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The ecological impact of using photothermal and photovoltaic installations for DHW preparation

Abstract: A domestic hot water (DHW) system has been modernized in a multi-family house, located in the southeastern part of Poland, inhabited by 105 people. The existing heating system (2 gas boilers) was extended by a solar system consisting of 32 evacuated tube collectors with a heat pipe (the absorber area: 38.72 m^2). On the basis of the system performance data, the ecological effect of the modernization, expressed in avoided CO_2 emission, was estimated. The use of the solar thermal system allows CO_2 emissions to be reduced up to 4.4 Mg annually. When analyzing the environmental effects of the application of the solar system, the production cycle of the most material-consuming components, namely: DHW storage tank and solar collectors, was taken into account. To further reduce CO_2 emission, a photovoltaic installation (PV), supplying electric power to the pump-control system of the solar thermal system has been proposed.

In the Matlab computing environment, based on the solar installation measurement data and the data of the total radiation intensity measurement, the area of photovoltaic panels and battery capacity has been optimized. It has been shown that the photovoltaic panel of approx. 1.8 m^2 and 12 V

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battery capacity of approx. 21 Ah gives the greatest ecological effects in the form of the lowest CO_2 emission. If a photovoltaic system was added it could reduce emissions by up to an additional 160 kg per year. The above calculations take also emissions resulting from the production of PV panels and batteries into account.

Keywords: photovoltaic panel, reduction of CO_2 emission, evacuated tube collector with heat pipe

Introduction

In Poland the microgeneration is the alternative for decreasing greenhouse gases emission from the housing sector (IEO and ZP FEO 2013). This applies, among others, two forms of solar energy: photothermal and photovoltaic conversion (Carotenuto 2017). Under low solar irradiation prevailing in Poland, thermal installations are mainly used for heating domestic hot water (DHW). This allows the use of fossil fuels to prepare DHW to be reduced and thus allows the emission of gaseous and particulate matter pollutants into the atmosphere to be reduced, particularly during the summer period (Mirowski 2016). In Polish conditions, the majority of solar installations are equipped with solar controllers and additional pumps, the aim of which is to help with the heat transport. Both devices are electrically powered. In Poland, 76.8% of electricity is generated in coal power plants (Statistics Poland 2019). Currently, the average CO_2 emission factor (Ec) of the Polish energy sector is 0.765 kg/kWh while the average emission factor foreseen (Ef) for the years 2019–2035 is 0.74 kg/kWh (Gawlik 2013; The National Center 2019). Upgrading the thermal system with the addition of PV panels generating energy that supplies the pump-control system allows the consumption of electricity produced from fossil fuels (mainly coal) to be reduced.

The aim of the study was to estimate the annual ecological impact on existing hybrid system supplied by 2 gas boilers and 32 solar collectors. On the basis of data on the amount of fuel saved and materials used for the production of the main components of the solar system, a comparative analysis of CO_2 emission has been performed. To further reduce CO_2 emissions, a photovoltaic installation (PV) with annual average efficiency 15% (Sornek 2018), supplying electric power to the pump-control system of the solar thermal system, has been proposed. Based on the measurements of operating parameters of the system in a multi-family house and the intensity of solar radiation (Fig. 1), the power of a PV panel and battery capacity, providing the lowest CO_2 emissions, has been determined.

Fig. 1. Installation – left side, pyranometer mounted between pipes – right side
Source: own study

Rys. 1. Instalacja – lewa strona, pyranometr montowany między rurami kolektorów – prawa strona

1. Methodology

The analysis was performed for an existing hybrid system used for central heating and domestic hot water preparation (Fig. 2). The daily demand for hot water is 4.5 m^3 with the temperature in the range from 3 to 17°C at the inlet and 55°C at the outlet of the installation. The heat source are 2 gas boilers (130 kW, Viessmann Paromat Triplex Boiler) with a nominal efficiency of 94% and a set of 32 evacuated tube collectors with heat pipe (ETCHP), (Energosol HP-15R) (ENERGOSOL 2017). The total area of absorbers is 38.72 m^2. The installation for heating DHW is equipped with two storage tanks with a total capacity of 1,000 dm^3 (GT1 and GT2) and two solar storage tanks with a total capacity of 3,000 dm^3 (ST1 and ST2). Both ST are made of steel and insulating material made of hard polyurethane foam with a thickness of 70 mm.

