Operating costs of air and ground source heat pumps

Koszty eksploatacyjne powietrznej i gruntowej pompy ciepła

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This study aims to determine how the variable operating parameters affect the efficiency and operating costs of the heat pump. A single-family house with a design heat load of 4,3 kW located in climate zone IV in Bialystok is analysed. The analysis concerns a brine-to-water heat pump and an air-to-water heat pump. Three values of bivalent temperature are assumed for the air source heat pump: – 10, – 9 and – 8°C. Five values of heating water temperature are considered: 35, 40, 45, 50 and 55°C. The basis for calculating the heat output and electricity consumption of the heat pumps is the outside air temperature determined for each hour of the heating season in the statistical year. The SCOP values are calculated. Electricity consumption and its cost are determined according to three tariffs offered by PGE: G11, G12 and G12w. A ground source heat pump ensures the lowest operating costs and highest SCOP values. In an air source heat pump the lower the bivalent temperature, the lower the operating costs. The most favourable electricity tariff is the weekend tariff G12w. The 24-hour tariff G11 with identical charges during the day and night is not recommended to use for heating purposes

Keywords: operating cost, seasonal coefficient of performance, upper heat source, ground source heat pump, air source heat pump

Celem niniejszego opracowania jest określenie, jak zmienne parametry pracy wpływają na efektywność i koszty eksploatacji pompy ciepła. Obliczenia przeprowadzono dla domu jednorodzinnego położonego w IV strefie klimatycznej w Białymstoku, o projektowym zapotrzebowaniu na ciepło 4,3 kW. Analiza obejmuje pompę gruntową typu solanka-woda oraz pompę typu powietrze-woda. Dla pompy powietrznej przyjęto trzy wartości temperatury biwalentnej: – 10, – 9 i – 8°C. Obliczenia zużycia energii elektrycznej przeprowadzono dla pięciu wartości temperatury górnego źródła: 35, 40, 45, 50 i 55°C. Podstawą do obliczeń mocy cieplnej i zużycia energii elektrycznej przez pompy ciepła była temperatura powietrza zewnętrznego określona dla każdej godziny sezonu grzewczego. Obliczono wartości współczynnika SCOP. Zużycie energii elektrycznej i jej koszt wyznaczono według trzech taryf oferowanych przez PGE: G11, G12 i G12w. Najniższe koszty eksploatacyjne i najwyższe wartości SCOP zapewnia gruntowa pompa ciepła. W pompie powietrznej im niższa temperatura biwalentna, tym niższe koszty eksploatacyjne. Najkorzystniejszą taryfą energii elektrycznej jest taryfa weekendowa G12w. Do ogrzewania budynku nie jest zalecana taryfa całodobowa G11 ze stałymi opłatami w strefie dziennej i nocnej.

Słowa kluczowe: koszty eksploatacyjne, sezonowy współczynnik efektywności, górne źródło ciepła, gruntowa pompa ciepła, powietrzna pompa ciepła

Introduction

The use of heat pumps in residential buildings is growing. In Poland, the ambient heat consumption of heat pumps (from the air, water and ground) increased by 90% over 4 years (2016-2022) [1]. This is due to the growing environmental awareness of society and restrictive energy consumption requirements for buildings. For the heating system users, apart from investment cost, the most important is the operating cost. It depends on the efficiency of the heat source and the type of heating system: radiant system or convection radiators.

The efficiency of heat pumps depends on many factors, including the temperature of the medium supplying the heating system. Anweiler and Masiukiewicz [2] determined experimentally that the low heating water temperature of 35°C results in a higher value of the SCOP and a lower dependence of the SCOP on the outside air temperature, compared to the average water temperature of 55°C. Dąbrowski and Hutnik [3] determined that the cooperation of a heat pump with convection radiators at the operating parameters of 45/35°C is associated with an increase in electricity consumption, compared to a low-temperature system (35°C). Consequently, the COP decreases, even by 25%. Thus, it is recommended to use low-temperature surface heating systems to ensure high heat pump efficiency [4]. The surface heating is characterised by a large water capacity. Therefore, the required water capacity is provided in the heat-pump-powered heating system and there is no need to install a heat buffer [5].

