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Research Article

Performance Analysis of Photovoltaic Water Heating System

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Performance of solar photovoltaic water heating systems with direct coupling of PV array to DC resistive heating elements has been studied and compared with solar photothermal systems. An analysis of optimum fixed load resistance for different climate conditions has been performed for simple PV heating systems. The optimum value of the fixed load resistance depends on the climate, especially on annual solar irradiation level. Use of maximum power point tracking compared to fixed optimized load resistance increases the annual yield by 20 to 35%. While total annual efficiency of the PV water heating systems in Europe ranges from 10% for PV systems without MPP tracking up to 15% for system with advanced MPP trackers, the efficiency of solar photothermal system for identical hot water load and climate conditions is more than 3 times higher.

1. Introduction

Significant decrease of photovoltaic (PV) technology cost in the last decade has opened a new market with simple solar water heating systems combining the PV modules and direct current (DC) electric heating elements. The public research exhibits a significant lack of publications on the photovoltaic technology dedicated for water heating only. On the other hand, there exist a number of patented photovoltaic water heating system configurations. Fanney and Dougherty [1] disclosed the PV water heater comprising a variable resistive load which is provided by a number of resistances sequentially switched by external controller according to actual irradiance to provide the maximum power output of PV array to DC resistive heating elements. Thomasson [2] uses the PV hot water system with the DC resistive heating elements immersed in two cascade hot water tanks with controlled charging according to priority and power available. Newman and Newman [3] suggested PV water heating system with new resistive heating element comprising an array of individual fixed resistance heating rods controlled by microprocessor unit to vary the resistance of heating element and provide maximum PV power for heating. Butler [4] has patented photovoltaic DC heater based on resistive heating element designed for immersion into the standard hot water tanks and which can be used also in other applications (open liquid containers, air heating, etc.). The market today offers a number of PV heating systems with a PV array directly coupled to DC electric heater. Simple PV water heating systems with optimized but fixed load resistance of DC resistive heating element do not need an extra control unit. Control of load resistance with the use of switching on and off the number of additional resistive elements by relays to match the load resistance to PV array conditions results in advanced microprocessor control units. A number of techniques and methods to maintain the PV array at maximum power conditions have been developed and widely applied in modern PV system controllers. Extensive summary and comparison of the maximum power point tracking devices can be found in numerous literature [5–8]. Apart from the PV water heating systems, there are conventional solar photothermal water heating systems, which can be considered as a mature technology, despite continuously ongoing research activities. Diverse forms of solar energy water heating systems have been extensively classified and reviewed by Norton [9]. Recent advances in the development of components for active and passive solar water heating systems have been reviewed in the work Shukla et al. [10]. Comprehensive

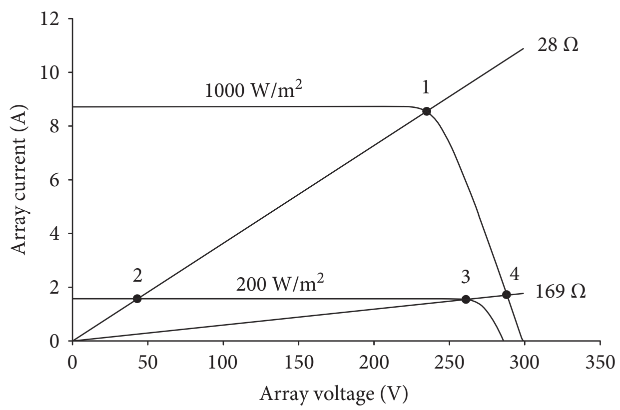

Figure 1: Electric (I-V) characteristics of photovoltaic array 2 kW_p (8×250 W_p in series).

review of drainback solar heating systems has been done by Botpaev et al. [11]. In the recent decades, water heating with use of photovoltaic-thermal (PV-T) collectors has been extensively investigated. Various designs of PV-T collectors and systems have been modelled and tested. Chow et al. [12] have studied the appropriateness of glass cover on a thermosyphon-based water-heating PV/T system under the influence of main system parameters. Mishra and Tiwari [13] have investigated the configuration of photothermal collector partially and fully covered by PV module. Lämmle et al. [14] have suggested a concept of PV-T collector with inflatable glass-film cushion to control thermal losses of the collector to combine advantages and disadvantages of unglazed and glazed PVT collector and to avoid overheating of PV encapsulation at stagnation conditions. Haurant et al. [15] have investigated glazed PV-T collector with exceptional conversion efficiencies operated in solar water heating system. Matuska et al. [16] have developed glazed PV-T collector with thermally resistant encapsulation and investigated the energy and economic performance in solar water heating system for a multifamily house.

