June 2004 ECN-RX--04-056

PV-Thermal collector development – an overview of the lessons learnt

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This paper has been presented at the "19th European PV Solar Energy Conference and Exhibition", 7-11 June 2004, Paris, France

ABSTRACT: Research on PV-Thermal (heat extraction from PV) started in 1974. Much experience has been gained, both on module and on systems level. The present paper aims at giving an overview of the most important lessons that can be drawn from the development for PV-liquid.

Keywords: PV-Thermal modules, module manufacturing, system

1 INTRODUCTION

PV-Thermal modules are modules that convert solar radiation into both electricity and heat. The field of PVT research is subdivided in PVT-air and PVT-liquid. The present paper will focus on flat-plate PVT-liquid. A typical PVT-liquid laminate is shown in Figure 1.

Figure 1: **PVT-liquid laminates**

The topic of PV-Thermal (heat extraction from PV) has attracted attention from 1974 onwards. However, at present, the only commercial PVT-water product seems to be the unglazed PVT collector of Millennium Electric [1], and possibly in the near future the unglazed PVT collector of SOLON AG. Most research projects in the PVT field were short and scattered over many institutions and often long-term commitment was lacking, leading to premature termination of many R&D projects. A PVT project overview is presented in Table 1

Netherlands	ECN with ZEN Solar and Shell Solar
Norway	University of Oslo with SolarNor
Denmark	Esbensen with Batec and Racell
Germany	Fraunhofer ISE with Zenit
	ISFH with Solarwerk / SOLON
	Solarwatt
Switzerland	EPFL with Enecolo and Ernst Schweizer
Sweden	Uppsala University with Vattenfall
Austria	Arsenal with Sollektor
Israel	Chromagen / Millennium Electric
USA	Powerlight
USA	SDA with Sunearth and Unisolar

Table 1: **PVT-liquid R&D with commercial partners involved**

In order to support the development of PVT, the EU Coordination Action PV-CATAPULT has been set up, bringing together researchers from various institutions having experience in PVT to provide a roadmap for PVT, taking the earlier IEA roadmap [2] as a starting point. As a preliminary step, an effort has been made to collect the various lessons that have been learnt both from the research at ECN and from publications worldwide.

2 SYSTEM LEVEL

2.1. Introduction

PV-liquid collectors have been manufactured for several types of systems. The PV-part can be autonomous or grid connected, the thermal part can be aimed at medium temperature heating (domestic hot water and possibly room heating) or low temperature heating (pool heating, preheating ventilation air, upgrading the source of a heat pump that is providing domestic heat). Which of these applications makes sense, depends on local conditions, such as energy infrastructure and energy prices, but also on climate, particularly the amount of irradiance during the winter.

In Europe, the domestic market is by far the largest of the solar thermal markets, consisting of purely hot water heating in Southern Europe and a combination of hot water and room heating in the North. Research on concentrating PVT has been carried out in Greece and in Sweden, while in other European countries the focus has been on flat plate applications. In contrast to the situation in Europe, in the USA, a very large part of the collector market consists of unglazed collectors for swimming pool heating, leading to PVT design adapted for this market. For certain countries in the Middle East and North Africa, PV cooling is a very important consideration in PVT development.

From an EU market point of view, it seems that the domestic market is the most promising. It is a very large market and because of the increasing energy requirements for dwellings there is a large potential for PV-Thermal. A particularly interesting niche within this market is apartments in high rise buildings because of the limited area per inhabitant available [3]. Within the domestic market, the focus is on tap water preheating, possibly supplemented by seasonal heat storage for room heating. For the domestic market, both covered and uncovered PVT systems can be developed. Covered systems are relatively expensive but can provide high thermal yield. Uncovered systems have lower initial cost and a slightly higher PV output but also a much lower thermal output, making them more suitable for the low-cost, low thermal yield option.

2.2. Domestic systems with covered PVT

Covered PVT can be applied in a solar DHW system, replacing conventional thermal absorbers. Due to the somewhat lower annual efficiency (due to additional reflection losses, radiative losses and electricity production), roughly 40% additional area is required to obtain the same thermal yield, leading to a typical area of 4-6 m^2. The electrical yield is somewhat less than a similar area of PV laminates, mainly due to additional reflection losses at the cover.

