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EXPERIMENTAL INVESTIGATIONS OF LARGE-SCALE SOLAR COLLECTOR INSTALLATIONS IN AN INHABITED CLOISTER: A 6-YEAR CASE STUDY

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Abstract: In consideration of limited fossil fuel resources and the prevention of pollutant emissions heating installations are preferred which use renewable energy sources. One such solution involves hot water preparation for large buildings using solar collectors. In this work, the results of a six year experimental investigation of a large-scale system of solar flat collectors are introduced. These collectors are located on the roof of a Cloister of Redemptorists in Tuchow, Poland. On average, the installed collectors covered 37 % of the annual thermal requirement for hot water; for the winter half-year 15.9 % and for the summer half-year 56.5 %. The costs of the hot water preparation in the installation with and without collectors were analysed. The Simple Pay Back Time of investment cost was calculated. Special attention was paid to factors which influence the coverage of thermal needs by the solar installation. The reduction in pollutant emissions from combustion of natural gas resulting from the use of solar collectors, was also calculated.

Keywords: cloister, solar thermal systems, large-scale collector system, hot water preparation.

In the face of exhaustible conventional energy resources and the consequences of fossil fuel combustion more and more often renewable energy sources are being promoted. In fact, they are among the most suitable instruments to solve these problems [1]. One such solution is the installation of solar collector systems supporting heating or hot water preparation; the prices of such units has fallen gradually over the last 30 years, while the prices of oil and gas fluctuate incessantly [2]. Much research has already been carried out on both small and large-scale solar [3–5] installations [6,7]. However, new findings and analyses are constantly necessary, both in relation to solar radiation, analysed recently in [8, 9], methods of defining the solar energy potential for

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hot water production in a selected area [10]. Further, the education and training of specialists, able to design, install and service such systems is also crucial to the success of such ventures – a point also made in [11]. On this score alone it is important that future specialists understand the minutiae of existing installations obtained on the basis of experimental research [12]. Therefore, the aim of this work was to demonstrate the long term operation of a large-scale solar collector installation sited in a specific building. The building selected was the world famous Cloister of Redemptorists in Tuchow, Poland.

Material and methods

Research was carried out in the Cloister of Redemptorists in Tuchow, Poland, where a large-scale solar collector installation for hot water preparation has been implemented. The installation was completed in 2001. It was planned for the preparation of hot water of about 45 ^{o}C. The individual demand for hot water can reach 70 dm^3 per day and person. Flat solar collector panels (70 pieces; total surface area of 127 m^2) were applied in the installation. Collectors were installed on two roof surfaces, as two independent batteries. The first battery of collectors was oriented toward the South-East and inclined to the ground plane at an angle of 60^o. The second one is directed South and inclined to the ground plane at the angle of 45 ^{o}C (Fig. 1).

Fig. 1. South oriented solar collectors on a roof at the Cloister of Redemptorists, Tuchow, Poland

In this case collectors prepare the hot water bivalently, requiring support from a gas boiler (power: 90 kW). This boiler was put into action during periods of insufficient solar radiation. Hot water generated by the system (Fig. 2) was transferred to accumulation tanks (total capacity ca 8.000 dm^3).

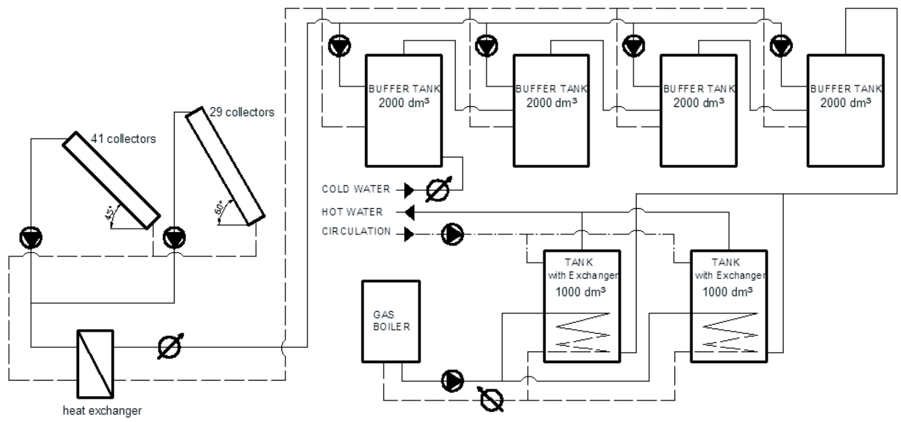

Fig. 2. Scheme of the solar installation at the Cloister of Redemptorists in Tuchow

