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HYBRID HEATING AND COOLING SYSTEM WITH RENEWABLE ENERGY SOURCES

HYBRYDOWA INSTALACJA GRZEWCZA I CHŁODNICZA Z ODNAWIALNYMI ŹRÓDŁAMI ENERGII

A b s t r a c t

This paper presents hybrid heating and cooling system with four heating devices, three of which are producing heat from renewable energy sources. The systems operate in real conditions in residential and commercial building near Cracow. Geothermal heat pumps have an additional working mode that can be used for passive cooling during summertime for the cooling of building interiors. Results from several years of installation operation with a particular emphasis upon performance, the consumption of electricity, and the amount of heating and cooling production achieved by the individual devices have been presented.

Keywords: hybrid installation, renewable energy sources, geothermal heat pump

S t r e s z c z e n i e

W artykule omówiono hybrydową instalację grzewczą i chłodniczą z czterema urządzeniami grzewczymi, przy czym trzy z nich wytwarzają ciepło z odnawialnych źródeł energii. System pracuje w warunkach rzeczywistych w budynku mieszkalno-usługowym w okolicy Krakowa. Gruntowa pompa ciepła posiada dodatkowy tryb pracy, tj. chłodzenia pasywnego, który jest używany w czasie lata do chłodzenia pomieszczeń budynku. Przedstawiono wyniki kilkuletniej pracy instalacji ze szczególnym uwzględnieniem uzyskiwanej sprawności, zużycia energii elektrycznej oraz ilości wyprodukowanego ciepła i chłodu przez poszczególne urządzenia.

Słowa kluczowe: instalacja hybrydowa, odnawialne źródła energii, gruntowe pompy ciepła

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1. Introduction

In recent decades, energy demands have been growing due to the increase in the global population, suburbanisation and industrial development [1]. This increase in energy consumption, and in particular fossil fuels, has had a considerable impact on the environment and this has become a substantial cause of universal concern. Utilising renewable energy sources (RES) as much as possible whilst simultaneously focussing on energy efficiency initiatives will probably direct countries on the path to decreasing greenhouse gas emissions and mitigating climate changes and environmental pollution [2].

Space conditioning of buildings is area with a high potential for effective energy production, carbon savings, and reducing energy demands where efficient devices which use RES can make a significant contribution. Households were responsible for approximately one quarter of the final energy consumption in the European Union and Poland in 2013 (Fig. 1).

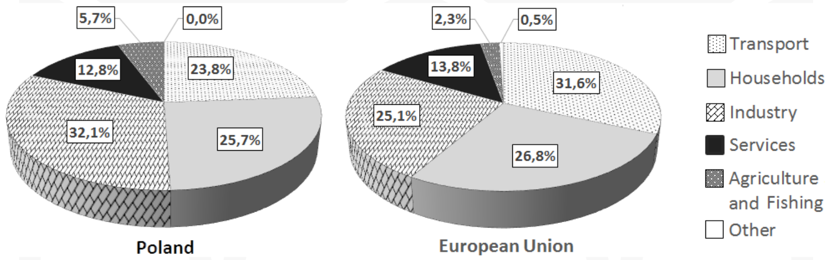

Fig. 1. Final energy consumption by sector in EU and Poland in 2013 [3]

In general, there is a need to develop heating and also, due to climate changes, cooling systems that are environmentally friendly and less reliant upon fossil fuels [4]. Such systems which meet economical and technical challenges often require a combination of technologies. Currently, hybrid installations are becoming more and more popular in central heating (CH) systems, as well as in systems for domestic hot water (DHW) preparation in residential buildings [5]. The work of these systems is based upon mutual cooperation of at least two devices using different energy sources, including renewable sources. In Polish conditions, such systems most commonly use heat pumps, solar panels and biomass boilers, as well as devices that use traditional fuels (gas boilers and solid fuel boilers). Combining different technologies significantly raises the reliability of systems but also complicates the process of their design and optimisation compared to single-technology systems, this is due to the need to integrate detailed control strategies in the design process [6].

