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The influence of excessive solar heat gains on heat loss in the hot water tank – case study

Abstract: The analysis of a solar installation operation was conducted on the example of a detached house in the Lesser Poland province in Poland. A gas boiler and three flat-plate collectors are located inside the house, which are used for heating water in the hot water tank with a volume of 220 dm^3. The installation was established in 2012. The heat measured system (for solar gains) was added in 2014. In 2015–2019 solar heat gains measured per area of absorber were higher than 340 kWh/m^2. During a two-week period in June 2015, the insolation on the horizontal plane and the temperature were measured in 4 different points of the hot water tank. On this basis, heat losses from the storage tank were determined, i.e. a decrease in temperature during periods with and without the consumption of hot water by the residents. During this period, a temperature higher than 80°C was observed several times in the hot water tank. In two parts of the hot water tank, rhe determined temperature decreases were used to obtain the heat loss amount. In the analyzed period (2 weeks), 9 days were observed with solar heat gains higher than 9 kWh/day. For these days, the value of heat loss from the solar hot water tank was estimated at over 6 kWh/day. This data corresponds to the actual heat demand for hot water preparation in the building at 7.3 kWh/day. The correlation between daily solar heat gains and solar hot water tank heat losses were also determined. In addition, based on the amount of heat losses, the value of the

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tank loss coefficient was estimated. The obtained value was compared with the manufacturer's data and reference data.

Keywords: renewable energy, solar energy, flat plate collector, hot water tank, tank loss coefficient

Introduction

At present, the increase in renewable energy production can be observed in Poland (Piwowar and Dzikuć 2019). This fact, along with the growth of social awareness of using environmental friendly technologies (Hansen et al. 2019; Smol et al. 2018) improves i.e. air quality (Jeleński et al. 2020; Kryzia and Pepłowska 2019). In Poland, not only does the typical use of renewable energy equipment such as wind energy turbines (Chmielniak 2019; Sornek et al. 2017), photovoltaic (Żołądek et al. 2019), photovoltaic/thermal (Calise et al. 2019; Olczak et al. 2020b), solar thermal collectors (Chwieduk 2010), biomass boilers (Drobnik et al. 2019) contribute to improving the environment, but gas cogeneration (Matuszewska et al. 2017; Szurlej et al. 2014) and clean coal technologies also contribute (Kryzia et al. 2016).

The article is limited to the use of solar energy, namely flat solar collectors, in which the correct selection of the absorber area is important to maximize the effect of the solar installation (Olczak et al. 2020a; Olek et al. 2016). In the case in which the size of the installation is small, its productivity can be increased by, for example, using mirrors (Baccoli et al. 2018) of the rack (Olczak et al. 2016) setting the angle of inclination at different times of the year (Olczak et al. 2018), trackers and others (Figaj et al. 2019). In turn, excess solar energy can be accumulated in a Phase Change Material tank (Kuta et al. 2016), concrete accumulator (Sacharczuk and Taler 2019), Thermo-Electric Energy Storage (Fiaschi et al. 2019) or used in installations with Organic Rankine Cycle (Freeman et al. 2015; Matuszewska et al. 2014). The article examined the real case of solar thermal installation for a detached house in Lesser Poland (Fig. 1) in order to show the impact of excessive daily heat energy productivity by flat plate collectors in relation to daily energy consumed and the amount of heat losses from the hot water tank. This happens when the water in the tank heats up to a temperature higher than required for hot water (in Poland it is 55°C (Ministry of Development 2015)).

1. Description of the installation in the detached house (domestic hot water)

The solar thermal system consists of 3 Biawar Sirius Plus f at collectors (placed on the roof of the building, absorber area = 5.61 m^2), solar hot water tank with a capacity (V_{hwt}) of 210 dm^3 (Fig. 1), pumping system, insulated piping and solar controller. The pipeline between the collectors and the lower coil of the solar storage tank is surrounded by a protective tube which runs through unused f ue and joins the attic of the building with the storage tank room. The upper coil of the storage tank is heated by a domestic gas f red boiler. The cold water comes either from the hydrophore (the primary source) or from the water supply (the backup source).

For this house, the value of heat demand for producing hot water is 7.3 kWh/day (Olczak et al. 2015). The measured solar heat gains are depicted in Figure 2 (daily results) and Figure 3 (yearly results).

