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Hybrid Domestic Hot Water System Performance in Industrial Hall

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Abstract: The renewable and waste heat sources implemented for the preparation of domestic hot water (DHW) allow for energy conservation and environment protection along with resource savings and economic benefits. The solutions, including non-conventional sources, are especially demanded in large halls in which energy and water consumption are crucial for maintenance costs. In this article, energy analysis of a DHW preparation system for workers' hygienic purposes in a industrial hall was performed. The DHW preparation system consisted of three sources: a flue gases heat exchanger as the waste heat source, solar collectors as the renewable heat source and a gas boiler as the conventional source. In the analysis, data of a variable-temperature supply of water and hourly water consumption data from the measurements in the industrial hall, located in Poland, were applied. The results for all of the 8760 h of one year were examined. The analysis outcomes show that implementation of non-conventional sources can supply 81.4% of energy needed for DHW preparation, avoiding a lot of running costs; just 18.6% of heat demand had to be obtained from a gas boiler. The analysis also confirms that the system may operate correctly when the appropriate device size is applied, along with a proper control strategy that avoids overheating water and uses alternative sources.

Keywords: waste sources; renewable sources; DHW load profile; water and energy consumption data; supply water temperature

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1. Introduction

The energy consumption in large-space buildings is important and can reach circa 400 kWh/(m^2·year) [1,2]. In recent years, an increase in the number of such buildings has been observed. There are more than 16.5 million m^2 of industrial and logistics buildings located in Poland and more than 750,000 m^2 is being built. Poland has been the biggest market for large-halls investors in Central Europe since 2015 [3,4]. Convection systems with air heaters (water, gas, oil, electric) and radiant ones (based on water, gas, electric radiant heaters) are the most popular solutions for heating such buildings [5,6]. Plenty of factors influencing the choice of heating system can be pinpointed [7,8]. It is advised to consider each project individually. Possibilities of design and investor requirements should be taken into account as well as the use of renewable energy sources, obtaining rational project costs connected with heating, safe usage and proper thermal conditions [9].

Industrial plants account for significant energy and water consumption, particularly freshwater [1,10]. Circa 651.6 hm^3 of water was consumed in Polish industrial halls in 2011 [11]. There are a lot of applications that contribute to water consumption: (sanitary/hygienic—cold and DHW; technological processes including steam production; fire-fighting and sprinkler installation; and other uses, e.g., cleaning/kitchen, service/irrigation/watering). All of the above should be included in an individual energy and water usage analysis in each branch of industry [12]. However, technological processes as well as sanitary needs are the most water-intensive in manufacturing buildings [13,14]. This is especially so in plants where large numbers of workers are hired [5]. Furthermore, a few other factors play a role, such as: sanitary equipment, the degree of soiling involved in the work and workers' gender influence on water usage [15,16]. In the literature on industrial halls, water and energy consumption data for washbasins varies from 15 to 30 L, and from 500 to 870 Wh respectively, and for showers varies from 50 to 80 L, and from 1450 to 2300 Wh respectively [17] (Table 1).

Table 1. Data of domestic hot water (DHW) and energy consumption in industrial hall bathrooms [17].

Place of Consumption	Water Consumption (L/min)	Duration of Water Consumption (min)	Single Use Consumption (L/(person·day))	Water Temperature (°C)	Heat Consumption (Wh)
Single washbasin	10	3	30	35	870
Collective washbasin	5–10	3	15–30	35	500–870
Shower in the collective bathroom	10	5	50	35	1450
Shower in the cabin	10	15	80	35	2300

Data of water consumption profiles and the form in which they are accumulated are crucial for various design scopes. These may be: design of domestic hot water preparation systems, efficient implementation of energy saving possibilities, optimization of the design and control and operation of systems [18–20]. This data is important when both conventional and renewable energy sources are used, solar collectors in particular [21,22]. However, there is demand for more research on DHW profiles in industrial buildings because the number of publications focused on this field is still limited [18]. Moreover, the research indicates that there are differences among profiles taken from referenced technical standards, and measured ones, with a tendency to overestimate design flow rate values [23,24]. Many analyses are based on profiles taken from technical standards, which are generally identical for each day of the year.

For the purposes of DHW systems design, energy analyses are commonly carried out. They usually use standardized profiles and constant temperature of supply water, but neglecting climate parameters' influence on the temperature of supply water leads to incorrect results in energy and economic analysis [25,26].