The paper analyses the annual energy performance of PV-only solar water heating system. First part of the paper is focused on the analysis of difference in electricity production of PV array for DC electric heater when using MPP tracking and fixed load resistance. Second part of the paper analyses the solar photovoltaic hot water system with the use of PV modules in both alternatives (MPPT, fixed load resistance) and compares its performance with a conventional solar hot water system with photothermal flat plate collectors operated at identical hot water load and climate conditions. The comparison of given water heating solar systems does not consider anyhow the economic parameters (investment costs, energy price, interest rate, etc.), which are dependent on the country and application field. On the other hand, because economic point of view could influence the optimal sizing of solar collector (photovoltaic, photothermal) area, the analyses have been performed always as parametric ones with a certain range of system size for different climates.

Table 1: Parameters of the 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 operating cell temperature NOCT	45°C

2. Power Output of PV Array for Water Heating

Photovoltaic hot water systems considered in the analysis combine the PV modules for direct current generation which is utilized for electric heating elements immersed in the hot water tank. Photovoltaic modules are electric generators with nonlinear current-voltage (I-V) characteristics. The produced electric power of the PV array is significantly influenced by solar irradiance, less by ambient temperature, but anyway, it depends on the connected electric load (load resistance). Figure 1 shows the I-V characteristics of the photovoltaic array assembled from 8 polycrystalline modules connected in series with a peak power 2 kW_p. I-V characteristics for two different levels of solar irradiance 200 W/m^2 and 1000 W/m^2 are given as an example how the load resistance value influences the power output of PV array. Application of load resistance 28 Ω results in maximum power 2000 W at point 1 for solar irradiance 1000 W/m^2, but the optimum load resistance to provide maximum power output for solar irradiance 200 W/m^2 (403 W at point 3) is 169 Ω. The application of different load resistance value than the optimum one results in lower electric power output as seen in point 2 (68 W for irradiance 200 W/m^2) and point 4 (502 W for irradiance 1000 W/m^2). It can be generally concluded that high load resistance values are suitable for low irradiance levels while low load resistance values provide maximum power output for high irradiance levels.

In order to maintain the PV array at maximum power output conditions, the load resistance has to vary and adapt to actual operation conditions of the PV array. Despite this fact, the low-cost PV water heaters available today on the market often miss any MPP tracking device and utilize the PV array directly connected to DC electric heating element with fixed load resistance value optimized from the point of annual performance.

An analysis has been performed to find the optimum load resistance value for given PV array to be used as fixed parameter during the whole year and to provide the maximum performance for given operation conditions. Typical PV arrays used in PV water heaters are based on polycrystalline technology. PV modules with peak power output 250 W_p have been considered in the analysis. Detailed parameters of the PV modules are shown in Table 1.

Table 2: Climate characteristics for selected locations.

Location	Average ambient temperature [°C]	Total irradiation horizontal [kWh/m^2.a]	Total irradiation south, tilted 45° [kWh/m^2.a]	Beam irradiation south, tilted 45° [kWh/m^2.a]
Madrid (ES)	13.9	1662	1864	1163
Istanbul (TR)	14.1	1627	1805	1088
Athens (GR)	17.6	1562	1696	914
Genova (IT)	15.8	1447	1637	944
Bordeaux (FR)	12.7	1270	1448	744
Milano (IT)	11.6	1188	1342	657
Zurich (CH)	9.1	1105	1237	585
Prague (CZ)	7.9	998	1115	487
Stockholm (SE)	5.3	980	1232	687

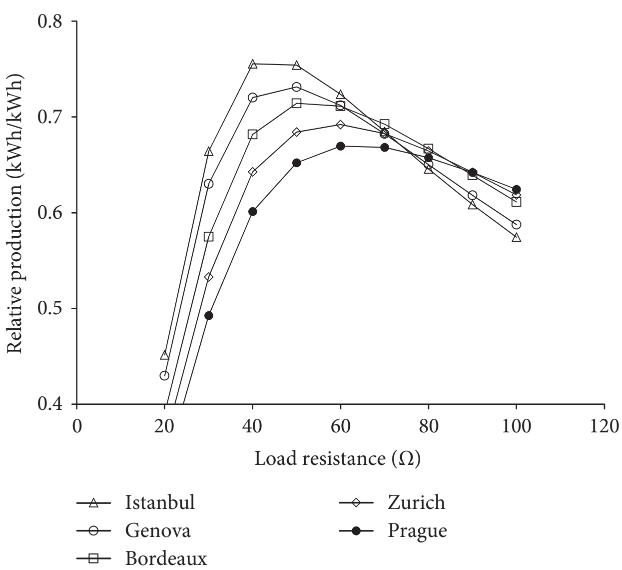

Figure 2: Dependence of 2 kW$_p$ PV array relative production on load resistance for selected locations.

