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Performance and costs of a roof-sized PV/thermal array combined with a ground coupled heat pump

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Abstract

A photovoltaic/thermal (PVT) panel is a combination of photovoltaic cells with a solar thermal collector, generating solar electricity and solar heat simultaneously. Hence, PVT panels are an alternative for a combination of separate PV panels and solar thermal collectors. A promising system concept, consisting of 25 m^2 of PVT panels and a ground coupled heat pump, has been simulated in TRNSYS. It has been found that this system is able to cover 100% of the total heat demand for a typical newly-built Dutch one-family dwelling, while covering nearly all of its own electricity use and keeping the long-term average ground temperature constant.

The cost of such a system has been compared to the cost of a reference system, where the PVT panels have been replaced with separate PV panels (26 m^2) and solar thermal collectors (7 m^2), but which is otherwise identical. The electrical and thermal yield of this reference system is equal to that of the PVT system. It has been found that both systems require a nearly identical initial investment.

Finally, a view on future PVT markets is given. In general, the residential market is by far the most promising market. The system discussed in this paper is expected to be most successful in newly-built low-energy housing concepts.

1. Introduction

A photovoltaic/thermal or PVT module is a combination of photovoltaic cells with a solar thermal collector, forming one device that converts solar radiation into electricity and heat simultaneously. The excess heat that is generated in the PV cells is removed and converted into useful thermal energy. As a result, PVT modules generate more solar energy per unit surface area than a combination of separate photovoltaic panels and solar thermal collectors. Moreover, PVT shares the aesthetic advantage of PV.

The present PVT research started with the PhD thesis of Vries (1998), who compared several PVT concepts in theory and practice. This research was continued at ECN, in a partnership with the Eindhoven University of Technology, Shell Solar Energy BV, and ZENSolar. Since then, several concepts have been investigated, developed and tested at the PVT test facility at ECN. These concepts have been compared in a series of numerical simulations by Zondag et al. (2001). In addition, a manufacturing process has been developed, where multi-crystalline PV cells are laminated directly

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onto a copper sheet-and-tube absorber (see Fig. 1). Currently, this manufacturing process has proven to provide PVT laminates with a constant and high quality.

With this manufacturing process, two general types of PVT can be distinguished: PVT collectors and PVT panels. PVT collectors are very similar in appearance to a regular solar thermal collector, consisting of a PV-covered absorber in an insulated collector box with a glass cover. This large amount of insulation leads to relatively high thermal efficiencies, at the cost of a slightly smaller electrical efficiency due to the extra reflection introduced by the glass cover. PVT panels, on the other hand, are similar in appearance to regular PV panels (see Fig. 2). Due to the lack of extra insulation and a glass cover, PVT panels have a lower thermal efficiency, but a higher electrical yield.

In January 2003, a first series of 54 m^2 of PVT collectors has been produced. Together with 116 m^2 of regular solar thermal collectors, these have been installed on an office complex in England, as part of a project funded by the European Commission (Van Helden and Zondag, 2002).

Fig. 1. Front and back of a PVT panel.

Fig. 2. Two PVT panels, installed on the PVT test facility at ECN.

2. System concept

In 1999, Leenders et al. have compared the energetic performance and the market potential of several system concepts with PVT panels and PVT collectors. They have found a combination of PVT panels with a ground coupled heat pump, used for both space and tap water heating, to be one of the most promising system concepts (Leenders et al., 1999).

In this system, the heat produced by a roof-sized array of PVT panels is primarily stored in a storage vessel via a heat exchanger. In summer, any excess heat from the PVT panels is stored in the ground via a set of ground loop heat exchangers. In winter, this heat is retrieved from the ground by a heat pump via the same heat exchangers: the heat from this heat pump can be directed to either the tap water storage vessel or the floor heating. A schematic overview of the system is shown in Fig. 3.

This system has several advantages. First, the average ground temperature can be kept constant, because the heat from the PVT panels is used to regenerate the ground. Especially in residential neighbourhoods, where many of such systems may be installed close to each other, this prevents long-term cooling of the ground. Second, the prevention of declining ground temperatures also guarantees a constant coefficient of performance (COP) of the heat pump. Third, the electricity consumption of the heat pump will be covered by the renewable electricity from the PVT panels. And finally, the electrical efficiency of the PVT panels will be increased, due to the strong cooling of the PV cells in summer.