If room heating is also applied, larger areas result, mainly because domestic solar heating systems suffer from substantial energy loss from the seasonal storage, while the collector efficiency is reduced over a large part of the year due to high storage temperatures. In addition, such storages are large and expensive. For the theoretical case of a room heating system without domestic hot water production, in [4] an optimum is found of about 10 m^2 of PVT area for a system with a 20 m^3 storage, resulting in a solar fraction of about 50% for a well insulated house in the Netherlands.

2.3. Domestic systems with uncovered PVT

Uncovered PV-Thermal collectors have several advantages, such as a better electrical performance and a lower stagnation temperature. However, their thermal efficiency is strongly reduced at higher temperatures. Therefore, a natural combination is an uncovered PVT providing low-temperature heat that is upgraded by a heat pump. This could be realised by letting a PVT regenerate the source of a heat pump with ground source heat exchanger. Due to the low temperature of the source, an uncovered PVT laminate of relatively small size is already sufficient to regenerate the source. In a simulation study [4], it was indicated that 3.3 m^2 of uncovered collector surface was sufficient to regenerate the low temperature source of a heat pump supplying all the room heating for a well insulated residence. Due to the low temperatures, very high annual collector efficiencies can be obtained. For such a small system, the power consumed by the heat pump was slightly larger than the electrical power produced by the PVT.

However, domestic heat pumps withdraw only a modest amount of heat from the soil. In the case that no regeneration is applied, the resulting temperature decrease of the soil seems to have only a limited effect on the efficiency of the heat pump. This effect becomes even less when also domestic cooling is provided by the heat pump. On the system level, therefore, the energetic performance can be improved by giving priority to tap water heating, using the excess heat for regeneration. For such a system it is shown that an uncovered PVT system of 25 m^2 was able to cover fully the building related electricity and heat consumption, and that the pay-back time of such as system was approximately two thirds of the payback time of a side-by-side system [5]. However, this study has also shown that for domestic applications, the heat supplied to the soil by the PVT had only a very small beneficial effect on the performance of the heat pump, whereas the direct tap water heating was also not very efficient, due to the fact that an uncovered collector was used.

From a cost perspective, an interesting application is to use uncovered PVT panels directly as the source of the heat pump, thereby foregoing the costs of the ground heat exchanger [6]. The thermal efficiency of such a system for domestic applications is reduced, however, due to the mismatch between solar supply and thermal demand.

As a general remark, a disadvantage of all these systems would be that the commercialisation of PVT along this line would make it dependent on the development of the heat pump.

2.4. Other systems

Various other PVT applications are possible, such as indoor and outdoor swimming pools, PV facades for preheating ventilation air and biomass drying (the latter two being PVT-air). Since the domestic market is the main EU market, these options are not explored here. An overview is given in [7].

3 MODULE LEVEL

3.1. Introduction

The different system options also lead to different collector design options. For uncovered systems, the focus is on low-cost, which may lead to plastic PVT collectors and use of standardised components. For covered systems, the focus is on high yield, which puts emphasis on increasing the efficiency by increasing the solar absorption over the entire solar spectrum and the possibilities of spectral selectivity. Due to the additional insulating cover, however, also additional problems are caused since the PV is subject to short but high stagnation temperatures, e.g. when pump failure occurs.

3.2. Manufacturing techniques

The most basic technique to fabricate a PVT collector is to glue a commercial PV laminate to the absorber of a commercial thermal collector (in theory also lamination could be used, but it is very difficult to avoid delamination when laminating an already laminated PV, as appeared in a PVT R&D project [8]). Drawbacks are that the PV laminate will not be optimal for thermal performance (e.g. due to low absorption in the spacing between the cells) and that the thermal resistance between the PV and the absorber may become to large for good thermal performance, especially when air enclosure in the glue layer is significant.

A more advanced technique is therefore to laminate the whole package of top cover, PV cells, electrical insulation and absorber together in one step. This requires a very flat absorber. If a metal absorber is used, good care should be taken that the electrical resistance between the PV cells and the metal absorber remains sufficiently large. High temperature lamination may result in a slight bend of the PVT laminate, due to the difference in thermal expansion between the glass and the metal.

While the encapsulant at the front of the cell needs to be transparent, for the encapsulant at the rear this is not required. PVT cells have been manufactured using a black rear encapsulant, which also functions as absorber [9]. While this eliminates one manufacturing step, care should be taken that the black encapsulant does nowhere come in front of the cells.