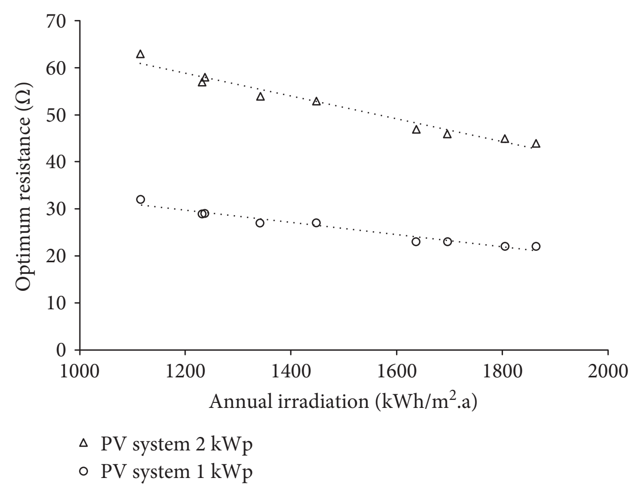

Figure 3: Optimum load resistance of PV arrays as a function of annual solar irradiation.

Annual performance of 4 PV modules (1 kW$_p$) and 8 PV modules (2 kW$_p$) connected in series to PV array has been analysed in the MPPT mode (MPPT-on) and with fixed load resistance (MPPT-off). To model the electricity production of PV array, four-parameter mathematical model [17] has been used. The model allows to evaluate the maximum power of the module (MPP tracking), but also with given electric load resistance (given load voltage applied, model determines the current as a function of load voltage). The analysis of the PV array electricity production in both modes (MPPT-on, MPPT-off) has been performed for different climates in Europe. Climate characteristics of the selected locations are shown in Table 2. PV modules were considered with south orientation and slope 45° in all alternatives.

Figure 2 shows the relative production as a ratio between the annual electricity production of PV array 2 kW$_p$ with fixed electric load resistance (MPPT-off) and annual electricity production under maximum power point tracking (MPPT-on). The trends are similar for other sizes of PV array with a serial connection of modules, and optimum load resistance value for MPPT-off mode is directly proportional to open circuit voltage V_{oc} of the PV array. It has been also proved that the optimum load resistance value is significantly influenced by climate conditions, especially by solar irradiation. Figure 3 shows the dependency of the optimum load resistance value on annual solar irradiation for different locations in Europe. Optimum load resistance value is indirectly proportional to the annual solar irradiation.

Figure 4 shows the difference between the specific electricity production of PV array for MPPT-on mode and for MPPT-off mode with fixed load resistance optimized for given European climates. The difference in performance between both modes ranges from 25% for sunny regions to 35% for regions with low solar irradiation.

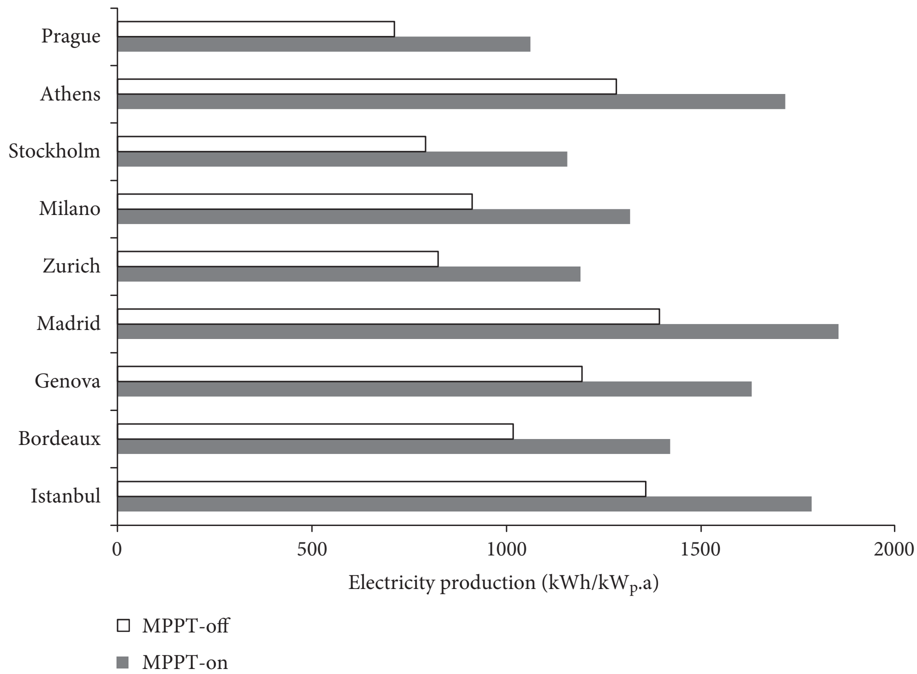

Figure 4: Specific electricity yields of PV array in different climates for maximum power point tracking mode (MPPT-on) and for optimized load resistance mode (MPPT-off).

