The Influence of Weather Conditions and Operating Parameters on the Efficiency of Solar Power Collectors Based on Empirical Evidence

Aldona Skotnicka-Siepsiak, Maciej Wesołowski, Maciej Neugebauer, Janusz Piechocki and Piotr Sołowiej

Abstract The influence of solar irradiance, ambient temperature and buffer tank temperature on the efficiency of solar collectors was evaluated in the climatic conditions of north-eastern Poland (climatic zone IV) characterized by relatively low irradiance (annual average of 900 kWh/m^2). Two types of solar power collectors (flat-plate and evacuated tube collectors) were compared in terms of energy gains, collector efficiency and glycol temperature between May and September 2016. The collectors were mounted on the roof of a building on the campus of the University of Warmia and Mazury in Olsztyn. The roof had a pitch of 45°, the collectors had a tilt angle of 30°, and they faced west of true south. Measurements were performed separately for the analyzed solar collector systems operating simultaneously in identical weather conditions. The combined absorber surface was 4.64 m^2 in flat-plate collectors and 3.23 m^2 in the evacuated tube collector. Both systems were connected to a water buffer tank. Empirical data were recorded with a controller and were processed and stored in a computer. The factors responsible for differences in the efficiency of the examined collectors are discussed in the paper.

Keywords Flat-plate solar collectors · Evacuated tube collectors
Efficiency of solar collectors

A. Skotnicka-Siepsiak (✉)
Institute of Building Engineering, University of Warmia and Mazury in Olsztyn, Olsztyn, Poland
e-mail: aldona.skotnicka-siepsiak@uwm.edu.pl

M. Wesołowski · M. Neugebauer · J. Piechocki · P. Sołowiej
Department of Electrical, Power, Electronic and Control Engineering, University of Warmia and Mazury in Olsztyn, Olsztyn, Poland
e-mail: mwesolowski@uwm.edu.pl

M. Neugebauer
e-mail: mak@uwm.edu.pl

J. Piechocki
e-mail: jpt@uwm.edu.pl

P. Sołowiej
e-mail: pit@uwm.edu.pl

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1 Introduction

The continued depletion of fossil fuel resources has increased the popularity of systems capable of harnessing solar energy. At the end of 2016, solar power collectors spanned a total area of 652 million square meters around the globe (456 GWth). However, this impressive result does not reflect current market trends, in particular in China and most European countries, where heat pumps and photovoltaic panels are gradually detracting from the popularity of domestic solar thermal systems [1]. A reverse trend is noted on the Polish market of renewable energy sources. According to the Institute for Renewable Energy, solar thermal collectors are the most popular renewable energy microgeneration systems in Poland with around 174,000 systems in place. In comparison, only around 25,000 heat pumps (including geothermal) and 90,000 automatic, dedicated biomass boilers have been installed in Poland to date [2].

In this study, the efficiency of solar thermal collectors was analyzed in the climate of north-eastern Poland. The experimental set-up was composed of flat-plate solar collectors (active absorber area of 4.64 m^2) and an evacuated tube collector (active area of 3.23 m^2) connected to a buffer storage tank with the volume of 1000 dm^3. The influence of selected factors on the efficiency of both solar collector systems was analyzed.

The tested weather conditions were the temperature of ambient air and solar irradiance which differ across geographic locations. In the present study, the measured parameters were compared with Typical Meteorological Year (TMY) data for 1971–2000 in the examined location [3]. The efficiency of solar collectors is frequently analyzed in a real-life environment due to global climate change and differences between statistical data and measured parameters. Halawa, Chang and Yoshinaga examined the applicability of solar power collectors for heating household water in Australia, Taiwan and Japan [4]. The potential of solar power collectors was evaluated in Beirut by Sakkal et al. [5]. Merrouni et al. [6] analyzed the location of solar power collectors in Morocco. The applicability of solar collectors for sustainable energy generation in Nigeria was evaluated by Giwa et al. [7]. The efficiency of solar power collectors in a cold climate was investigated by Musard [8].