The heating system is shown in Figure 2 and the operating principle is described by (Olczak and Zabagło 2015). The heat transfer medium circulating between the ETCHP and the storage tanks is a water/glycol mixture. The power of installed solar pumping system is 75 W. The solar system is fitted with five temperature sensors. The operation of the system is controlled by a Steca TR 0603mc solar thermal controller with a maximum power of 2 W, which collects temperature data and operation time of the pump at 1-minute intervals. The monthly total solar yield is measured by a CF Echo II heat meter, while the solar radiation available on the collector surface is measured using an Eppley Pyranometer.

The avoided CO_2 emission resulting from the extension of the central heating and DHW preparation system with the addition of the thermal solar system was estimated from the general formula (1):

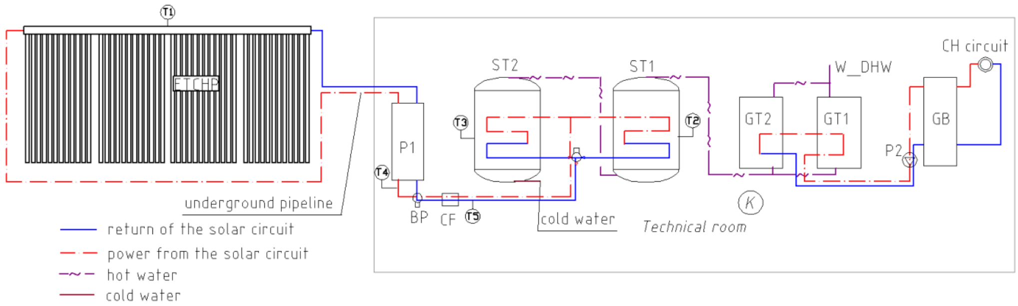

Fig. 2. Installation scheme: GT1 and GT2 – storage tanks supplied by gas boilers; GB – gas boiler; W_DHW – DHW outlet to the building; CH – the central heating circuit, P1 – solar circulation pump; P2 – boiler circulation pump; ST1 and ST2 – solar storage tanks, ETCHP – 15 tube evacuated tube collectors; BP – by-pass; CF – heat meter; T1...5 – temperature sensors; CW – cold water inlet
Source: own study

Rys. 2. Schemat instalacji: GT1 i GT2 – zasobniki ciepłej wody użytkowej zasilane z kotłów gazowych; GB – kocioł gazowy; W_DHW – zasilanie budynku w ciepła wodę użytkową; CO – obieg CO, P1 – solarna pompa obiegowa; P2 – pompa obiegowa kotła; ST1 i ST2 – zasobnik ciepłej wody użytkowej zasilany z instalacji kolektorów słonecznych, ETCHP – 15 rurowych kolektorów próżniowych; BP – by-pass; CF – licznik ciepła; T1...5 – czujniki temperatury; CW – ujęcie zimnej wody

$$\textit{reduction of } CO_2 \textit{ emission} = f\,(\textit{the demand for heat for DHW, saved natural gas, emission during the production of the system components expressed as equivalent of } CO_2) \quad (1)$$

In the analysis used data of pump run time (PRT), time ST1 or ST2 recharge (RT), solar heat gains from 2013 (SY13), which resembles the average solar heat gains during the system operation in the period of X.2011 – IX.2015 (SY11_15) (Table 1). As a result of the expansion of the heating system by renewable energy sources (Table 1) for the preparation of DHW, reduction in natural gas consumption from 11,800 m^3 to 9,280 m^3, has been stated. Assuming the CO_2 emission factor for the combustion of gas at a level of 2 kg/m^3 (The National Center 2015) the avoided CO_2 emission was determined. This value is diminished by the amount of CO_2 emission resulting from the operation of the pump-control system powered by electric power. The above-mentioned emission was estimated on the basis of the pump power, the control system power, and the operation time (Table 1), the efficiency of energy conversion in power plant (38%), the losses in electricity transmission (7.3%) (BBN 2012), energy losses of the power plant (10%) and factor Ec (0.765 kg/kWh).

The measured annual solar yield amounted to 92.84 GJ. Since the heat meter is suitable for temperature measurements of water, and the solar system is filled with water/glycol mixture, solar yields were adjusted according to the average monthly temperature (Table 1). The adjusted solar yield amounted to 82.94 GJ.

