PERFORMANCE ANALYSIS AND YIELD ASSESSMENT OF SEVERAL UNCOVERED PHOTOVOLTAIC-THERMAL COLLECTORS: RESULTS OF FIELD MEASUREMENTS AND SYSTEM SIMULATIONS

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ABSTRACT: A PVT collector combines a PV module with a solar thermal absorber and produces electricity and heat. Interest in PVT systems is growing, since these potentially generate more energy per m^2 than PV-only systems. Furthermore, a large share of the residential energy use consists of heat. Within the Dutch project WenSDak, a consortium of eight companies and three knowledge institutes developed five different PVT concepts and evaluated their thermal and electrical performance. In this paper, we focus on three types of uncovered PVT collectors. There is a large difference between the measured thermal performance of the three different collectors. These differences can be explained by the PVT collector design. The absorption of all PVT modules is quite good (0.9 – 0.94). A good heat conduction from the PV cells to the absorber leads to a high peak collector efficiency, while insulation at the back of the PVT module improves the performance at higher temperatures. Performance of some collectors can be improved by e.g. heat conducting paste, however, this is also more expensive. System simulations with PVT as part of a solar heating system are carried out in TRNSYS and will yield valuable information on the annual yield for a specific system.

Keywords: Building Integrated PV (BIPV), Thermal Performance, PVT Systems

1 INTRODUCTION

Hybrid PV-thermal (PVT) systems have been around for several decades [1]. Currently, there is a renewed interest in the development and application of PVT systems. In the Netherlands, this mainly holds for uncovered PVT systems, often in combination with a (ground source) heat pump. The renewed interest for PV-T collectors is, besides declining PV prices, related to European regulations aiming towards (near) zero-energy buildings in the near future. Several full-roof (BI)PV solutions have been developed for such buildings, limiting the roof space available for solar thermal. Since a large share of the energy demand in the built environment in continental Europe consists of heat, PVT systems may result in higher energy and exergy yields and a more aesthetic uniform appearance of the roof. Furthermore, they may result in higher combined efficiencies, with relatively little additional costs in comparison to standard PV.

The research presented in this paper is part of the Dutch WenSDak project in which 8 industrial partners and 3 research institutes develop and analyse 5 different concepts for the combination of solar heat and solar electricity in one roof. This paper focuses on the electrical and thermal performance of the three uncovered PVT systems in the project that were developed by different project partners. Uncovered PVT modules do not have an additional air or gas layer with a glass cover and therefore, show lower PV temperatures than covered PVT systems and lower thermal performance at higher fluid temperature.

The thermal and electrical performance of three different types of PVT collectors was analysed in a field test at SEAC's field test facility 'SolarBEAT'. The performance data of the different collectors can be used as input for annual simulations of a typical system.

2 METHOD

2.1 Definition of the PVT collectors

The different types of PVT collectors are (see also Figure 1):

- A: CIGS panel with clamped absorber and insulation produced by Solartech (Energiedak MEP panels)
- B: c-Si PV with uninsulated absorber clamped to the back of the module, produced by GEO Holland
- C: building integrated c-Si PV with in-roof absorber and insulation produced by Dimark Solar

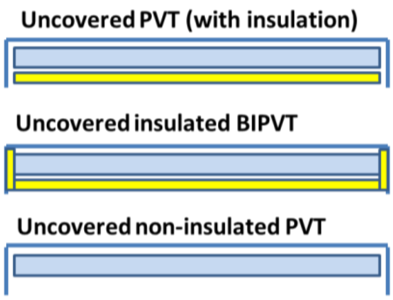

Figure 1: Three different PVT concepts (bright blue line: PV module, blue block: thermal absorber with fluid channels, yellow: insulation)

2.2 Field test design and operation

The three uncovered PVT systems were installed on the experimental outdoor field test facility of SEAC as shown in Figure 2. The following setup was installed:

- System A: 4 PVT collectors and 4 PV modules; results are shown for 4 PVT collectors, gross area of 4.4 m^2, flow rate 24 l/m^2h
- System B: 5 PV collectors and 3 thermal absorbers; results are shown for 2 PVT collectors, gross area of 3.3 m^2, fluid flow rate 74 l/m^2h
- System C: 3 PVT collectors and 3 thermal collectors; analysis of 2 PVT collectors, gross area of 3.5 m^2, flow rate 18 l/m^2h

The outdoor facility includes a solar measurement station with which direct, diffuse and global horizontal irradiance are measured, as well as wind speed and direction and ambient temperature.

Figure 2: Field test with three types of uncovered PVT systems on the dummy roof in the middle

Furthermore, a thermal loop was designed and installed to allow for measurements on solar thermal collectors and PVT systems. Excess heat produced by the thermal systems is dumped in the university's aquifer. A combination of heaters, valves, chillers and control technology make sure the liquid is preconditioned to the specified temperature. The input temperature for the systems can be set between 7 and 80°C. A 25 % glycol solution is used in the PVT loop.

The collectors of each system are thermally connected in series. For each system, different flow rates are defined. However, the inlet temperature of the first collector of each system is the same. The flow rates were decided upon by the supplier of the system, to match the flows that are used in real systems. Each PVT panel is electrically connected to a DC/DC SolarEdge power optimizer. The power optimizers are in series connected to the SolarEdge AC/DC inverter. Therefore, the electrical and thermal performance of the PVT modules is measured at maximum power point.

The following measurement equipment is installed:

- Meteorological measurements: Global tilted irradiance (secondary standard pyranometer), pyrgeometer, in-plane wind speed and direction, ambient temperature.
- PV performance measurements: Measurements are done at MPP (maximum power point). DC voltage and DC current (via a shunt) are measured for each PVT collector separately.
- Thermal performance measurements: input and output temperature of each collector (Pt100, 1/3B) and flow rate (Electromagnetic sensor, one per series of collectors).
- Datalogging: All sensors are connected to a Yokogawa MW100 datalogger. Data is recorded every minute and uploaded every night to a database.

The field test has been running for a full year, from June 2015 to May 2016.

2.3 Evaluation of thermal performance

For analyzing the thermal efficiency, we followed the steady state analysis for unglazed collectors as described in the ISO 9806 norm [2], though there are some differences , like building integration of the PVT modules in our test site and the flow rate. The thermal efficiency (η_{th}) is calculated by Equation 1. The effective irradiance is calculated by equation 2, with the in-plane irradiance as an input. Furthermore, the pyrgeometer is used to calculate the long-wave irradiance (EL). The coefficients η_{th}, b_u, b_1 and b_2 are fitted by using a least squares method and equation 3.

Equation 1

$$\eta_{th} = \frac{\dot{Q}}{A_G \cdot G''} = \frac{\rho \cdot c_p \cdot \dot{V} \cdot (T_{out} - T_{in})}{A_G \cdot G''}$$

Equation 2

$$G'' = G_{POA} + \frac{\varepsilon}{\alpha}(E_L - \sigma T_a^4) \text{ with } \varepsilon/\alpha = 0.98$$

Equation 3

$$\eta_{th} = \eta_{0,th}(1 - b_u u) - (b_1 + b_2 u)\frac{(T_m - T_a)}{G''}$$

With:

A_G Gross collector area (m^2)
b_1 heat loss coefficient (W/m^2K)
b_2 wind dependence of the heat loss coefficient (J/m^3K)
b_u collector efficiency coefficient (wind dependence) (s/m)
c_p Specific heat capacity (J/kgK)
G_{POA} Global irradiance in plane-of-array (W/m^2)
G''/G_{eff} Net irradiance (W/m^2)
T_a Ambient temperature (K)
T_m Mean collector temperature (Tin+Tout)/2 (K)
T_{in} Input temperature (K)
T_{out} Output temperature (K)
$\dot{Q}_{th}$ Heat flow (W)
u Wind speed (m/s)
$\dot{V}$ Volume flow (l/s)
α Solar absorptance (%)
ε hemispherical emittance (%)
$\eta_{0,th}$ Peak collector efficiency (η_{th} at $T_m = T_a$)
η_{th} Thermal collector efficiency, with reference to T_m
ρ Density (kg/l)
σ Stefan-Boltzmann constant (W/m^2K^4)

3 FIELD TEST RESULTS

3.1 Introduction

PVT collectors produce both heat and power. The energy yield depends on different factors, of which the most important factors are: Irradiance, ambient temperature, average fluid temperature and wind speed. Figures 3a and 3b show the produced power (heat and electricity) in W/m^2 for the three collector types. We chose two sunny days with a low (7˚C) and a high (35˚C) inlet temperature in summer 2015.

Irradiance in the plane-of-array is shown in green. The thermal heat is depicted by continuous lines, while in the dotted lines the electrical power is added. System B (red) does not have any insulation at the back and therefore acts as a heat exchanger at night and produces heat in Figure 3b, when the ambient temperature is higher than the collector temperature. While the PV yield is in a similar range on the two days, the thermal yield depends largely on the inlet temperature of the water.

Please note, that the average collector temperature is very different for the different collectors. System C operates at higher temperatures and therefore, produces more useful heat. System A and C perform better at higher temperatures due to the insulation at the back.

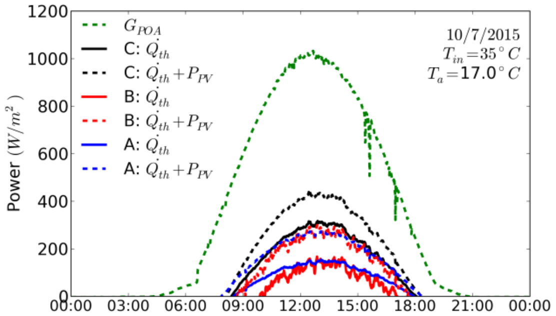

Figure 3a: Thermal (continuous lines, $\dot{Q}_{th}$) and additional electrical power output (dashed lines, $\dot{Q}_{th}+P_{PV}$) per m^2 for a day with a fluid input temperature of 35°C. In-plane irradiance (G_{POA}) is shown in green.

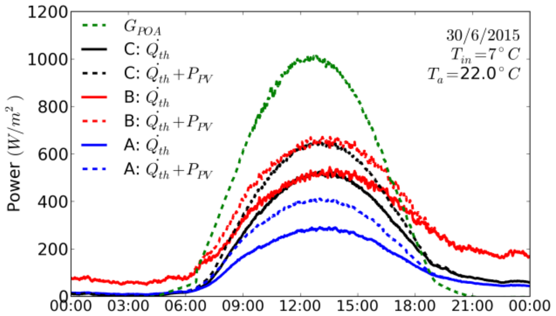

Figure 3b: Thermal (continuous lines, $\dot{Q}_{th}$) and additional electrical power output (dashed lines, $\dot{Q}_{th}+P_{PV}$) per m^2 for a day with a fluid input temperature of 7°C. In-plane irradiance (G_{POA}) is shown in green.

3.2 Thermal performance

The thermal efficiency is calculated based on measured data for a one year period from June 2015 to May 2016. The absorption of the different PVT panels was measured by ECN with an integrating sphere and was between 0.90 and 0.94 for the different panels. The emission is approximately 0.9.

The thermal collector efficiency curves for collector A, B and C are shown in Figure 4 for a wind speed of 0 and 3 m/s, with the PV in MPP. The PV efficiency (12-14%) is additional. The collectors show very different performance features. Collector C performs the best of the three measured collectors. The other collectors can also perform well in system configurations that have a low demand temperature. E.g. systems that are connected to a ground-source heat pump, often operate below ambient temperature.