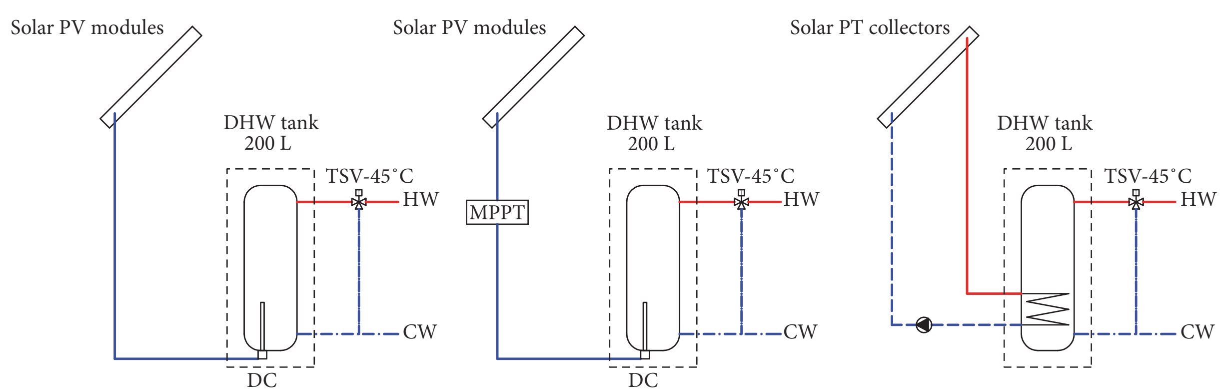

Figure 5: Scheme of solar hot water systems (PV without MPPT, PV with MPPT, and solar thermal).

3. Solar Hot Water Systems Analysis

Detailed mathematical models have been used for the solar photovoltaic and solar photothermal hot water systems for family houses to compare the energy performance at identical boundary conditions. Solar systems have been simulated in TRNSYS [18] in the following alternatives (see Figure 5):

(i) Photovoltaic hot water system without MPPT (MPPT-off)

(ii) Photovoltaic hot water system with MPPT (MPPT-on)

(iii) Photothermal hot water system.

Each solar system alternative has been used only for hot water preparation. Daily hot water load 200 l (3 to 4 persons) for typical household has been considered with required hot water temperature 45°C and cold water temperature 10°C (considered constant during the whole year in all alternatives to keep the same heat demand for comparison). Relative daily profile of hot water load has been taken from Mandate 324 [19] as profile M. Total hot water heat demand is 2974 kWh/a. Solar water tank volume 200 l with a heat loss 1.4 kWh/day has been considered in all alternatives. The water tank was used as a preheating stage for conventional water heater. Maximum temperature in solar water tank has been set to 85°C as recommended by manufacturer for all systems. Output hot water temperature from the solar

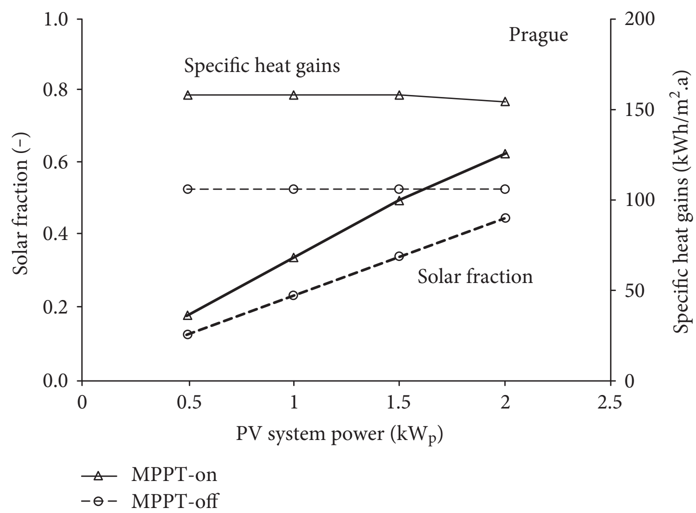

Figure 6: Performance characteristics of solar PV hot water system in the climate of Prague.

