Maximum Efficiency of Low Concentrating PV-T Collectors and Optical Boundary Conditions

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1. Abstract

Photovoltaic thermal hybrid solar collectors (PV-T) allow the additional use of heat while the generation of electrical power by a photovoltaic absorber. This technique achieves a much higher total efficiency of the conversion of solar radiation. Further, the concentration of solar radiation reduces the need for PV material, and thereby costs.

Currently, most commercial PV-T products focus on the cooling of the PV cell only and thereby on maximizing the electrical energy output. However, this thermal yield is due to its low temperature not usable in most applications. The presented collector concept is designed to increase the temperature of the thermal output by minimizing the heat losses. It will be shown that the optimum operation temperature of a PV-T collector is at higher temperatures of around 60 to 80 °C, although the electric efficiency decreases with raising collector temperature. In order to provide heat at this temperature, one has to switch to a low concentrating system. Reaching these higher temperatures with good thermal efficiencies enable the supply of classical solar thermal applications. To minimize the thermal resistance between PV cell and heat carrier fluid, the backside heat transfer is realized through a full surface direct flow aluminum absorber profile. Further advantages of such a system would be the reduction of PV material and the variable stationary mounting through asymmetric reflector configuration.

To determine the optimum collector working temperature, the saving of CO_2 emissions and primary energy of the PV-T collector is simulated on a yearly basis, and the collector working temperature is varied. Also an analysis of the exergy gain of the collector is regarded to determine the ideal operating temperature.

Experimental studies have been conducted on a prototype. The problem of non-uniform illumination of the CPC reflector on the PV absorber unit could be solved and its influence on the efficiency reduction of the PV cell quantified.

The Bavarian Center for Applied Energy Research (ZAE Bayern) developed the concept of a stationary low concentrating PV-T hybrid collector, with focus on the overall collector efficiency. Also research on optical geometries has been done, in order to optimize the electrical output.

2. State of the Art

Research on low concentrating PV-T collectors has been done by Brogren, Nilsson und Karlsson (2001). Hatwaambo (2008) measured the electrical efficiency of PV cells under variation of the incidence angle, with optimization of reflector materials.

The „PV-T Roadmap“ of the IEA SHC task 35 still sees the need for research on the thermal efficiency. The here presented approach is based on a direct flow aluminum absorber onto which the PV cells are laminated.

At ZAE Bayern preliminary research has been conducted by Thoma (2010), Hilt (2011), Selig (2010) and Knauer (2009).

3. Motivation

The collector concept is based on the supply of higher temperatures and on a higher overall efficiency compared to PV module. A key issue is the question of an optimum collector working temperature. As mentioned before, most commercial PV-T collectors focus on cooling of the PV cell and maximizing the electrical output.

For a maximum energy yield, low temperature applications are preferable, as both, electrical and thermal efficiency, decrease with higher temperatures. Taking into account the temperature level of the thermal energy yield also the exergy has to be considered. In comparison to fossil fuels, the yearly savings of primary energy of PV-T collector, PV module and solar thermal collector have been calculated for different working temperatures.

Overall efficiency

This first part regards the power output of the PV-T collector and the included exergy ratio. The electrical power of the PV absorber is treated as pure exergy. To calculate the exergy ratio of the thermal power, the Carnot efficiency is used. As the Carnot efficiency by definition describes the transformation of heat into work, a more realistic approach is used in this context.

Using the PV-T collector outlet as heat source for the heat pump enables higher evaporator temperatures compared to the ambient, which leads to higher COPs and thereby saves exergy in the form of electrical operating power. The heat is provided at a condenser temperature of 80 °C (e.g. space heating). The COP is calculated by $0.5 / \eta_{Carnot}$. Fig. 1 shows the exergy savings of the PV-T collector separated into electrical and thermal exergy savings. A maximum of the PV-T exergy saving around 60 to 80 °C outlet temperature can be seen.