An important issue is the operation of the hybrid system in the way that compensate advantages and disadvantages of system devices, because most of RES produce a variable stream of energy in the course of the year, day and even hour [1]. The heat is usually produced by the device which has the lowest operating costs. In addition, hybrid systems use the fluctuating energy more efficiently by matching the energy supply with demand [7]. The enormous energetic potential of hybrid systems that use RES is as important as the ecological aspect of their application because of the reduced emissions of air pollutants and greenhouse gases. By contributing to energy efficiency, it significantly reduces the negative environmental impact from conventional energy sources, it increases the potential uptake of some renewable energy technologies, it amplifies the potential of sustainable energy development and it subsequently leads to better energy security.

The great importance of hybrid systems that contribute to the development of efficient and affordable technologies based on renewable sources has been strongly highlighted by adding them to the list of strategic priorities for research and innovation of the European Technology Platform on Renewable Heating and Cooling [8].

The aim of this work is to present and analyse selected operational aspects of hybrid system for CH, cooling and DHW preparation in residential and commercial building around Cracow since September 2011. The systems consist of four heat sources, including three which use RES as well as other components and loops. The integration of all heat sources takes place through an advanced cascade combination of two control systems which play an important role in energetic and ecological balance of system. Additionally control systems enables the continuous recording and acquisition of measurements among other temperatures of fluids, generated heat streams by individual heat source devices, solar irradiance.

2. Description of hybrid installation

2.1. Heating and cooling devices

Table 1 presents basic technical data of heating and cooling devices in the considered installation. The bottom heat source (BHS) for a geothermal, brine-water heat pump is a vertical ground heat exchanger in the form of three boreholes, each of which have a depth of 70 meters. The boreholes with diameters of 135mm was made in one line, with seven meters intervals and at six meters distance from the northern wall of the building. In each borehole, a single polyethylene U-tube was mounted. The intermediate fluid which passes energy from the ground to the evaporator is 40% v/v aqueous propylene glycol solution with a freezing point of -21.7ºC.

In the summertime, at high ambient temperatures, the heat pump can operate in a passive cooling mode which involves the use of the additional heat exchanger and appropriately controlled three-way valves. In this mode, the heat from the interior of the building is transferred to the soil which surrounds the bottom heat source without using the compressor of the heat pump. This process occurs because in temperate climates, during the year the soil temperature below 10 meters is constant at around 10-11°C, which is lower than the interior of the building [9]. The temperature of the upper layers of the soil varies sinusoidally throughout the year [10].

In a biomass boiler, which is actually a fireplace with a heat exchanger and water jacket, heat is generated from the combustion of beech common (*Fagus sylvatica*) wood logs. Thermal energy produced in the process is transported to the buffer tank with a capacity of 1500 L without coils, loaded directly (Fig. 2).

Table 1

Basic technical data of heating and cooling devices in the installation

Device	Technical data	
Heat pump	Heating power in B0/W35, B5/W55	10.4kW, 11.0kW
	COP in B0/W35, B5/W55	4.4, 3.2
	Cooling power in 18/22ºC	6.2kW
Biomass boiler	Total heating power	24kW
	Heating power of water circuit	21kW
Solar collectors	Number of collectors	five collectors with 20 tubes each one collector with 12 tubes
	Type	vacuum-tube with heat-pipe
	Aperture area	1.866m^2 for 20 tubes and 1.200m^2 for 20 tube collector
	Optical efficiency	61.8%
Gas condensing boiler	Heating power	adjustable from 7.2kW to 19.5kW

Solar collectors mounted on the south-facing slope of the building with a roof pitch of 35° is composed of two parallel connected groups of collectors (three collectors for each group). The total aperture area of collectors participating in the collection of solar radiation is 10.53 m^2. Generated heat in the first instance is used for the heating of the water surrounding the inner tank of the combined tank (total capacity 800 L; 200 L for inner tank). If the appropriate temperature of the DHW is reached, the three-way valve is triggered and heat from the collectors is directed to the buffer tank (Fig. 2). Solar fluid, which mediates in the transferring of heat from the collectors to the tanks, is de-ionised water.