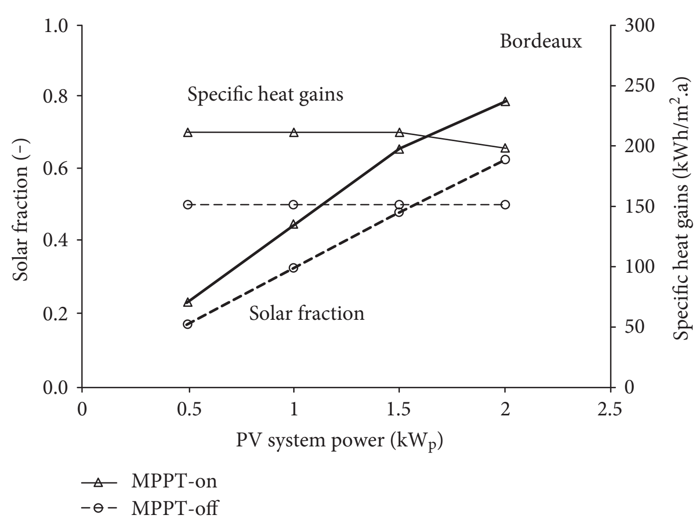

Figure 7: Performance characteristics of solar PV hot water systems in the climate of Bordeaux.

preheating systems has been controlled by a thermostatic valve to 45°C (upper limit). Back-up energy has been evaluated from actual water load and temperature difference between thermostatic valve output and required hot water temperature. Solar water tanks have been modelled uniformly with TRNSYS model (type 340) [20], which allows to model the solar water tanks with electric heating elements and with tube heat exchangers. Solar systems have been considered in different climates and with different sizes of the solar source (PV array size, solar thermal collector area).

3.1. Solar Photovoltaic Hot Water System. Annual performance of photovoltaic hot water system has been investigated in two mentioned alternatives of operation mode for PV array: photovoltaic system with MPPT device (MPPT-on) and without MPPT (MPPT-off). PV array has been modelled with use of TRNSYS model (type 180) including electrical and thermal model. PV hot water system has been designed in several alternatives available on the market today. PV array was considered with a peak power output from $0.5\,kW_p$ to $2\,kW_p$ assembled from standard $250\,W_p$ polycrystalline modules (for parameters see Table 1). Solar PV hot water system has been considered in different climate zones. Dependence of solar fraction and specific heat gains of the system has been evaluated in detail for three selected locations (Prague, Bordeaux, and Istanbul). Results are shown in Figures 6–8 (mind the different scales of graphs for specific heat gains). Optimum load resistance has been used for the PV array operated in MPPT-off mode according to Table 3.

Whole year modelling of PV hot water system performance has considered change of module electric power with solar irradiance incident angle (optical characteristic, incidence angle modifier IAM). Total cable electric losses of the system have been considered 2%. Simulation has not considered long-term degradation of PV module power, usually referred from 0.5 to 1% annually.

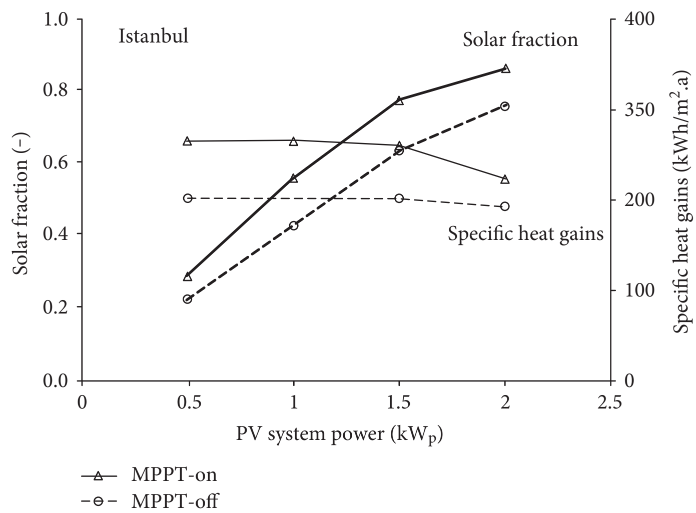

Figure 8: Performance characteristics of solar PV hot water systems in the climate of Istanbul.

Table 3: Optimum load resistance for different sizes of PV array in different climates.

Number of modules/power [kW_p]	2/0.5	4/1.0	6/1.5	8/2.0
Madrid	11	22	33	44
Istanbul	11	23	34	45
Athens	12	23	35	46
Genova	12	24	35	47
Bordeaux	13	27	40	53
Milano	14	27	41	54
Zurich	15	29	44	58
Prague	16	32	47	63
Stockholm	14	29	43	57

As shown in graphs, the solar fraction increases almost linearly with peak power of PV array, until excess heat gains are present during the summer season when the PV array is oversized. This results in lower energy production for heating than the available potential is. Similarly, the specific heat gains are in principle constant with no dependence on applied size of the system. Only in the case of oversized PV array with respect to hot water load, the specific heat gains are reduced.