Fig. 1. The detached house and the solar storage tank inside
Source: own study

Rys. 1. Budynek i zasobnik solarny

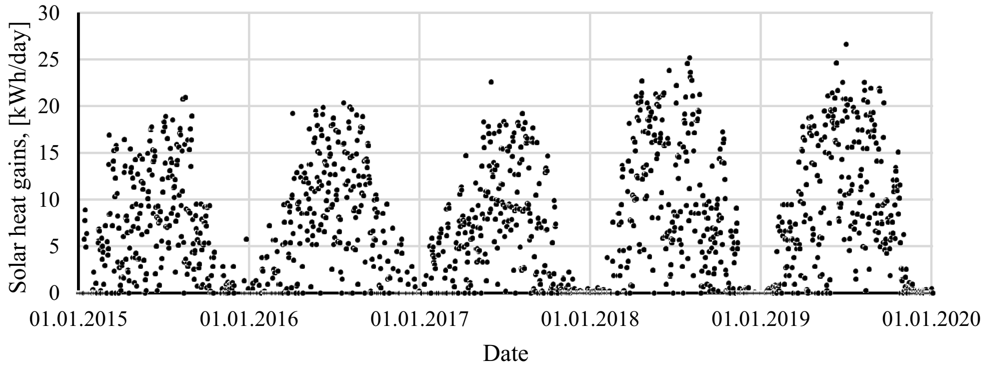

Fig. 2. Measured daily solar heat gains in installation
Source: own study

Rys. 2. Zmierzone dzienne uzyski solarne w instalacji

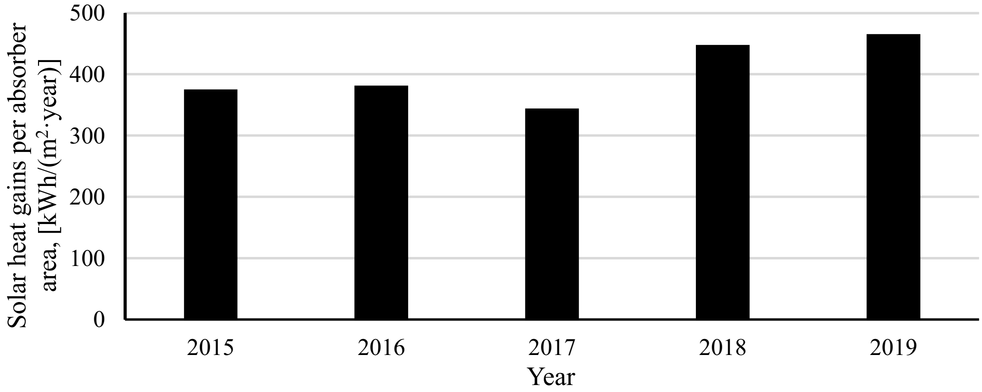

Fig. 3. Measured yearly solar heat gains in installation per absorber area
Source: own study

Rys. 3. Zmierzone roczne uzyski solarne w instalacji przeliczone na powierzchnię absorbera

2. Measurement system

The study was conducted in the period of June 2015 with the use of the following devices:

- BIAWAR solar controller (type PLUM) with the heat meter (one of the basic solar system components),
- thermistors joined with the PLUM solar controller,

- thermocouples (meter type PROVA 800), serving the designation of the temperature at diferent points of the installation (Fig. 4). Basic accuracy 0.1% ± 1°C (PROVA 2020),
- EPLAB pyranometer (Eplab), accuracy class (2%) (EPLAB 2015).

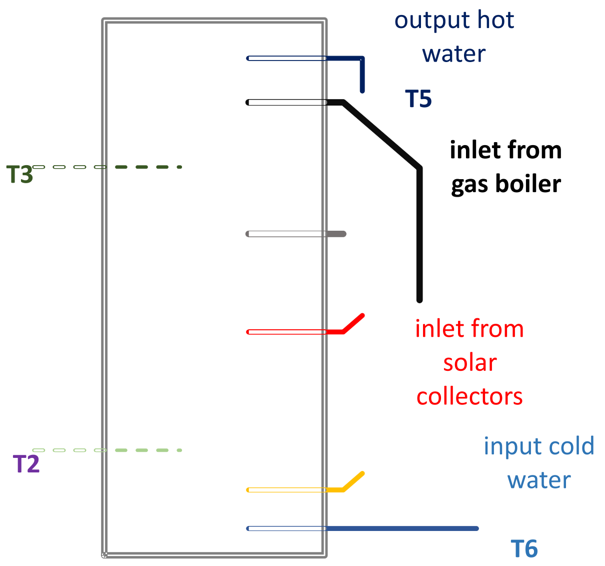

Fig. 4. Placement of the sensors (thermocouples T2, T3, T5, T6) in the hot water tank
Source: own study

