Conference Proceedings

EuroSun 2014
Aix-les-Bains (France), 16 – 19 September 2014

Comparison of Solar Photovoltaic and Photothermal Domestic Hot Water Systems

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Abstract

Solar domestic hot water (DHW) systems with photovoltaic modules have appeared on the solar market for buildings in recent years. Presented energy and economic analysis compares the competing photovoltaic and photothermal systems for domestic hot water preparation at identical load and climate conditions. Results have shown that given simple photovoltaic DHW only systems despite the significant cost reduction of photovoltaic technology in last decade still cannot economically compete with solar thermal DHW systems due to worse performance.

1. Introduction

Significant decrease of photovoltaic (PV) technology cost has opened a new market with simple photovoltaic DHW only solar systems combining the PV modules and DC electric heating elements in DHW storage tank with or without use of maximum power point tracker (MPPT). Presented analysis shows the comparison of energy yields and economic parameters of the main competitors: photovoltaic DHW system in two alternatives (with and without MPPT) and adequate photothermal (PT) system operated at identical hot water load and climate conditions.

2. Solar DHW system alternatives

Detailed mathematical models were used for the solar photovoltaic and photothermal DHW systems to compare the energy performance at identical boundary conditions. Solar systems were simulated in TRNSYS (2012) in following alternatives:

- photovoltaic DHW system without MPPT (MPPT off);
- photovoltaic DHW system with MPPT (MPPT on);
- photothermal DHW system.

Each solar system alternative has been used only for DHW preparation. Daily hot water load 160 l for typical household with required hot water temperature 55 °C and cold water temperature 10 °C was considered. Daily profile of hot water load was taken from EN 15450 (2011). Total hot water heat demand was 2767 kWh/a. Climate conditions used for simulation analysis were considered in the form of typical meteorological year (TMY) for Prague (Czech Republic). TMY data give a relatively conservative incident solar irradiation for horizontal plane 998 kWh/m^2.a and annual average outdoor temperature 8,9 °C.

Comparison has been done for the realistic solar DHW systems available at the European market for given DHW load. All alternatives of solar DHW systems have been based on a hot water storage tank with volume 200 l and daily heat loss 1.4 kWh/24 h. Despite the fact, that the storage tanks have integrated electric elements for back-up heating, their function has not been considered for the purpose of clear comparison (external backup). The backup energy has been evaluated from actual water load and temperature difference between

doi:10.18086/eurosun.2014.03.20 Available at http://proceedings.ises.org

the tank output and required DHW temperature. Maximum temperature 85 °C in storage tank recommended by its manufacturer was set for all systems. Losses and gains of the storage tanks were considered and modelled. Storage tanks in the solar system alternatives were modelled uniformly with TRNSYS type340, which allows to model the solar water tanks with electric elements and tube heat exchangers.

2.1. Photovoltaic DHW system

Solar PV system was sized according to the manufacturer with 8 polycrystalline modules with peak power 8 x 250 W_p connected in series into a DC electric heating element with power 2 kW. Total peak power output of the PV field is 2 kW_p at total PV modules area 13.2 m^2. The 5-parameter one-diode model (TRNSYS type180) of PV module was used in the PV system model. Main electric parameters of PV modules are required by the model: maximum power P_{max}, maximum power voltage V_{pm}, maximum power current I_{pm} (all for standard testing conditions, irradiance 1000 W/m^2, module temperature 25 °C), open circuit voltage V_{oc}, short circuit current I_{sc}, temperature coefficient of voltage β_{Voc} and current β_{Isc} and nominal operation condition temperature *NOCT* (for irradiance 800 W/m^2, outdoor temperature 20 °C, wind velocity 1 m/s). Parameters of considered PV modules are shown in Table 1.

