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Analysis of CO_2 emissions in the context of the application of selected heat pumps in fossil-fuel-based power systems

Abstract: In the context of the global increase in energy demand and the progressive depletion of fossil fuel resources, there is a noticeable intensification of efforts aimed at reducing the use of non-renewable raw materials in favor of developing and implementing technologies based on renewable energy sources. This study presents the potential of heat pumps as an efficient and sustainable tool for acquiring thermal energy within heating, ventilation, and domestic hot water systems. The analysis focused on various types of lower heat sources, considering their energy performance characteristics and availability under the climatic and geographical conditions of Poland. Variants of heat pump integration with selected renewable energy carriers-ambient air, ground, and surface or groundwater were considered. Particular attention was given to two configurations of ground heat exchangers: systems with vertical borehole probes and those employing horizontal ground collectors. A well-established methodology for calculating the seasonal demand for useful energy was applied, enabling the determination of final and primary energy consumption for each analyzed scenario, including auxiliary energy demand. Subsequently, the carbon dioxide emissions generated by each considered variant were evaluated and compared with the emissions resulting from the operation of conventional heat sources – a gas boiler and district heating. The obtained results allow

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for the identification of the most energy-efficient and environmentally beneficial configurations, highlighting the advantages of ground-source systems over air-source solutions under Polish climatic conditions.

Keywords: heat pump, carbon dioxide emission, renewable energy sources, ground heat exchanger

1. Preface

At present, the vast majority of energy used in the industrial sector originates from fossil fuels, which constitute key yet non-renewable sources of primary energy. The reserves of these resources are finite, and their continuous exploitation leads to a systematic depletion of available deposits, which, in the coming decades, may result in their complete exhaustion. At the same time, a steady increase in the costs of extracting energy resources is observed, accompanied by a growing global demand, particularly in countries undergoing rapid economic development. This situation consistently contributes to the rising prices of energy obtained from conventional sources. Due to increasingly stringent regulations aimed at reducing greenhouse gas emissions, particularly carbon dioxide, many countries are implementing energy transition strategies designed to significantly increase the share of energy generated from renewable and low-emission sources (Lee et al. 2006; Park and Kim 2022; Rabczak 2012).

Non-conventional primary energy carriers represent an independent category of energy acquisition methods. This group includes both hydropower and broadly defined renewable energy sources (RES), encompassing, among others, solar radiation energy, wind kinetic energy, geothermal resources, tidal and wave energy, as well as other forms of energy that can be recovered through cyclical and renewable processes (Jeong et al. 2025).

One of the key objectives of the European Union's climate and energy policy was to achieve a 20% share of renewable energy sources (RES) in the gross final energy consumption by 2020. In Poland, a less ambitious target was adopted: 15% by 2020, with a projected increase to 42.5% by 2030. Despite the dynamic development of the RES sector, its share in the global structure of primary energy production remains relatively low (Kim et al. 2022; EU 2023/2413).

2. Alternative power sources

Currently, hydropower plants account for approximately 20% of global electricity production. This generation is based on the utilization of the kinetic energy of flowing rivers or the potential energy resulting from the height difference between a watercourse and a reservoir. An alternative approach involves the conversion of energy contained in the movements of ocean water masses (Killingtvei 2019; Moran et al. 2018).

Wind energy has been utilized in Europe since the Middle Ages, primarily in windmills for mechanical applications such as grain milling and water pumping; however, its use for electricity generation began in the 19th century. Rapid development has occurred only in recent decades. Wind turbines are typically located in areas characterized by strong and consistent wind conditions – particularly in elevated terrains, mountain passes, and coastal zones. According to industry-level assessment, average annual wind speeds at hub height of approximately 6.5 m/s (23.4 km/h) are considered the minimum for commercial viability of wind power installations (Center for Sustainable Systems 2025).

Solar radiation energy is utilized in three principal forms:

- photovoltaic conversion, implemented through PV modules,
- photothermal conversion, employing solar collectors for heat generation,
- indirect solar energy conversion, applied, for instance, in solar furnaces and industrial processes (De León-Ruiz 2021; Sawicka-Chudy et al. 2016).