3.2. Photothermal Hot Water System. Solar photothermal hot water system has been considered with flat plate solar thermal collectors with forced circulation. Main parameters of solar photothermal collectors required by TRNSYS model type 1b are shown in Table 4. Collector loop flowrate has been considered 40 l/h.m^2 of collector area. Collector loop consists of copper pipes 18×1 mm at total length 30 m equipped with thermal insulation 19 mm thick. The loop is connected to tube heat exchanger immersed in the lower part of solar water tank identical with tank used in PV hot water system. Tube heat exchanger has a surface area 1 m^2. Nominal specific heat capacity of the heat exchanger has been considered 170 W/K. Solar water tank model considers also the influence of flowrate, temperature difference, and mean temperature on the heat transfer capacity of the heat exchanger.

Table 4: Main parameters of solar photothermal collectors used in analysis.

Parameter	Value
Zero-loss efficiency η_0 [−]	0.79
Linear heat loss coefficient a_1 [W/m^{2}K]	4.0
Quadratic heat loss coefficient a_2 [W/m^{2}K^2]	0.015
Incidence angle modifier for 50° IAM_{50}	0.95

Solar thermal hot water system has been analysed with different sizes of solar collector array. Alternatives with solar collector area from 1 to 4 m^2 have been considered. Detailed results are shown in Figures 9–11 for selected locations with different climates (Prague, Bordeaux, and Istanbul). While solar fraction increases with large area of solar collectors, the annual specific heat gains decrease. This is caused by significant dependence of solar collector yields on the operation temperature. Larger collector area delivering higher absolute energy gains into storage tank leads to higher average operation temperatures of solar system and thus lower collector efficiency and higher loss of collector loop piping. Excess solar heat gains in summer, especially present for sunny climates due to oversized collector area, result in worse usability of the system and further decrease in specific heat gains.

4. Experimental Analysis

Three investigated types of solar water heating systems have been analysed also experimentally (see Figure 12). Photothermal system has used two conventional flat plate collectors

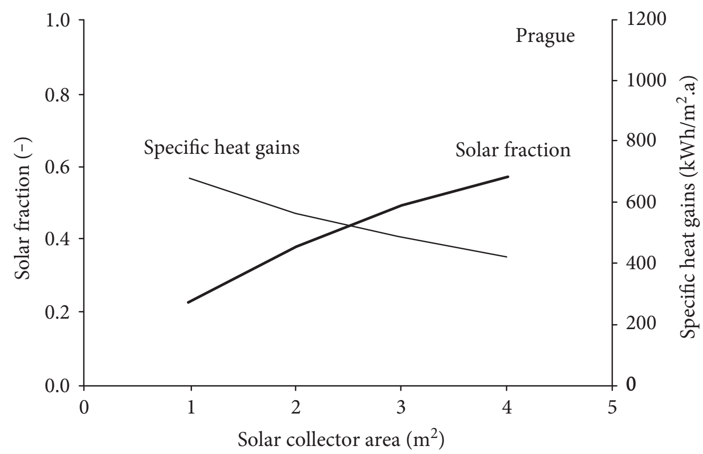

Figure 9: Performance characteristics of solar photothermal hot water systems in the climate of Prague.

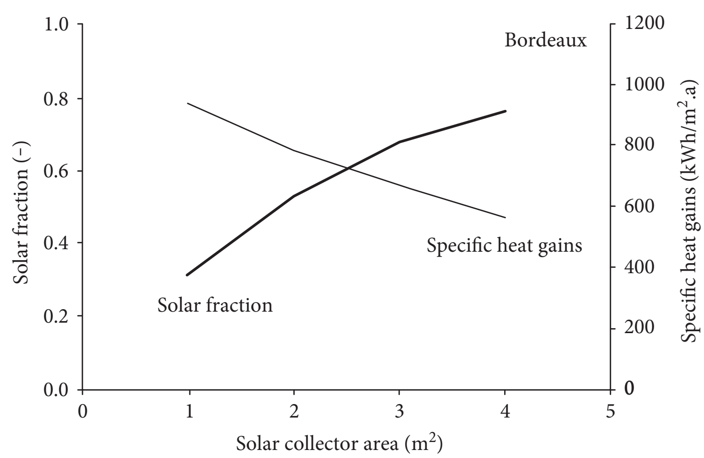

Figure 10: Performance characteristics of solar photothermal hot water systems in the climate of Bordeaux.