The influence of selected operating parameters on the efficiency of solar power collectors was also evaluated in the literature. Solar collectors are influenced by many factors that are unrelated to climate. In a study by Elbreki et al., these factors were divided into climate parameters, design parameters and operational parameters [9]. Flow rate is one of the key determinants of the efficiency of solar power systems. This parameter is often analyzed in the literature. Heat transfer under laminar flow conditions was investigated by Weitbrecht et al. [10]. Gao et al. [11] analyzed the influence of thermal mass and flow rate on the efficiency of water-in-glass and U-pipe evacuated tube solar collectors. Cunio and Sproul [12] examined a typical solar pool heating system and found that systems with a low-power pump and reduced flow rate did not significantly compromise the efficiency of solar power collectors. Razika et al. demonstrated that collector efficiency is a linear function of mass flow rate, volume flow rate, velocity and inclination angle. When the inclination angle and the volumetric flow rate increase, collector efficiency increases [13]. Some authors have proposed optimal flow rates. Hobbi and Siddiqui [14] analyzed flat-plate collectors in a solar water heating system with forced circulation and noted that the collector loop flow rate should range from 20 to 40 kg/h m^2. Bava et al. [15] developed a numerical model to evaluate flow distribution. In some studies, the influence of flow rate on collector efficiency was evaluated [16]. In the collector system described in this study, the effects of flow rate will be addressed by future research. In the present experiment, flow rate was kept constant (5 l/min for flat-plate collectors and 7 l/min for evacuated tube collectors) to eliminate the influence of variable flow on system efficiency.

The influence of the following factors was also analyzed: (1) water temperature in the buffer storage tank, (2) temperature of glycol at the collector outlet, and (3) difference between the temperature of the working fluid at the collector outlet and ambient temperature. The above parameters were selected to facilitate measurements in small domestic systems. In the literature, various operating parameters have been analyzed to determine their impact on the operation and efficiency of solar power systems. They include temperature stratification in the buffer tank and its influence on system efficiency. Cristofari et al. [17] demonstrated that a stratified tank significantly outperforms a fully mixed tank. A stratified tank produced greater energy savings (5.25% per year) than a fully mixed tank. Stratification and its influence on energy accumulation were analyzed by Haller et al. [18]. Rodríguez-Hidalgo et al. [19] demonstrated that the average annual efficiency of a solar collector was most significantly influenced by wind losses (−15.6%), collector aging (−15.0%), incident angle modifier (−7.6%), thermal inertia (−3.2%) and external radiation losses (−1.3%).

2 Materials and Methods

2.1 Test Stand

The experiment was carried out between 1 May and 30 September 2016 at the Institute of Construction Engineering of the University of Warmia and Mazury in Olsztyn. Data for 6–11 July 2016 were not recorded due to technical problems. The hydraulic design of the analyzed solar power collector systems is presented in Fig. 1.

The tested systems were composed of an evacuated tube collector and flat-plate collectors mounted on a roof with 45° pitch and facing west of true south. Solar irradiance, temperature of ambient air, temperature at the collector inlet and outlet (measured separately for the evacuated tube collector and flat-plate collectors), flow

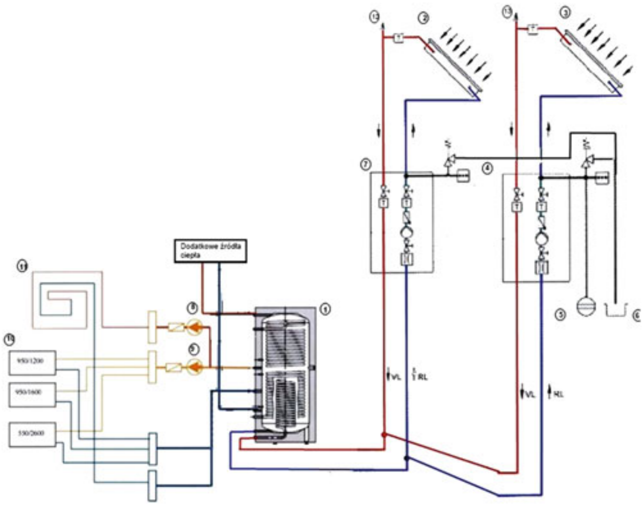

Fig. 1 Hydraulic design of the analyzed system. (1) Water buffer tank, (2) flat-plate collectors (absorber area of 4.64 m^2), (3) evacuated tube collector (absorber area of 3.23 m^2), (4) pump module of an evacuated tube collector, (5) expansion vessel, (6) emptying tank, (7) pump module of a flat-plate collector, (8) floor circuit pump, (9) radiator circuit pump, (10) radiators, (11) floor heating (4.75 m^2), (12) vent valves in the flat-plate collector system, (13) vent valves in the evacuated tube collector system