The gas condensing boiler (the only conventional heating device in the installation) passes generated heat either directly to the water in the buffer tank or by the upper coil to the DHW in the inner tank of the combined tank (Fig. 2). Fuel which is delivered from the gas network for the combustion process in the boiler is natural methane gas (Group E) with a gross calorific value of not less than 38.0MJ/m^3.

2.2. The heating circuits, ventilation system, other components

During the year, the appropriate thermal comfort in most rooms of the building is maintained by blowing heated or cooled air into them by the air handling unit. In the building, four ventilation zones were separated. For each zone, was assigned channel, water air heater– the heat for these appliance is provided by four heating circuits (OB 1-4 in Fig. 2). Circuit OB 4 is a heating circuit of convection heaters installed in basement rooms, bathrooms and two rooms of the building. Circuit OB 6 is a heating circuit of the industrial air heater mounted in the storage room of the building. One more circuit, named OB 7, can be also distinguished in the installation – this delivers and receives heat from air in the air handling unit during cooperation with a heat pump.

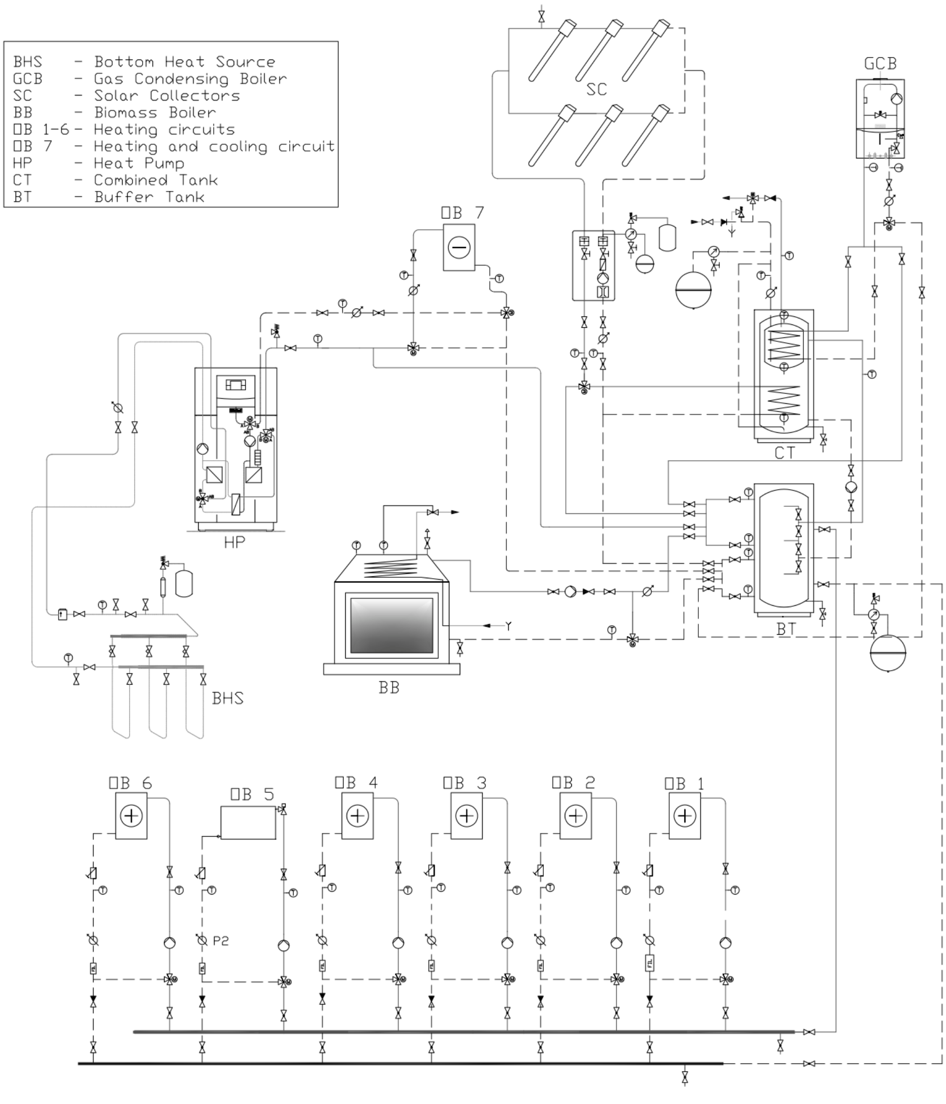

Fig. 2. Simplified layout of hybrid installation with the main components and loops

The fluid temperatures in the installation was measured by temperature sensors with platinum resistance sensing element Pt1000 belonging to accuracy class A according to EN 60751:2009 and outer casing type OG.