Measurements were performed everyday at ca 21.45 from November 2001 to November 2007 and included, among other parameters, the following:

– the hot water consumption in m^3;

– the amount of energy (GJ) delivered to the hot water preparation system by the gas boiler.

– the amount of energy (GJ) delivered to the hot water preparation by the solar collectors;

– the amount of energy (GJ) lost during the circulation of hot water in the building.

In consideration of the vast amount of data collected, mean values were used in the further analysis.

Results and discussion

Solar energy in the total energy on hot water preparation

The solar panel installation used in bivalent model for hot water preparation reduces the total energy consumption, delivered from conventional sources. This can be expressed for the individual years of the measuring period by the ratio of the heat delivered from collectors to the total heat used for hot water preparation in % (Fig. 3).

On the basis of Figure 3, it is easily seen that, in the large-scale system using solar collectors for hot water preparation, the *contribution of solar collectors* (SPT) is in the range 24.2–47.8 %. For this reason, it is not easy to establish a mean annual level of the contribution of solar collectors over extended periods. Their dependence on ambient weather conditions, particularly the insolation, thwarts such calculations. In Fig. 3, the average daily hot water consumption in the analysed installation is also presented. Clearly no great influence on SPT on an annual scale is evident.

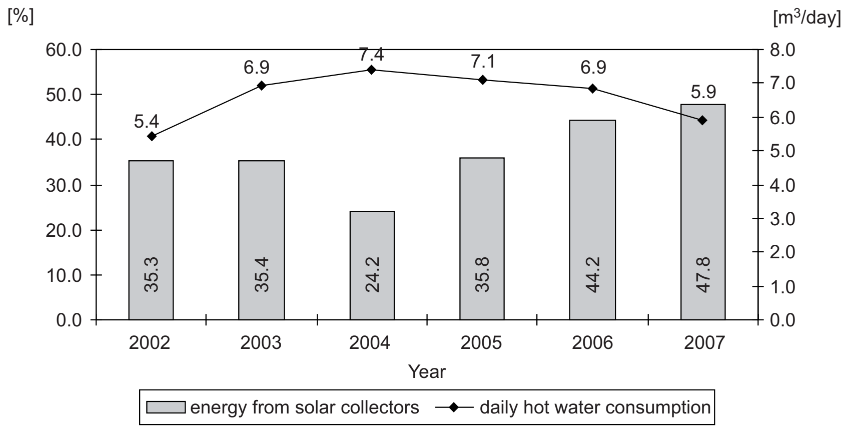

Fig. 3. The average annual level of coverage of thermal needs for hot water preparation by solar collectors for the measuring period (November 2001 to November 2007)

Another factor which did have an influence on SPT on an annual scale was the amount of energy required for the preparation of 1 m^3 of hot water, (see Fig. 4.).

Figure 4 shows that the amount of energy for hot water preparation declines – this has a considerable influence on the value of the SPT indicator.

