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# Development of a seawater-proof hybrid photovoltaic/thermal (PV/T) solar collector

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**Abstract**

Hybrid photovoltaic/thermal (PV/T) systems provide both electrical and thermal energy. The development of seawater-proof PV/T systems can enlarge the, by now, very limited PV/T application fields to a new one: sustainable reverse osmosis (RO) desalination. There, the PV/T systems' disadvantage of heat at low temperature level can redound to its advantage: the RO freshwater output is increased at elevated seawater temperatures while the PV efficiency is improved due to cooling with seawater. In this paper, the development of a novel seawater-proof PV/T system with the aim of low cost and high electrical and thermal performance is presented. Low-cost is achieved by using standard components combining a polypropylene thermal absorber with a commercial PV system. Experimental investigations on a PV/T prototype include thermal and electrical efficiency characterization at different fluid temperature levels, mass flow rates and ambient conditions. The results are compared the state-of-the-art PV/T systems.


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*Keywords:* hybrid; photovoltaic; polymer; PV/T; thermal

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## 1. Introduction

Hybrid photovoltaic/thermal (PV/T) systems provide both electrical and thermal energy. Developing seawater-proof PV/T systems can extend their, by now, very limited application fields to a new one: desalination, especially sustainable reverse osmosis (RO) membrane desalination. According to [1], the PV/T systems' disadvantage of heat at low temperature level can redound to its advantage: the PV efficiency is improved due to cooling with seawater and the RO water permeability, which means also the freshwater output is increased due to the elevated seawater temperatures. The potential of PV/T-powered RO plants is identified as an increase of fresh water production of about 30 % [1] in comparison to only PV-powered RO plants.

## 2. Literature Review

PV/T development is pushed forward since the 1970s [2] and extensive review papers [2, 3, 4] provide a very good overview of its state-of-the-art. In PV/T literature, two application focuses are distinguished: (1) focus on electrical efficiency meaning low PV and thus low temperature level of the fluid or (2) focus on high fluid outlet temperature level meaning low electrical efficiency due to the negative temperature coefficient of PV cell power. Due to the lack of PV/T norms, the PV/T collector testing standards as well as PV/T theory are adapted from solar thermal collectors, mainly Hotel-Whillier-Bliss [5] and Florschuetz [6], and diode models for PV cells [7]. Comparing literature data from research and industry is often not directly possible. Collector area can be gross area, absorber area and aperture area. Water mass flow rates and wind velocity are also critical parameters. Very important is the temperature difference $\Delta T$ for which the thermal efficiency equation is given [5]:

$$\eta = \eta_o - k \cdot \frac{\Delta T}{G}, \quad (1)$$

where $\eta$ is the thermal efficiency, $\eta_o$ is the optical efficiency, $k$ is related to the heat transfer coefficient, meaning heat losses to the ambient, and $G$ is the solar irradiance. $\Delta T$ can be the difference between ambient temperature and fluid inlet temperature, $\Delta T = T_i - T_\infty$, mean fluid temperature, $\Delta T = T_m - T_\infty$, or fluid outlet temperature, $\Delta T = T_o - T_\infty$.

The focus of this work lies on PV/T application in desalination. For this purpose, a strict requirement of a PV/T concept is its seawater-resistance and, as PV power supply is to be replaced by PV/T power supply, low cost is also a strong criterion. As a consequence, commercially well-established PV/T systems with copper or aluminum absorbers are ruled out. Instead, polymer materials fulfill both criteria and are, in comparison to copper absorbers, a very light-weight solution. The disadvantage of polymer is its low thermal conductivity. A brief review about important polymer PV/T developments is given in the following.