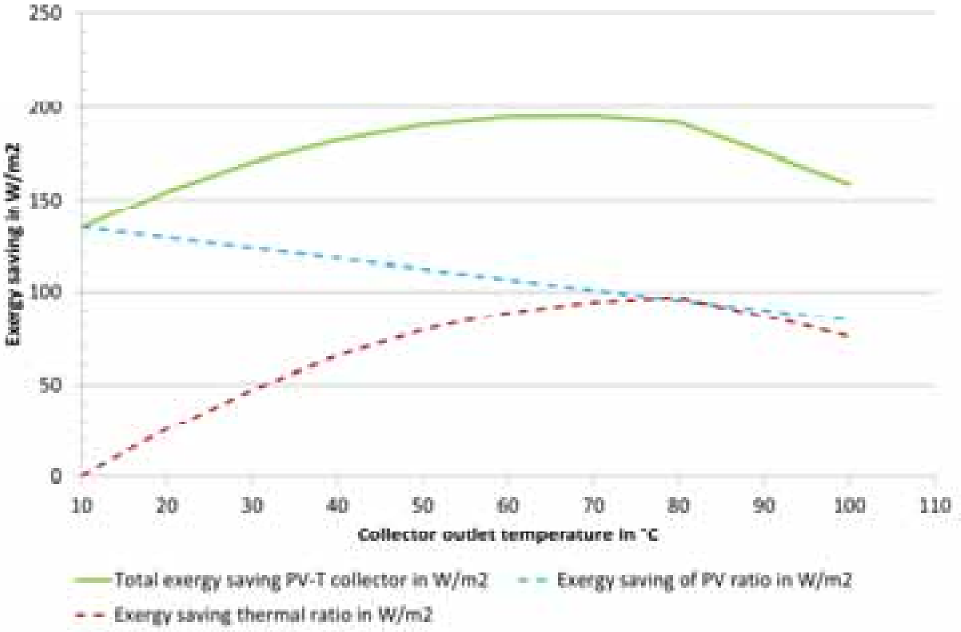

Fig. 1: Exergy saving by lifting the source temperature of a heat pump cycle with OPC = $0.5 / \eta_{Carnot}$.

Thermal efficiency:	*PV-efficiency:*
$\eta 0 = 0.78$	$\eta PV = 0.14$
a1 = 3.4 W/m2.K	aPV = 0.004 1/K
a2 = 0.013 W/m2.K2	
Quality grade of heat pump Carnot cycle:	*Temperature level of heating application:*
GG=0.5	Theat = 80°C
Tamb = 10°C	

Table 1: Simulations boundary conditions

Primary Energy Savings

To evaluate the reduction of PV efficiency with increasing collector temperature, TRNSYS simulations[1] on an annual basis were performed for 3 systems: The PV-T collector, a PV module with identical efficiency parameters and a typical solar thermal flat collector. For these simulations mass flow of the PV-T and the solar thermal flat collector is controlled, in order to provide heat at a constant nominal outlet temperature. The thermal behavior of a normal PV module has to be considered as such modules also stagnate at a temperature of 40 to 60 °C. For the PV-T CPC reflectors an acceptance half angle of ± 30° has been taken into account.

Fig. 2 shows that the PV-T yields higher savings of primary energy until a working temperature of 80 °C.