3. Numerical model

To determine the performance of the system described above, a system study has been performed, using a numerical model of the system in TRNSYS.

As a basis for the model, a Dutch reference dwelling has been used (Novem, 1999). This dwelling, with an annual heat demand of 8.9 GJ for space heating and 10.5 GJ for tap water heating, complies with the Dutch building standards of 2000, and is therefore typical for a newly-built Dutch one-family dwelling. It is south-oriented, and consists of three floors, with a total floor area of 132 m^2, of which only the first and second floor are heated (the heated area is 88 m^2). The dwelling is heated by floor heating, and is ventilated mechanically. A standard hot tap water usage pattern is used, with a total

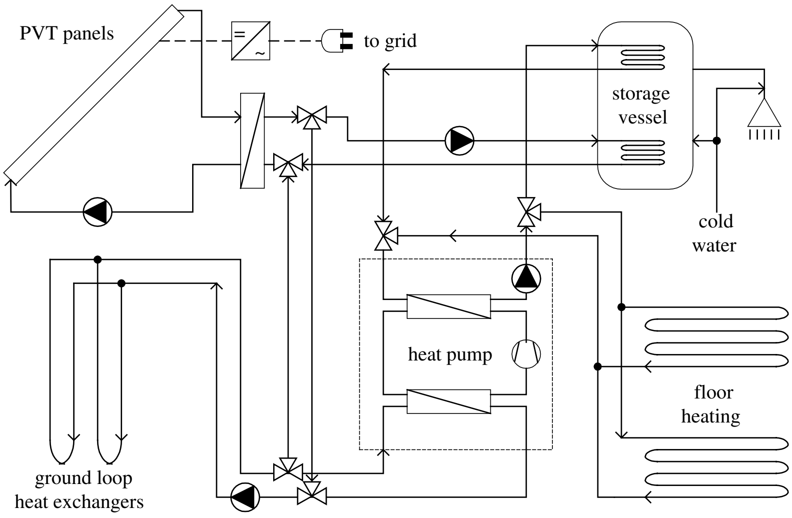

Fig. 3. Schematic overview of the system.

daily tap volume of 170 l. Both space and tap water heating are provided by the system described above.

The PVT panels, with a total surface area of $25\,\mathrm{m}^2$, have been modelled with thermal and electrical efficiency curves that have been determined previously by several series of measurements on PVT panel prototypes. As a function of temperature, the electrical efficiency has been found to be

$$\eta_{\mathrm{el}} = 0.0968 - 0.00045(T_{\mathrm{PV}} - 25), \tag{1}$$

where T_{PV} is the PV temperature in °C. Although this expression is only strictly valid for small incidence angles and direct radiation, the error made by applying it to all angles and total radiation is less than 5% (Zondag et al., 2003). The thermal efficiency of the PVT panels is expressed in terms of the inlet temperature T_{i}, the ambient temperature T_{a}, and the irradiance I

$$\eta_{\mathrm{th}} = \eta_0 - a_1 \frac{T_{\mathrm{i}} - T_{\mathrm{a}}}{I}.$$

As the PVT panels are uncovered and hence not very well insulated, the thermal efficiency is strongly dependent on wind speed. The calculated thermal efficiency curves for various wind speeds are shown in Fig. 4.