[8] reports about a Powerlight company (2007 acquired by SunPower Corporation) project, from 1997 until 2003, with a PV/T collector consisting of a flexible Unisolar PV module laminated to an Ethylene Propylene Diene Monomer (EPDM) absorber. However, the project was postponed because of occurring delamination and no efficiency data are available. [9] presents experimental results about a solar thermal absorber with monocrystalline (mc) PV cells attached to its top side. The different thermal expansion between PV and absorber (PPO) was compensated via a ~0.5 mm adhesive layer. A PV/T collector using polycrystalline (pc) silicon cells in combination with a polycarbonate (PC) thermal solar collector under low flow rate (around 20 l/h) is simulated, but not experimentally investigated, for a Mediterranean site by

[10]. For improving the thermal contact between the PV cells and the absorber, a thermal adhesive is recommended. [11] merges a commercial pc PV module with a heat-collecting corrugated polycarbonate plate adhered by thermal grease. Measured, daily efficiencies are presented. [12] investigates experimentally a PV/T collector with bifacial crystalline cells and a front cooling. First, a water-tight plastic box was glued to the Aluminum frame above the PV cells and, as the plastic started to loose transparency after a few months, it was replaced by a box consisting of a glass plate, which finally lead to a reduction of electrical efficiency of 10 % relatively due to reduced transmittance of the top glass layer. [13] presents a dual flow PV/T concept in which the PV cells, encapsulated by two tempered glass sheets, are cooled circularly from the top to the bottom, thus a collector with two absorber channels, one above and one below the PV cells. While high thermal efficiencies are reached, about 15 % lower electrical energy compared to an uncovered PV module has to be accepted due to lower transmittance from top glass and fluid layer to PV. In view of commercially available seawater-proof PV/T collectors, only one system is known – the ²Power solar hybrid system of PA-ID GmbH [14, 15]. About the absorber itself, no information is available and the thermal efficiency of the ²Power PV/T system, however, is rather low compared to the other systems presented above.

It can be concluded that the systems investigated by now either face short- to long-term degradation and failed therefore in the development stage or have poor thermal efficiency characteristics. For a breakthrough of seawater-proof PV/T systems in RO desalination in the near future, further research has to be carried out.

## 3. Purpose of the Work

In the present paper, the development of a novel seawater-proof PV/T system with the aim of low cost and high electrical and thermal performance is described. The focus of the PV/T collector design lies on an application of PV/T systems in desalination, however cost-effective and high-performance developments lead also to competitiveness in application fields where seawater-resistance of the absorber is not necessary. This work also concludes the lessons learned gained in developing and testing of three prototype-generations of seawater-proof polymer PV/T collectors.

## 4. Approach

### *4.1. Methodology*

The goal of a low-cost but energy efficient product is achieved by using standard system components combining a polypropylene thermal absorber with a commercial PV system. Polypropylene has three main advantages compared to established absorber materials like copper or aluminum: it is seawater-proof, material cost is low and the absorber becomes very light-weight. The main challenge of polymer absorbers is its low heat conductivity increasing the heat transfer resistance from the PV cells to the cooling fluid. To minimize this effect, the interface between the absorber and the PV module has to be optimized. During the development of three prototype-generations [16, 17, 18], different absorber designs and different strategies to reduce thermal resistance of the PV-absorber contact were investigated.

### *4.2. PV/T System Design*

Exemplarily, only the design of the latest development, the third generation of the PV/T prototypes, is described here. It is based on a standard PV module (Solon Blue 230/7, $A_{PV,cell} = 1.46$ m²) and a flat-plate polypropylene thermal absorber with a honeycomb-structure (MEFA energy systems, $A_{abs}$ = 1.38 m²) as it can be seen in Figure 1.

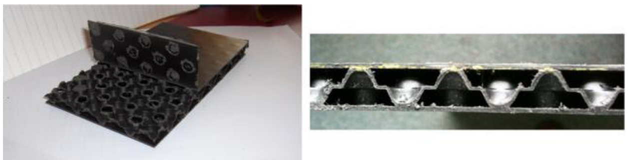

Fig. 1. Polypropylene absorber with honeycomb-structure of MEFA.

Due to propagation of turbulent flow, this structure achieves very effective heat-transfer between the absorber and the coolant fluid inside the absorber.

The polypropylene absorber is fixed on the back of the PV module by a construction consisting of five aluminum rods, springs and aluminum sheets (see Figure 2). Pressing the absorber against the PV module and using a heat-conductive paste, an optimum thermal heat transfer between PV module and absorber is tried to be guaranteed. Furthermore, the backside of the PV/T system is insulated thermally.