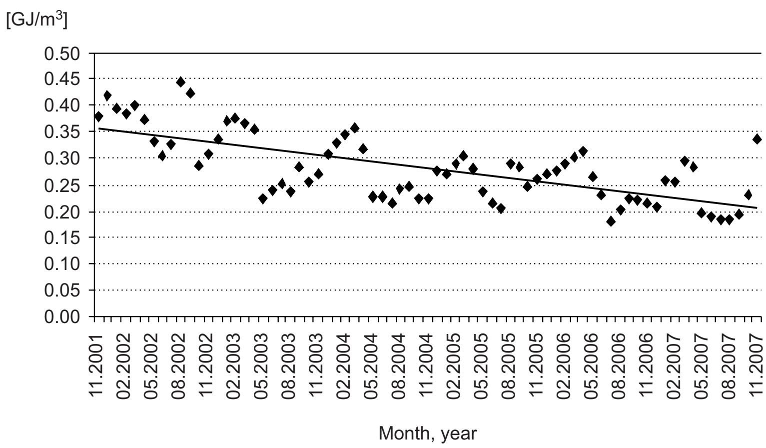

Fig. 4. The coefficient of the heat demand for the preparation of 1m^3 of hot water in the measuring period November 2001 – November 2007

This decrease in energy consumption resulted from renovation of the thermal isolation of the distribution and hot water circulation pipes. Besides, the required or given temperature on the outflow at the recipient has an influence on the energy required for preparation 1m^3 of hot water. The smaller the required temperature, the larger the SPT indicator.

To facilitate a more detailed analysis, Fig. 5 provides seasonal data on the system. The summer season is defined as the three months June, July and August. The

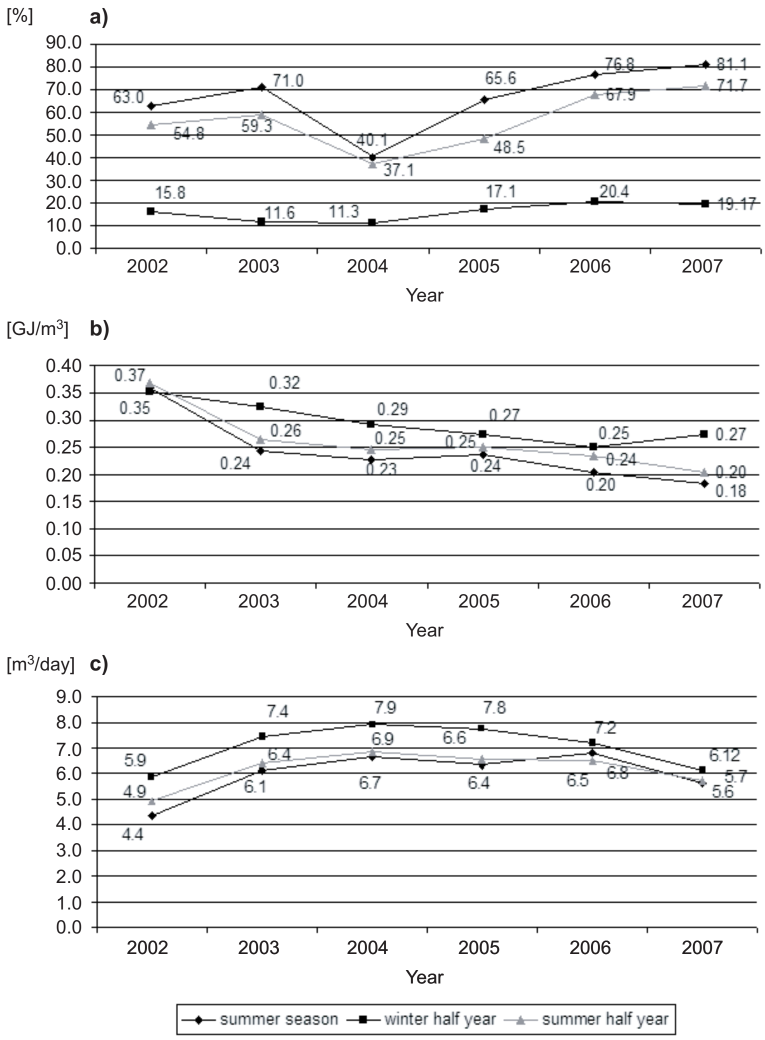

Fig. 5. Characteristics of the investigated installation in the summer and the winter and the summer half-years: a) SPT; b) the coefficient of the energy consumption for the preparation of 1 m^3 hot water; c) the average daily hot water requirement

winter-half-year is the period from October to January, and the summer-half-year lasts from April to September.