The heat pump efficiency is also affected by the temperature of the low-temperature heat source: ground, water or air [6]. Another aspect is the choice of the bivalent temperature, at which the second heat

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source will switch on: e.g. a gas boiler (bivalent mode) or an electric heater (mono-energetic mode). The heat pump efficiency is also influenced by the way of heating curve regulation. It can be increased by the optimisation of the heat pump operation time [7].

The operating cost of the heat pump depends on the electricity tariff adopted. In Poland, the electricity company PGE [8] offers a single-zone tariff (G11), in which the electricity charge is the same 24 hours a day and all year round. For home heating purposes dual-zone tariffs (G12, G12w) are recommended, with a division into night and day zones. The night zone is characterised by lower charges for electricity compared to day one.

The aim of this study is to determine the operating costs of an air source and ground source heat pump for heating a single-family building located in Białystok. The variable heating water temperature in the range of 35-55°C is analysed. For the air source heat pump, calculations are made for three values of bivalent temperature: – 10, – 9 and – 8°C. The seasonal coefficient of performance SCOP is determined. Electricity costs are calculated for three tariffs: G11, G12 and G12w. Calculations are performed for hourly values of outside air temperature during the heating season [9].

Methodology

A single-family building located in the IV climatic zone in Białystok is considered, with a design heat load of 4,3 kW. The analysis covers the electricity consumption for heating purposes and does not include domestic hot water.

Calculations of the heat pump efficiency and the electricity consumption are made for each hour of the heating season, which runs from 21.09 to 10.05 [10]. The outside air temperature at which the heating system is switched off is 15°C. The analysis uses data for energy calculations presented by the Ministry of Investment and Development for the city of Białystok [9], which presents the outside temperature for every hour of the statistical year (Figure 1). The total number of hours for which the analysis is carried out is 5592 h.

Two heat pumps are considered: a brine-to-water pump and an air-to-water pump. The selection of the heat pumps and their operating parameters is by the requirements of the Polish Heat Pump Technology Development Organisation PORT PC [11] and the guidelines of the heat pumps producer [5].

The ground source heat pump works in a monovalent mode and cooperates with a vertical heat exchanger. The ground temperature changes with the depth of the borehole and as a result of the varying outside temperature and insolation [7][12]. A constant annual ground temperature along the whole length of the heat exchanger is assumed to be 7.407659°C, which was determined by Biernacka for Białystok [13]. The change of ground temperature in the neighbourhood of a heat exchanger is not included in the calculations. The brine temperature is 5K lower than the ground temperature.

A mono-energetic operation mode of the air source heat pump is considered. Three values of the bivalent temperature t_{biv} are assumed, at which the second heat source (electric heater) is switched on: – 10, – 9 and – 8°C. The heat pump operates between 21.09 and 10.05 when the outside air temperature t_{out} is in the range of $t_{biv} \leq t_{out} < 15°C$. The share of the electric heater in covering the heat demand is less than 5% for each bivalent temperature, according to PORT PC guidelines [11].

A Vitocal 222-A type 221.06 air source heat pump and a Vitocal 333G type 331.C06 ground source heat pump from Viessman are selected. The technical parameters are presented in Table 1.

Table 1. Technical data of heat pumps [14][15]
Tabela 1. Dane techniczne pomp ciepła [14][15]

No	Parameter	Air-to-water heat pump Vitocal 222-A type 221.06	Brine-to-water heat pump Vitocal 333G type 331.C06
		EN 14511	
		A2/W35 temperature difference 5K	B0/W35 temperature difference 5K
1	Rated heat output	3,11 kW	4,28 kW
2	Electrical power consumption	0,82 kW	0,91 kW
3	COP	3,78	4,70
4	Heating modulation range	2,4-5,5 kW	1,7-8,6 kW
5	DHW tank capacity	220 dm^3	220 dm^3
6	DHW temperature	up to 70°C	up to 60°C
7	Energy efficiency category	A++	A+++
8	DHW Energy efficiency category	A	A+
		UE 813/2013 (average climatic conditions)	
9	SCOP (W35)	4,38	5,43
10	SCOP (W55)	3,21	4,00