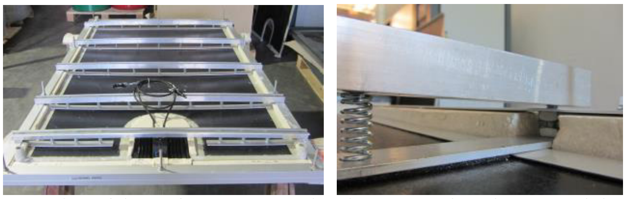

Fig. 2. Assembling the third generation of the PV/T prototypes: absorber mounted on the PV module (left) and detailed view on the fixing rods with springs (right).

### *4.3. Experimental Setup*

The prototype was tested in a closed-loop test setup at the outdoor solar test facilities of ZAE Bayern on the roof top of the Lehrstuhl für Thermodynamik (TU München) in Garching, Germany, in August 2012. The tests were carried out in a "load off" configuration meaning that the system was not integrated in an electrical circuit. The electrical efficiency data presented in this work are taken from the PV module data sheet. The electrical efficiency of the PV/T system is 14.02 % at Standard Test Conditions (STC) having a temperature-coefficient of power of -0.44 %/K.

## 5. Results

The PV/T prototype was investigated in steady-state conditions in order to gain the characteristic curve of thermal efficiency depending on the temperature difference between the coolant fluid and the ambient temperature. Additionally, daily performance data were recorded. As a conclusion, an infrared camera analysis is presented.

### 5.1. Steady-State Results

In Figure 3, the thermal efficiency curve of the PV/T prototype is presented for two mass flow rates, 100 l/h and 200 l/h, as a function of $\Delta T / G$ with $\Delta T$ being the temperature difference between the fluid inlet temperature and the ambient temperature $(T_i - T_\infty)$.

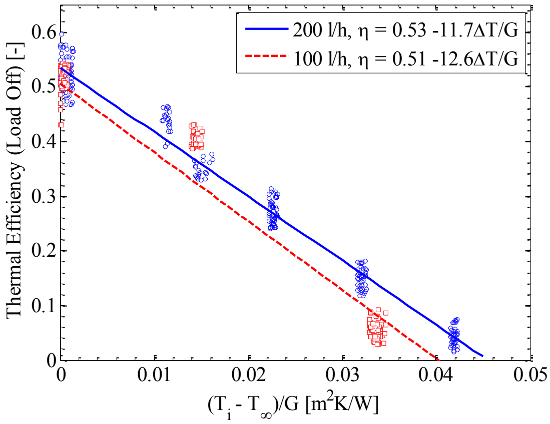


Fig. 3. Thermal efficiency curve (load-off) as a function of $\Delta T = T_i - T_\infty$ for two different mass flow rates, 100 l/h and 200 l/h.

The optical efficiency, i.e. the efficiency where $\Delta T = 0$, reaches values above 50 %. Referring to the $\Delta T / G$-axis interception, the stagnation point, it corresponds to a stagnation temperature of about 80°C. This temperature level is not critical for the polypropylene absorber material. Both optical efficiency and stagnation temperature are lower compared to conventional solar thermal collectors but higher compared to state-of-the-art commercial seawater-proof PV/T collectors. A more detailed comparison with the state-of-the-art is presented in section 7.

To give an idea about how the efficiency curves change for different expressions of the thermal efficiency equation, the results depicted in Figure 3 are also shown in dependency of $\Delta T = T_m - T_\infty$, i.e. mean fluid temperature minus the ambient temperature, in Figure 4.