The SPT coefficient reaches 66.25 % in summer season and is > ca 9.7 % of the SPT for the summer half-year and ca. 50.34 % in comparison with the winter half-year. For the winter half-year, the SPT coefficient assumed the equal mean value of 15.91 %, which indicates that supporting hot water preparation by the solar collectors in the winter half-year, exists. It was also noted that the value of the coefficient of required heat quantity for hot water preparation was greatest in the winter-half-year amounting to

0.29 GJ/m^3. This is caused, among other things, by enlarged heat losses in the circulation of hot water and increased demand on useful hot water in the winter half-year (Fig. 5c).

It should also be noted that on occasions in which the large-scale installation is able to cover thermal needs of the hot water preparation to a greater degree (the summer season), this demand on hot water drops. This is very important at the design stage as it determines whether a hot water installation design will work at maximum efficiency or lower. This problem often appears in schools or higher colleges, which are closed in summer and in multi-family buildings, where a fall of the hot water consumption can be observed during holidays due to the absence of residents. In the analysed object, the above case was observed in August (Fig. 6), when the average daily hot water consumption fell to 4.2 m^3 per day, because in this period a large number of the occupants left the cloister.

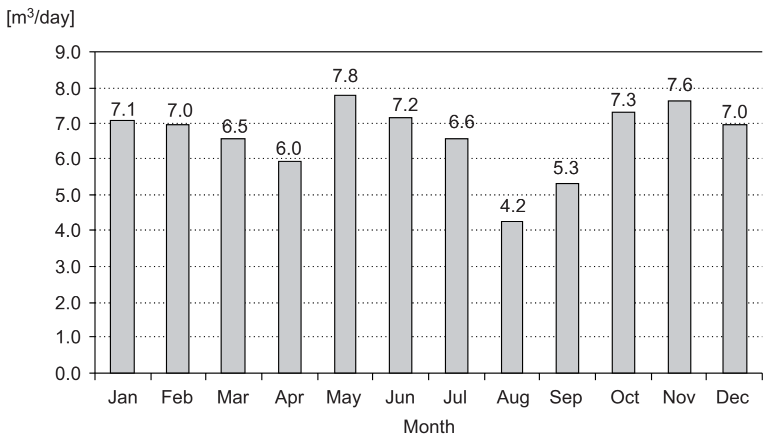

Fig. 6. Average daily hot water consumption during the months of the measuring period

The SPT for individual months of the measuring period together with the monthly average number of solar hours are shown in Fig. 7. August is characterized by the highest average SPT coefficient (75.5 %) in the analyzed period of six years and January, the least (6.9 %).

Such diversity in the values of the SPT is not only a result of weather conditions eg the number of solar hours per month, but also heat losses due to circulation of hot water as presented in Fig. 8. Situations like this occur because the greater heat loss and the greater is the required water temperature on the outflow from the storage tank. This results in a reduction of SPT, which is especially notable for the months of the winter-half-year.

It should be remembered that in using solar collectors to the hot water preparation, it is necessary to be aware that, although the average level of coverage for a given month may be high, days can occur in which thermal requirements can only be covered by the conventional source. For our installation this is shown in Fig. 9.