The reduction of energy used for the preparation of DHW is required to decrease costs of energy supplies and for EU environmental policy fulfilment [27,28]. This is possible with the implementation of non-conventional energy and hybrid water heating systems [29,30]. All over the world, heating installations and DHW preparation systems using renewable energy sources have been becoming much more common [31]. The most popular are inter alia solar energy and geothermal energy [12,32]. Numerous publications describe working conditions and applications of solar collectors in DHW systems [33,34]. It is really important for the system's energy production and economic performance to optimize the design of solar collectors [22,35]. The required water temperature is one of the factors influencing the profitability of solar collectors' installation, which is why the requirements for temperature of water should always be considered during the system design. The characteristics of Polish climate conditions require an additional heat source (non-related to the weather parameters) during the winter season for solar collector-based systems, while in summer these systems are practically independent from auxiliary sources [36]. In the Polish latitude, up to 60% of the annual energy demand for DHW may be covered by solar collectors. In the summer months (May to September), the systems cover about 90% of actual demand, while in other months this value falls to not more than approximately 30% [37].

State-of-the-art technological systems make waste heat recovery from conventional heating systems possible in industrial halls [8,9]. However, the significance of waste heat is neglected, which means that most of it is unproductively discharged to the environment [38,39]. Heat exchangers (HEX) are the most common solution for recovering waste heat. Nowadays it is possible to recover the waste heat from flue gases of radiant gas heaters, which are one of the most popular heating systems in large-space buildings [40]. Different types of HEX, such as flue gases/air or flue gases/water, allow use of the recovered energy for various goals or needs [41,42]. The waste heat from flue gases seems to be a suitable alternative energy source, especially in industrial halls, because the demand for domestic tap water during the year is constant [43].

In previous work, the authors analyzed a DHW preparation system implementing renewable and waste sources using the theoretical water consumption profile presented in literature and a constant value of cold water temperature [30]. The real water consumption profile data has influence on the energy gained from renewable and waste sources [44], and the changes in inlet water temperature influence energy demand [45]. The consumption profile data measured by the author and data on supply water temperature allowed for state-of-art analysis. The aim of this article is to assess a DHW preparation system using heat from the exhaust gases from gas tube heaters and solar collectors in an industrial hall. The novelty of the analysis is taking into account both data: the change of inlet water temperature in the water supply system and the factual water consumption profile.

2. Materials and Methods

The analysis of the DHW preparation system was performed using the hour-by-hour method developed by the authors and described in detail in a previous publication [30]. The method uses statistical climatic data for the industrial hall location, the linear model for solar collectors' gain calculation, the hourly heat demand for spatial heating calculated using EDSL Tas (software for buildings modeling), and the assessment of temperature in the hot water tank after each source activation and after DHW consumption. The previous analyses assumed the constant temperature of mains water and a DHW profile adopted from literature, while in the current analysis they were changed. The detailed assumptions made for the current analysis are described below.

2.1. Industrial Hall Description

The measurements concerning consumption of the hot water were performed in a industrial hall located in Lower Silesia (Poland) in 2017. The sanitary units were located in each of the industrial hall's departments. The work in the factory is arranged in three shifts with different numbers of workers. There were 16 shifts during the week—15 from Monday to Friday and one on Saturday. There were 235 workers employed—all male. The first shift, working from 6 am to 2 pm, had the highest quantity of workers. Bathrooms in the factory were equipped with 24 shower enclosures and 22 washbasins because of the high degree of soiling from the work. The main conditions of work in the analyzed hall are presented in Table 2.

Table 2. Working conditions in the industrial hall.

Type of Data	Data for the Industrial Hall
Work shifts	3
Working days per week/shifts per week	6/16
Number of workers per day	235
Degree of soiling work	high
DHW sanitary equipment:	Washbasins and showers

2.2. Energy Consumption for Hall Heating

The energy demand for the purposes of the gas radiant heaters' space heating in the industrial hall, in one-hour steps, has been calculated using the EDSL Tas (software for building simulation) [46]. The local climatic data (for Wrocław) and the introduced building model were the basis of the calculation. The energy demand for the space heating Q_{hall} of the industrial hall (summed for each month) is provided in the Table 3. Yearly energy demand was equal to 150.3 MWh. The industrial hall was heated during the working shifts and turned off during breaks and holidays.

