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PVT PANELS: FULLY RENEWABLE AND COMPETITIVE

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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. PVT panels generate more solar energy per unit surface area than a combination of separate PV panels and solar thermal collectors, and share the aesthetic advantage of PV. After several years of research, PVT panels have been developed into a product that is now ready for market introduction. One of the most promising system concepts, consisting of 25 m^2 of PVT panels and a ground coupled heat pump, has been simulated in TRNSYS, and has been found to be able to fully cover both the building related electricity and heat consumption, while keeping the long-term average ground temperature constant. The cost and payback time of such a system have been determined; it has been found that the payback time of this system is approximately two-thirds of the payback time of an identical system but with 21 m^2 of PV panels and 4 m^2 of solar thermal collectors. Finally, by looking at the expected growth in the PV and solar thermal collector market, the market potential for for PVT panels has been found to be very large.

1. INTRODUCTION

A photovoltaic/thermal panel, or PVT panel, 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 panels generate more solar energy per unit surface area than a combination of separate photovoltaic panels and solar thermal collectors. Moreover, PVT panels share the aesthetic advantage of PV.

Figure 1 – Front and back of a PVT panel.

PVT research in the Netherlands started with the PhD thesis of De 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, and ZENSolar. Since then, several concepts have been researched, developed and tested at the dedicated test facility at ECN. In addition, a manufacturing process has been developed, where multi-crystalline PV cells are laminated directly onto a copper sheet-and-tube absorber. Currently, this manufacturing process has proven to provide PVT panels with a constant and high quality.

With this manufacturing process, two general types of PVT can be distinguished: PVT collectors and PVT panels. The former 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 high thermal efficiencies, at the cost of a slightly smaller electrical efficiency due to the extra reflection introduced by the glass cover. The latter are similar in appearance to regular PV panels. Due to the lack of extra insulation, PVT panels have a lower thermal efficiency, but the relatively simple construction keeps their cost down.

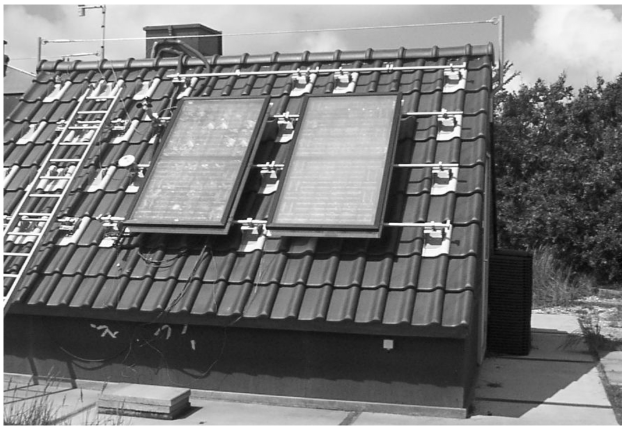

Figure 2 – Two PVT collectors, installed on the PVT test facility at ECN.

In January 2003, a first series of 45 m^2 of PVT collectors has been produced. Together with 150 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 Union.

In addition to the development of a manufacturing process, PVT research at ECN includes materials research, system studies, and design, construction and testing of prototypes.

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 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, 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 ground 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 Figure 3.

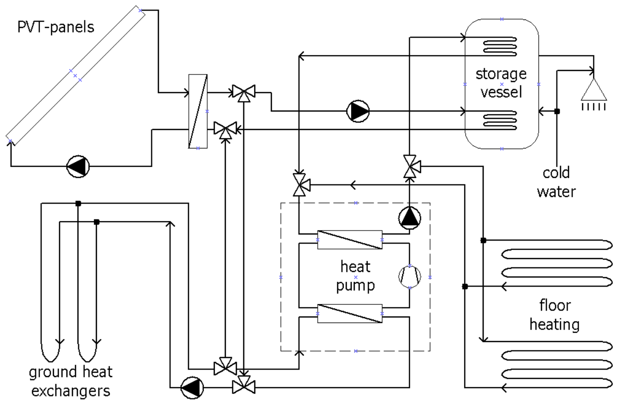

Figure 3 – Schematic overview of the system.

This system has several advantages. First, the average ground temperature can be kept constant on a yearly basis, because the heat from the PVT panels is used to regenerate the ground. Especially in residential neighbourhoods, where many 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 at least partially 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 investigate 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, as defined by Novem (1999). This dwelling has an insulation value of $R_C = 3.0$ m^{2}K/W for floor, wall, and roof, and $U = 1.7$ W/m^{2}K for the windows. The dwelling is heated by floor heating on the first and second floor, and is ventilated mechanically. Both space and tap water heating are provided by the system described above.