Instead of lamination, a low temperature encapsulation technique may be used, such as the application of silicones, which have a very high resistance to high temperature. However, this implies a two component liquid encapsulant, that will be cumbersome to apply and has the risk of air entrapment.

For uncovered modules, a low-cost plastic channel-plate absorber may be applied, such as the one developed by Solarnor [10]. In this case, only low temperature and low pressure solutions present itself, since otherwise the plastic absorber will not withstand the lamination step.

Another aspect that requires attention is the mounting of the collector tubes to the absorber. This may be done either before or after the mounting of the PV. If it is done before, care should be taken that the absorber surface remains sufficiently level, since the soldering of the tube may cause severe problems [11]. In addition, the tubes provide a non-level rear that complicates the lamination procedure, leading to increased handling time during production. At the other hand, if the tube is connected after mounting of the PV, soldering temperatures would damage the encapsulant.

3.3. Resistance to high temperature

In thermal systems, the heat extraction may fail, leading to stagnation. This may occur because of pump failure, or because the thermal storage capacity of the system is exceeded. In this case, the absorber can only lose the absorber heat trough convection and radiation losses to the ambient. Whereas for an unglazed PVT this leads to normal PV-temperatures of up to 85 °C, for glazed PVT collectors much higher temperatures can be found. Measurements in the Netherlands indicated a stagnation temperature for a PVT collector of 126 °C. Such high temperatures are very demanding for most encapsulation techniques, including the commonly used EVA, and specific attention should be paid to prevent delamination or yellowing of the encapsulant. A similar warning applies for some plastic superstrate materials.

3.4. Thermal shock

It may happen that after a period of stagnation, a PVT collector is switched on again and cold water flows through the very hot collector. This phenomenon is called ‘internal thermal shock’, which is a standard test criterion for thermal collectors. Internal thermal shock leads to the formation of steam and the sudden and non-uniform thermal contraction of the absorber. In PVT collectors, care should be taken that this effect does not lead to breaking of the PV cells. In the PVT literature, no attention is paid to this phenomenon. However, a PVT collector tested at ECN did not turn out to have any difficulty in passing this test.

3.5. Absorption

For a PV-Thermal collector, it is important to absorb as much as possible of the incoming radiation, including the fraction that is not useful for photovoltaic conversion.

PV cells are fairly efficient absorbers for radiation with energy larger than the bandgap, but for radiation with less energy, a relatively large part is reflected, largely at the rear contact but also at the cell surface, since the AR-coating is not optimised reduction of the longwave reflection. Absorption measurements have been carried out by Affolter [12] and Platz [13]. For various types of a-Si cells, Affolter found that the absorption varied between 71% and 89%. Platz found the absorption to be within the range 78%-90% for various encapsulated a-Si cells, while 88% was found for an encapsulated multi-crystalline Si cell.

A first step to optimise the absorption of the PV is the use of black rear material instead of the standard white rear foils, to maximize the absorption in the spacing between the cells. A next step would be to optimise the cell absorption itself – including the wavelengths longer than the bandgap. Care should be taken that radiation is absorbed at the rear contact, rather than reflected. A more advanced design could use a secondary absorber, absorbing the longwave radiation that is transmitted through the PV. Such a technique would require a (partially) transparent rear contact, combined with antireflection techniques at the rear of the cells. In addition, surface treatments promoting broadband absorption (such as texturisation) are to be preferred over coatings with a more narrow absorption window (such as AR coatings).

Finally, attempts have been made in the past to blacken the top grid of the cells. However, it was concluded that the additional investment required for this could not be justified by the small increase in thermal efficiency [14]. The reduction of top grid reflection due to buried grid techniques further underscores this statement.

To the extent in which optimisation of the PV for PV-Thermal applications requires non-standard PV components, the production requires large investments. Therefore, it is expected that, given the very small market share of PV-Thermal systems today and in the near future, the PV-Thermal industry will probably limit itself to PV cells that are commercially available, choosing from these the cells with the best thermal performance. This will particularly be the case for the low-cost, low-yield side of the market, with its focus on uncovered PVT with air as the collector medium.