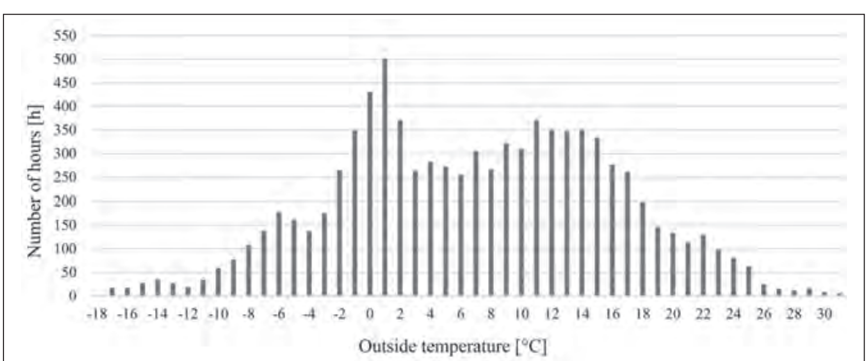

Fig. 1.
Number of hours per year at a given outside air temperature in Białystok [9]
Rys. 1. Liczba godzin w roku o danej temperaturze powietrza zewnętrznego w Białymstoku [9]

Heat pumps are equipped with the Vitotronic 200 weather-compensated controller with integral heating curves. The heating curves define the relationship between the supply water temperature t_f and the outside air temperature t_{out}. Five heating water temperatures are considered: 35, 40, 45, 50 and 55°C. Heating curves are selected for each water temperature so that under the design conditions of the outside air (t^d_{out} =-22°C) the heat pump delivers water at a required temperature. The lowest heating water temperature is assumed of 25°C. It should be noted that according to the heating curve and outside air temperature values for a statistical year [9], the set water temperature will rarely be reached. This can be observed from the frequency of occurrence of the specified outside air temperature per year shown in Figure 1. The design outside air temperature for the city of Białystok (-22°C) in a statistical year does not occur.

Based on the producer data, the equations describing the individual heating curves (1)-(5) are determined, for which the linear correlation coefficients R^2 are respectively:

– water temperature $t_f = 35°C$, formula (1):

$$t_f = -6 \cdot 10^{-5}\, t^3_{out} - 0{,}0008 t^2_{out} - 0{,}2618 t_{out} + 28{,}984;\ R^2 = 0{,}997, \quad (1)$$

– $t_f = 40°C$, formula (2):

$$t_f = -0{,}0001 t^3_{out} - 0{,}0024 t^2_{out} - 0{,}3537 t_{out} + 31{,}873;\ R^2 = 0{,}999, \quad (2)$$

– $t_f = 45°C$, formula (3):

$$t_f = -0{,}0001 t^3_{out} - 0{,}0024 t^2_{out} - 0{,}4537 t_{out} + 34{,}873;\ R^2 = 0{,}999, \quad (3)$$

– $t_f = 50°C$, formula (4):

$$t_f = -0{,}0002 t^3_{out} - 0{,}0032 t^2_{out} - 0{,}6155 t_{out} + 35{,}857;\ R^2 = 0{,}999, \quad (4)$$

– $t_f = 55°C$, formula (5):

$$t_f = -0{,}0002 t^3_{out} - 0{,}0044 t^2_{out} - 0{,}6808 t_{out} + 40{,}27;\ R^2 = 0{,}999, \quad (5)$$

where:

t_{out} – the outside air temperature [°C].

Equations (1)-(5) are used to determine the heating water temperature for each hour of the heating season. Then, the hourly heat demand of the building P_h is determined (6) [10]:

$$P_h = Q_L \frac{t_{in} - t^h_{out}}{t_{in} - t^d_{out}}\ [kW] \quad (6)$$

where:

Q_L – design heat load of the building for design outside air temperature in Białystok [kW],

t_{in} – design internal temperature in the room $t_{in} = 20°C$,

t^d_{out} – design outside temperature for Białystok $t^d_{out} = -22°C$,

t^h_{out} – the outside temperature in the hour under consideration [°C].