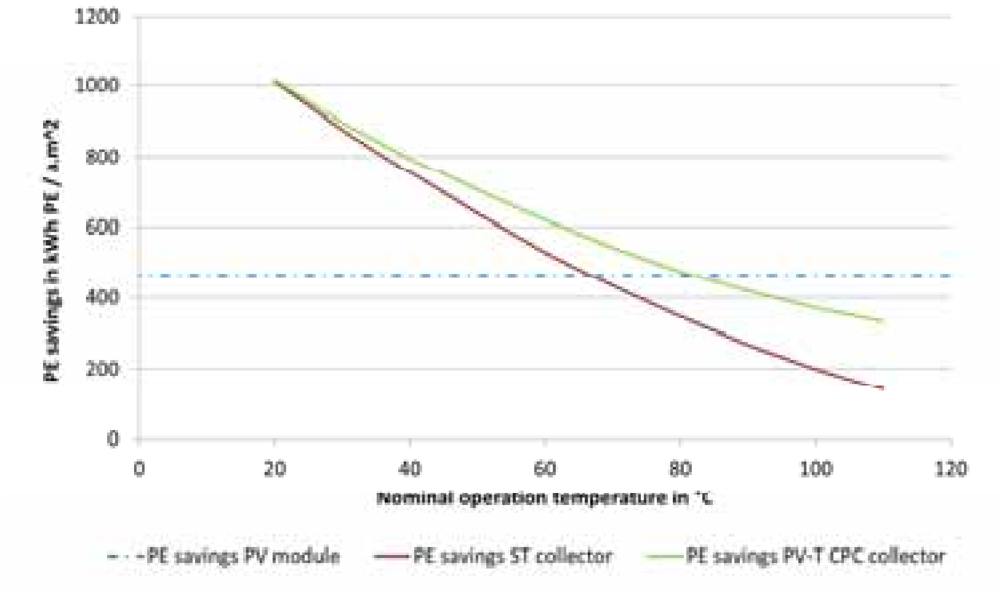

Fig. 2: Annual savings of primary energy (PE). Comparison of the CPC PV-T collector, PV module and solar thermal flat collector.

The proportion of thermal and electrical PV-T primary energy savings are shown in Fig. 3. One can see, that the loss in electrical energy yield of the PV-T collector is overcompensated by the primary energy saving of the thermal income up to a collector working temperature of approx. 80 °C.

[1] Location Munich, Germany. Stationary collector with slope 45°. 5 K temperature difference in- and outlet temperature. Controlled nominal outlet temperature with ideal heat sink. Ideal Reflector IAM considered with $\theta a = \pm 30°$.

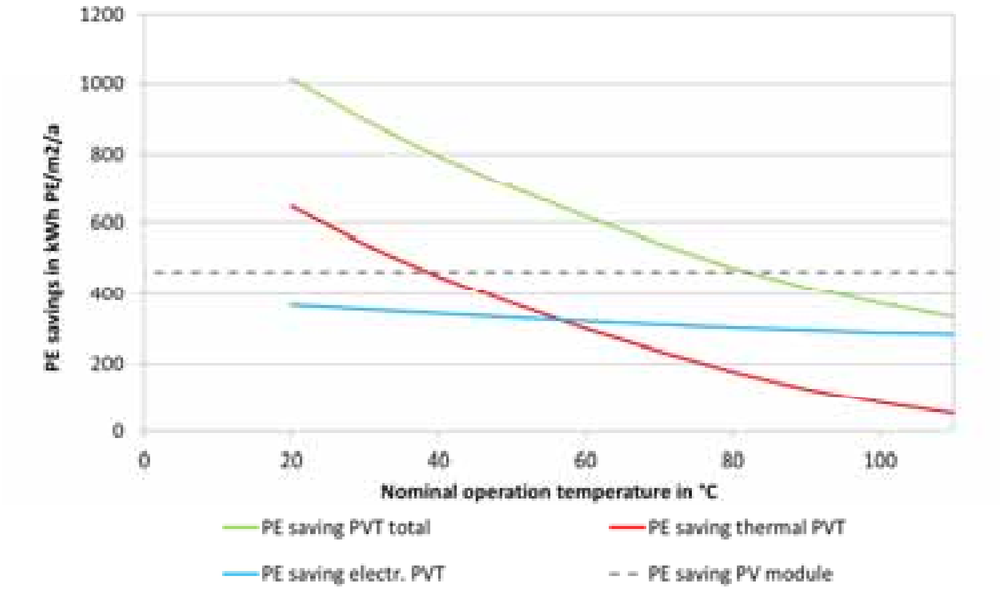

Fig. 3: Composition of PE savings of the CPC PV-T collector compared to a PV module.

4. Simulation and Experiment

An experimental collector was built with directly laminated c-Si cells onto the absorber. This collector was designed to determine influences of the boundary conditions of the CPC PV-T setup on the electric efficiency of the PV cell. For this reason an acceptance half angle of $\theta a = 18°$, with a concentration ratio of $C = 3$ was chosen. For real applications, concentration and acceptance half angle must be designed according to latitude and nominal temperature level of the heat load.

The predicted effects of the dependency of the PV efficiency of the solar incident angle due to a non-uniform distribution of irradiation in the absorber plane could be proved. This effect could be minimized through the development of an improved absorber-reflector geometry and experimentally validated.

Fig. 4: PV-T CPC trough while outdoor measurement.