Table 1 The efficiency and heat loss factors of solar power collectors determined in Solar Keymark tests [20]

	Flat-plate	Evacuated tube
Optical efficiency [%]	74.3	78.9
Heat loss factor k_1 [W/(m^2 K^2)]	4.16	1.36
Heat loss factor k_2 [W/(m^2 K^2)]	0.0124	0.0075

rate in the evacuated tube collector and flat-plate collectors were measured at hourly intervals. Solar irradiance was measured with the use of the Kipp&Zonnen CMP3 pyranometer (directional error at 80° with 1000 W/m^2 beam <20 W/m^2). Temperature was measured with Siemens QAP21.2 cable temperature sensors, Siemens QAE2111.010 immersion temperature sensors and Siemens QAC22 outside temperature sensor to the nearest 0.4 °C. The efficiency and heat loss factors of the analyzed solar power collectors determined in Solar Keymark tests are presented in Table 1.

2.2 Calculations

The measured parameters were used to calculate the efficiency of solar power collectors with the use of the following formula:

$$\eta = \eta_0 - \frac{k_1 \cdot \Delta T}{E_g} - \frac{k_2 \cdot \Delta T^2}{E_g} \quad (1)$$

where: η_0—optical efficiency; k_1, k_2—heat loss factors; ΔT—temperature differential between the absorber and ambient outside air temperature; E_g—irradiance.

Instantaneous efficiency was calculated with the below formula:

$$\eta = \frac{Q}{A \cdot E_g} = \frac{\sum_{i=1}^{n} \rho(i) * c_w(i) * V'(i) * (\vartheta_v(i) - \vartheta_R(i))}{A \cdot E_g} \quad (2)$$

where: Q—heat expressed in [W]; $\rho(i)$—liquid density, expressed in [kg/m^3]; $c_w(i)$—specific heat of liquid, expressed in [Wh/kg deg]; $V'(i)$—average flow rate of liquid, expressed in [m^3/h]; $\vartheta_v(i)$—liquid temperature at collector outlet, expressed in [°C]; $\vartheta_R(i)$—liquid temperature at collector inlet, expressed in [°C]; i—time interval 1 h; A—collector gross area [m^2].

The influence of the above parameters on the efficiency of the solar collector system was determined by linear regression analysis in the Analysis ToolPak add-in program in Excel.

3 Results

3.1 Weather Conditions

Weather conditions were favorable for the operation of solar power collectors in the experimental period between May and September 2016.

The average hourly temperatures of ambient air measured in the experiment and obtained from a TMY database [3] are presented in Fig. 2. The measured average hourly temperature was 17.5 °C, and it was 2.8 °C higher than the average TMY temperature of 14.7 °C. The minimum average hourly temperature was determined at 5.4 °C based on measured data and at −3.2 °C based on TMY data. The measured maximum average hourly temperature was 32.1 °C, and it was 1.1 °C higher than the maximum TMY value of 31.0 °C.

The analyzed data covered a total of 3552 h (data for 6–11 July 2016 are not available), including 1371 h with zero irradiation in experimental measurements and 1504 h with zero irradiation in the TMY database. Irradiation exceeded 800 Wh/m^2 during 366 h of measurements and only 67 h in the TMY database.