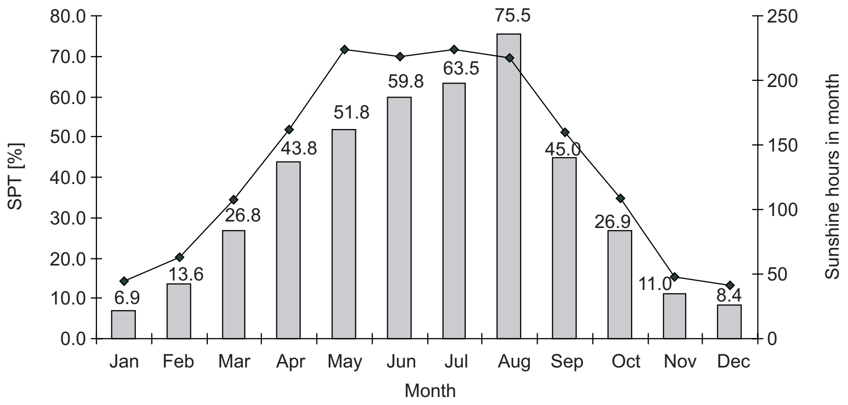

Fig. 7. The SPT coefficient during the months of the measuring period

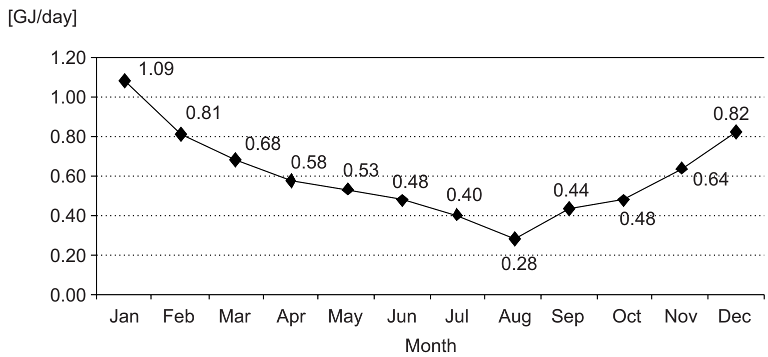

Fig. 8. Average daily heat losses in circulation during the measuring period

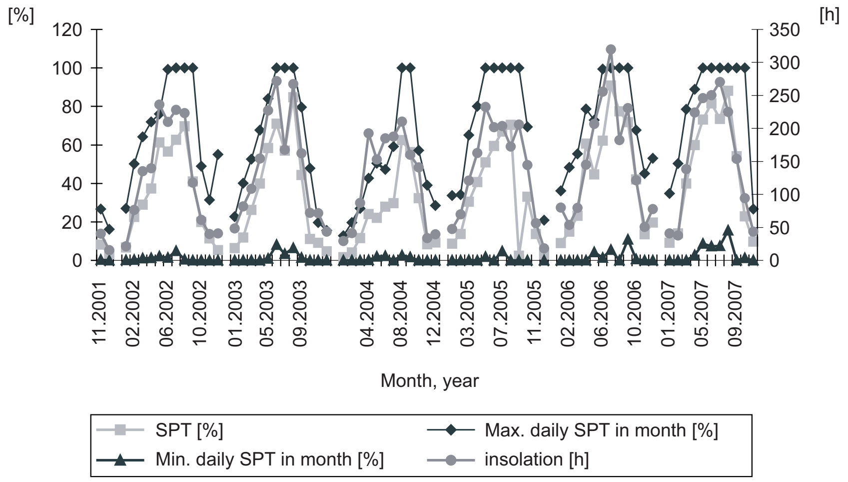

Fig. 9. The average, maximum and minimum daily SPT coefficient during a measuring period together with average monthly insolation

Therefore it is essential to examine the deviations of the average value of the SPT coefficient in Fig. 10. The deviation values of the mean value were calculated by Equations 1 and 2.

$$\sigma = [(1/(n-1) \cdot \Sigma (d_i - d_{śr})^2]^{0.5} \tag{1}$$

$$\sigma_{śr} = \sigma / n^{-2} \tag{2}$$

where: n – is the number of measurements used in the statistical analysis; d_i – the value of i-measurement; $d_{śr}$ – the mean value from measurements taken for the statistical analysis.