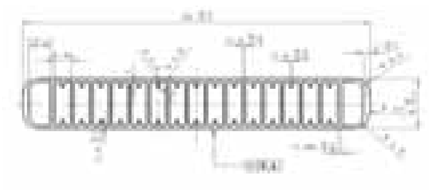

Fig. 5: Technical drawing of the direct flow aluminum absorber.

Simulation

Using the ray tracing software ASAP (Breault), the distribution of solar irradiation in the PV plane caused by the CPC concentrator could be calculated. Fig. 6 shows the irradiation distribution for perpendicular incidence angle θi = 0°. The simulation shows good agreement with a measurement with lower resolution.

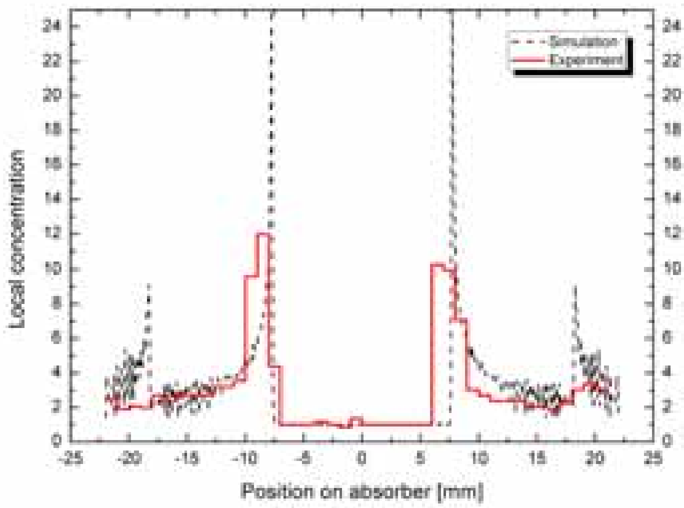

Fig. 6: Comparison of simulated and measured distribution of irradiance in the absorber plan for perpendicular incident radiation onto a regular CPC reflector.

In order to quantify the effect of this distribution on the PV efficiency, a combined thermal and electric simulation model was developed. The thermal modeling described the temperature distribution caused by the simulated irradiation distribution using 2D finite elements. The electric model calculates the voltage/current (U-I) characteristic considering both, temperature and irradiation distribution in the PV plane. Therefore, the cell is described through 2D finite elements of Shockley diode models.

Fig. 7 and Fig. 8 show for perpendicular irradiation and for an incidence angle of θ_i=18° the U-I characteristic of the PV cell for a normal CPC and for the assumption of perfect uniform irradiation. The results for the CPC show for both incident angles a reduction of the Maximum Power Point (MPP) and therefore of the PV efficiency. For the high incidence angle of θ_i=18° the effect is much stronger, which can be directly explained by the irradiance distribution.

Within these studies at the ZAE Bayern, an improved reflector-absorber geometry was developed which results in a nearly uniform distribution of irradiation. Fig. 7 and Fig. 8 further show the theoretical improvement in PV efficiency using the improved reflector geometry instead of a standard CPC.