Table 3. The hall space heating energy demand (MWh).

Jan	Feb	Mar	Apr	May	Jun
28.09	27.06	22.20	10.92	1.32	0.00
Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0.00	0.00	1.32	1.29	2.73	32.55

2.3. Hot Water Preparation System and Analysis Methodology

The hybrid DHW preparation system consisted of three sources: waste, renewable and conventional. The flue gases heat exchanger is considered as a waste source, solar collectors are a renewable heat source (and the main source in summer) and the gas boiler acted as the conventional source (used in case of energy deficiency, as previously mentioned). Figure 1 shows a simplified system scheme.

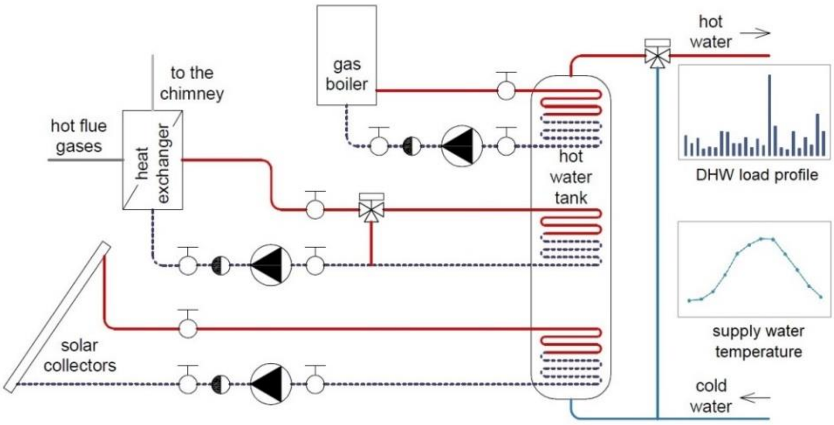

Figure 1. The simplified hybrid hot water preparation system's scheme.

The analysis was conducted using the hour-by-hour method created by the authors [30]. The method assumes energy balancing for each of the 8760 h of the year and shows how the heat sources work with the water tank. More precisely: the energy gained from solar collectors, heat recovered from flue gases of gas heaters, the amount of energy delivered from the gas boiler, the heat demand for DHW preparation purposes (taking into account the measured hot water consumption profile and inlet water temperature changes instead of assumed profile and constant water temperature) and the actual temperature in the water tank were calculated.

2.3.1. Solar Sources

The gains of energy, for the solar collectors' sizing purposes, were calculated using the f-chart method. Climatic data (average air temperature and total radiation on southern surface inclined at 45° during each month) required for the f-chart method were taken from the Ministry of Infrastructure and Construction website [47]. Solar collectors were sized using average water consumption data (taken from DHW profile measurements instead of assumed from standards and thus more realistic), equal to 4.50 m^3 during the whole week, and not only working days (5.65 m^3). This approach prevents the water overheating in the tank on non-working days [30]. The solar collectors selected for the analysis were flat plate, (the heat loss coefficient—4.1 W/(m^2·K), the optical efficiency—84.5%, the surface area—1.873 m^2). The number of collectors that allowed for optimal use in summer was 38. The volume of capacity water heater V_z was usually calculated using standardized values of the demand for DHW per person and day (L/person·day) and the energy consumption (Wh) or integral chart during the use of the sanitary equipment, but in the investigated system the volume of water storage tank, equal to 6000 L, was calculated in proportion to area of the solar collectors (around 75 L/m^2) [48] and did not exceed the measured daily water consumption. The energy gains from solar collectors were calculated in one-hour steps using the linear solar collectors model:

$$Q_{sol} = A_a \times [F_R(\tau\alpha)_e \times G - F_R U_L \times (t_{in} - t_a)], \text{Wh} \quad (1)$$

where A_a—is the surface of the solar collectors' battery or solar collectors' aperture (m^2), $F_R(\tau\alpha)_e$—the solar collector maximum efficiency ($t_{in} = t_a$) (-), $F_R U_L$—the solar collector heat loss coefficient (W/(m^2·K)), G—the solar radiation intensity (W/m^2), t_{in}—the working fluid temperature in the solar collector inlet (°C), t_a—the outside air temperature (°C).