The producer [14][15] provides values for heating power and electricity consumption of the heat pumps for specific operating parameters. For a ground source heat pump, these are the temperatures of the brine (-10 – 25°C) and the heating water (35-65°C). For an air source heat pump, these are the outside air temperature (-20-30°C) and the heating water temperature (35-60°C). Based on the producer data, the heating power and electricity consumption of the heat pump for each hour of the heating season is determined by interpolation. The heating power of the air source heat pump included a 9kW electric heater which is used as a second heat source when the outside air temperature is lower than the assumed bivalent temperature.

Based on the electricity consumption and the heat output of the pump, the seasonal performance factor of the pump SCOP (7) is determined [10].

$$SCOP = \frac{\sum_{i=1}^{5592} P_{hi} \cdot \tau_i}{\sum_{i=1}^{5592} W_{hi}}\ [kWh] \quad (7)$$

where:

P_{hi} – heat output of the heat pump in the hour of the heating season [kW],

τ_i – operating time of the heat pump in a given hour of the heating season [h],

W_{hi} – electricity consumption of the heat pump in the analysed hour of the heating season [kWh],

5592 h – number of hours in the heating season.

Determining the electricity consumption of the heat pump for each hour of the heating season makes it possible to calculate electricity costs broken down by specific days and hours. This allows the calculation of electricity consumption according to the three electricity tariffs offered by PGE: G11, G12 and G12w [8].

The G11 tariff assumes one electricity rate per day. The G12 tariff applies a division into day and night zones, for which active energy charges are different. In the G12w tariff, as in the G12 tariff, there is a division into day and night zones, and additionally, the night zone lasts on Saturdays, Sundays and public holidays. In the weekend tariff G12w, it was necessary to assume which days in the heating season will be treated as Saturdays and Sundays. Thus it was assumed that 1 January falls on a Monday. Details of the tariffs are shown in Table 2.

$$C = \sum_{i=1}^{n} C_{vneti} \cdot E_i + \sum_{i=1}^{n} C_{Ei} \cdot E_i + C_{cnet} \cdot m + C_q \cdot E + C_t \cdot m + C_{RES} \cdot E + C_{co} \cdot E + C_p \cdot m + C_{sub} \left(\frac{zł\,net}{year}\right) \quad (8)$$

where:

C – cost of electricity [PLN/settlement period],

C_E – fee for active electricity in a given billing zone [PLN/kWh],

C_{cnet} – fixed network fee [PLN/month],

C_{vnet} – variable network fees in a given billing zone [PLN/kWh],

E_i – the amount of electricity taken from the grid in a given billing zone [kWh],

E – the amount of electricity taken from the grid by the user [kWh],

n – number of time zones where electricity is consumed [-],

C_q – quality fee [PLN/kWh],

m – the number of months for which the charge for electricity consumption is billed [-],

C_t – transition fee [PLN/month],

C_{RES} – renewable energy sources fee [PLN/MWh],

C_{co} – cogeneration fee [PLN/MWh],

C_P – power fee [PLN/month],

C_{sub} – subscription fee [PLN].

Results and discussion

The SCOP values (Figure 2) show significant variation depending on the heat pump type and the operational parameters. A significant difference is observed between the SCOP for a ground source heat pump (COP up to 5,36) and an air source heat pump (COP up to 3,80). This is due to the different temperatures of the low-temperature energy source. The ground temperature is more stable and is higher than the outside air temperature in winter.

In an air source heat pump, it is important to correctly choose a bivalent temperature at which the heat pump stops operating and a second heat source is switched

Table 2. Characteristics of electricity tariffs [8]

Tabela 2. Charakterystyka taryf energii elektrycznej [8]

Tariff	G11	G12		G12w	
zone	24/7	day-time	night-time	day-time	night-time
hours	24 h	6.00-13.00 15.00-22.00 (winter season) 6.00-15.00 17.00-22.00 (summer season)	22.00-6.00 13.00-15.00 (winter season) 15.00-17.00 (summer season)	6.00-13.00 15.00-22.00 (winter season) 6.00-15.00 17.00-22.00 (summer season)	22.00-6.00 13.00-15.00 (winter season) 15.00-17.00 (summer season) + Saturdays, Sundays and public holidays
net active energy price	0,4295 PLN/kWh	0,4901 PLN/kWh	0,3082 PLN/kWh	0,5068 PLN/kWh	0,3548 PLN/kWh

The total cost of electricity consists of a fee for active energy and fees related to the distribution of electricity. Distribution fees consist of renewable energy sources fee, co-generation fee, quality fee, variable and fixed network fees, transitional fee, subscription fee, commercial fee and fixed power fee (8) [8]. The rates of these fees are determined by PGE Dystrybucja for each tariff and the location of the electricity consumption site. The calculations include fees for Białystok Branch [8].