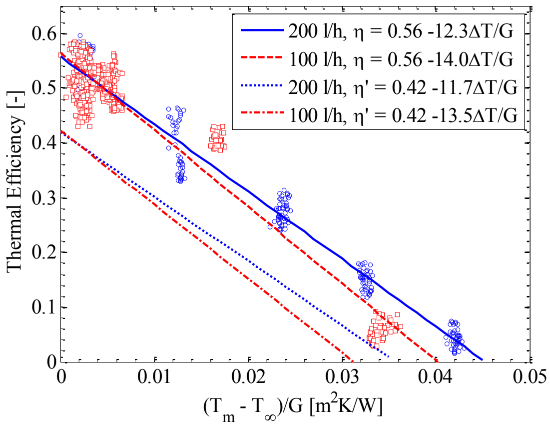


Fig. 4. Thermal efficiency curve (load-on/off) as a function of $\Delta T = T_m - T_\infty$ for two different mass flow rates, 100 l/h and 200 l/h.

Compared to the results in Figure 3, the optical efficiencies are higher while the collector stagnation point remains unchanged. This was expected as in stagnation no heat is extracted from the system and thus PV cells, absorber and fluid inlet and outlet have to have uniform temperature distribution. Additionally, Figure 4 illustrates the collector performance $\eta'$ for “load on” conditions, i.e. when the electrical energy is extracted from the system. As mentioned, these curves were not measured but can be calculated from the experimentally gained thermal data and the electrical efficiency data from the PV module data sheet.

The load on optical efficiency $\eta'_o$ and the corresponding slope $k'$ were derived applying the theory of Florschuetz [6]:

$$\eta'_o = \eta_o - \eta_{el,\infty} \tag{2}$$

$$k' = \left(\frac{k}{G} + \eta_{el,STC} \cdot t_p\right) \cdot G \tag{3}$$

Here, $\eta_{el,\infty}$ is the electrical efficiency at ambient temperature, $\eta_{el,STC}$ is the one at STC and $t_p$ is the temperature-coefficient of power. It is assumed that the mean fluid temperature is approximately the PV/T cell temperature. It results in a lower thermal efficiency for the “load on” case as the electrical energy has then to be subtracted from the total available energy collected by the PV/T system. As the electrical power gained is decreasing with increasing temperature, the differences between the “load on” and “load off” curves are decreasing for increasing $\Delta T / G$.

Table 1 concludes further experimental results showing the optical efficiency as a function of different ambient conditions and mass flow rates. Corresponding to PV/T theory, the optical efficiency decreases with decreasing mass flow rates. When performing outdoor measurements, it is very important to obtain data at almost constant ambient conditions; this is especially valid for solar irradiance and wind velocities.

Table 1. Comparison of optical efficiencies of the present PV/T collector for different mass flow rates and ambient conditions (load-off)

| Mass Flow Rate | Optical Efficiency | Mean Wind Speed | Standard Deviation Wind | Mean Solar Irradiance | Standard Deviation Irradiance | Weather Note |
|---|---|---|---|---|---|---|
| [l/h] | [%] | [m/s] | [m/s] | [W/m²] | [W/m²] | [-] |
| 200.2 | 53.4 | 2.3 | 0.7 | 988.4 | 9.3 | perfect |
| 100.1 | 50.6 | 1.8 | 0.7 | 908.9 | 8.6 | perfect |
| 50.0 | 55.9 | 1.0 | 0.4 | 928.0 | 67.6 | cloudy |
| 50.0 | 41.0 | 3.2 | 0.8 | 978.0 | 17.0 | windy |
| 52.6 | 50.3 | 1.8 | 0.7 | 908.9 | 8.6 | perfect |
| 35.3 | 45.0 | 1.8 | 0.7 | 908.9 | 8.6 | perfect |

On days with cloudy skies, efficiency measurements tend to gain too high results, while high wind velocities can drastically reduce the thermal efficiency, especially near the collector stagnation point.

### *5.2. Dynamic Results*

The PV/T performance measurements include day-tests indicating the prototype’s performance for transient power supply. Exemplarily, a measurement day (19th August 2012, Munich) is discussed in Figure 5. The feed water inlet temperature (17 °C) was chosen to represent the mean annual seawater temperature of a beach well in 30 m depth in Malta and also the mean seawater temperature of the open sea near Almería (Spain) in June.