The PVT panels 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

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

where T_{PV} is the PV temperature in °C. The thermal efficiency is expressed in terms of the inlet temperature T_i, the ambient temperature T_a, and the irradiation *I*. As the PVT panels are not very well insulated, the thermal efficiency is also strongly dependent on wind speed. The calculated thermal efficiency curves for various wind speeds are shown in Figure 4.

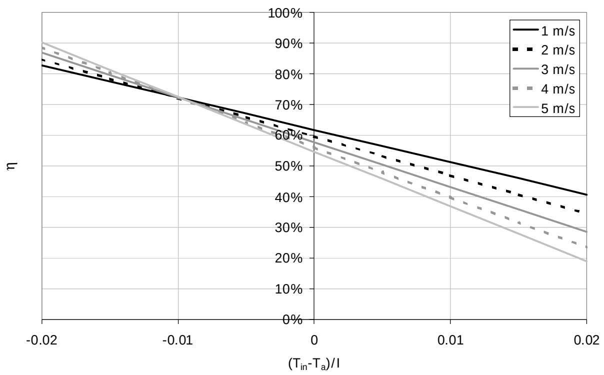

Figure 4 – PVT thermal efficiency curves as a function of wind speed.

The heat from the PVT panels is primarily used to heat a storage vessel to a certain switch temperature T_S. 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 dependent on the difference between the evaporator inlet temperature and the condensor outlet temperature, and is calculated according to the method described in the IKARUS study

(Günther-Pomhoff, 1994). As the condensor outlet temperature is kept constant at 55°C, the COP can be calculated as a function of evaporator temperature:

$$\mathrm{COP} = 2.4551 + 0.0706\,T_{evap}\,.$$

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. This assumption 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 overestimation 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, the meteorological data from the test reference year (TRY) for De Bilt, The Netherlands have been used. All simulations have been run for a period of 10 years.

4. RESULTS

An initial optimisation has been performed, in which all relevant system parameters have been varied. The most important optimisation results for the thermal and electrical yield of the PVT panels are shown in Figure 5.

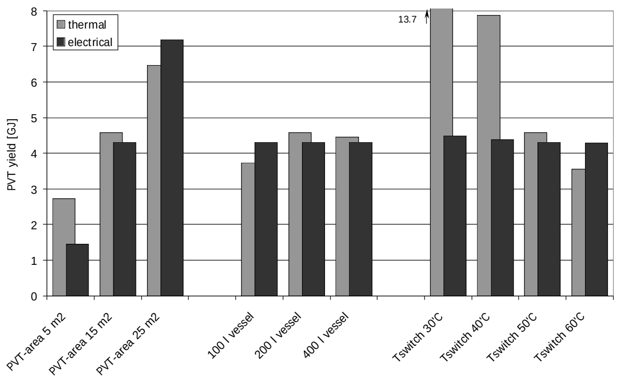

Figure 5 – Optimisation results for PVT surface area, storage vessel volume, and switch temperature. During the optimisation, the default PVT-area is 15 m^2, the default vessel size is 200 liter, and the default switch temperature is 50°C.

With the results of this optimisation, an optimal reference system has been defined, consisting of 25 m^2 of PVT panels, a 200 liter storage vessel with a switch temperature of 30°C, and 2 ground heat exchangers of 35 m length each.

The ten-year average energy balance of this reference system is shown in Figure 6. It can be seen that the PVT system is able to cover nearly all (96%) of the building related electricity use. 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, the latter is partially coverd by heat from the PVT panels, and partially by the heat pump. In addition, Figure 6 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.

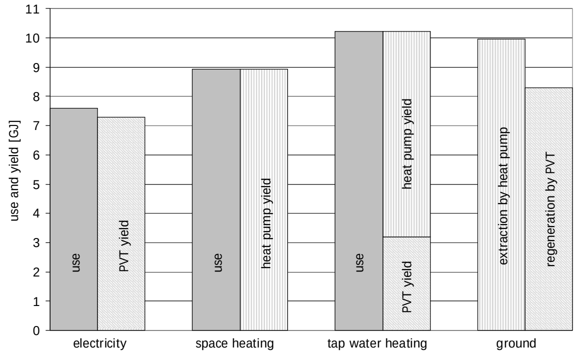

Figure 6 – Energy balance for electricity, space heating, tap water heating and ground.