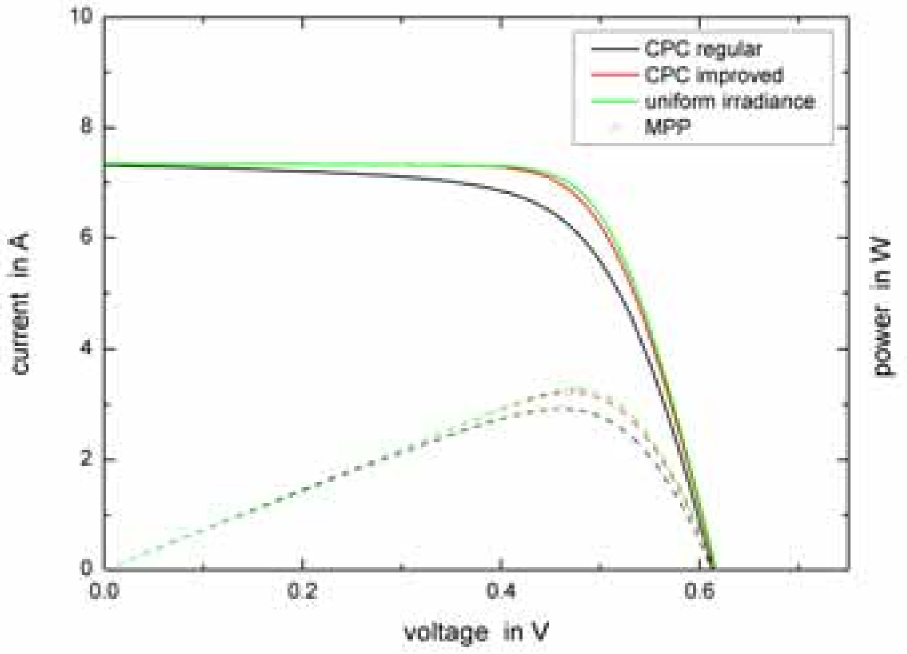

Fig. 7: Result of the simulation of the U-I characteristic for a regular and the improved CPC reflector geometry, with perpendicular irradiation.

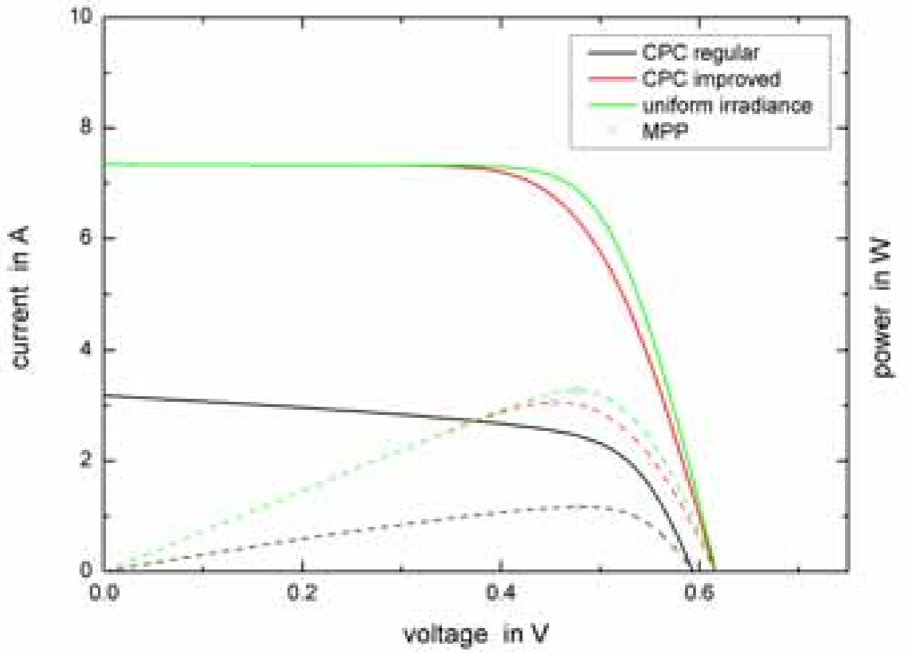

Fig. 8: Extreme case: Incidence angle is the acceptance half angle θ_i=18°.

Experiment

The theoretically predicted effects (see above) were confirmed with an experimental collector at the outdoor solar test rig of the Bavarian Center for Applied Energy Research (ZAE Bayern). As already mentioned, c-Si cells were laminated onto a full surface direct flow absorber while controlling the backside fluid temperature at high mass flow rates.

The electric PV efficiency was measured while varying the solar incidence angle Θ_i and the backside fluid temperature T_c. Fig. 9 shows the comparison of the experimental results for a regular CPC reflector and the improved geometry. The y-axis shows the relative loss of PV efficiency η_{rel} compared to non concentrating illumination (C_{ave} = 1) at standard conditions (Tc = 20°C). One can see the predicted loss of efficiency for higher incidence angles Θ_i for the regular CPC, as non-uniform illumination increases with higher incidence angles. Due to hot spots in the illumination, one can also see the influence of the front side contacts of the PV cell, resulting in sinusoidal fluctuations. The improvement of the developed reflector geometry could be validated. The PV efficiency shows almost no dependency of the solar incidence angle within the half acceptance angle.

$$\eta_{rel}(T_c, \theta_i) = \frac{\eta(C_{ave} = 3, T_c, \theta_i)}{\eta(C_{ave} = 1, T_c = 20°C, \theta_i = 0°)}$$