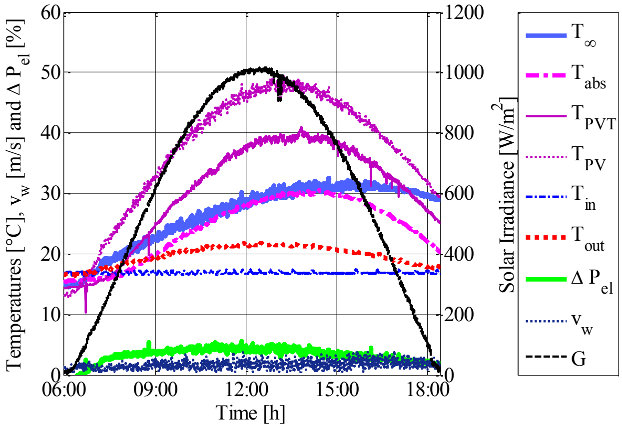


Fig. 5. Day-performance of the PV/T prototype, Munich, August 2012: ambient temperature $T_\infty$, mean absorber temperature $T_{abs}$, PV/T cell temperature $T_{PVT}$, calculated standard PV cell temperature $T_{PV}$, fluid inlet temperature $T_{in}$, fluid outlet temperature $T_{out}$, calculated gain in electrical power compared to a not-cooled PV module $\Delta P_{el}$ (in %), wind velocity $v_w$ and solar irradiance $G$.

During the almost perfect course of the solar irradiance development, the ambient is warming up from 15 °C in the morning to max. 32.5 °C at 3:00 p.m. The mean thermal efficiency of the PV/T prototype is 69 % ("load off" condition), which seems to be quite high. The reason for this is that the fluid inlet temperature is most of the time lower than the ambient temperature, which means that the PV/T collector is operating near the optical efficiency. The mass flow rate in the collector is 200 l/h.

In a daily average, a difference between fluid inlet and outlet temperature of 3 K is observed; the maximum temperature increase of one PV/T module is 5 K. In RO desalination, water production is increased of about 2 % to 3 % per K [20]. Thus, due to preheating of seawater in the present PV/T prototype, an RO plant could produce about 10 % more fresh water.

The maximum PV/T solar cell temperature which is observed during the day is 40 °C. Calculating the PV temperature of a standard PV module [21] at the same boundary conditions (ambient temperature, solar irradiance) a maximum PV cell temperature of 50 °C could result.

In Figure 5, also the relative increase of the PV cell performance due to the lower PV cell temperature level is shown ($\Delta P_{el}$, green); the daily average is an increase of 3.2 % in electrical efficiency and thus electrical power gained. This means that, beside the preheating effect of the seawater, another advantage for the application of the present PV/T system in RO desalination occurs: higher gain in electrical energy also resulting in more fresh water production.

### *5.3. Infrared Camera Analysis*

For PV/T collector designs, it is important that all serially arranged PV cells are cooled equally to maintain the same temperature level as otherwise the overall electrical performance is reduced. Figure 6 illustrates the temperature distribution development during a decrease of the fluid inlet temperature and thus a decrease in PV cell temperatures.

It has to be stated that the temperature distribution of the current PV/T prototype module is almost uniformly distributed across the PV/T module except for a hot spot in the center top region where the electrical junction box is located directly behind the PV cells. Here, the thermal absorber could not be installed (see the right picture in Figure 6) leaving some PV cells without cooling. Thus, it would be advantageous to move the junction box from the PV back side to the module frame.