Other factors reducing the positive ecological effect are materials used for the construction of the installation and the energy required for their production. The analysis took the three heaviest

TABLE 1. The measurement results obtained in 2013 and average values from 10/ 2011 to 9/2015

TABELA 1. Wyniki pomiarów uzyskane w 2013 roku oraz średnie wartości dla okresu od X 2011 do IX 2015

Month	1	2	3	4	5	6	7	8	9	10	11	12
PRT [h]	69.5	91.8	190.2	263.4	296.1	306.8	316.8	276.1	224.4	205.1	98.3	103.9
RT [h]	62.4	84.2	182.9	260.4	295.2	305.7	314.6	274.5	223.1	204	96.1	98
T2 or T3 [°C]*	10.3	13	18.4	30.3	33.5	35.1	42.4	41.6	30	23.7	16.8	11.1
SY13 [GJ]	1.29	2.03	6.68	11.78	12.33	11.65	15.03	13.09	7.97	6.87	1.99	2.13
SY11_15 [GJ]	1.73	3.62	8.87	11.03	12.54	12.74	14.17	12.97	8.88	6.54	2.79	1.6

* The average temperature of the currently supplied ST1 or ST2 storage tank.
Source: own study.

components of the thermal installation into account, namely: collectors (ETCHP), solar storage tanks (ST), and copper pipes (Table 2).

TABLE 2. The demand for materials and CO_2 emission factors

TABELA 2. Zapotrzebowanie na materiały i wskaźniki emisji CO_2

Material	ETCHP	ST	pipe	CO_2 emission factor [$kg_{CO_2}/kg_{material}$]
Copper [kg]	418.176		164.6	2.711
Steel [kg]	929.28	990.4		1.487
Glass [kg]	542.08			1.35
Elastomer [kg]	154.88			2.85
Insulation [kg]	77.44	75.8		1.86
Electrical energy [MJ]	2361.92	475.2		0.226
Natural gas [MJ]	638.88	583		0.063

Source: own work based on (Hill et al. 2012; Greening and Azapagic 2014).

The calculations excluded some of pollutant emissions resulting from e.g. transport, extraction of raw materials, or disposal of the installation after the end of the life cycle. It was considered that these emissions are relatively small, and thus have a negligible impact on the achieved ecological effect.

To minimize the negative ecological impact of supplying the pump-control system with electricity, the use of PV system has been suggested. An analysis of the measurement data on the operation time of the pump of the solar system has shown that the pump operated during periods of no solar radiation. In addition, solar controller requires continuous power supply. It was assumed that the target power supply system is not autonomous but connected to the backup power supply from the power grid. The autonomous system was not analyzed, due to it is usually oversized, and the overriding objective of this study is to minimize CO_2 emissions.

The avoided CO_2 emissions resulting from the expansion of the thermal system with the addition of the PV system was estimated from the general formula (2):

$$\textit{reduction of } CO_2 \textit{ emission} = f\,(\textit{electricity produced in the PV system, emission during the production of the system components expressed as equivalent of } CO_2\textit{, fossil fuel consumption for the electricity production}) \tag{2}$$

During the simulation, the power supply system consists of PV panels arranged at an angle of 45°, an inverter, and batteries connected in a way that prevents the sale of energy to the grid. On the basis of the measurement data regarding the solar system operation and the measured solar radiation over spring and summer period, a calculation model, whose aim has to determine the relationship between CO_2 emission reduction, the size of PV panel and battery capacity, was developed using the Matlab computing environment.

The PV panel area and capacity of 12V battery were selected according to the following algorithm. The electric power that can be produced at each minute of the calculation period, given the currently assumed PV panel area, is determined on the basis of data on solar radiation, which is multiplied by panel efficiency and panel area. It was assumed that the efficiency of the PV panel and inverter is 14%, and the battery efficiency as well as the efficiency of charging sum up to 80% (Bortolini et al. 2015). The calculated electric power value is comparable to the energy required for supplying the pump-control system. When the amount of electric power that can be produced is lower than the demand for it, the difference is compared with the battery charge status, which is followed by charging (up to 100% capacity) or discharging (not below 50% of the battery capacity). If the demand for electric power exceeds the production of electricity from PV panels and when it leads to the battery discharge dropping below 50% of the maximum capacity, the system is supplied with energy from the power grid. The reduction in demand for electricity resulting from the use of PV system is determined as the difference between the energy demand and the energy supplied from the power grid. The calculated reduction is converted into the amount of the avoided CO_2 emission resulting from the electricity production (Ef = 0.74 $kgCO_2$/kWh). What is more, the calculated CO_2 emission reduction is diminished by CO_2 emission resulting from the production of PV panels and batteries. It was assumed that the rate of CO_2 emission per 1 m^2 of PV panel is 160 kg (Bortolini et al. 2015). With the assumed ratio of CO_2 emission related to the battery weight (p1 = 1.14 $kgCO_2/kg_{batteries}$) (Schneider Electric 2017), the relationship between the emission and the battery capacity has been determined on the basis of linear regression model (3). This model is based on the battery capacity and the corresponding battery weight (Soltec 2017):