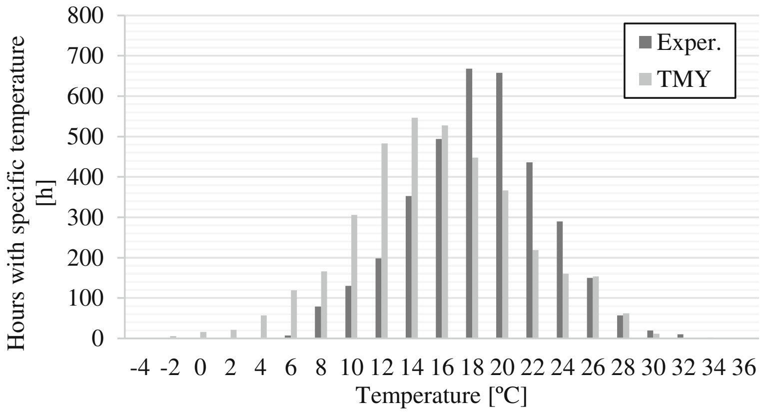

Fig. 2 Distribution of air temperatures between May and September 2016 in Olsztyn based on the performed measurements and a meteorological database (TMY) [3]

3.2 Energy Gains in the Analyzed Solar Power Collectors

In the analyzed period, total energy gains per 1 m^2 for the whole period, reached 87.0 kWh/m^2 in the flat-plate collector system and 265.6 kWh/m^2 in the evacuated tube collector system (Table 2). Maximum hourly energy gain was determined at 0.13 kWh/m^2 in the flat-plate collector at 2 PM on 14 August, and at 1.00 kWh/m^2 in the evacuated tube collector at 3 PM on 26 May.

3.3 Efficiency of the Analyzed Solar Power Collectors

Based on the results of the calculations performed with the use of formula (1), the average efficiency of a flat-plate solar collector was 63% (median of 67%) and the average efficiency of an evacuated tube collector was 72% (median of 71%).

Table 2 Montly energy gains from solar installations kWh and per 1 m^2 kollektor in [kWh/m^2]

Month	Flat-plate, kWh [kWh/m^2]	Evacuated tube, kWh [kWh/m^2]
May	84.6 [18.2]	193.8 [60.0]
June	96.0 [20.7]	205.9 [63.7]
July	73.4 [15.8][a]	145.0 [44.9][a]
August	81.4 [17.5]	165.4 [51.2]
September	68.9 [14.8]	148.1 [45.8]
Total	404.3 [87.0]	858.2 [265.6]

[a]Data not available for 6–11 July 2016

In a real-life environment, flat-plate collectors were characterized by a smaller difference between ambient temperature and absorber temperature (average difference of 7.9 K for a flat-plate collector and 10.0 K for an evacuated tube collector). The measured efficiency of flat-plate collectors was also lower than that given by the manufacturer (Fig. 3). Figure 3 shows the tendency of changes in measured values for analyzed collectors.

The influence of the following explanatory variables on the efficiency of solar power collectors was determined in a linear regression analysis based on hourly values:

- X_1 solar irradiance;
- X_2 temperature of ambient air;
- X_3 temperature at the bottom of the buffer storage tank;
- X_4 temperature of the working fluid at collector outlet;
- X_5 difference in temperature between ambient temperature and temperature at collector outlet.

The influence of the analyzed parameters on collector efficiency is presented in Table 3.

The values X_n in Table 3 refer to statistical functions of linear regression analysis which explains the influence of the analyzed factors on the investigated variable.

Formulas 1 and 2 are explained in Sect. 2.2 Calculations. Coefficient of determination R^2 reaches higher values when the percentage of explained variation of dependent variable by a given predictor is higher. Coefficient “b” in the equation $y = bX_n + a$ is an unstandardized regression coefficient and reflects the slope of regression line.

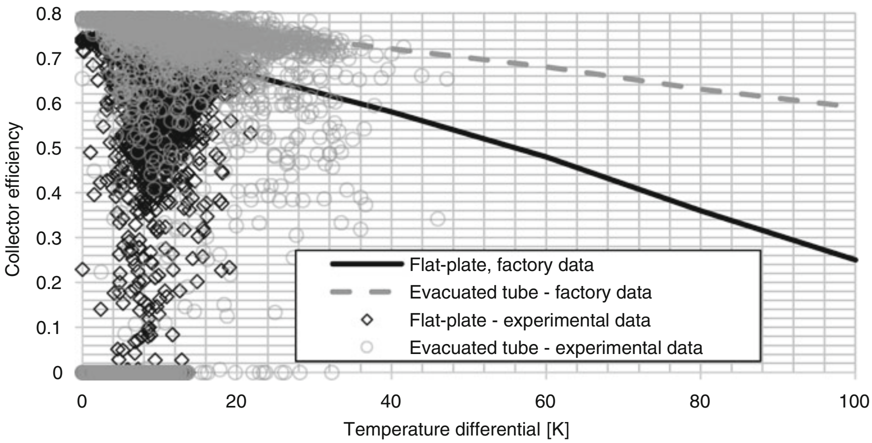

Fig. 3 Efficiency of solar power collectors—comparison of experimental and published data [20]