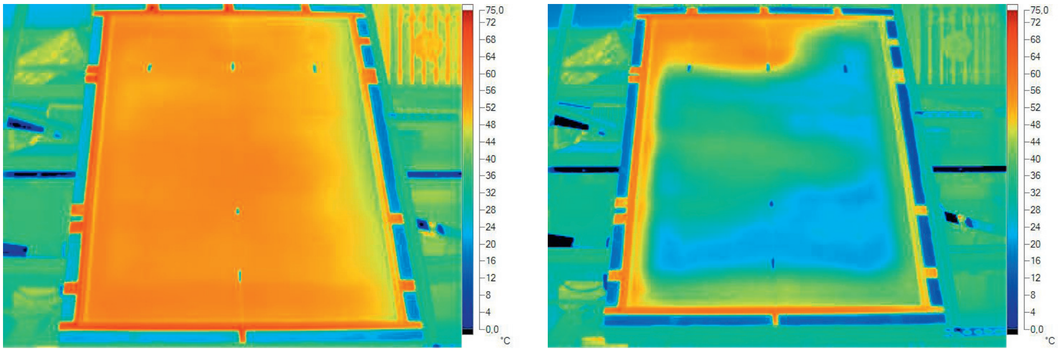


Fig. 6. Qualitative IR analysis using the same temperature scale in each graphic: before (left) and after (right) cooling the PV/T collector for 15 minutes

## 6. Lessons Learned

Developing three generations of PV/T prototypes, three main topics have been learned: a flat-plate absorber with a honeycomb geometry (third generation, [18]) is better than an absorber consisting of three registers with polymer pipes having a rectangular profile (first generation, experimentally investigated at the Physics Department of University in Patras, Greece, [16, 17]), which was taken from a standard wall heating and cooling system as it is used in buildings. Additionally, the thermal contact between absorber and PV module is crucial for the overall collector performance. Furthermore, the electrical junction box of standard PV modules has to be replaced from the module back to the aluminum frame to avoid non-uniform temperature distributions of the serially connected PV cells.

## 7. Comparison with State-of-the-Art

Comparing PV/T efficiencies, both electrical and thermal, which can be found in literature is a challenging task due to a lack of testing standards. [5] provides analytical solutions to convert thermal efficiency data of solar collectors for different operating conditions. This concludes different mass flow rates and different reference areas as well as different $\eta = f(\Delta T)$. Converting the efficiency data of different PV/T collectors, a comparison with the newly developed PV/T prototype can be carried out resulting in Table 2.

Table 2. Comparison of optical efficiencies and slopes of efficiency for different mass flow rates and ambient conditions.

| Ref. | Original (O) or Converted (C) | Mass Flow Rate | Ratio Absorber-/ PV-Area | PV Type | Absorber-material | $\Delta T = ... - T_\infty$ | Wind Velocity | PV Load | Optical Efficiency | Slope of Efficiency Curve |
|---|---|---|---|---|---|---|---|---|---|---|
| [-] | [-] | [l/h] | [-] | [-] | [-] | [°C] | [m/s] | [-] | [-] | [W/m²K] |
| Current work | O | 100 | ~1 | pc | polymer | $T_i$ | 1.8 | off | 0.51 | 12.6 |
| | C | 100 | ~1 | pc | polymer | $T_i$ | 1.8 | on | 0.39[1)] | 12.1[1)] |
| [10] | O | 19 | ~1 | pc | polymer | $T_o$ | NA | on | 0.67[2)] | 9.7[2)] |
| | C | 100 | ~1 | pc | polymer | $T_i$ | NA | on | 0.45 | 6.6 |
| [9] | O | NA | ~1.5 | mc | polymer | $T_i$ | NA | off | 0.76[3)] | 14.9[3)] |
| [15] | O | 170 | ~1 | pc | polymer | $T_m$ | 1.9 | off | 0.44 | 9.3 |
| | O | 170 | ~1 | pc | polymer | $T_m$ | 1.9 | on | 0.30 | 9.0 |
| | C | 100 | ~1 | pc | polymer | $T_i$ | 1.9 | off | 0.41 | 8.7 |
| | C | 100 | ~1 | pc | polymer | $T_i$ | 1.9 | on | 0.28 | 8.5 |
| [11] | O | NA | ~1 | pc | polymer | $T_i$ | NA | NA | 0.38[4)] | NA |
| [13] | O | 30 | ~1 | a | glass | $T_i$ | <2 | NA | 0.7 | 5.1 |
| | C | 100 | ~1 | a | glass | $T_i$ | <2 | NA | 0.72 | 5.3 |
| [12] | O | 18 | NA | c bifacial | glass | NA | NA | NA | ~0.50[4)5)] | NA |
| [22] | O | 101 | ~1 | pc | steel | $T_m$ | 1.5 | off | 0.68 | 17.9 |
| | C | 100 | ~1 | pc | steel | $T_i$ | 1.5 | off | 0.62 | 16.3 |
| [19] | O | 72 | ~1 | pc | copper | $T_i$ | 1-2 | off | 0.68 | 12.6 |
| | O | 72 | ~1 | a | copper | $T_i$ | 1-2 | off | 0.72 | 12.1 |
| | O | 72 | ~1 | pc | copper | $T_i$ | 1-2 | on | 0.55 | 12.0 |
| | O | 72 | ~1 | a | copper | $T_i$ | 1-2 | on | 0.60 | 12.0 |
| | C | 100 | ~1 | pc | copper | $T_i$ | 1-2 | off | 0.69 | 12.7 |
| | C | 100 | ~1 | a | copper | $T_i$ | 1-2 | off | 0.72 | 12.2 |
| | C | 100 | ~1 | pc | copper | $T_i$ | 1-2 | on | 0.56 | 12.1 |
| | C | 100 | ~1 | a | copper | $T_i$ | 1-2 | on | 0.60 | 12.1 |