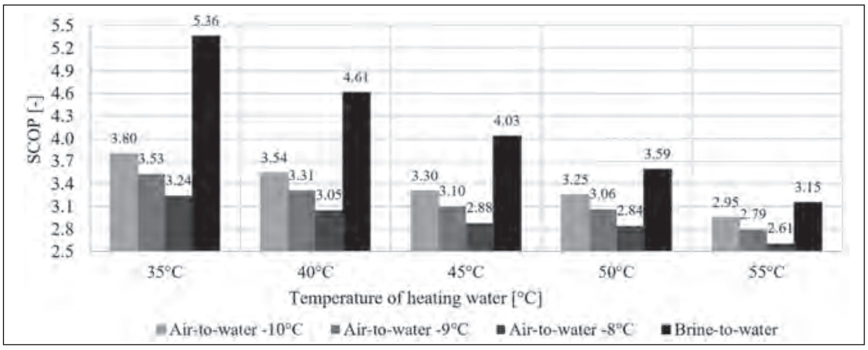

Fig. 2.
SCOP for the variable temperature of low-temperature heat source and heating water temperature – air source and ground source heat pump
Rys. 2. Współczynnik SCOP dla zmiennej temperatury górnego i dolnego źródła ciepła – pompa powietrzna i gruntowa

on. In the mono-energetic operating mode, an electric heater is the additional heat source. The higher the bivalent temperature, the greater the contribution of the heater to the building heating and the lower the SCOP. When the bivalent temperature changes by 1K, coefficient SCOP decreases by a value of 0,16-0,29 depending on the heating water temperature. For example, increasing the bivalent temperature from – 10 to – 9°C reduces the SCOP from 3,54 to 3,31 for a heating water temperature of 40°C, and from 2,95 to 2,61 for a water temperature of 55°C. The higher the heating water temperature, the smaller the effect of the bivalent temperature on the SCOP decrease.

The SCOP value is highly dependent on the heating water temperature: the higher the temperature, the lower the SCOP. Especially for an air source heat pump with a low SCOP, the choice of water temperature significantly influences the sense of using it. A water temperature greater than or equal to 45°C with an assumed bivalent temperature of – 10°C to – 8°C results in a SCOP<3,30. For a ground source heat pump, the SCOP value is lower than 3,20 only for a water temperature of 55°C. For the temperatures in the range of 35-50°C, it is higher than 3,59.

Table 2 summarises the electricity consumption for the different tariffs. The electricity consumption for the two-zone tariffs is divided into night and day-time. In the G12 tariff, electricity consumption in the night and day zones is at a similar level, the difference is 3-6% for the air source pump and about 9% for the ground source pump. In the G12w tariff, which additionally includes Saturdays, Sundays and public holidays, the difference between the electricity consumption in the day and night zone is significant. The electricity consumption in the day zone is almost twice as low as in the night zone.

A summary of electricity costs according to the three electricity tariffs is shown in Figures 3-6. All costs are quoted exclusive of tax (net values only).

Table 2. Electricity consumption of the heat pumps at different electricity tariffs
Tabela 2. Zużycie energii elektrycznej przez pompy ciepła w różnych taryfach energii elektrycznej

Heat pump	Water temp. [°C]	Electricity consumption [kWh/heating season]				
		G11	G12		G12w	
		24 h	day-time	night-time	day-time	night-time
Air-to-water t_{biv}=-10°C	35	3488	1690	1798	1233	2255
	40	3707	1805	1902	1315	2392
	45	3944	1929	2015	1405	2539
	50	4017	1967	2050	1435	2582
	55	4358	2148	2210	1564	2794
Air-to-water t_{biv}=-9°C	35	3781	1837	1944	1363	2418
	40	3998	1951	2047	1445	2553
	45	4232	2073	2158	1533	2699
	50	4303	2111	2193	1563	2740
	55	4639	2288	2350	1689	2950
Air-to-water t_{biv}=-8°C	35	4123	2004	2119	1507	2616
	40	4338	2117	2221	1588	2750
	45	4570	2239	2331	1676	2894
	50	4640	2275	2365	1705	2935
	55	4970	2450	2520	1829	3141
Brine-to-water	35	1894	987	907	675	1219
	40	2206	1150	1056	785	1421
	45	2529	1318	1211	900	1629
	50	2847	1483	1364	1013	1834
	55	3244	1690	1554	1155	2089