$$Epa = p1 \cdot \left(p2 \cdot pa - p3\right) \tag{3}$$

where:

Epa – CO_2 emission produced during battery production [$kgCO_2$],
pa – 12 V battery capacity [Ah],

$p2$ – the slope of the regression line, 3.265 kg_{bat}/Ah,
$p3$ – the constant coefficient, 0.387 kg_{bat}.

It was assumed that the typical service life of the installation is 20 years. Carbon dioxide loads, resulting from the production of the system components, were referenced to a period of 20 years. It was assumed that during this period the batteries will be replaced three times.

2. Results

2.1. The environmental effectiveness of the use of solar installation

Annually the DHW heating used 82.94 GJ of solar energy thereby saving 2520 m^3 of natural gas – calculated for calorific value 37 MJ/m^3 (igaz 2019), and gas boiler efficiency ~ 90% (Matuszewska 2017). This means a reduction of CO_2 emission by 5040 kg/year. This value must be diminished by the amount of CO_2 associated with the demand for electricity of the solar system, amounting to 270.8 kWh/year. Taking into account the efficiency of the energy conversion in power plants, energy losses during the transmission, and the own demand of the power plant, it is required to produce 343.4 kWh of energy. The amount of emitted CO_2 in the process is 278.8 kg. When analyzing the environmental effects of the application of the solar system, the production cycle of the most material-consuming components, namely: solar collector, DHW storage tank, and solar collectors, was taken into account. Based on the data from Table 2, CO_2 emission for the collector area of 38.72 m^2 and the total capacity of storage tanks amounting to 3000 dm^3 are approximately 6611 kg of CO_2. Taking into account the fact that the solar system will operate for about 20 years, the CO_2 emissions can be estimated at a level of approximately 330.5 kg of CO_2 per year.

In order to evaluate the environmental effect of the use of the solar installation, all changes in CO_2 emission resulting from the use of natural gas (–5040.0 kg/year), electricity (278.8 kg/year), and solar installation (330.5 kg/year), giving a total value of –4430.7 kg of CO_2 per year, should be taken into account.

2.2. Optimization of panel size and battery capacity

Simulation variants, with different sizes of the area of the panel (ranging from 0 to 3 m^2) and 12 V battery capacities (from 0 to 100 Ah) were considered. The annual environmental effect, expressed in avoided CO_2 emissions as a function of the area of the panels and the battery capacity, is shown in Figure 3.