The volume flow rate of water in the heating circuits in the system was determined by dry running single-jet water meters. For other circuits, dry running multi-jet water meters were used. Both meters were equipped with transmitters of electric pulses.

A secondary standard-class pyranometer was used for measuring the direct and diffused solar radiation intensity, this was mounted on the roof of the building parallel to the surface of the solar collectors. Measuring the amount of electricity consumed by the main devices in the system, the control system and the air-handling unit was performed by single-phase and three-phase electricity meters which had a SO pulse output.

The volume of high-methane gas consumed by the gas boiler was measured using a bellows gas meter with a 2 L measurement chamber and freely suspended synthetic membranes in the measuring mechanism.

2.3. Control system

For the sake on presence of several heating and one cooling devices was used dedicated especially for hybrid systems [11] two DigiENERGY control systems in a cascade control. The master DigiENERGY is directly responsible for the work of the heat pump, gas boiler, solar collectors, three heating/cooling circuits, and the preparation of DHW; it also takes part in the transfer of control signals for the automation of the air-handling unit. In the main window (Fig. 3), the part of the installation and the current parameters are presented.

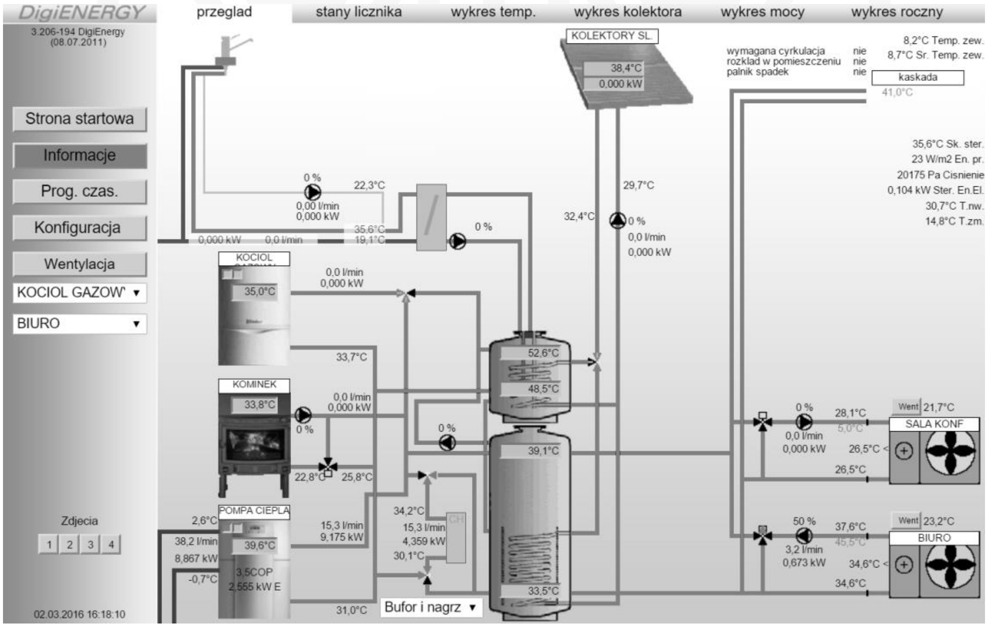

Fig. 3. The main window of the installation of the master DigiENERGY control system

The slave DigiENERGY is directly responsible for the work of the biomass boiler, four heating circuits, the registration data from the pyranometer and taking part in the transfer of control signals for the automation of the air-handling unit.