Tab. 1: Main parameters of PV modules used in analysis

Parameter	Value
maximum power P_{max}	250 W
maximum power voltage V_{pm}	29,8 V
maximum power current I_{pm}	8,39 A
open circuit voltage V_{oc}	36,9 V
short circuit current I_{sc}	9,09 A
temperature coefficient of voltage β_{Voc}	-0,36 %/K
temperature coefficient of current β_{Isc}	0,06 %/K
nominal operation condition temperature *NOCT*	45 °C
STC efficiency of module η_r	15,1 %

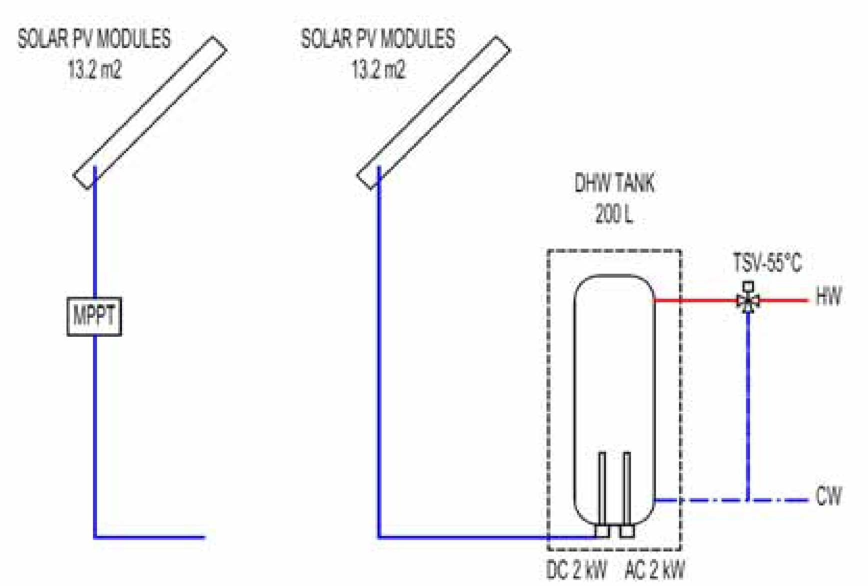

Fig. 1: Scheme of solar photovoltaic DHW systems (with MPPT, without MPPT)

PV systems both with and without maximum power point tracking were considered (schemes are shown in Figure 1). Maximum power point tracker allows to maintain the maximum PV electricity generation at variable operation conditions (solar irradiance, temperature of PV module). Solar irradiance affects the generated electric current, temperature of PV module affects mainly the module voltage. Electricity production of PV system without MPPT is dependent on the actual generated current and the heating element resistance (25 Ω).

The PV module with an uncontrolled electric load operates out of optimum range and achieves considerably lower PV electricity production than the PV module under MPPT operation.

Modelling of the PV system considered a change of module electric power with solar irradiance incident angle (optical characteristic, incidence angle modifier *IAM*). Total cable electric losses of the system were considered 2 %. Simulation did not considered a long-term degradation of the PV module power, usually referred from 0,5 to 1 % annually.

2.2. Photothermal DHW system

Solar photothermal DHW system with two solar thermal flat-plate collectors with total aperture area 4.5 m^2 was used. Main parameters of the solar photothermal collectors required by used TRNSYS type1b are shown in Table 2.

Tab. 2: Main parameters of PT collectors used in analysis

Parameter	Value
zero-loss efficiency η_0	0,809
linear heat loss coefficient a_1	3,59 W/m^{2}K
quadratic heat loss coefficient a_2	0,011 W/m^{2}K^2
incidence angle modifier for 50° IAM_{50}	0,95

Collector loop flowrate 50 l/h.m^2 was considered. Collector loop consists of 18x1 mm copper pipes at total length of 40 m equipped with 19 mm thick thermal insulation. Electricity consumption of circulation pump in the collector loop was included into the system electricity demand. Tube heat exchanger inside the DHW storage tank has a surface area 1 m^2. Heat transfer coefficient of the considered heat exchanger was 170 W/m^2.K. DHW tank model also considers the influence of flowrate, temperature difference and mean temperature on the heat transfer capacity.