3.6. Electrical efficiency

For an uncovered PVT module the electrical efficiency will generally be larger than for a PV laminate. However, for a covered PVT module, the electrical efficiency is reduced due to the reflection at the top cover and the relatively high temperatures to which the PV is exposed (depending on the solar fraction of the system). The high temperatures have been used as an argument for the application of a-Si, since its efficiency has a lower temperature dependence and the high temperatures cause a reversal of the Staebler Wronski degradation [15]. However, the temperature effect is small for all cell types [16] and in most of the PVT research c-Si is used, among others because of its larger electrical efficiency. The top cover reflection can be reduced by the application of highly transparent glass [17].

3.7. Heat transfer

A recurring problem in the PVT literature is the thermal resistance between the PV and the thermal absorber. If this resistance is too high, this implies a relatively large temperature difference between the PV and the collector medium, leading to increased thermal losses and a reduced PV performance. The magnitude of the additional losses depends on the thermal insulation of the PVT collector; for an unglazed collector this is more severe than for a glazed collector. The effect of the thermal resistance on the collector efficiency is indicated in Figure 2. An unglazed PVT collector corresponds roughly to UL=15 W/m^{2}K, while a glazed PVT collector corresponds roughly to UL = 5 W/m^{2}K. It is clear that this effect is very severe for uncovered collectors.

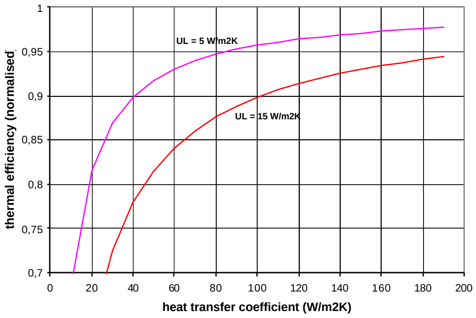

Figure 2: **Effect of the thermal resistance on the normalised thermal PVT efficiency**

The thermal resistance is increased substantially by air enclosure, which should therefore be avoided. For this reason, clamp connections between PV and absorber are not recommended.

3.8. Spectral selectivity

A widely applied technique to raise the performance of a thermal collector, is to use a spectrally selective absorber. This absorber has a high absorptivity for solar light, but a low emissivity for longwave thermal radiation.

In PVT collectors, the surface of the PV will often consist of glass, which has a very high emissivity of 90%. This leads to much higher radiative losses than those from a conventional solar thermal absorber. This can be remedied by applying a coating on top of the glass, that reflects in the IR part of the spectrum, while being transparent in the solar part of the spectrum. Such coatings are now also applied in HR glass. However, the coatings that are presently used in commercial high efficiency glass have a transmission in the solar spectrum that is too low for this application.

A different approach would be to use cells that have a low emissivity themselves, and encapsulate these with a material that is largely transparent in the IR. The emissivity of various PV cells was measured by Affolter and by Platz et al. Their results are summarised in Table 2. To make optimal use of this property, PVT prototypes have been built in which PV cells were not encapsulated, but just glued directly to the absorber. However, it can be expected that in the longer run this will generate moisture problems and degeneration of the cells or the electrical contacts.

	Emissivity (Affolter)	Emissivity (Platz et al)
ZnO	30%	41%
SnO2	-	17%
ITO	42%	60%-65%
p-Si	-	40%
glass	88%-90%	86%
EVA (a-Si)	86%	-
Tefzel (a-Si)	95%	-

Table 2: **PV emissivities (from Affolter [12] and Platz [13])**

3.9. Electrical wiring

In a PV-Thermal collector, a temperature gradient will occur over the thermal collector, due to the fluid heating up. This implies that not all PV cells will be operating at the same temperature. Since the PV current is much less temperature dependent than the PV voltage, good electrical performance is obtained by a series connection of PV cells operating at different temperature, while a parallel connection of cells at different temperature will cause significant power losses.

Due to the high temperature demands on the encapsulant under stagnation, it is even more important to prevent the possibility of hot spots. Care should be taken that, due to the PVT thermal insulation, bypass diodes in the junction box may become very hot when bypassing the PV current.

4 CONCLUSIONS

Both covered and uncovered PVT system designs are explored and many techniques have been tried for PVT manufacturing. It is important to pursue this research further to obtain commercially viable PVT systems. The PV-CAtapult roadmap aims at playing a guiding role in this field.

ACKNOWLEDGEMENT

This study was supported by the EU as part of the project PV-Catapult.

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