The operation of the heat pump, the biomass boiler and the gas boiler is controlled by DigiENERGY through the determination of the on and off heating hysteresis, the minimum and maximum working temperatures, breaks in work caused by exceeding the limits of the allowable working temperatures, delay time of temperature measurement and time period of the priority in preparation of DHW. Other parameters of the boilers are chosen by their built-in drivers.

3. Results and discussion

The daily values of heat production by the individual heating devices of the considered installation and the average daily ambient temperature values from January 2012 until January 2016 are shown in Fig. 4. The heat pump was connected to the installation on 22 January 2012 and from that moment, it started the production of heat. In the winter months, due to the low outside temperature and the simultaneous increase in energy demand for heating the rooms of the building, all heating devices were working. The gas condensing boiler, the biomass boiler and the heat pump generated heat mainly from the beginning of November until the end of April when the average daily ambient temperature was below 10°C.

In the period from early May to the end of September each year, energy produced by solar collectors was, on most days, sufficient to cover 100% of the heat demand for central heating and preparation of the DHW. From November until the beginning of March, the amount of heat produced by the collectors, compared to other heating devices in the installation were much smaller. During these periods were several dozen days when the solar collectors didn’t produced a single unit of heat – for example, from 1 November 2014 until 15 March 2015, there were 68 such days.

From February 2015 to October 2015, the biomass boiler wasn’t working because in the installation was tested bivalent cooperation of heat pump and gas condensing boiler. Therefore, a much higher level of heat production by the gas boiler for this period in comparison to such periods in the other years can be observed.

The device which globally supplied the biggest amount of heat in each of the first three years of operation of the investigated system was the biomass boiler (Fig. 5). In 2015, the quantity of heat produced by the heat pump (i.e. 35.2 GJ) was only slightly higher than by the biomass boiler. In each year, the least heat was generated by the solar collectors and reached a maximum value of 14.34GJ (3.98 MWh) in 2012. From 2012 to 2015, the total annual heat production did not differ much from each other and was approximately 110GJ (30.6 MWh).

Heat from RES amounted to 69.2%, 73.4%, 76.7% and 64.0% for the years 2012, 2013, 2014 and 2015, respectively, considering the fact that in the case of the heat pump, energy was partially produced from the electricity consumed by the scroll compressor. The gradual increase of this value in first three years was the result of the application of appropriate improvements in the control system. The result obtained in 2015 was caused by suspending use of the biomass boiler for several months.

The electricity consumption of the following units of the installation was measured:

- heat pump (electronics, compressor and circulation pumps of the lower and upper heat sources);
- air-handling unit (electronics, fans and actuators);

- control system and additional electrical devices (circulation pumps, three-way and mixing valves, electronics of gas and biomass boilers).