Table 3 Statistical distribution of parameters influencing the efficiency of solar collectors

Explanatory variable	Flat-plate		Evacuated tube	
	Formula (1)	Formula (2)	Formula (1)	Formula (2)
X_1	$R^2 = 0.3465$	$R^2 = 0.081$	$R^2 = 0.3083$	$R^2 = 0.0770$
	$y = 0.007X_1 + 0.2422$	$y = -0.0198X_1 + 0.3075$	$y = 0.007X_1 + 0.3033$	$y = -0.0131X_1 + 0.4294$
X_2	$R^2 = 0.0265$	$R^2 = 0.0010$	$R^2 = 0.0470$	$R^2 = 0.0133$
	$y = 0.0119X_2 + 0.1607$	$y = 0.0005X_2 - 0.2086$	$y = 0.0177X_2 + 0.1279$	$y = 0.0028X_2 - 0.3216$
X_3	$R^2 = 0.0011$	$R^2 = 0.0770$	$R^2 = 0.0091$	$R^2 = 0.0106$
	$y = 0.0032X_3 + 0.2884$	$y = -0.0067X_3 + 0.3847$	$y = 0.0104X_3 + 0.1765$	$y = -0.0038X_3 - 0.4643$
X_4	$R^2 = 0.1820$	$R^2 = 0.0749$	$R^2 = 0.1400$	$R^2 = 0.0787$
	$y = 0.0180X_4 - 0.1221$	$y = -0.0050X_4 - 0.3540$	$y = 0.0097X_4 + 0.1402$	$y = 0.0056X_4 - 0.2004$
X_5	$R^2 = 0.2510$	$R^2 = 0.1508$	$R^2 = 0.1126$	$R^2 = 0.0492$
	$y = 0.0348X_5 + 0.2346$	$y = -0.0089X_5 + 0.3043$	$y = 0.0118X_5 + 0.3668$	$y = 0.0053X_5 + 0.3012$

Solar irradiance had the greatest influence on the efficiency of both collector systems (Fig. 3). In comparison with the evacuated tube collector, flat-plate solar collectors were more than twice as susceptible to the difference between ambient temperature and the temperature at the collector outlet. This is the second key predictor of the efficiency of flat-plate collectors, whereas the efficiency of the evacuated tube collector was more significantly influenced by the temperature at the collector outlet. The next predictor was the temperature of ambient air which exerted nearly a twice greater influence on the evacuated tube collector than on flat-plate collectors. System efficiency increased with a rise in ambient temperature. The temperature inside the buffer was the least influential variable. However, the unstandardized regression coefficient was more than three-fold higher in the evacuated tube collector, which indicates that collector efficiency increased at a faster rate with a rise in buffer tank temperature (Fig. 4).

Significant variations were also observed in the rate of changes in collector efficiency resulting from differences between ambient temperature and the temperature at the collector outlet. The above temperature differential led to a nearly