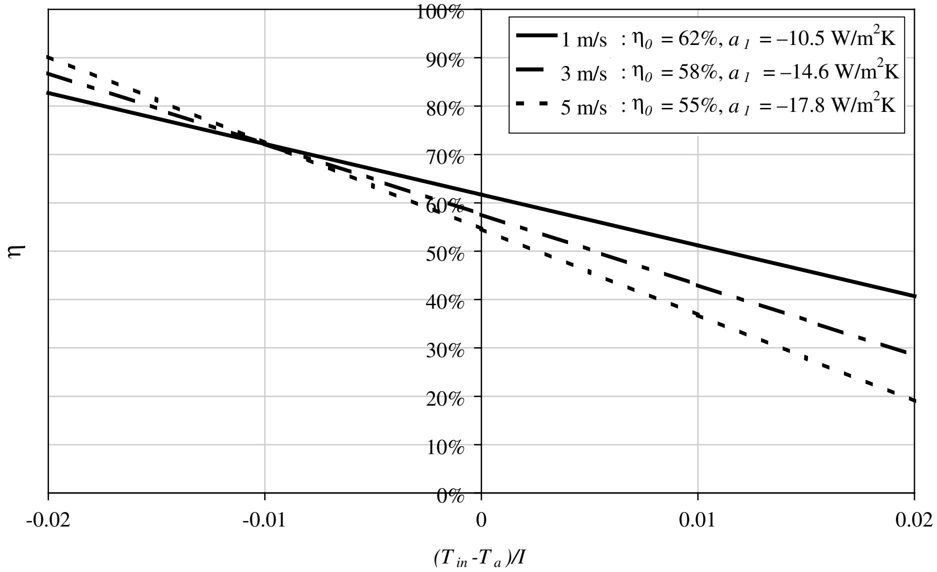

Fig. 4. PVT thermal efficiency curves as a function of wind speed.

The heat from the PVT panels is primarily used to heat a storage vessel with a volume of 200l to a certain switch temperature. When the vessel temperature has reached this switch temperature, any excess PVT heat is stored in the ground, for later extraction by the heat pump. After being preheated by the PVT panels, the storage vessel is heated further by the heat pump to a temperature of 55 °C. In addition, an electrical heater heats the vessel to 65 °C once a week, to comply with legionella regulations.

The COP of the heat pump is is calculated according to the data in the IKARUS study (Günther-Pomhoff and Pfitzner, 1994). This study gives an overview of performance data for various types of heat pumps, for various applications, and for specific condensor outlet temperatures. For this system, data for a condensor outlet temperature of 55 °C have been used. As the condensor temperature is fixed, the COP now depends only on the evaporator temperature T_{evap}:

$$\text{COP} = 2.4551 + 0.0706 T_{\text{evap}}, \tag{2}$$

with T_{evap} in °C.

As a result of the above description, the heat pump always delivers heat of a constant temperature level of 55 °C. This temperature level is fine for tap water heating, but too high for space heating purposes. Therefore, the supply for the floor heating is a mixture of the hot water delivered by the heat pump and the return water from the floor heating. The supply temperature is 30 °C.

Two ground loop heat exchangers of 35 m length each have been used, spaced 10 m apart—an average configuration for a Dutch dwelling with this heating demand. The ground loop heat exchangers have been modelled using Eskilson's model, implemented in TRNSYS type 81. This model assumes that the thermal properties of the ground are homogeneous, which is justified as long as the model is only used to describe long-term processes. In addition, Eskilson's model neglects heat transport by ground water flow. For denser soils such as rock, clay, and silt, this assumption is quite justified; for more porous soils such as gravel and sand, this assumption results in an underestimation of the thermal conductivity of the ground, and hence an underestimation of its regenerative capacity. Based on work by Chiasson (1999), the maximum error caused by this assumption is estimated to be 25% for porous soils, and 5% for denser soils.

Finally, meteorological data from the test reference year (TRY) for De Bilt, The Netherlands have been used. For the dwelling used in the simulations, these meteorological conditions translate to a heating season which lasts from 28 September until 12 May. All simulations have been run for a period of 10 years.

4. Results

The ten-year average energy balance of this reference system is shown in Fig. 5. It can be seen that the PVT system is able to cover nearly all (96%) of its own electricity use (including pumps, electrical heater, and heat pump). And by definition, the system is able to cover 100% of the heat use for space and tap water heating: the former is fully covered by the ground source heat pump using PVT supplied heat, while the latter is partially covered by the PVT panels, and partially by the heat pump. In addition, Fig. 5 shows that the ground is almost completely (83%) regenerated by the heat from the PVT. Combined with the natural regeneration by the surrounding ground and solar irradiation, this is enough to keep the long-term average ground temperature constant (see also Fig. 6).

