lower than in the case of crystalline silicon solar cells (being around 3450 kWh/y, compare figure 3), because of the much lower cell efficiency at STC.

6 Conclusions

The application of AR coatings in covered PVT collectors is quite favorable because it increases the annual thermal efficiency up to 5% relative and the annual electrical efficiency up to 10% relative. The application of a low-e coating is very favorable for the annual thermal efficiency, because a gain up to about 10% can be obtained. However, the electrical efficiency is reduced significantly, up to 10%. This reduction is in particular caused by the higher cell temperatures caused by the lower emissivity of the low-e coating. Whether it is advantageous to apply a low-e coating, in general, depends both on the cell

Table 4: The annual electrical and thermal efficiencies of both a SDHW system and a combined SDHW and RH system with sheet-and tube collectors with amorphous silicon solar cells.

Cover: Laminate:	Cover without ARC	Cover with ARC	
	No coating	ARC	ARC/low-e
Electrical efficiency at STC (%)	5.81	6.46	6.16
Absorption factor (%)	80.29	86.92	85.75
SDHW system			
Annual electrical efficiency (%)	4.87	5.38	5.02
Annual thermal efficiency (%)	25.5	26.6	29.0
Combined SDHW and RH system			
Annual electrical efficiency (%)	4.84	5.35	4.99
Annual thermal efficiency (%)	16.0	16.9	18.6

technology used in the PVT collectors and on the temperature of the transporting fluid, being closely related to the type of application. In the SDHW application investigated here, there is no advantage if crystalline silicon solar cells are used and only little advantages if amorphous silicon solar cells are used. Since a low-e coating reduces the electrical efficiency, its application is less favorable in terms of avoided primary energy in case more efficient solar cells are used.

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