2.3.2. Waste Sources

In the analyzed installation the waste heat recovery system from tube gas radiant heaters' exhaust gases was assumed. System provided heat whenever the space heating system operated. At the outlet from the gas tube heater, the flue gases temperature reached almost 200 °C for high-efficiency units (η_R = 72%). The fan delivered hot flue gases to the heat exchanger via insulated pipes [8,9]. The recovered heat was used for DHW preparation in the capacity water heater (Figure 1). The amount of energy supplied by the heat exchanger was calculated as a share of the industrial hall space heating demand (Table 2). The heat exchanger was equipped with bypass against circulation water overheating.

2.3.3. Gas Boiler

In order to cover the energy deficiency from the heat exchanger and thermal solar collectors, the gas boiler was used as the conventional heat source in the analyzed system. Appropriate boiler heat output enabled maintaining the minimum DHW temperature of 45 °C for bath [48] in the capacity water heater. The constant demand for DHW during the day created the necessity of keeping the water temperature at an appropriate level all the time, which is why the gas boiler needed to operate always when the energy gain from renewable and waste sources was too low, because the provision of the waste heat and renewable energy depended on weather conditions.

2.4. Data of Supply Water Temperature Change

The energy demand for DHW preparation varies during the year. It depends on the hot water consumption level and on the temperature of cold water at the DHW preparation system inlet. The assumption of the unchangeable temperature of the cold inlet water in the design process leads to a large incompatibility in the calculation of energy use in relation to the real values, even at the level of 20% in summer [45]. This fact had not been taken into account until recently. The seasonal change of the mains water temperature is correlated to the temperature of the ambient air and is dependent on the water treatment plant's intake source type. The data of cold water temperature were adopted based on previous research [45], and as presented in Figure 2 were incorporated into the analysis.

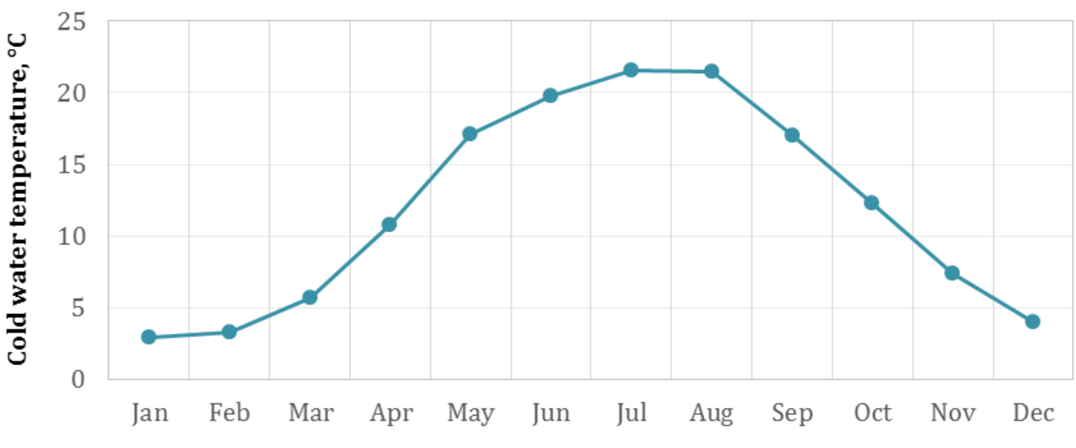

Figure 2. The change of supply water temperature (data source: [45]).

2.5. Hot Water Consumption Profile Data

As a rule, hot water demand for sanitary purposes in industrial halls has regular peaks at work shifts' endings, when workers are taking showers. The duration of installation operation is dependent on the working shifts' number and the occurrence of holidays during a year. Water consumption periods last for about 30 min. During shifts, a considerably lower water demand is observed. Figure 3 presents an exemplary dynamics profile of the hot water consumption during one chosen day, prepared basing on data collected in the investigated hall. After the first (at 2 pm) and second (at 10 pm) shifts, strong peaks were observed. The slighter peak after the third shift is also visible. The consumption of hot water lasts all day and is irregular. For the considered industrial hall, a constant demand for water throughout the year was observed. It was caused by running production process and the constant number of workers. Seasonal variations were not observed.