The effect of the constant cycle of heat extraction and regeneration on the ground temperature profile is shown in Figs. 6 and 7. Both figures clearly show the oscillation of the ground temperatures as a function of time. It can

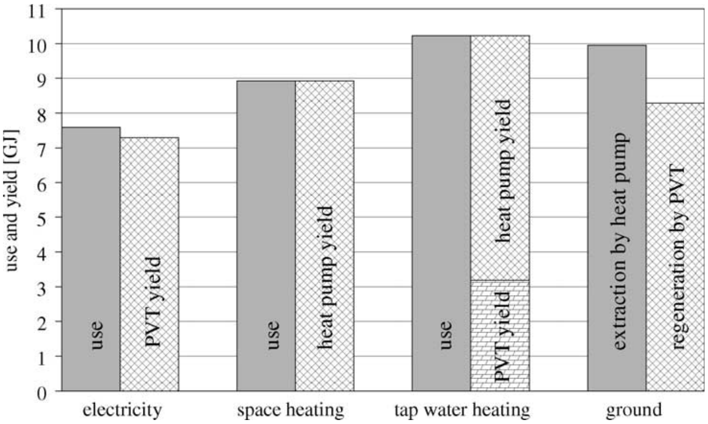

Fig. 5. Ten-year average energy balance for electricity, space heating, tap water heating and ground.

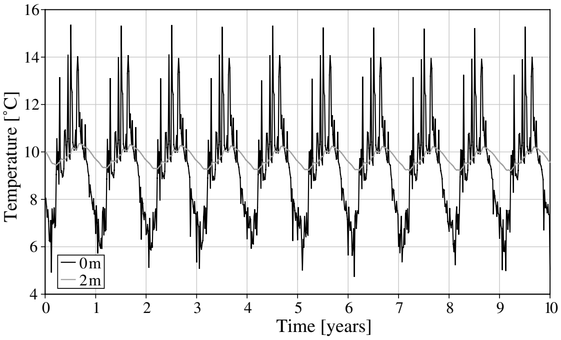

Fig. 6. Ground temperature at 0m and 2m from the ground heat exchanger at 10m depth, during 10 consecutive years.

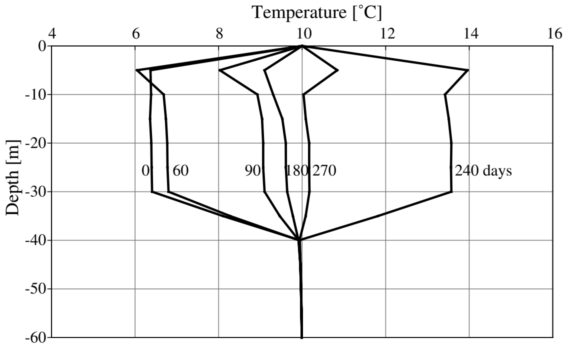

Fig. 7. Ground temperature profile at the center of the ground heat exchanger, at several times during the tenth year.

be seen that the ground temperature is influenced to a depth of approximately 40m—only 5m below the tip of the ground heat exchanger. The horizontal range of influence is approximately 3m.

In addition to the reference system, several variations on this system have been simulated. First of all, the thermal properties of the ground have been varied. For this purpose, three soil qualities have been defined: low, medium and high. The effect on the COP is less than 5%, as can be seen in Table 1. Consequently, the effect on the total energy use of the system is less than 5% as well (see Fig. 8).

Note that the average COP of the heat pump is rather low for a modern heat pump. The main reason for this is that the data that have been used to determine Eq. (2) are taken from a study from 1994, and are therefore somewhat outdated. The COP of a modern heat pump would be higher, typically higher than 3 for this type of system. For the system currently under investigation, this would lead to a slightly (~15%) lower total electricity use, and an equally larger heat extraction from the ground.

Table 1
Heat pump COP for varying soil quality

Soil quality	λ [W/m K]	c_p [MJ/m^3 K]	COP
Low	1.5	2.2	2.59
Medium	1.8	2.3	2.66
High	2.4	2.5	2.71