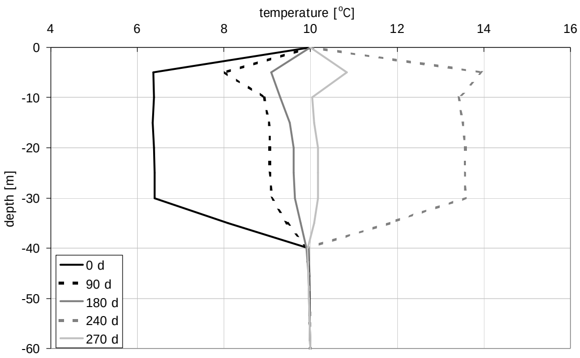

Figure 7 – Ground temperature profile at the center of the ground heat exchanger, at several times of the year.

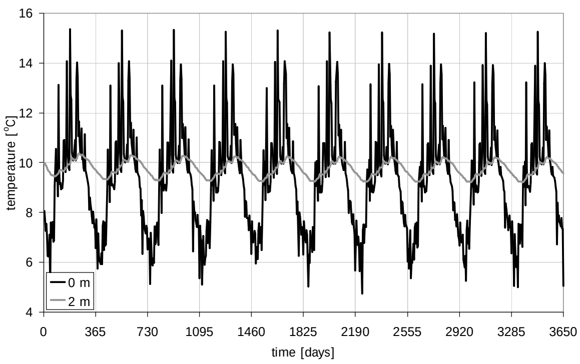

Figure 8 – Ground temperature at 0 m and 2 m from the ground heat exchanger at 10 m depth, during 10 consecutive years.

The effect of the constant cycle of heat extraction and regeneration on the ground temperature profile is shown in Figure 7 and Figure 8. Both figures clearly show the oscillation of the ground temperatures as a function of time. It can be seen that the ground temperature is influenced to a depth of approximately 40 m—only 5 m below the tip of the ground heat exchanger. From the calculations, it has been found that the horizontal range of influence is approximately 3 m.

In addition to the reference system, several variations on this system have been simulated. First of all, the thermal properties 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 use of the dwelling is less than 5% as well (see Figure 9).

soil quality	l [W/mK]	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

Table 1 – Heat pump COP for varying soil quality.

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 Figure 9, the presence of PVT panels lowers the total electricity use by approximately 0.8 GJ. This is a combined effect: with PVT, more pumps are 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, even more pump energy is needed. 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.

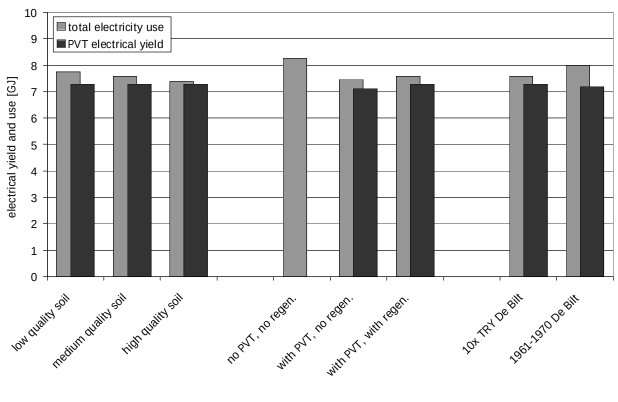

Figure 9 – Comparison of PVT yield for different soil qualities, with and without PVT or regeneration, and for 10 TRYs versus 10 actual meteorological years.

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%.

5. COSTS

In order to be able to judge the market potential of the described combination of PVT panels with a ground coupled heat pump, the estimated costs of this system have been compared to an identical system, but with separate PV panels and solar thermal collectors.

In comparing these two systems, the problem of comparing electricity and heat presents itself. The two systems under comparison may be dimensioned for either equal electricity output, equal heat output, or equal surface area. All three comparisons will yield slightly different results. In this case, a comparison based on equal surface area has been chosen, as in practice, this is often the limiting factor in dimensioning high-yield solar energy systems for residential areas[†].

Moreover, the thermal yield for both solar thermal collectors and PVT panels is strongly dependent on the system—e.g. storage vessel size, and whether the heat is used for space or tap water heating. In particular, solar thermal collectors are typically better insulated and covered with glass, giving a higher thermal efficiency and a higher outlet temperature. Although this has been taken into account in the following calculation, the calculated thermal yield should only be interpreted as a rough indication of the actual yield.