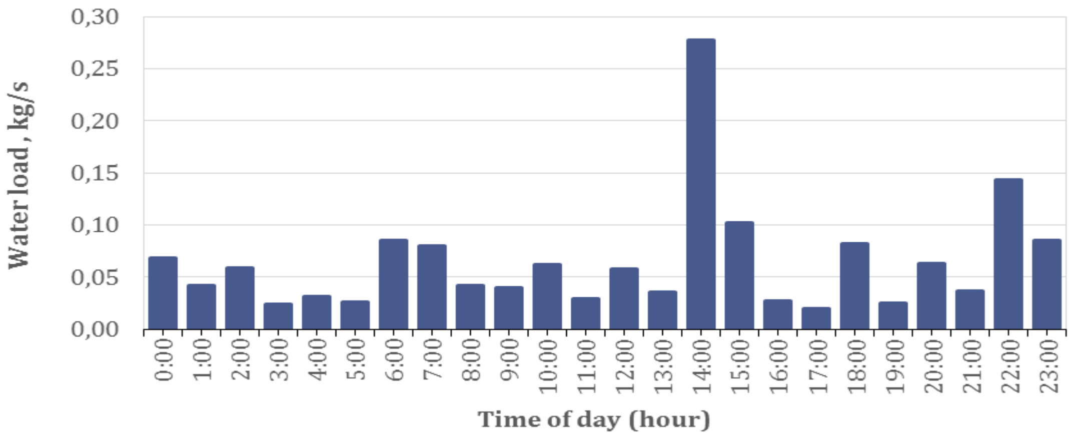

Figure 3. Actual hourly DHW consumption profile (based on [15]).

The energy demand for the DHW preparation purposes have been calculated in one-hour steps using the current water consumption (taken from the measurements), the supply water temperature (value dependent on the season, novel in the analysis) and the temperature of water used for bath purposes. The calculation of the energy demand included the additional energy for circulation (which also had not previously been taken into consideration):

$$Q_{dhw} = m_{wl} \times (t_{dhw}{}^{dem} - t_{cw}) \times c_w + m_{cir} \times \Delta t_{cir} \times c_w,\ \mathrm{Wh} \quad (2)$$

where: Q_{dhw}—is the energy needed for DHW preparation and circulation during one hour (Wh), m_{wl}—the hourly hot water flow rate (kg/s), $t_{dhw}{}^{dem}$—demanded water temperature (K), t_{cw}—temperature of the cold water (°C), c_w—specific heat of water (kJ/(kg·K)), m_{cir}—the circulating water flow rate (kg/s), Δt_{cir}—the temperature difference in circulation system (K).

3. Results and Discussion

Considering all parameters described above, data linked with water and energy consumption in the industrial hall were calculated. Table 4 shows the basic results including mean amounts of water and energy consumption. Average daily DHW consumption was calculated taking into account only working days (when three shifts were working). The average heat and water consumption per person differed from values used for DHW systems design (Table 1). In the examined hall, those values were lower. Monthly average energy demand for DHW preparation purposes was 6201 kWh. Due to the seasonal changes of the mains water temperature and various numbers of working days, monthly energy demand for DHW preparation varied during the year. Figure 4 presents the influence of variable supplied water temperature on energy demand (kWh) for DHW preheating in particular months. As a rule in the design process of domestic water heating systems, a constant inlet water temperature during the year is assumed. However, the change of cold water temperature shouldn't be neglected. In Figure 4, the significant correlation between the lowest values of the estimated heat consumption for water heating and the highest values of the inlet water temperature is visible. The amount of energy demand in particular months substantially differed (from 4786 kWh in August to 7626 kWh in December). It is obviously connected with increasing temperature differences between the fluids. The analysis shows that when taking into account the variable temperature of supply water, heat demand is lower than when considering its temperature constant.

Table 4. The achieved results connected with water and energy consumption in hall.

Type of Data	Outcome for Industrial Hall
Mean temperature in tank of hot water (°C)	55
Mean daily DHW consumption per person (l/person)	24 *
Mean daily DHW consumption G_d (m^3)	5.65 *
Mean weekly DHW consumption (m^3)	31.7
Daily DHW energy demand (kWh)	263
Daily heat consumption per person (Wh/person)	1120
Weekly DHW energy demand (kWh)	1474
Mean monthly DHW energy demand (kWh)	6201

* during work day.