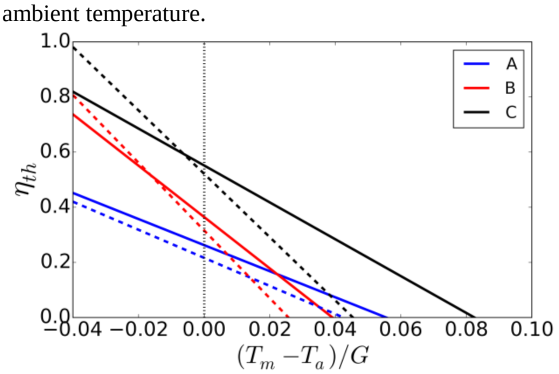

Figure 4: Collector curve for PVT collector A, B and C with a wind speed of 0 (solid) and 3 m/s (dashed), based on measured data from June 2015 to May 2016, with PV operational and measured in MPP

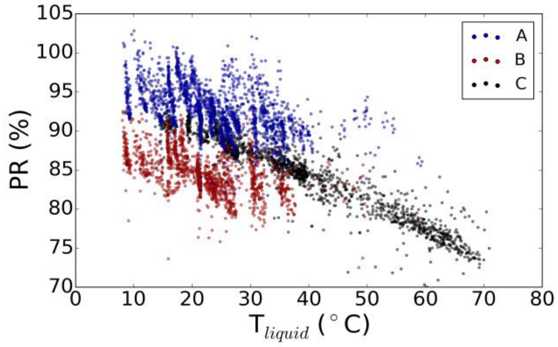

Figure 5: Correlation between the DC performance ratio and the average fluid temperature.

3.2 Overall performance

The electric performance of PVT modules is influenced by the thermal part. Figure 5 shows the correlation of the DC PV performance ratio (PR) on the average fluid temperature of the PVT collectors. It shows that the heat conduction between the PV cells and the thermal absorber of PVT collector C is good, the PR reduces with higher liquid temperatures. The mean fluid temperature is one of the main drivers of the PR for collector C. It also shows that the heat conduction between the PV cells and the thermal absorber for systems A and B is not very good.

The coefficients and the average electrical efficiency for all collectors are shown in Table I.

Table I: Performance indicators

Col-lector	η_{th}	b_u (s/m)	b_1 (W/m^2 K)	b_2 (J/m^3K)	η_{el} (DC)
A	26 %	0.06	4.7	0.1	12.2 %
B	37 %	0.04	9.3	1.0	13.8 %
C	55 %	0.02	6.7	1.6	12.7 %

The electrical average efficiency of the three uncovered PVT systems is between 12.2 and 13.8 %. The difference is partially caused by a different peak power per square meter. The thermal efficiency parameters are for a large part caused by the thermal conduction between the PV and the thermal collector together with the insulation on the back of the system. A better thermal contact leads to a higher η_0, but also to higher heat loss (b_1) and wind dependency of the heat loss (b_2) parameters, also if the back of the panel is insulated or integrated in the roof.

4 CONCLUSIONs

There is a large difference between the measured thermal performance of the three different collectors. These differences can be explained by the PVT collector design:

- The absorption of all PVT modules is quite good (0.9 – 0.94).
- A good heat conduction from the PV cells to the absorber leads to a high peak collector efficiency

- Insulation at the back of the PVT module improves the performance at higher temperatures.

PVT collector C performs the best, since it has a good heat conduction and insulation at the back. However, for systems that need low temperature heat, the other systems also can supply heat. Furthermore, the performance of some collectors can be improved by e.g. heat conducting paste, however, this may not lead to a techno-financial optimal situation.

System simulations with PVT as part of a solar heating system are carried out in TRNSYS and will yield valuable information on the annual yield for a specific system.

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