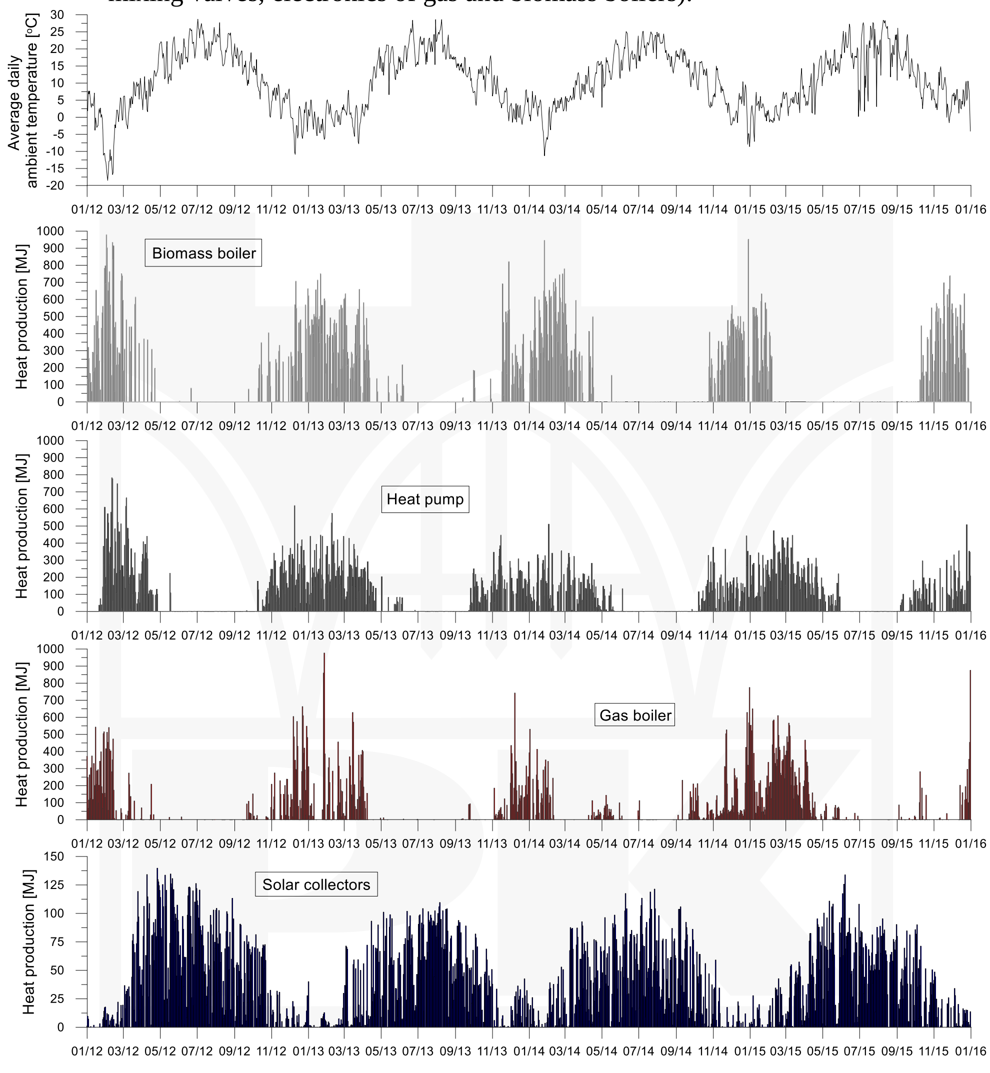

Fig. 4. Daily values of heat production by individual heating devices and the average daily ambient temperature values in the installation from January 2012 until January 2016

The highest electricity consumption (Table 2) in each year was recorded for the heat pump (about 60% of the total electrical energy consumed), which works both in the heating and cooling mode. The second highest electricity consumption was that of the air handling unit.

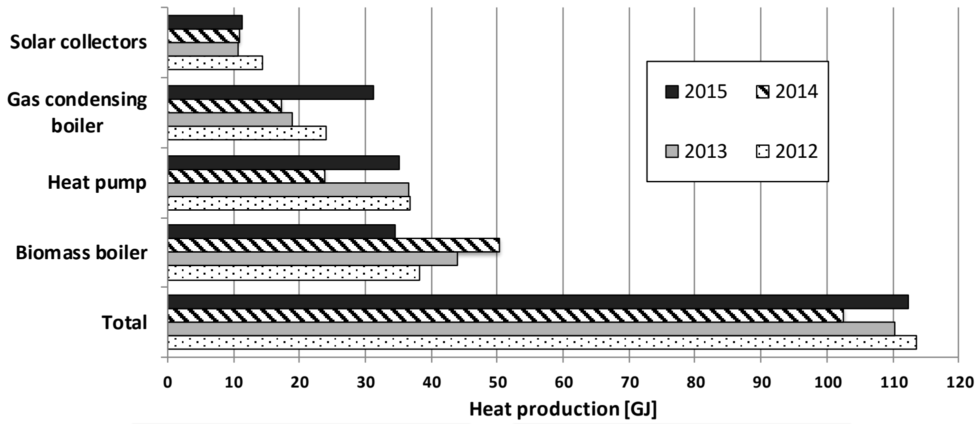

Fig. 5. Annual production of heat by each heating device in the installation for years 2012-2015

Table 2

Electricity consumption in the installation

Device	Annual electricity consumption			
	2012 [GJ]	**2013 [GJ]**	**2014 [GJ]**	**2015 [GJ]**
Control system and additional electrical devices	2.59	2.94	3.00	3.36
Air-handling unit	4.41	4.49	3.24	2.97
Heat pump	11.19	10.80	6.76	9.63
Total	**18.19**	**18.24**	**11.64**	**15.96**