NOTES: [1)] approximation, based on results in Figure 4; [2)] simulated, but not experimentally gained results, [3)] averaged data from [9], it is noted that only two third of the absorber are covered by PV cells; [4)] daily performance; [5)] incl. reflection set; NA = not available.

It can be stated that the performance of the new PV/T collector is much higher than the commercially available ²Power collector [15] (about absolutely 10 % higher optical efficiency in “load off” condition). A comparison with [9] is not directly possible as the PV cell area is just about 2/3 of the absorber area. Furthermore, trying to compare with [11] and [12] is difficult as thermal efficiency curves are not provided but daily efficiencies or rough estimations, respectively. [10] predicts, only via simulation, a slightly higher efficiency, which has not been experimentally proved yet. The dual flow collector [13] shows a much higher efficiency than the new development, however problems with mechanical stability and heavy design are reported. It is also not sure if the collector can be operated at around 100 l/h. Comparing the polymer-prototype with state-of-the-art systems with copper absorber, the commercially available system of [22] has around 11 % higher optical efficiency. [19] reports about measurement results exceeding the optical efficiency for “load off” around 17 %. According to Hottel-Whillier-Bliss theory [5], optical efficiency depends not only on optical properties of the collector like transmittance and absorptivity but also on the heat removal factor which takes, amongst others, also heat transfer coefficients from the fluid to the ambient into account. This might explain the rather high differences in optical efficiencies of conventional and seawater-proof PV/T collectors.

## 8. Conclusion and Outlook

This work is the continuation of [1], [16] and [17]. A PV/T system was developed with optimized design for a novel application field, namely reverse osmosis seawater desalination. In this special application field, the maximum obtainable, low fluid temperature level is even an advantage. The design properties, especially the polymer absorber material, make the novel PV/T collector cost-effective and very light-weight while guaranteeing a higher electrical and thermal performance than commercially available seawater-proof PV/T collectors. Furthermore, low-cost, light PV/T systems might be also an interesting alternative to established, rather heavy PV/T systems in domestic applications. In view of combining the PV/T prototype with RO, the dynamic experiments showed that one of the most important design parameters is the optical efficiency of the collector. As seawater temperatures, thus the collector inlet temperatures, are often lower than or equal the ambient temperature, the PV/T collector is operated near the optical efficiency.

The PV/T prototype described in this paper will be combined with a reverse osmosis desalination plant to experimentally prove the high potential of PV/T in reverse osmosis desalination. The experimental results of the coupled PV/T-RO system are to be published soon.

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## References

[1] Kroiß A, Spinnler M, Sattelmayer T. Analysis of hybrid photovoltaic/thermal (PV/T) solar systems for small scale reverse osmosis desalination plants. *25th European Photovoltaic Solar Energy Conference and Exhibition (PVSEC 2010),* Valencia, Spain; 2010.