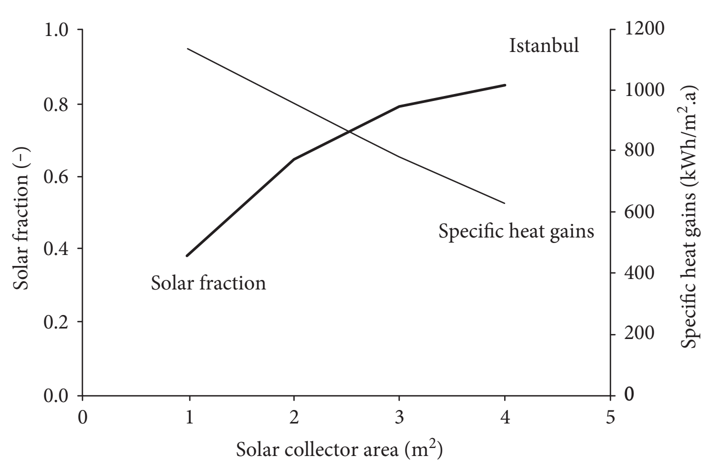

Figure 11: Performance characteristics of solar photothermal hot water systems in the climate of Istanbul.

Figure 12: View on solar photothermal and photovoltaic collectors installed for experimentally tested system.

Table 5: Main parameters of experimental solar water heating systems.

	PV system without MPPT	PV system with MPPT	Photothermal system
Solar collector area	$12.8\,m^2/1.92\,kW_p$	$12.8\,m^2/1.92\,kW_p$	$3.56\,m^2$
Storage tank volume	200 l	200 l	200 l

with active collector area $3.56\,m^2$. Both photovoltaic systems (with MPPT, without MPPT) have used 8 polycrystalline PV modules each with peak power $240\,kW_p$. All solar water heating systems have been equipped with identical solar storage tank (volume 200 l, daily heat loss 1.4 kWh/day). The main parameters of the solar water heating systems are listed in the Table 5. The storage tank for the solar photothermal system has a tube heat exchanger; storage tank for solar photovoltaic systems has a DC heating element with nominal power 2 kW. Storage tanks were not equipped by any additional back-up heater; the solar water heating systems have been used as a preheating stage. The orientation and the slope of solar collectors and PV modules have been the same: orientation 15° to east (from south) and slope 45°. Thus, the identical climate conditions (Ziar nad Hronom, Slovakia) have been ensured for all experimentally tested systems.

The daily hot water load for the solar water heating systems has been 200 l of water at temperature 45°C. The usable solar heat gains from water heating systems have been evaluated.

The experimental testing of solar systems has started in September 2013. In the beginning, only solar photothermal system and solar photovoltaic system without MPPT have been operated for water heating. Later in 2014, solar photovoltaic alternative with MPPT has been added for comparison to both water heating systems. The results from experimental testing are shown in Table 6 and in the graph in Figure 13 for all solar water heating systems.

Systems were compared for the first season from the beginning of September 2013 to the end of August 2014. The annual heat gains of the photothermal system are 1544 kWh/a, that is $434\,kWh/m^2$.a. Annual heat gains of photovoltaic system without MPPT are 1322 kWh/a, that is $103\,kWh/m^2$.a. Both results are in line with values graphically presented in Figure 6 (considering PV module power $1.92\,kW_p$) and Figure 9 (considering collector area $3.56\,m^2$). The climate of the location with tested systems (Ziar nad Hronom) and climate of Prague used for simulations have similar weather conditions. Comparison of PV heating systems with MPPT and without MPPT control has shown about 20% higher usable heat gain for system with MPPT control, which confirms presented theoretical simulations.

Table 6: Experimental evaluation of solar water heating systems.

Month	PV system without MPPT [kWh]	PV system with MPPT [kWh]	Photothermal system [kWh]
Sept 2013	138	0	154
Oct 2013	117	0	134
Nov 2013	37	0	47
Dec 2013	24	0	36
Jan 2014	19	0	29
Feb 2014	54	0	72
Mar 2014	139	0	155
Apr 2014	144	0	172
May 2014	155	0	181
Jun 2014	194	227	220
Jul 2014	171	188	197
Aug 2014	131	143	147
Sept 2014	87	107	116
Oct 2014	74	88	93
Nov 2014	31	46	45
Dec 2014	33	53	42
Jan 2015	26	40	36
Feb 2015	78	110	89

5. Comparison and Discussion

When comparing the performance of solar water heating systems, the total system efficiency can be taken as parameter which shows the demand of the system on available roof area. Figure 14 shows the dependence of annual specific heat gains on the annual incident solar irradiation for all investigated alternatives (size, climate). Ratio of these quantities results in total system efficiency.