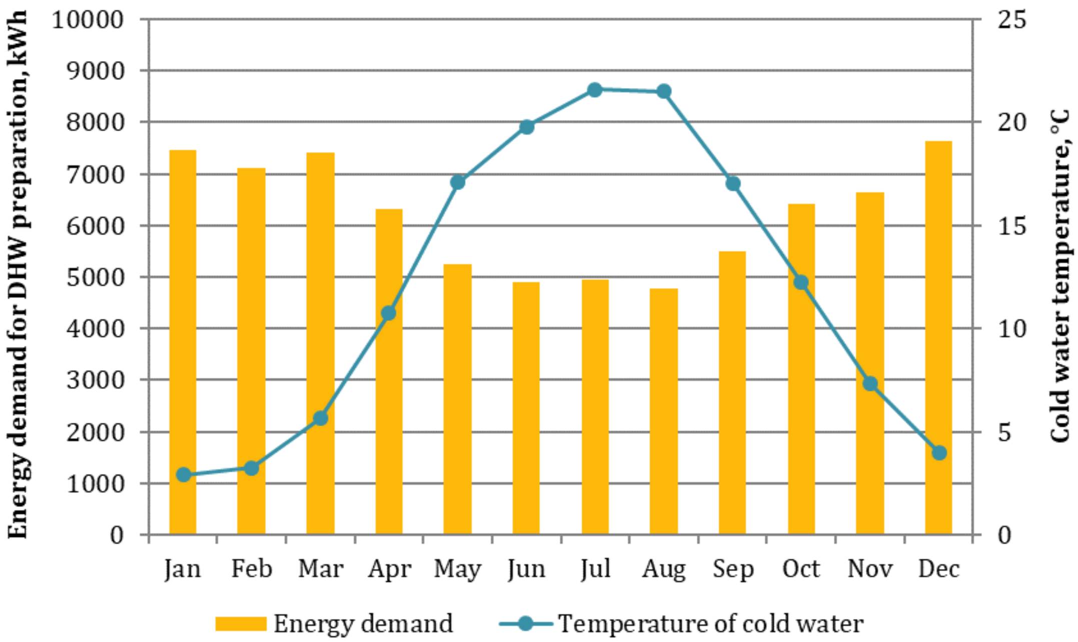

Figure 4. Monthly energy demand for DHW purposes.

Figure 5 shows the data of DHW temperature changes in the water tank throughout the year (blue dotted line). It can be seen that the system overheated (exceeding the temperature of 90 °C indicated with red line) if a number of unfavorable conditions occurred, for example, when high intensity of solar radiation came together with a lack of water usage (during the weekend) and high external temperature during the night (no dissipation possibility). Because of that, the three-way mixing valve on the hot water tank outlet is necessary for safety reasons (it mixes hot water from the tank with cold supply water if the temperature in main hot water pipe exceeds a certain level, i.e., 60 °C). In the tank, the mean temperature of DHW was never lower than 45 °C. At the end of each shower after a working shift, the mean temperature of DHW in the tank decreased by about 5 °C.

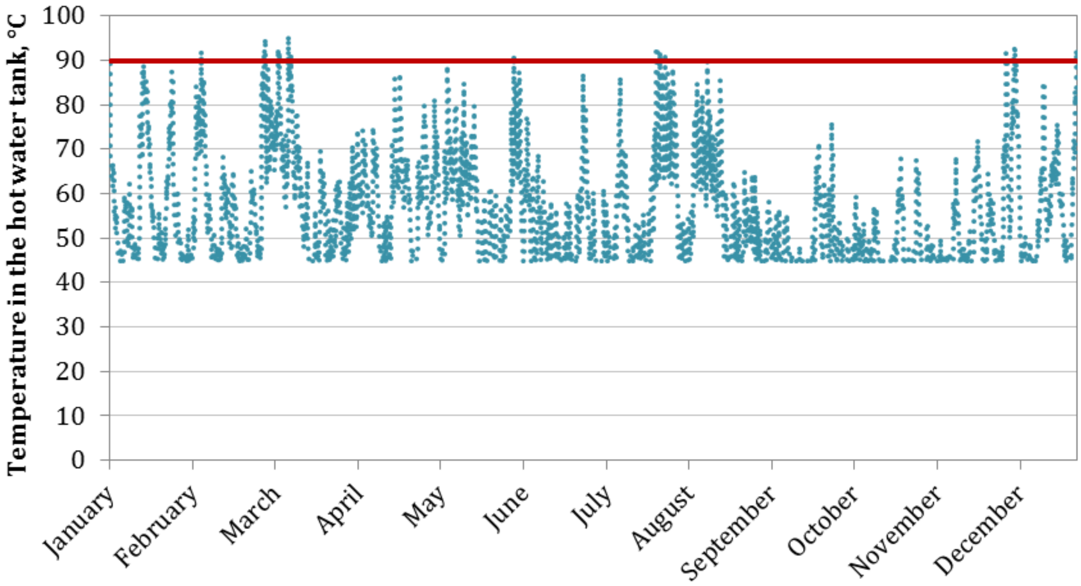

Figure 5. Temperature in hot water tank during the year (blue dotted line) against overheating conditions (red line).