Rys. 4. Umiejscowienie czujników temperatury (T2, T3, T4, T5, T6) w zasobniku ciepłej wody użytkowej

3. Methodology and results

During the test, the temperature was measured at 5 interesting points (selected out of 8) recorded by PROVA 800 and presented in Figure 5. Due to the T5 sensor installation place (point – Fig. 4) and the condition that was always fulflled in the analyzed period of 16 days (T5> ambient temperature), when hot water was taken from the hot water tank, this occurred due to a temperature increase (T5). When the next condition is fulflled (T3>T5) the lack of water intake results in a temperature decrease observed at T5.

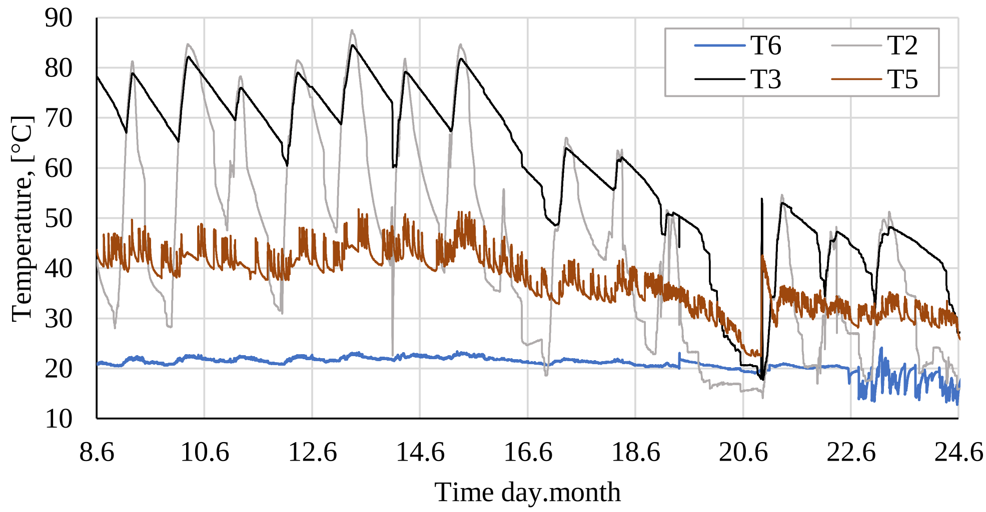

Fig. 5. The temperature measurements from June 8–24, 2015
Source: own study

Rys. 5. Pomiary temperatury w okresie 8.06.2015–24.06.2015

For further analysis, a number of time periods were chosen. The chosen periods included only those during which hot water wasn't used for at least one hour, which took place usually at night. To visualize the outcome of these actions the chosen time periods were presented in Figure 6 as a function of the onset temperature and the duration time of each chosen time period.

Diﬀerent slopes of the curves are connected with various external conditions in the boiler room and the temperature stratiﬁcation in the hot water tank.

In the next stage, the observed temperature decreases were grouped to obtain the values of the temperature drop per minute. Finally, the linear regression function for the obtained results was calculated. The results for the upper and lower part of the hot water tank were shown separately in Figure 7.

The regression functions (red and red dashed line – Fig. 7) were allowed to determine the equation for the temperature decrease function depending on the temperature in two parts of the hot water tank: the upper part (*up*) of the hot water tank – eq. 1. (R^2 = 0.91) and the lower part (*lp*) of the hot water tank – eq. 2 (R^2 = 0.62).

$$\Delta T3up(T3) = 0.000185 \cdot T3 - 0.003 \text{ [K/min]} \quad (1)$$

$$\Delta T2lp(T2) = 0.000544 \cdot T2 - 0.004 \text{ [K/min]} \quad (2)$$

The hot water tank heat capacity and the temperatures decreases deﬁned by equations number 1 and 2 were allowed to assess heat losses in the hot water tank per minute – eq. 3 and eq. 4.