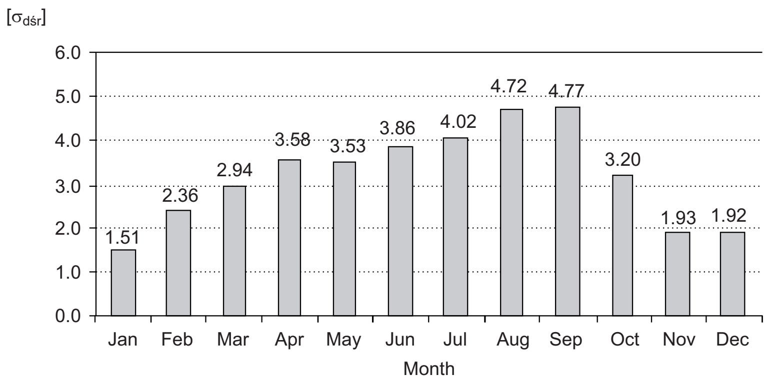

Fig. 10. Values of the deviation from the mean value during the months of the measuring period

Figure 10 shows that the installation was most stable in January, because the value of the deviation from the mean value assumed the value of 1.51. The installation worked was least stable in September, when this deviation from the average value amounted to 4.77, while the average for the measuring period reached 3.19.

Economic and environmental advantages

Investors who decide to purchase solar collectors for hot water preparation hope, among other things, they will save money. Such savings could be noticed when analyzing the cost of hot water preparation in an installation equipped with solar collectors and without them. The data for the cloister are shown in Fig. 11. The cost of hot water preparation in the installation with solar collectors is lower when energy is delivered from collectors, than if it had to be produced from conventional energy. We estimated the savings (S) obtained from the lower natural gas consumption using formulas (3) and (4).

$$V = Q / (Wg \cdot \eta) \tag{3}$$

where: V – the quantity of saved natural gas in m^3; Q – the quantity of heat saved thanks to solar collectors in MJ; Wg – the heat value of natural gas, equal Wg = 31 MJ/m^3; η – the efficiency of gas boiler, whose power amounted to 90 kW, η = 0.7.

$$S = V \cdot K \tag{4}$$

where: K – the cost of natural gas, K = 0.32 $euro/m^3$.

From Figure 11 it can be seen that the cost of hot water preparation in the installation with solar collectors is on average about 1.84 times smaller than the cost of hot water preparation using only the gas boiler. The greatest difference in costs is in the summer months the cost is ca 2.98 times less in the case of the solar collector installation.

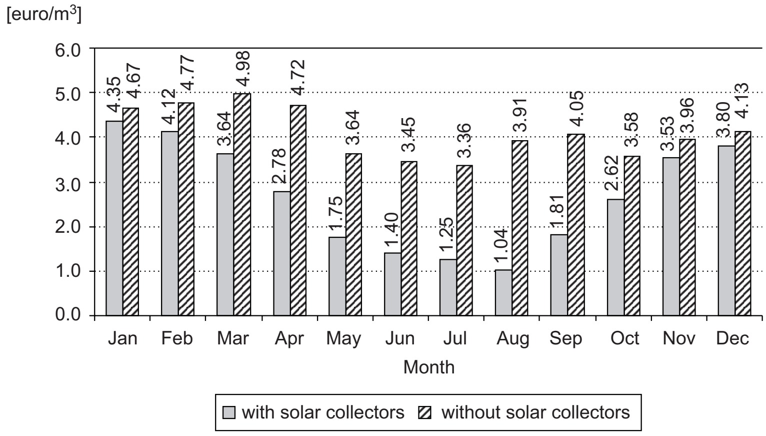

Fig. 11. Installations with and without solar collectors: comparison of monthly costs of preparation of 1 m^3 of hot water during the months of the measurement campaign

In the case of solar collectors it is important, especially for investors, that the installation costs amortize as soon as possible. Therefore, we calculated the Simple Pay Back Time – (SPBT) for our installation, using the Equation 5.

$$SPBT = N/S_a, \text{ years} \tag{5}$$

where: N – the investment costs in euro; S_a – the sum of annual savings with relation to the reference case in euro/per year.

The investment costs for the modernization of the complete hot water installation including the boiler room amounted to 113,902 euro and the average savings of conventional fuel, resulting from use of solar energy were 3155 euro/per year. However, the cost of the solar installation (including instrumentation) amounted to 65,853 euro, yielding an SPBT value of 20.9 years. Additionally the average rise in energy prices during the campaign time was taken as 8 % per year. Taking these facts into account the SPBT will then amount to almost 7 years. Moreover, the investment was refinanced at a rate of 87 %, therefore only 13 % of the total investment sum was actually paid by the

Cloister. For this case, resources invested by the Cloister into the entire modernization of the installation of the hot water and the boiler room (113,902 euro) were returned only 4.7 years after the completion of the installation. It should be pointed out that the solar energy – friendly policy in the country in the form of grants, tax concessions and similar are, and will be, very important in encouraging wider acceptance of solar installations, a view also shared by [13, 14].