The distribution of the energy gains form solar panels, heat exchanger and the gas boiler is presented in Figure 6. It can be seen that the share of energy gained due to implementation of waste and renewable energy depends on the weather parameters. Additionally, its irregularity may be visible. The conventional source covered the energy shortage and its power should be enough to provide the demanded DHW temperature in an appropriate short time.

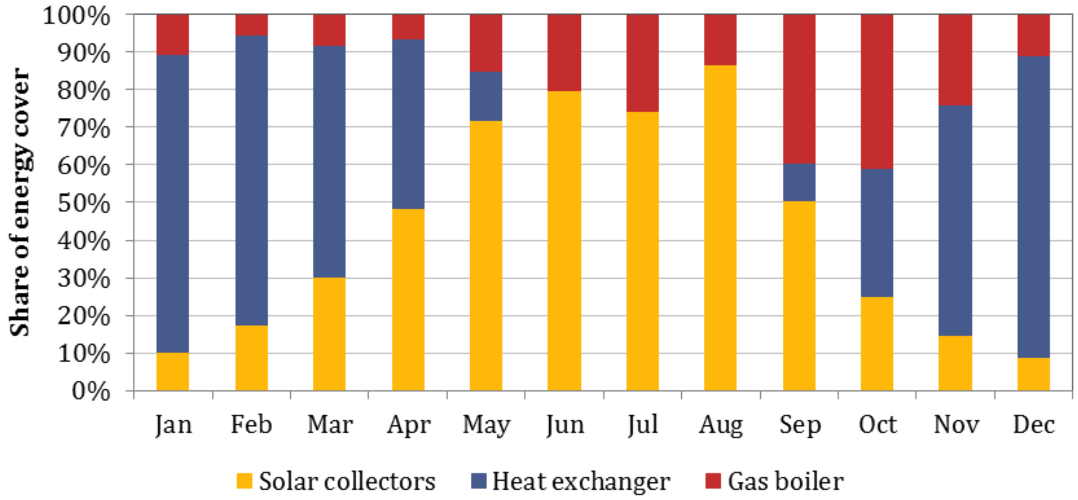

Figure 6. Distribution of the energy share from solar collectors, heat exchanger and gas boiler for DHW preheating.

Heat demands of large-space buildings influence the amount of heat gained from waste heat recovery installation from flue gases. Lower temperatures on colder days causes more heat to be gained than on ones with higher temperatures. Hence, such a DHW preheating system requires an auxiliary source of heat for the preparation of hot water in case of scarcity of energy delivered from the waste source, and in summer outside the heating season. Systems with solar collectors, the most efficient in summer, are an appropriate supplement for DHW preparation. This was confirmed also by other analyses [30,44]. The cooperation of the solar collectors and heat exchanger (HEXW) enables water cooling (to prevent overheating) in the tank. For example, overheating could happen in cases when the hall is heated intensively because of low outdoor temperatures, but less DHW is consumed (for example, during second and third shifts in this specific hall or partial absence of workers) as well as during really sunny weekends and holidays. If the temperature of water in the tank exceeds a set value and the temperature of collectors is lower than water in the tank (for example, during the night or even a cloudy day in winter) the solar collectors' circuit may be used to dissipate the excess heat stored in the tank.