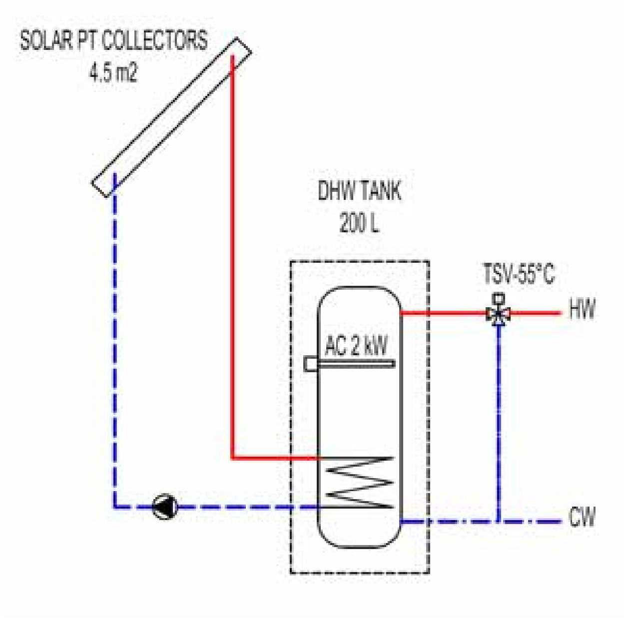

Fig. 2: Scheme of solar photothermal DHW system

3. Results

3.1. Energy performance

Energy performance for three solar DHW system alternatives was modelled in TRNSYS with one minute step to input a detailed definition of DHW load profile. Figure 3 shows the monthly results of simulated alternatives. Solar photothermal system produce more energy than solar photovoltaic systems even during the winter months. Table 3 shows the annual figures. The solar photothermal DHW system alternative supplies 25 %

more heat than equivalent photovoltaic DHW system alternative with MPPT and more than double amount of energy if compared with PV system without MPPT. Due to variation of solar irradiance and PV module operation temperature the difference between the electricity production with and without MPPT is about 40 %.

The main problem for given PV system without MPPT is unsuitable electric resistance 25 Ω of DC heating element, given by its power output 2 kW at nominal voltage 230 V. Optimization of electric resistance for the given PV system could reduce the difference between MPPT on and MPPT off systems to approx. 30 %. However, it is clear that simple solar photovoltaic DHW systems without MPPT are inefficient and the customer cannot count with the energy gains comparable to usual PV grid-on systems.

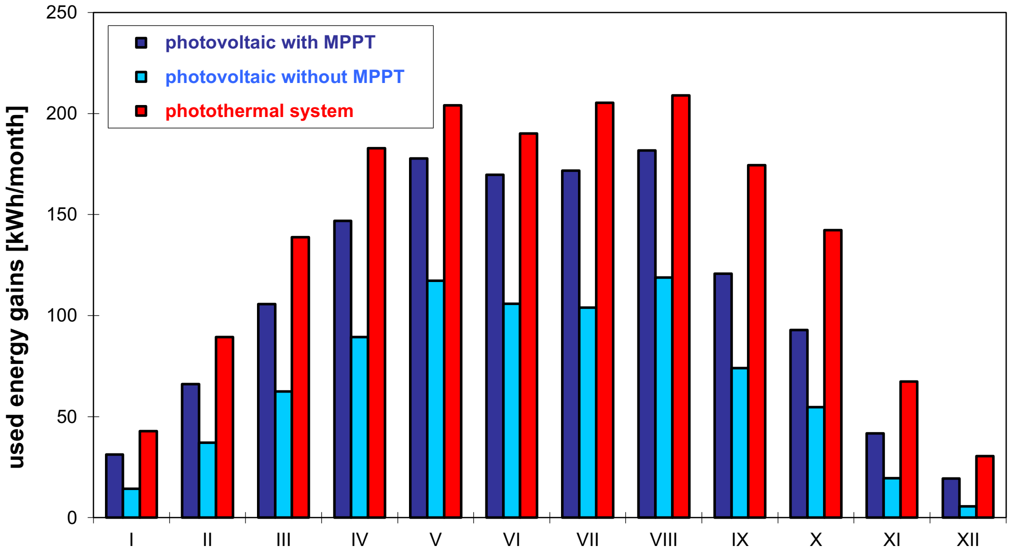

Fig. 3: Monthly energy balance of solar DHW alternatives

Solar thermal system for DHW preparation achieves the solar fraction of more than 60 % and specific heat gains are 370 kWh/m^2.a even despite the fact that the heat loss of the collector loop and storage tank attains about 25 % of heat produced by the solar thermal collectors.

Tab. 3: Simulation results for solar DHW system alternatives

Alternatives	Backup energy [kWh]	Solar gains [kWh]	Solar fraction [%]
PV MPPT off	1964	803	29
PV MPPT on	1442	1325	48
PT	1090	1677	61

3.2. Economic figures

Economic parameters of solar DHW systems have been analyzed and compared. Investment costs of solar DHW system alternatives including installation costs have been taken from the real commercial offers made by solar system installers (turnkey offers). Cost structure of alternatives is shown in Table 4. All costs are considered without VAT.