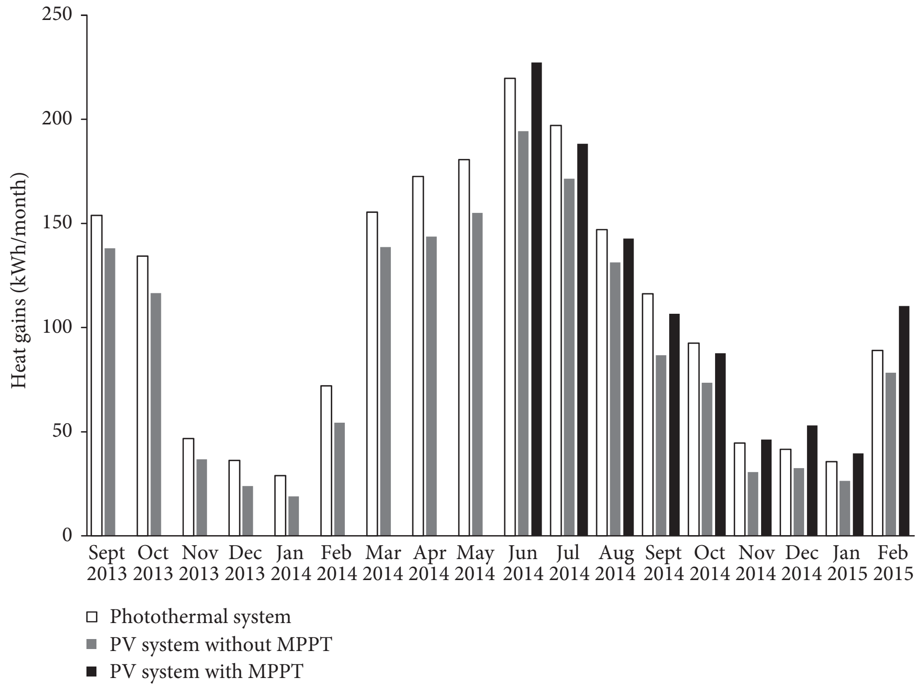

Figure 13: Experimental evaluation of solar water heating systems.

Efficiency of PV water heating systems depends only on usability of PV array production for water heating. Excess heat gains during summer season which cannot be utilized degrade the total system efficiency. Difference between the efficiency of PV systems with MPP tracking and with fixed load resistance has been monitored in the analysis. While efficiency of PV water heating system with MPP tracking ranges between 13 and 15% for all climates, the efficiency of simple system without MPPT achieve the efficiency between 10 and 11%.

Performance of the solar thermal systems is much more dependent on the operation conditions. While electricity generation from PV array is independent on the storage tank temperature, heat generation of solar thermal collector decreases with the tank temperature, because it directly influences the collector fluid operation temperature and thus thermal losses of solar collector and collector loop. This is the reason for large dispersion of points in the graph in Figure 14 for solar photothermal (PT) system case. The total efficiency of photothermal systems ranges from 35 to 68%.

The comparison of total system efficiency clearly states that solar thermal system demands about 3 to 6 times less roof area for water heating than the PV water heating system.

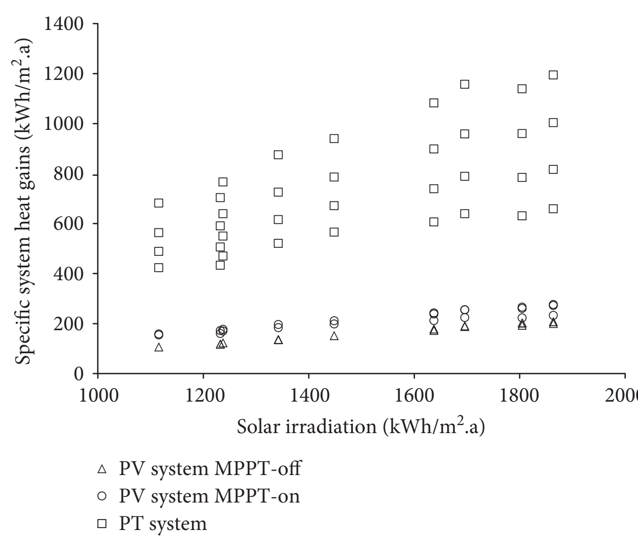

Figure 14: Relationship between specific heat gains and solar irradiation for solar hot water systems.

6. Conclusion

Solar photovoltaic water heating systems based on direct coupling of PV array to DC resistive heating elements immersed in hot water tank have been studied. Use of maximum power point tracking compared to fixed optimized load resistance increases the annual yield by 20 to 35%. The optimum value of the fixed load resistance depends on the climate, especially on annual solar irradiation level. The total annual efficiency of the PV water heating systems in Europe ranges from 10% for PV systems without MPP tracking up to 15% for system with advanced MPP trackers. However, such values are dramatically lower than the efficiency of solar photothermal system for identical hot water load and climate conditions. Despite the fact that efficiency of solar photothermal system is influenced by sizing more than PV heating system, the efficiency is more than 3 times higher. The theoretical analysis has been verified by experimental testing of the solar water heating systems.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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