This being said, a system with 25 m^2 of PVT panels and a ground coupled heat pump has been compared with an identical system, but with 21 m^2 of PV panels and 4 m^2 of solar thermal collectors.

To keep the cost comparison as fair as possible, each system has been subdivided into components, so-called ‘building blocks’. Next, the cost of each building block has been determined; examples of selected building blocks are the collector housing, storage vessel, PV laminate, inverter, heat pump, and installation and manufacturing costs. Finally, a list of required building blocks has been made for each system, and the cost of each system has been determined by calculating the sum of the costs of all building blocks on the list. Note that not all components are required in each system: for example, there is no collector housing in the PVT system, as these are uncovered panels; conversely, no PVT

[†] To be sure, an additional comparison has been made, based on equal electricity *and* heat output: this required 25 m^2 of PV and 17 m^2 of thermal collectors, and led to similar results and identical conclusions.

manufacturing costs are included in the separate system. The relative total cost of the two systems is shown in Table 2.

In addition, Table 2 shows the relative thermal and electrical yield of the two systems. It can be seen that the PVT system generates more heat and electricity. Finally, the relative payback time is shown in Table 2. This is the simple payback time, i.e. the time in which the savings in energy cost are equal to the initial investment. From Table 2, it can be concluded that although the system with PVT panels requires a larger initial investment, the additional savings due to the higher energy yield are more than enough to compensate for this: the payback time of the PVT system is approximately two-thirds of the payback time of the separate system.

performance indices	separate	PVT
total cost	100	111
thermal yield	100	414
electrical yield	100	119
payback time	100	67

Table 2 – Comparison of the relative cost, performance and payback time of a PVT system and a system with separate PV and thermal collectors.

6. MARKET POTENTIAL

In general, three market segments can be distinguished for the application of PVT panels: the residential market, the utility market, and the remainder, consisting mainly of recreational, agricultural, and industrial applications. Of these, the residential market is by far the most promising market 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.

The residential market for PVT panels extends over three existing market segments: the photovoltaic market, the solar thermal collector market, and a market for new low-energy system concepts. In each of these markets, PVT has its specific advantages.

Compared to existing PV installations, PVT panels offer the advantage of combined heat generation, and a much higher specific solar energy yield. Especially in installations where a large part of a roof is covered with PV, there is often no room left for solar thermal collectors. Moreover, the combination of PV with solar thermal collectors in one building often gives rise to aesthethic problems due to the different appearance of the two systems. Therefore, PV panels and solar thermal collectors are generally not combined. With PVT panels, this combination is much simpler: both the specific electricity yield and the high-tech appearance are equally advantageous for PVT and for PV, but PVT panels have the added benefit of 'hidden' heat generation.

Compared to existing solar thermal installations, the greatest advantage of PVT panels is aesthetics. One of the issues that the 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 additional electricity production.

Finally, PVT panels are an essential part of several new low- and zero-energy system concepts, of which one has been discussed in this paper. For such concepts, a new market is rapidly forming, not in the least by strong stimulation by national governments and the European Union.

As an indication of the market potential for PVT, the targets set by the European Union for PV and solar thermal collectors may be used. According to the EU, the total installed area of solar thermal collectors will reach 100,000,000 m^2 in 2010. For PV, the target is set at 3 GWp installed in 2010; at approximately 100 Wp per square meter, this corresponds to 30,000,000 m^2. Combined, the total market size of the two technologies is 130,000,000 m^2. This means that every percent of market penetration that PVT has gained in 2010 corresponds to an increase of the PVT market by 1,300,000 m^2. Therefore, even with conservative estimates, the total market potential for PVT in 2010 is very large.

7. CONCLUSIONS

Since the beginning of PVT research in the Netherlands in 1998, PVT panels and collectors have been developed into a cost-effective product, that is now ready for market introduction.

The combination of a roof-sized PVT array with a ground coupled heat pump has been found to be able to fully cover both the building related electricity and heat consumption. In addition, the long-term average ground temperature can be kept constant.

By determining the cost of all their components, the cost of a system with a roof-sized PVT array has been compared to the cost of an identical system with separate PV panels and solar thermal collectors. It has been found that the payback time of the PVT system is approximately two-thirds of the payback time of the separate system.

The market for PVT panels can be separated into three segments: the existing PV market, the existing solar thermal collector market, and a market for new low-energy system concepts. In all three, PVT panels have distinct advantages. Even with a small initial market share, the expected market potential for PVT panels is very large.

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