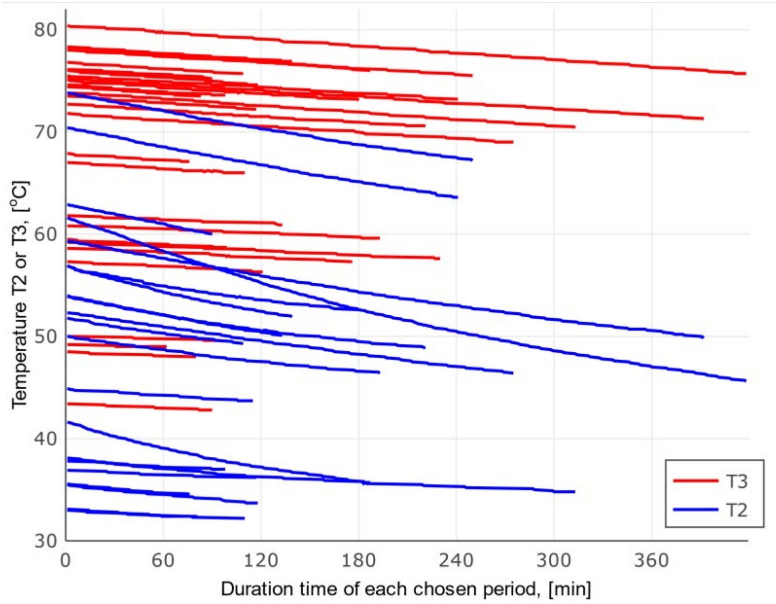

Fig. 6. The observed temperature decreases of T3 and T2
Source: own study

Rys. 6. Zaobserwowane spadki temperatury mierzonej w punkcie T3 i T2

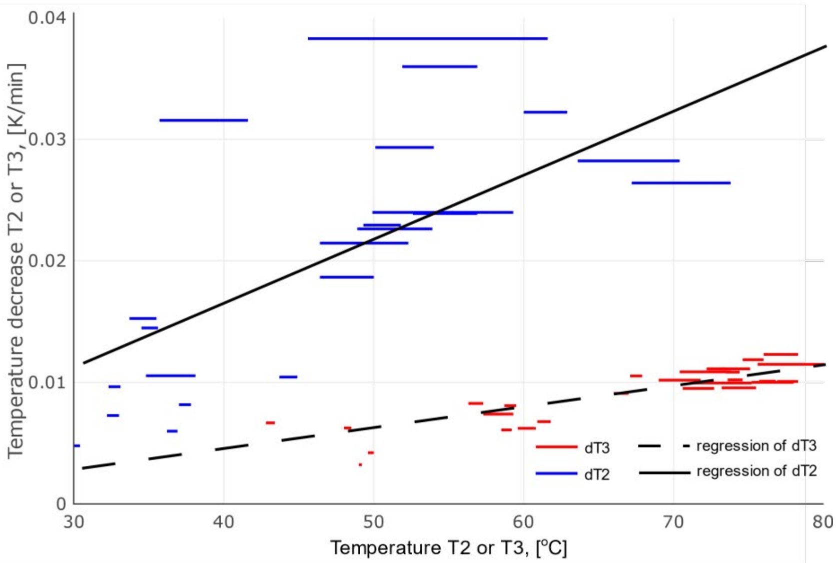

Fig. 7. Temperature decreases (dT2 and dT3) per minute presented as a present temperature function
Source: own study

Rys. 7. Zarejestrowane spadki temperatury (dT2 i dT3) w ciągu minuty jako funkcja aktualnej temperatury

$$HL(T3)up = \Delta T3up \cdot 1/2 \cdot V_{hwt} \cdot \rho_{water(T3)} \cdot c_{water} \quad \text{[kJ/min]} \tag{3}$$

$$HL(T2)lp = \Delta T2lp \cdot 1/2 \cdot V_{hwt} \cdot \rho_{water(T2)} \cdot c_{water} \quad \text{[kJ/min]} \tag{4}$$

where:

V_{hwt} = 0,21 m^3.

Density (Fan and Furbo 2012):

$$\rho_{water}(T\ldots) = 863 + 1.21 \cdot (T\ldots) - 0.00257 \cdot (T\ldots)^2 \quad \text{[kg/m}^3\text{]} \tag{5}$$

$$T\ldots = T2 \text{ or } T3 + 273.15 \text{ [K]} \tag{6}$$

c_{water} = 4180 J/(kg·K) constant speci f c heat of water (Fan and Furbo 2012).