Figure 7 presents the annual energy balance for the analyzed industrial hall. Solar collectors covered on average 34.4% of demand (94.5% in August; 10.1% in December). The fact that solar collectors do not cover 100% during summer months can be explained by the discrepancy between the water load profile and hours of sunshine (most water prepared using solar energy is used till 2 pm, and boiler assistance is needed for the preparation of hot water for second and third shift workers). It is said that climatic conditions in Poland allow halls to obtain as much as 60% of energy needs from solar collectors [37,44]. This article [44] shows that the gains of solar energy vary from 65.5% to 56.3% depending on the number of shifts and assuming a fixed inlet water temperature. The lower gain from solar collectors (34.4%) was due to the lower energy demand in summer (caused by the higher inlet water temperature). To avoid the system overheating in summer, a smaller collectors' area is required and hence less energy is delivered in winter, when the temperature of inlet water is lower. A three-shifts work schedule in industrial hall demands heating the hall during the entire day. This causes a yield from waste sources that is quite significant. The previous analysis [30] showed the gain from waste sources equaled 17.5%; this was due to the assumption of two working shifts with an equal number of workers. Considering three shifts and a real consumption profile, the heat recovered from flue gases reached 47.0%, which is more than the values presented in other research [49]. The share from the gas boiler was 18.6%. The share of energy to be dissipated equaled 7.4% and that which could not be utilized was 0.9%.

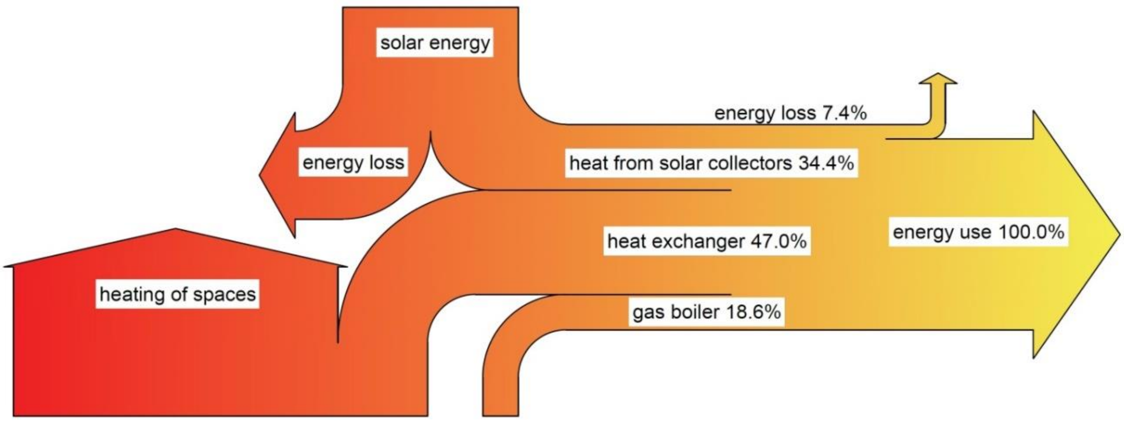

Figure 7. Annual energy balance.

4. Conclusions

The method of DHW preparation and the system selection depends on the heating system in the industrial hall. Popular in large-space buildings, gas radiant heaters enable halls to recover heat from flue gases. Solar collectors are the proper supplement for flue-gas heat exchangers because of their seasonal work characteristics (solar collectors in summer and flue-gas exchangers in winter). Both sources allow design of hybrid DHW preparation systems.

The analysis confirmed that HEXW and solar collectors would cooperate well. The water consumption profile, based on collected data and data of fluctuating supply-water temperature, influences shares of gained energy but does not affect the system's functionality. Proper devices sizing allows for optimal use of the sources' potential and dissipates a minimum amount of excess energy.

The volume of the water tank is dependent on the area of solar collectors and daily hot water use. In sizing of the DHW cylinder, assuming 75 L per 1 m^2 of collector area secures the proper system capacity (however the tank capacity should not generally exceed daily water use).

The data provided by the hour-by-hour method allowed for assessing and checking, in each of the 8760 h during the year, the amount of energy gain from the solar collectors, heat recovered from flue gases of gas heaters, the amount of energy supplied by the gas boiler, the heat demand for DHW preparation and the actual temperature in the water tank. The analysis, based on energy balancing, scrutinized the cooperation of heat sources in relation to the temperature of the water storage tank. Taking into account the effect of the variable supply-water temperature shows that, in fact, less energy is gained than when a constant cold water temperature is assumed throughout the year. Furthermore, both the heating schedule and the water consumption profile influence the energy gain from flue gases.

A significant share (81.4%) of energy was obtained from non-conventional energy sources. The solar collectors delivered 34.4% of energy demanded for hot water preparation, and flue gases/water heat exchanger gave 47.0%. The traditional source, a gas boiler, covered 18.6% of energy demand.

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