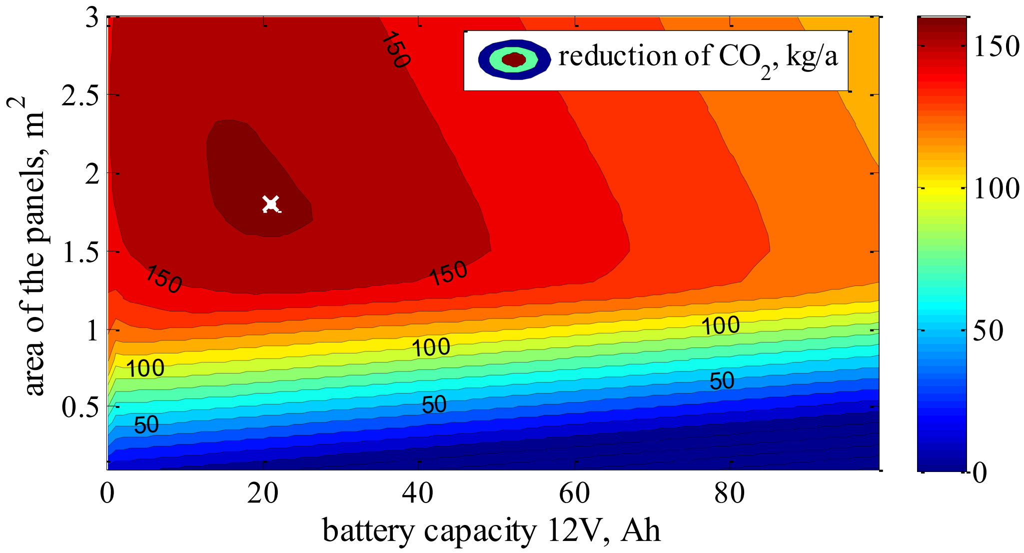

Fig. 3. Annually reduction of CO_2 emissions by PV systems as a function the battery capacity and the area of the panels
Source: own study

Rys. 3. Roczna redukcja emisji CO_2 przez systemy fotowoltaiczny w zależności od pojemności akumulatora i powierzchni paneli PV

For PV panels area in the range from 0 m^2 to approx. 1.2 m^2 the CO_2 reduction benefits will change linearly. For larger PV panel area, the real impact of the battery, not just the emission resulting from its production, can be observed. The obtained results indicate that in the case of the tested DHW system the best option in terms of CO_2 emission is a combination of PV panels with an area of 1.8 m^2 and the battery with a capacity of 21 Ah.

Conclusions

Solar installation operating in southeastern Poland, with an area of 38.72 m^2 of the absorber, and inclined at an angle of 45° towards the south, produces 23 MWh per annum. This energy is used to heat DHW. The annual reduction in CO_2 emission diminished by CO_2 generated during the production of solar collectors or solar storage tank is 4430 kg. The pump-control system of the solar system consumes 343.4 kWh of electricity per year. The addition of the PV installation with an area of 1.8 m^2 and the battery with a capacity of 21 Ah will increase the environmental effect by approximately 160 kg/year. The above calculations also take into account emissions resulting from the production of PV panels and batteries. Minor differences arise from the fact that 1 up to 2% of solar yields in the form of electricity is used for the operation of the thermal installation. The obtained values of the possible CO_2 emission reduction are determined by emission factors characteristic for the Polish energy sector.

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Ekologiczny wpływ zastosowania instalacji fototermicznej i fotowoltaicznej do przygotowania ciepłej wody użytkowej

Streszczenie

W budynku wielorodzinnym położonym w południowo-wschodniej części Polski, zamieszkałym przez 105 osób, zmodernizowano system przygotowania ciepłej wody użytkowej. Istniejący system grzewczy (2 kotły gazowe) został rozbudowany o układ kolektorów słonecznych składający się z 32 próżniowych kolektorów rurowych (powierzchnia absorbera wynosi 38,72 m^2). Na podstawie danych o wydajności systemu oszacowano ekologiczny efekt modernizacji, wyrażony jako uniknięta emisja CO_2. Zastosowanie systemu kolektorów słonecznych pozwala zmniejszyć emisję CO_2 do 4,4 Mg rocznie. Analizując skutki środowiskowe zastosowania instalacji kolektorów słonecznych, wzięto pod uwagę cykl produkcyjny najbardziej materiałochłonnych komponentów instalacji, a mianowicie zasobnika ciepłej wody użytkowej i kolektorów słonecznych. Aby jeszcze bardziej ograniczyć emisję CO_2, zaproponowano instalację fotowoltaiczną, dostarczającą energię elektryczną do napędu pompy obiegowej instalacji kolektorów słonecznych.

W środowisku obliczeniowym Matlab, na podstawie danych pomiarowych z instalacji kolektorów słonecznych i danych pomiarowych całkowitego natężenia promieniowania, zoptymalizowano powierzchnię paneli fotowoltaicznych i pojemność akumulatorów. Wykazano, że układ paneli fotowoltaicznych o powierzchni ok. 1,8 m^2 oraz akumulatorów 12 V o pojemności ok. 21 Ah zapewnia największy efekt ekologiczny w postaci najniższej emisji CO_2. Dodanie paneli fotowoltaicznych może zmniejszyć roczną emisję CO_2 nawet o dodatkowe 160 kg. Powyższe obliczenia uwzględniają również emisje wynikające z tytułu produkcji paneli fotowoltaicznych i akumulatorów.

Słowa kluczowe: panel fotowoltaiczny, redukcja emisji CO_2, próżniowe kolektory rurowe typu *heat pipe*