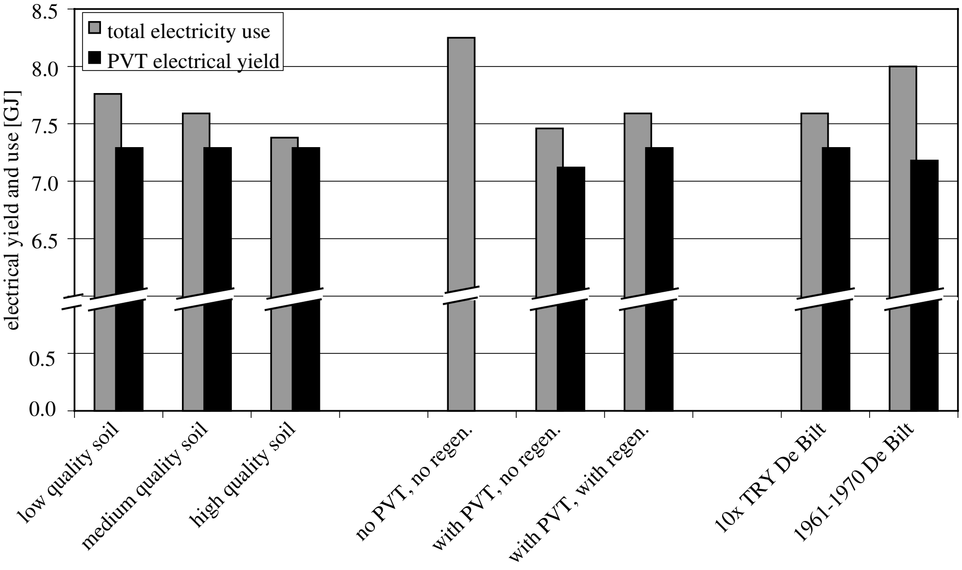

Fig. 8. Comparison of PVT yield for different soil qualities, with and without PVT or regeneration, and for 10 TRYs versus 10 actual meteorological years.

Second, the effect of PVT panels and regeneration has been investigated by simulating the reference system with and without PVT panels, and with and without ground regeneration. As can be seen in Fig. 8, the presence of PVT panels lowers the total electricity use of the system by approximately 0.8 GJ. This is a combined effect: with PVT, an additional pump is required, increasing the electricity use; however, the heat pump can be turned off for longer periods of time, resulting in an overall decrease in electricity use. When regeneration is added, the required pump energy increases. However, due to the lower PV temperatures, this extra energy is completely covered by the increased PVT electrical yield. In addition, the COP of the heat pump increases from 2.60 to 2.66 due to the increased average ground temperature caused by regeneration.

Third, the effect of the regularity in the meteorological data in the test reference year (TRY) has been investigated by running two identical simulations: one with 10 consecutive TRYs, and one with 10 years of actual meteorological data. The period of 1961–1970 has been selected for this test, as this period contains both an extremely cold winter and an extremely warm summer. On average, this period is slightly colder than the TRY, requiring more heating and hence a higher electricity use. The effect on the results is small, however: the change in PVT yield, use, and COP is less than 5%. In addition, the total irradiation in this period is slightly lower than in the TRY, leading to a slightly lower PVT electricity yield.

5. Cost comparison

In order to be able to judge the economical feasibility of the described combination of PVT panels with a ground coupled heat pump, the costs of this system have been estimated and compared to a reference system, which produces the same amount of electricity and heat, but with separate PV panels and solar thermal collectors instead of PVT panels. Both the electrical efficiency and the temperature dependence of the PV panels has been assumed to be identical to that of the PVT panels (see Eq. (1)). For the collectors, spectral selective flat plate collectors have been used, with $\eta_0 = 76\%$ and $a_1 = -3.6\,\mathrm{W\,m^{-2}\,K^{-1}}$.

In this cost comparison, a subdivision has been made into fixed costs, which are the same for both systems, and variable costs, which depend on the installed area of PV, collectors, or PVT panels. These costs, shown in Table 2, are estimates based in part on earlier work by Elswijk et al. (2003) and Bakker et al. (2003) and in part on price information from manufacturers. The estimated additional PVT manufacturing costs include personnel costs for additional handling required during production.