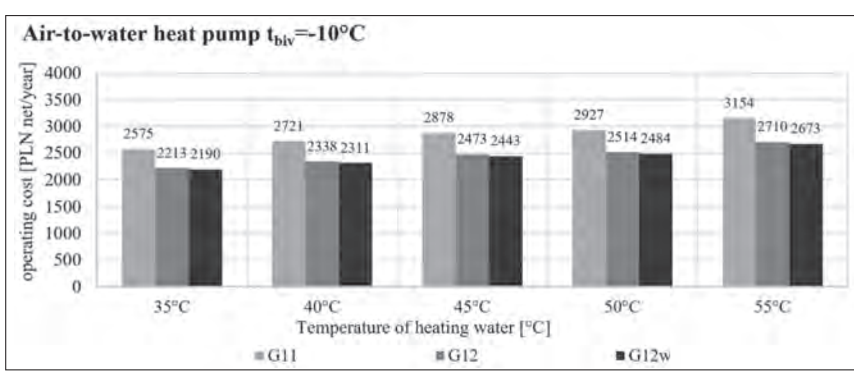

Fig. 3.
Operating costs for air source heat pump for the bivalent temperature of t_{biv}=-10°C
Rys. 3. Koszty eksploatacyjne powietrznej pompy ciepła dla temperatury biwalentnej t_{biv}=-10°C

The most expensive solution is the 24/7 G11 tariff. The operating costs of an air source heat pump on a G11 tariff are 16-17% higher than on a G12 tariff and 17-18% higher than on a G12w tariff. The operating costs for a ground source heat pump on a G11 tariff are 11-13% higher than on a G12 tariff and 14-17% higher on a G12w tariff. This corresponds to annual savings of 361-512 PLN for an air source pump and 153-351 PLN for a ground source pump. Lower differences in costs occur at the lowest analysed heating water temperature (35°C). The higher the water temperature, the greater the difference in operating costs between the tariffs.

The cost of electricity in the G12 and G12w tariffs is at a similar level, despite the significant difference in electricity consumption in the night and day zones. This is due to higher active energy fees and higher network variable fees in the G12w tariff compared to the G12 tariff. The operating costs for an air source heat pump using the G12w tariff are approximately 1% lower than the costs in the G12 tariff, which corresponds to 12-36 PLN per year. In a ground source pump, the difference is about 3%, which corresponds to 35-65 PLN.

The effect of the heating water temperature on the operating costs of the heat pump is noticeable. In an air source heat pump a 5°C change in the water temperature

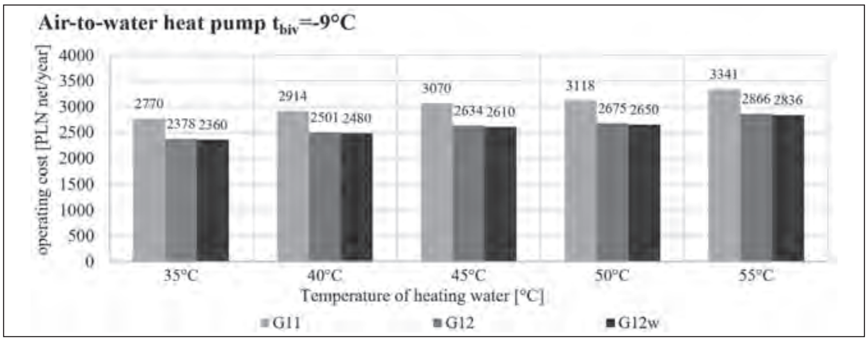

Fig. 4.
Operating costs for air source heat pump for the bivalent temperature of t_{biv}=-9°C
Rys. 4. Koszty eksploatacyjne powietrznej pompy ciepła dla temperatury biwalentnej t_{biv}=-9°C