Tab. 4: Investment costs for solar DHW system alternatives

System	Material [EUR]	Installation [EUR]	Total [EUR]
PV MPPT off	2400	200	2600
PV MPPT on	3400	200	3600
PT	2800	600	3400

Material specified for PV system consists of 8 pcs of PV polycrystalline modules with peak power 250 W_p, supporting structure for sloped roof, cables, electric protection devices and 200 l DHW tank with DC and AC heating elements. Alternative with power point tracker (MPPT on) includes also the tracker.

Material specified for PT system consists of 2 pcs of flat-plate solar collectors at given area, supporting structure for sloped roof, copper pipes with thermal insulation at 40 m length, controller with sensors, solar pump module incl. expansion vessel, solar liquid, plumbing material and 200 l DHW tank with the immersed tube heat exchanger and AC heating element. Annual costs for photothermal system also included the replacement of solar liquid every 5 years and the pumps electricity consumption.

Payback time for given alternatives has been determined with electricity price at 0.10 EUR/kWh (valid for DHW heating in Czech Republic) and assumption of 5 % annual increase. Interest rate was considered at very low level of 0,1 % with the assumption that solar systems are completely financed by the system owner with money deposited at usual checking account in a bank (with almost zero price of money).

Results of the economic comparison are shown in Figure 4. Usual electric DHW heating system was added into the graph as a reference. It is obvious that the solar thermal system achieves the shortest payback time at the given conditions. The cheapest photovoltaic DHW system without MPPT has too high needs for backup heating and it costs almost 2000 EUR more than photothermal system for 20 years of operation.

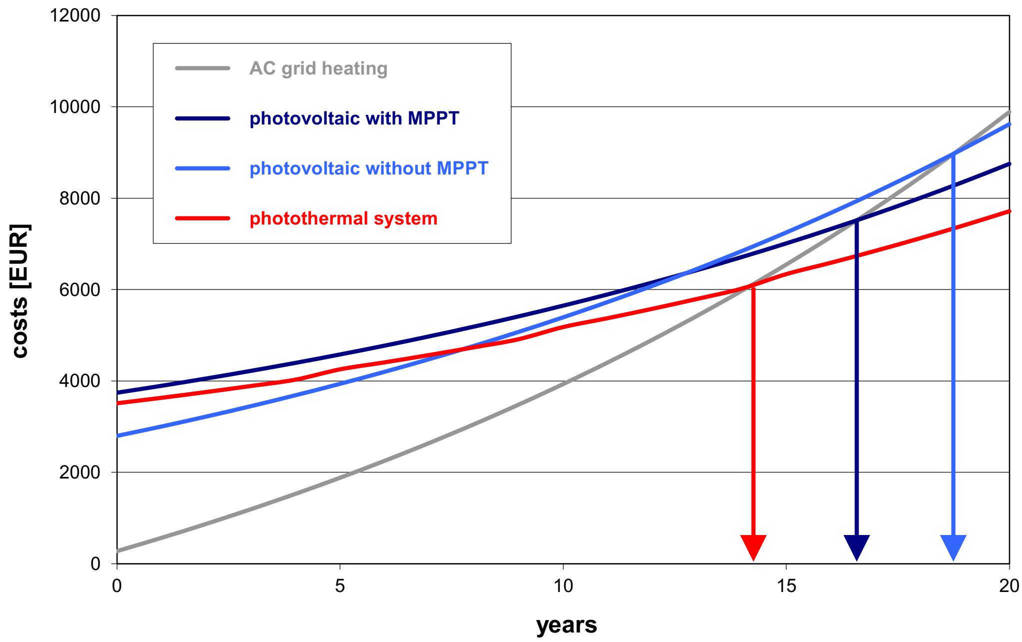

Fig. 4: Economic balance and payback time for solar DHW alternatives

4. Conclusion

Three solar DHW system alternatives was modelled in TRNSYS simulation environment and annual yields have been determined at given operation conditions. The analysis has shown that the simplest photovoltaic DHW system without MPPT would supply 40 % less energy than photovoltaic DHW system with MPPT and half amount of energy than the equivalent photothermal system. Solar thermal DHW systems are still more economic than photovoltaic DHW only systems available at the market if compared under identical conditions.

5. Acknowlegement

The research leading to these results has received funding from European Union project OP VaVpI no. CZ.1.05/2.1.00/03.0091 – University Centre for Energy Efficient Buildings.

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