[2] Chow TT. A review on photovoltaic/thermal hybrid solar technology. *Applied Energy* 2010; **87**:365–379.

[3] Chow TT, Tiwari GN, Menezo C. Hybrid solar: a review on photovoltaic and thermal power integration. *International Journal of Photoenergy* 2012, Article ID 307287, 17 pages.

[4] Hasan MA, Sumathy K. Photovoltaic thermal module concepts and their performance analysis: a review. *Renewable and Sustainable Energy Reviews* 2010; **14**:1845–1859.

[5] Duffie JA and Beckman WA. *Solar Engineering of Thermal Processes*. 3rd ed. New Jersey: John Wiley and Son Inc., Hoboken; 2006.

[6] Florschuetz LW. Extension of the Hottel–Whiller model to the analysis of combined photovoltaic/thermal flat plate collectors. *Solar Energy* 1979; **22**:361–6.

[7] Wagner A. *Photovoltaik Engineering – Handbuch für Planung, Entwicklung und Anwendung*. 3rd ed. Springer Verlag; 2010.

[8] PVT Roadmap – a European guide for the development and market introduction of PV-thermal technology. Technical report, EU PVT forum: www.pvtforum.org; 2006.

[9] Sandnes B and Reskstad J. A photovoltaic/thermal (PV/T) collector with a polymer absorber plate. Experimental study and analytical model. *Solar Energy* 2002; **72**:63–73.

[10] Cristofari C, Notton G, Canaletti JL. Thermal behavior of a copolymer PV/Th solar system in low flow rate conditions. *Solar Energy* 2009; **83**:1123–1138.

[11] Huang BJ, Lin TH, Hung WC, Sun S. Performance evaluation of solar photovoltaic/thermal systems. *Solar Energy* 2001; **70**:443-448.

[12] Robles-Ocampoa B, Ruíz-Vasquez E, Canseco-Sánchez H, Cornejo-Meza C, Trápaga-Martínez G, García-Rodriguez FJ, González-Hernández J, Vorobiev YV. Photovoltaic/thermal solar hybrid system with bifacial PV module and transparent plane collector. *Solar Energy Materials and Solar Cells* 2007; **91**:1966–1971.

[13] Bakker M, Zondag HA, Van Helden WGJ. Design of a dual flow photovoltaic/thermal combi panel. *Proceedings of PV in Europe–From PV Technology to Energy Solutions Conference and Exhibition,* Rome; 2002.

[14] TÜV Rheinland Energie und Umwelt GmbH; *Test Report-No. 21217968_P_Mono*, Cologne; 2012.

[15] TÜV Rheinland Energie und Umwelt GmbH; *Test Report-No. 21217968a_P_poly*, Cologne; 2012.

[16] Kroiß A, Spinnler M, Sattelmayer T. A novel PV/T collector using polymer absorber – design, building and testing, *Term Paper*, Lehrstuhl für Thermodynamik, Technische Universität München; 2010.

[17] Präbst A, Spinnler M, Sattelmayer T. Optimization of a novel PV/T collector with polymer absorber, *Term Paper*, Lehrstuhl für Thermodynamik, Technische Universität München; 2011.

[18] Hamberger S, Kroiß A, Spinnler M, Sattelmayer T. Optimization of a seawater proof PV/T collector, *Term Paper*, Lehrstuhl für Thermodynamik, Technische Universität München; 2012.

[19] Tripanagnostopoulos Y, Nousia TH, Souliotis M, Yianoulis P. Hybrid photovoltaic/thermal solar systems. *Solar Energy*, 2002; **72**:217–234.

[20] Al-Mutaz I and Al-Ghunaimi M. Performance of reverse osmosis units at high temperatures. *IDA World Congress on desalination and water reuse,* Bahrain; 2001.

[21] Lasnier F, Ang TG. *Photovoltaic Engineering Handbook*. Adam Hilger; 1990.

[22] WIOSUN GmbH & Co. KG, *PVT-P Kombimodul, data sheet*, www.wiosun.de; 2013.