Table 2
Overview of the fixed and variable costs used in the cost comparison

System component	Cost [€]
Solar thermal collectors	
Absorber [$\mathrm{m^{-2}}$]	70
Collector housing [$\mathrm{m^{-2}}$]	115
Collector installation costs [$\mathrm{m^{-2}}$]	200
Total solar thermal collector costs [$\mathrm{m^{-2}}$]	385
PV panels	
PV laminates [$\mathrm{m^{-2}}$]	350
PV framing and support [$\mathrm{m^{-2}}$]	90
Inverter [$\mathrm{m^{-2}}$]	60
PV installation costs [$\mathrm{m^{-2}}$]	90
Total PV costs [$\mathrm{m^{-2}}$]	590
PVT panels	
Additional PVT manufacturing costs [$\mathrm{m^{-2}}$]	20
Fixed system costs	
Storage vessel (200 l) + drainback vessel	955
Pumps and pipework	535
Heat pump	3000
Ground heat exchangers	2750
Installation costs of above components	840
Total fixed system costs	8080

To keep the comparison as fair as possible, the reference system has been dimensioned such that the heat and electricity output of the total system is equal to that of the PVT system, and such that the net energy extraction from the ground (and hence the long-term average ground temperature) is equal to that of the PVT system.

When dimensioning the reference system, the problem of comparing electricity and heat presents itself. Due to the presence of the heat pump, electricity and heat have become completely exchangeable. If the collector area is decreased, less heat is delivered by the collectors to the storage vessel. This forces the heat pump to work harder to compensate for the decreased amount of solar heat, which results in a higher electricity use by the heat pump. This in turn requires a larger PV area to compensate for this increased energy use. In short: a decrease in collector area can be compensated by an increase in PV area. Hence, there are many possible reference systems, each with a different ratio of PV versus thermal collectors. As collectors and PV panels have different costs per unit surface area, the costs of all these reference systems is different. A 'cost optimized reference system' must therefore be defined, before a fair cost comparison with the PVT system can be made.

This cost optimized reference system has been defined by varying the collector surface area while adjusting the PV surface area to compensate for the varying electricity

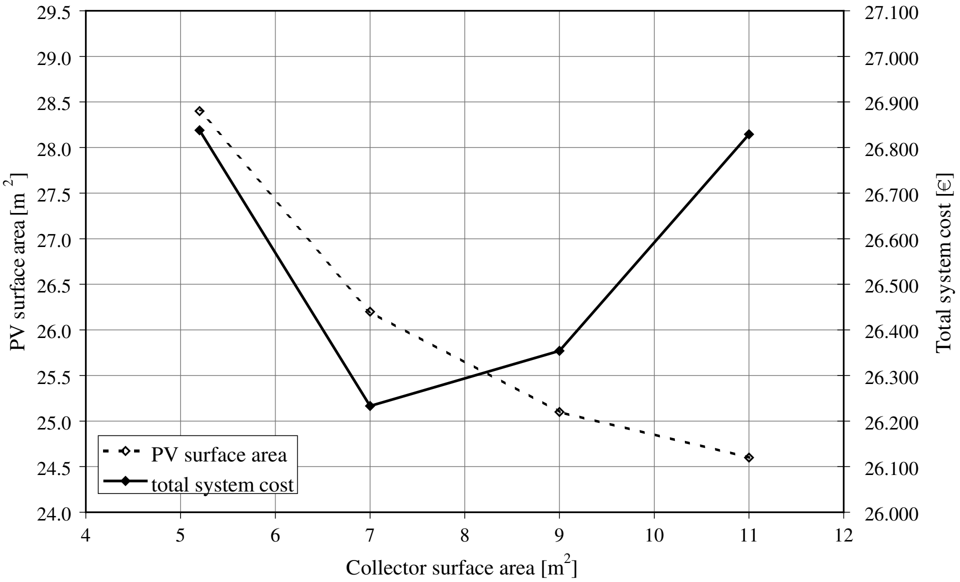

Fig. 9. Total system costs of the reference system (solid line) and PV surface area required to balance the heat pump electricity use (dotted line), both as a function of collector surface area.

use of the heat pump, and while adjusting the switch temperature to keep the net energy extraction from the ground constant. During this optimization, both the total thermal system yield and the total net energy use (electricity use of heat pump, pumps, and electrical heater minus electrical yield of the PV) is kept constant within 5%. From Fig. 9, it can be seen that the total system costs are minimal for a system with a collector surface area of approximately 7 m^2 and a PV surface area of 26.2 m^2. This configuration has therefore been used as reference system. Note that the difference in required surface area between PV and PVT is caused by a temperature effect: on average, the cell temperature in the PVT panels is slightly lower than in the PV panels.