In the years under consideration, the passive cooling mode of heat pump was used in the period from the beginning of June until the end of August (such a period in the year will be henceforth be referred to as the cooling season). Cooling was carried out in office rooms and the conference hall located on the north-west side of the ground floor of the building, with a total usable area of 103 m^2. During the process, the central heating coil inside the air handling unit was working as an air cooler, lowering the temperature of the air blowing into the rooms. Due to the nature of the use of facilities, passive cooling was mainly carried out during the working hours of office workers (between 0700 and 1800 on business days excluding holiday breaks, vacations) when the outside air temperature exceeded 25°C.

The value of the seasonal cooling performance factor (SPF_C) of the heat pump in the cooling seasons was defined by Formulas 1 and 2. Equation 2 also takes into account the electricity consumption in the standby mode of the heat pump.

$$SPF_{C1} = \frac{Q_C}{P_C} \tag{1}$$

$$\mathrm{SPF}_{C2} = \frac{Q_C}{P_C + P_P} \tag{2}$$

where

Q_C – amount of cooling energy produced by heat pump in the season, J,
P_C – amount of electricity consumed by compressor, controller, circulation pumps of heat pump in the cooling season, J,
P_p – amount of electricity used in standby mode of heat pump in season, J.

From 2012 to 2014, the number of days with active passive cooling were similar and reached approximately twenty-five days, whereas in 2015, there were forty-six such days. The highest SPF_C values were achieved in the year 2014 (Table 3). Taking into account the amount of electricity consumed in standby mode in the calculation reduces the SPF_C values by an average of 15÷24%.

Table 3

SPF_C values of heat pump in cooling seasons

Cooling season	2012	2013	2014	2015
SPF_{C1}	8.38	8.77	11.45	8.50
SPF_{C2}	6.43	6.92	8.69	7.17

The seasonal performance factor (SPF) of the heat pump in the heating mode (excluding months in which the heat pump was working in the cooling mode) had a maximum value of 3.83 in 2015 and a minimum value of 3.37 in 2012. SPF obtained in 2015 was satisfactory in comparison to data submitted in [12], where dozens of installations with ground heat pumps cooperating with low temperature heating in real conditions achieved average SPF values from 3.63 to 3.79.

The average annual efficiency of heat generation by the gas condensing boiler varied from 78% to 82%, which was a result similar to that noticed in [13] where dozens of boilers received an annual performance of 82.5% ± 4.0%. However, the average efficiency of the water circuit of the biomass boiler was identified at the level 47.9%.

The annual efficiency of solar collectors in the installation varied in the range from 32% to 38%. Taking into account the fact that some part of the heat generated by collectors was consumed for the needs of the frost protection system of solar fluid in the calculation, the annual efficiency was reduced to approximately 3%.

4. Conclusions

Through the integration of several heating devices and by applying appropriate improvements in the control system of the hybrid installation, up to 76.7% coverage of annual heat demand for CH and preparation of DHW from renewable energy sources was achieved in 2014 while maintaining high energy efficiency of individual heating units.

Additionally, owing to the passive cooling mode of the heat pump, it was possible to obtain a suitable thermal comfort in the occupied rooms of the building during summertime and with low energy consumption by the cooling process.

Stimulation of growth with rational use of conventional resources while simultaneously respecting the environment is one of the challenges confronting the Polish. It seems that the logic of the near future will be to increase the use of RES because of their wide availability, ecological purity, the possibility of decentralisation of their use, and thus increasing the energy security of country. The latter aspect plays a large role in the global, political and economic trends.

Already, special emphasis is placed on the solutions lowering the energy consumption of residential buildings. The presented work includes such solutions and at the same time, fits into popular trends in the development of environmentally friendly technologies.

Abbreviations

RES – Renewable Energy Sources
CH – Central Heating
DHW – Domestic Hot Water
BHS – Bottom Heat Source
SPF – Seasonal Performance Factor
SPF_C – Seasonal Cooling Performance Factor

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