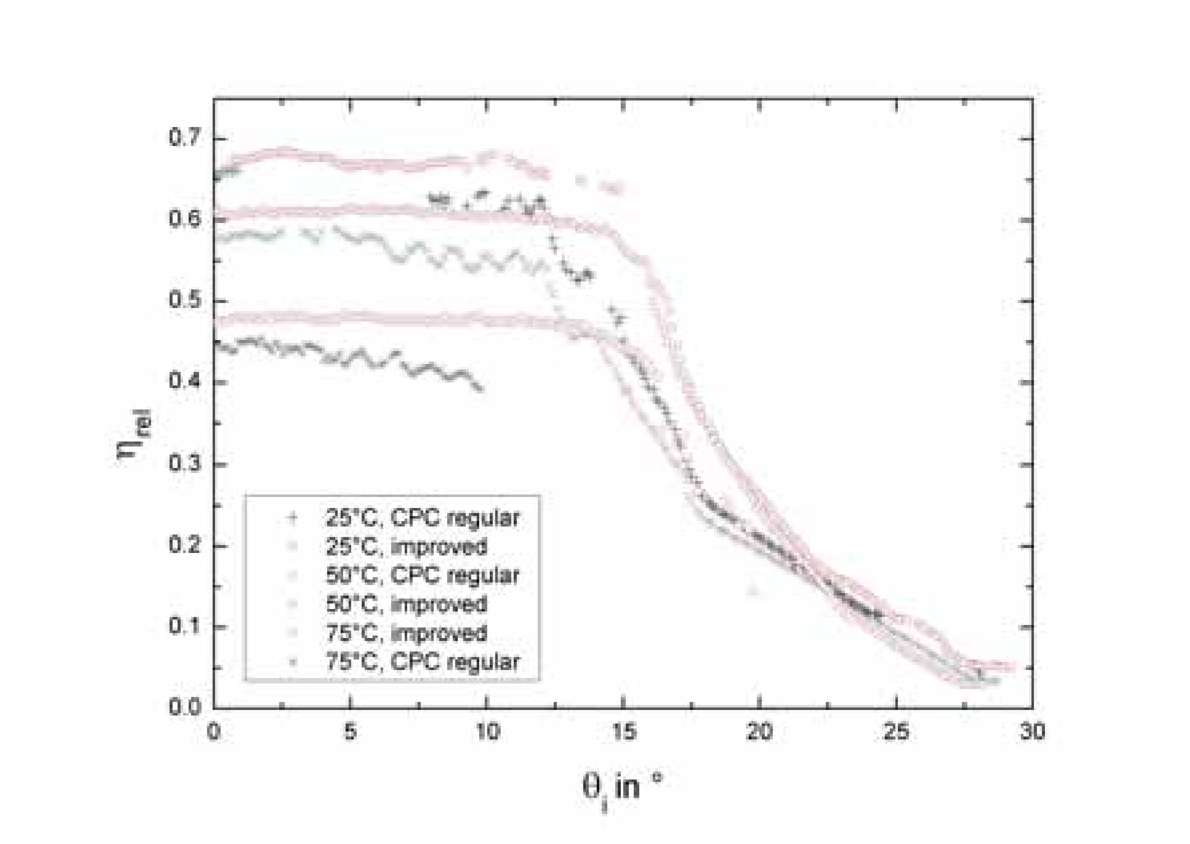

Fig. 9: Experimental determination of the electric PV efficiency with variation of incidence angle and backside fluid temperature for both reflector types.

5. Conclusions

The Bavarian Center for Applied Energy Research conducted studies on the development of a low concentrating CPC PV-T collector for higher temperatures. The increment in primary energy and exergy saving of the collector could be shown. Ray tracing simulation predicted the loss of PV efficiency due to non uniform illumination and the results could be confirmed on an experimental collector on the outdoor test rig. An improved CPC reflector geometry could minimize this effect by improving the irradiation distribution in the PV layer.

Further research will concentrate on the improvement of the thermal coupling between PV cell and absorber. Also different types of cell material shall be tested and electrical front contacts on the PV cell must be improved. The increment in energy yield, CO_2 and primary energy savings as well as financial profitability has to be proven on specific applications. Therefore the reflector has be to designed for these purposes and control strategies must be developed.

6. References

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