From the results of the cost comparison, shown in Table 3, it can be seen that the PVT system requires a 6% larger initial investment than the reference system. As the total electrical and thermal yield of both systems is equal within 5%, it can be concluded that in this system configuration, PVT panels are cost competitive with a separate installation of PV and solar thermal collectors. However, in applications where space is limited, the PVT system has a slight advantage, as it only requires 25 m^2 of roof space, as opposed to 33 m^2 for the reference system.

Table 3
Cost comparison of the PVT system and the cost optimized reference system

	Reference	PVT
Surface area		
Collector surface area [m^2]	7	25
PV surface area [m^2]	26.2	25
Total surface area [m^2]	33	25
Cost component		
Absorber [m^{-2}]	490	1750
Collector housing [m^{-2}]	805	–
Collector installation costs [m^{-2}]	1400	5000
PV laminates [m^{-2}]	9170	8750
PV framing and support [m^{-2}]	2358	2250
Inverter [m^{-2}]	1572	1500
PV installation costs [m^{-2}]	2358	–
Additional PVT manufacturing costs [m^{-2}]	–	500
Fixed system costs	8080	8080
Total costs [€]	26,233	27,830

6. Future PVT markets

The market for PVT technology is a combination of the PV market and the solar thermal collector market. Depending on the type of installation, PVT technology offers a number advantages over each of these technologies.

When compared to PV panels, PVT modules offer the added benefit of 'hidden' heat generation, and a much higher specific solar energy yield. As PV and thermal collectors are quite different in appearance, they are often not combined on one roof. With PVT modules, these technologies can be uniformly integrated. Moreover, in applications where a large part of the roof is covered with PV, there is often no room left for solar thermal

Table 4
Overview of possible future market segments for PVT

Market segment	
Residential market	One-family dwellings
	Multi-family dwellings and apartment buildings
Service building market	Hotels
	Hospitals and care facilities
	Office buildings
Recreation market	Swimming pools
	Holiday bungalows
	Sport facilities
	Saunas
Agricultural market	Crop drying
	Stock breeders
	Desalination

collectors. With PVT, the building envelope can be used much more efficiently.

Compared to solar thermal collectors, PVT modules also offer an important esthetic advantage. One of the issues that the solar thermal collector market currently faces is the lack of ‘sex appeal’ of solar collectors. In this light, PVT panels can be seen as solar thermal collectors with the high-tech appearance of PV and the additional benefit of electricity production.

There are several interesting market segments for PVT; an overview of the most important ones is given in Table 4. Of these markets, the residential market is by far the most promising for PVT. In residential buildings, both heat and electricity are required, and roof space is generally limited. These requirements correspond exactly with the strong points of PVT: its simultaneous generation of heat and electricity and its high efficiency per unit surface area. For the same reason, other particularly interesting markets are crop drying and care facilities.

It is expected that on the short term, multi-family houses and apartment buildings will be the most interesting areas for demonstration projects and market introduction of PVT. For small-scale applications, particularly for existing one-family houses, the most promising system concept seems to be a tap water heating system, with a relatively small amount of PVT modules (~6 m^2). The system concept discussed in this paper—a roof-sized PVT array combined with a ground coupled heat pump—is expected to be most successful in newly-built low-energy housing concepts.

7. Summary

The system studies described in the preceding text have shown that a system consisting of a ground coupled heat pump and 25 m^2 of uncovered PVT panels is able to cover 100% of the total heat demand for a typical newly-built Dutch one-family dwelling, while covering nearly all of its own electricity use and keeping the long-term average ground temperature constant.

In addition, the costs of such a system have been estimated and compared to a reference system, where the 25 m^2 of PVT panels have been replaced by separate solar thermal collectors (7 m^2) and PV panels (26 m^2), keeping all other components unchanged. The electrical and thermal yield of this reference system are equal to that of the PVT system, as well as the net heat extraction from the ground. It has been found that the total investment required for the PVT system is equal to that required for the reference system. However, the PVT system requires less roof space, and offers a uniform appearance on the roof.

Finally, a view on future PVT markets has been given. In general, the residential market is by far the most promising market for PVT. The system discussed in this paper is expected to be most successful in newly-built low-energy housing concepts.

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