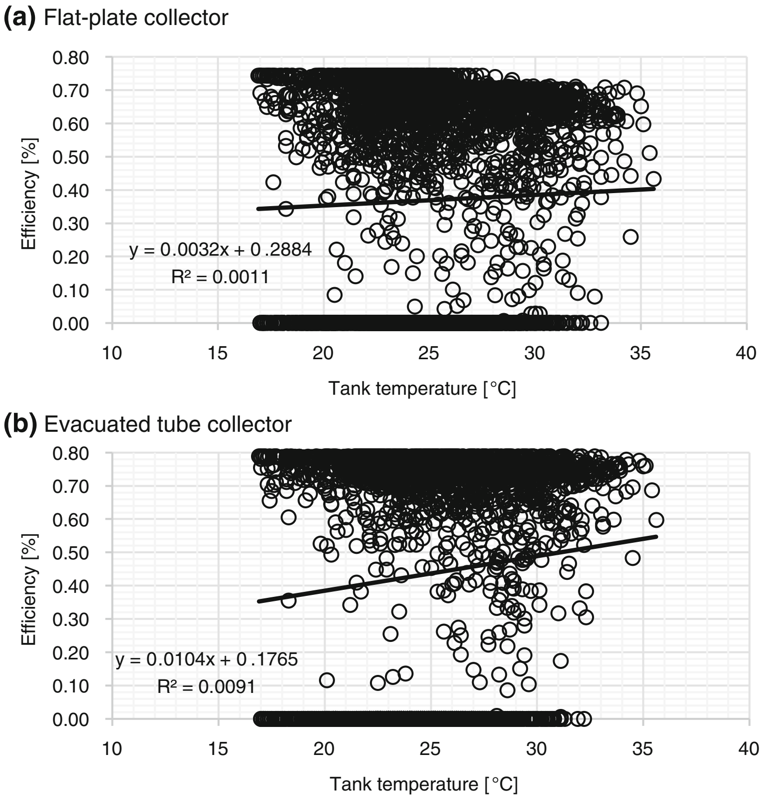

Fig. 4 Correlations between the efficiency of flat-plate collectors

2.5-fold higher increase in the efficiency of the evacuated tube collector than flat-plate collectors.

An efficiency analysis based on formula (2) supported the determination of the statistical distribution of parameters influencing the efficiency of solar collectors (Table 3). It should be noted that formula (2) produced significantly lower efficiency values than formula (1). Average hourly efficiency (calculated based on hours with positive energy gain) reached 22% in flat-plate collectors and 37% in the evacuated tube collector, whereas the median was determined at 14% in flat-plate collectors and 33% in the evacuated tube collector. Due to the inertia of the analyzed collectors and delayed responses of hydraulic actuator devices to changes in external conditions during steady flow of the working fluid, the relevant calculations were performed for daily values.

The average daily efficiency of flat-plate collectors was most significantly influenced by the difference between ambient temperature and the temperature at the collector outlet. Daily efficiency increased with a drop in the above temperature differential. In the evacuated tube collector, the temperature differential was 1.8-fold less significant and was characterized by a reverse correlation—daily efficiency increased with a rise in the temperature differential. The daily efficiency of the evacuated tube collector was most significantly influenced by the temperature at the collector outlet, and an increase in this parameter led to a rise in collector efficiency. Solar irradiance has a similar impact on the efficiency of the evacuated tube collector (R^2 of approx. 0.08), whereas the efficiency of flat-plate collectors was also influenced by buffer tank temperature and the temperature of the working fluid at the collector outlet. The influence of buffer tank temperature on the efficiency of the evacuated tube collector was approximately 7-fold lower. The strength of the association between daily efficiency of the evacuated tube collector and ambient temperature was similar. The influence of ambient temperature on the efficiency of flat-plate collectors was even 10-fold lower.

4 Conclusions

1. The measured average hourly temperatures of ambient air were 2.8 °C higher than TMY data, and the number of hours with irradiance higher than 800 Wh/m^2 was 300 higher in the measured dataset than in the TMY database.
2. Between May and September 2016, the specific heat capacity of flat-plate collectors was determined at 87 kWh/m^2 when average hourly efficiency reached 22% in the performed calculations (formula 2) and 63% in the Solar Keymark test (formula 1). The energy gain of the evacuated tube collector was 178.6 kWh/m^2 (according Table 2) higher when average hourly efficiency reached 37% in the performed calculations (formula 2) and 72% in the Solar Keymark test (formula 1). The observed variations in efficiency could be attributed to differences between the standard testing conditions in the Solar Keymark test and the parameters measured in a real-life environment.

3. The results of linear regression analysis revealed that solar irradiance is the key determinant of efficiency in both collector systems. The difference between the temperature of the working fluid inside the collector and ambient temperature had a negative effect on the efficiency of both types of collectors, where the drop in efficiency associated with an increase in the above temperature differential was more than twice higher in flat-plate collectors than in the evacuated tube collector. As buffer temperature increased, the resulting drop in efficiency was three-times higher in flat-plate collectors than in the evacuated tube collector.

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