In consequence, it is possible to calculate the sum of heat losses for one day depending on $T3$ and $T2$ temperatures per each minute of the day:

$$HL(T2, T3, \tau) = \frac{1}{3600}\sum_{\tau=1}^{1440}\left(HL(T3)up + HL(T2)lp\right) \quad \text{[kWh/day]} \tag{7}$$

Numerical values calculated on the basis of eq. 7 and density solar radiation, insolation for collector area and solar energy heat gains are shown in Figure 8.

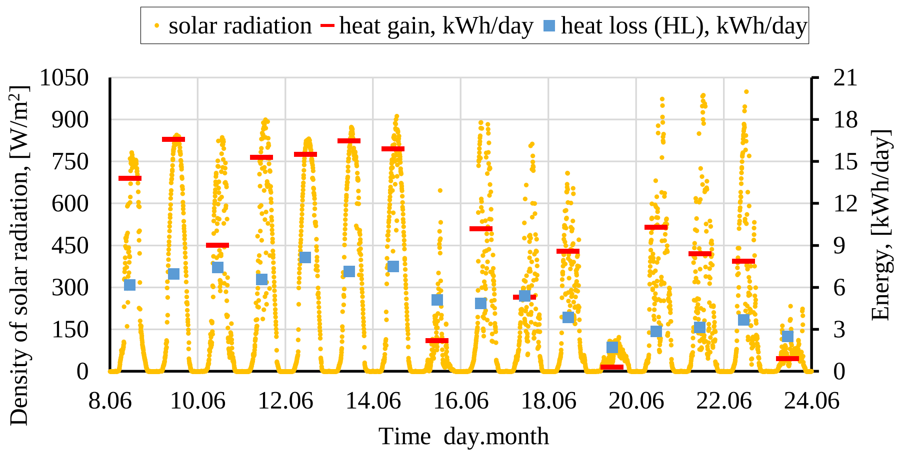

Fig. 8. Comparison between solar radiation density, measured solar heat gains (energy) and assessed heat losses from the hot water tank (energy)
Source: own study

Rys. 8. Porównanie pomiędzy: natężeniem promieniowania słonecznego, zmierzonymi solarnymi uzyskami ciepła oraz stratami ciepła z zasobnika

The correlation between the daily amount of heat losses and daily sum of solar heat gains was analyzed was calculated, and it is 0.76. The obtained value of the correlation coefficient was diminished by the occurrence of the time shift between heat gains and losses.

As a result of the analysis, it was possible to find the correlation between the amount of heat losses and the hot water tank temperature, which is determined by the type of the hot water tank and its location. Moreover how the solar heat gains influence the heat losses was also assessed.

Additionally, the tank loss coefficient (TLC) was calculated for temperature *T*2 and *T*3 55°C and the temperature of the boiler room (where the hot water tank is located) 20°C using Eq. 8. The results are shown in Table 1. In this real case, the TLC value was more than three times higher than the value taken from the producer's data and from the reference data. This was mostly dependent on the uncertainty of heat loss assumption from the lower part of the hot water tank.

$$TLC\left(T2,T3\right)=\left(HL\left(T3\right)up+HL\left(T2\right)lp\right)/\,TD\cdot 60\frac{min}{h}/\,HWTS\ \ [\mathrm{kJ/(h{\cdot}m^2{\cdot}K)}] \tag{8}$$

where:

HWTS – hot water tank surface, HWTS = 3.5 m^2 (Biawar 2019),

TD – difference between hot water tank and boiler room temperature (35 K).

Table 1. Hot water tank – results and references

Tabela 1. Zasobnik ciepłej wody – charakterystyka i wyniki

Thermal storage – results	Unit	Value
Tank volume (V_{hwt})	m^3	0.21
TLC (*T*2 = 55, *T*3 = 55)	kJ/(h·m^2·K)	7.7
Tank Loss Coefficient (for 0.3 m^3), Reference 3	kJ/(h·m^2·K)	2.5
Tank Loss Coefficient (for 0.45 m^3), Reference 4	kJ/(h·m^2·K)	1.6
Heat Loss per day	kWh/day	6.2
Heat Loss	W	260
Heat Loss, Reference 2	W	81
Heat Loss (producer data – Reference 1)	W	86

Source: own study based on (Biawar 2019; En 2007; Mehdaoui et al. 2014; Sokhansefat et al. 2018).

Summary

The heat losses from solar hot water installed in a single-family house depending on solar heat gains were analyzed. As a result of the analysis, it was possible to find the correlation (0.76) between heat losses and the present hot water tank temperature, which is determined by the type