Another point worth mentioning in the estimation of SPBT is that additional costs arising from, for example environmental remediation or the costs of pollution-related illnesses to society as a whole were not considered. The use of solar collectors can also result in the diminution of the pollutant emissions to the atmosphere [15–17]. The amount of pollutants avoided by delivering energy for hot water preparation from the solar collectors instead of from the gas boiler is presented in Table 1.

Table 1

A comparison of the annual amount of gas saved [m^3] and resulting abatement in pollutant emission for the installation at Tuchow, Poland

Year	Saved gas	Emission [kg/a]			
		NO_2	CO	CO_2	Dust
2002	11 004	14.1	4.0	21 611.2	0.2
2003	10 470	13.4	3.8	20 563.2	0.2
2004	6 871	8.8	2.5	13 494.6	0.1
2005	10 546	13.5	3.8	20 712.5	0.2
2006	11 136	14.3	4.0	21 871.0	0.2
2007	9 136	11.7	3.3	17 943.9	0.1

Conclusions

Analysis of six years of operational data from the large-scale solar collector installation in the Cloister of Redemptorists at Tuchow showed that the use of solar collectors could cover 37 % of the annual thermal needs for hot water preparation. August provided the greatest coverage level amounting to 75.5 %. August was also the month in which the highest financial savings were evident. At that time 1 m^3 of solar generated hot water cost 3.78 times less than that supplied by the gas boiler.

The feasibility of supporting the preparation of hot water by solar collectors even during the winter period when their contribution was only 15.91 %, was also demonstrated.

For large installations with solar collectors, the Simple Pay Back Time (20.9 years) of the investment is not particularly encouraging. However, taking the increase in fuel price as 8 % per year, the SPBT lowered to 7 years. Moreover, when dealing with large installations for which financial support allowing the inclusion of the investment costs into the total modernization of the hot water installation (including boiler room) is available, the SPBT reduces to 7 years.

Installations using solar collectors for hot water preparation not only generate financial savings, but also play an important part in improving the environment. Thus, they may provide an alternative to existing conventional installations for hot water preparation especially in the light of the global moves to reduce emissions of greenhouse gases to the atmosphere.

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Abstrakt: W obecnych czasach preferuje się rozwiązania instalacji grzewczych wykorzystujących odnawialne źródła energii, z uwagi na ograniczone zasoby paliw kopalnych oraz zapobieganie emisji zanieczyszczeń do atmosfery. Jednym z takich rozwiązań są instalacje przygotowania ciepłej wody w dużych budynkach wspomagane kolektorami słonecznymi. W pracy przedstawiono wyniki 6-letnich badań eksploatacyjnych wielkoskalowej instalacji kolektorów słonecznych płaskich zlokalizowanych na dachu klasztoru redemptorystów w Tuchowie w Polsce.

Kolektory słoneczne pokrywały średnio 37 % potrzeb cieplnych instalacji ciepłej wody w skali roku, w półroczu zimowym 15.9 %, a w półroczu letnim 56.5 %. Przeanalizowano koszty przygotowania ciepłej wody w instalacji z kolektorami i bez, oraz obliczono czas zwrotu nakładów inwestycyjnych. Zwrócono uwagę na czynniki mogące wpływać na stopień pokrycia potrzeb cieplnych przez instalację słoneczną oraz obliczono redukcję ilość zanieczyszczeń powstających przy spalaniu gazu ziemnego, dzięki zastosowaniu kolektorów słonecznych.

Słowa kluczowe: badania eksperymentalne, klasztor, wielkoskalowy system solarny, przygotowanie ciepłej wody