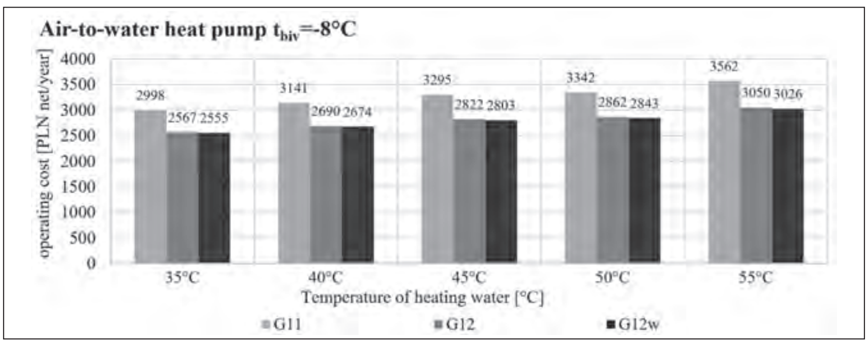

Fig. 5.
Operating costs for air source heat pump for the bivalent temperature of t_{biv}=-8°C
Rys. 5. Koszty eksploatacyjne powietrznej pompy ciepła dla temperatury biwalentnej t_{biv}=-8°C

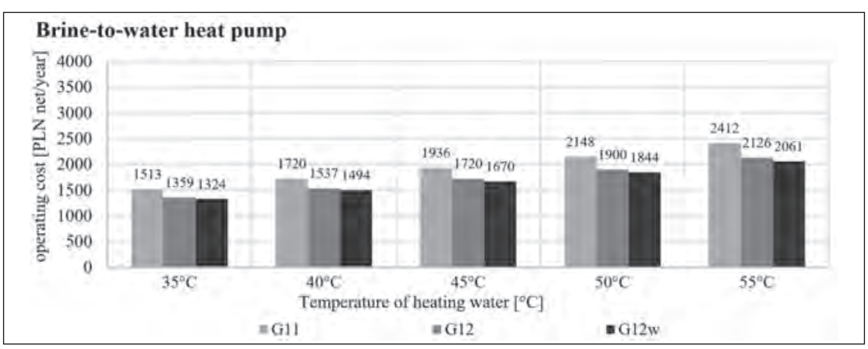

Fig. 6.
Operating costs for ground source heat pump
Rys. 6. Koszty eksploatacyjne gruntowej pompy ciepła

results in a 5-7% increase in operating costs, which corresponds to 143-227 PLN per year. An exception is a change in temperature from 45 to 50°C which increases costs by 2% (49 PLN). This is due to the heating characteristics of the pump for this temperature range. For the ground source pump, an increase in the water temperature by 5°C causes an increase in costs by 11-14%, which corresponds to 208-265 PLN. This means that the use of a low-temperature heating system (35°C) compared to a medium-temperature system (55°C) results in an increase in annual operating costs depending on the electricity tariff for an air source pump by 18-23% (470-580 PLN), and for a ground source pump by 56-59% (737-899 PLN).

Changing the bivalent temperature by 1°C results in an increase in the operating costs of the air source pump by 6-8%, which corresponds to 157-228 PLN per year depending on the electricity tariff.

Summary

The operating costs of heat pumps depend on the type of pump (air source, ground source) and the operating parameters of the heating system: the temperature of the heating water and the bivalent temperature. The lowest operating costs are ensured with a ground source heat pump. With an air source heat pump operating in monoenergetic mode, it is important to choose the bivalent temperature at which the second heat source switches on. The lower the bivalent temperature, the lower the operating costs. When selecting the value of the bivalent temperature, it must not be too low. Otherwise, the heat pump will have to be oversized in order to provide the required heat output. This results in high investment costs and low system efficiency. The lowest operating costs occur at low heating medium parameters. It is recommended to use heat pumps with surface heating systems which ensure high heat pump efficiency, low operating costs and large water capacity of the system (no additional heat buffer).

The most favourable electricity tariff is the weekend tariff G12w. For heating the building, the 24-hour tariff G11 with equal charges during the day and night is not recommended.

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