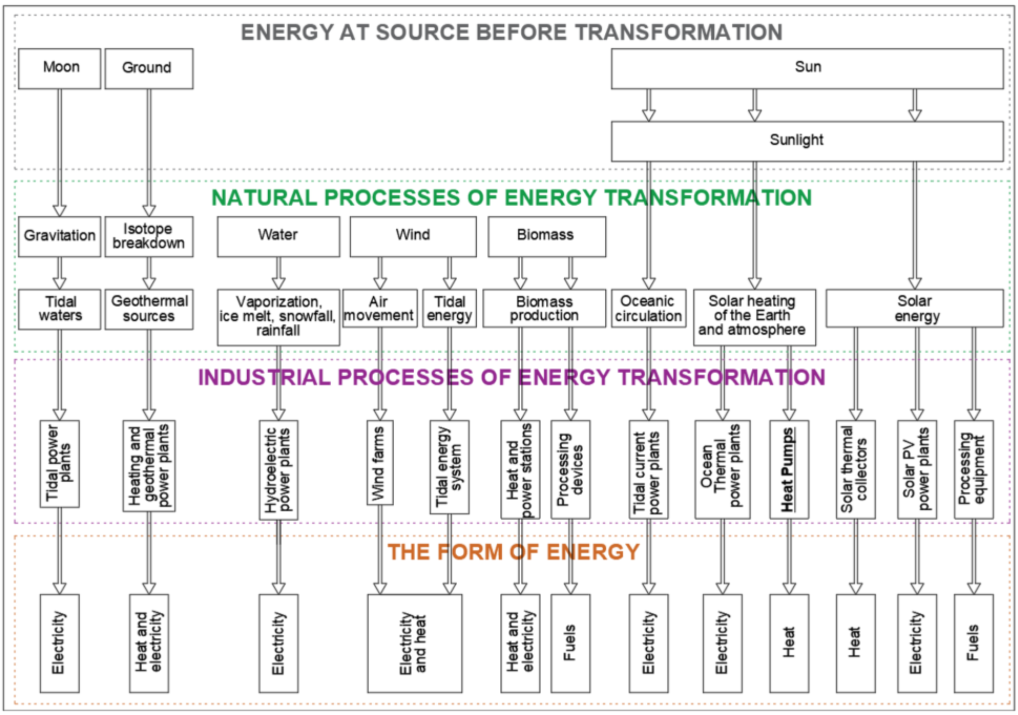

Fig. 1. Classification of alternative energy sources (own elaboration)

Rys. 1. Klasyfikacja niekonwencjonalnych źródeł energii

The main limitations of solar technologies include their dependence on solar radiation intensity and the inability to generate energy during nighttime, which highlights the critical importance of efficient energy storage systems. Biomass constitutes a carrier of solar energy stored through the process of photosynthesis. Although carbon dioxide is emitted during its combustion, this effect is balanced by the reabsorption of CO_2 by plants. While biomass is regarded as a renewable and environmentally friendly energy source, in practice only about 7% of its total energy potential is currently utilized (Kim et al. 2022).

Geothermal energy represents a form of endogenous energy originating from the Earth's interior – both from the residual heat of the planetary core (so-called primordial heat) and from energy released through the radioactive decay of isotopes such as potassium (K), uranium (U), and thorium (Th). Additionally, a portion of this heat derives from the absorption of solar radiation by the surface layers of the lithosphere. The ground temperature increases on average by 1°C for every 30–50 meters of depth. This energy can be utilized either directly, for example, through natural thermal springs, or indirectly, using closed-loop heat exchange systems. Its wider application, however, is limited by the relatively high investment costs associated with the installation infrastructure (Chwieduk 2025).

Nuclear energy is generated through the controlled fission process of uranium atomic nuclei, primarily of the U-235 isotope. Uranium is classified as a radioactive heavy metal and occurs naturally on Earth mainly in two isotopic forms: U-238 and U-235. Uranium ore is extracted both through open-pit mining and underground mining methods. The extraction process requires the removal and processing of large quantities of rock material. After mining, the uranium ore is crushed and subsequently treated with sulfuric acid to extract uranium. The extracted element, known as "yellowcake" (uranium concentrate), is filtered and dried. The prepared material is then subjected to enrichment in the U-235 isotope. The resulting enriched uranium, in the form of uranium dioxide (UO_2) – commonly referred to as "brown powder" – contains between 3% and 5% of the U-235 isotope and serves as fuel for nuclear reactors. In the subsequent processing stage, it is formed into pellets with a diameter of approximately 1 cm and a thickness of 1.5 cm, which are then placed into thin–walled tubes to form so-called fuel rods. The fission of U-235 nuclei releases large amounts of energy, which is used to generate electricity in nuclear power plants. This reaction produces substantial thermal energy, which is utilized to generate steam that drives generator turbines. Among the key challenges of nuclear technology remain the high radioactivity of nuclear waste and the significant costs associated with the extraction and processing of nuclear fuel (Piegdoń et al. 2018; Zhan et al. 2021).

According to data published by Statistics Poland, renewable energy sources accounted for 17.7% of gross final energy consumption within the national energy balance structure, while their share in electricity consumption exceeded 30%. The main renewable energy sources used include biomass, biogas, and hydropower. Despite the dynamic development of the renewable energy sector, hard coal continues to hold a dominant position. Although it supports energy security, it remains inconsistent with climate policy objectives. Wind power installations are gaining increasing importance, particularly in the central and southern regions of Poland (GUS 2025).

3. Methodology for preparing energy performance certificates

The energy performance calculations for the reference single-family building, the results of which are presented in Chapter 4, were carried out in accordance with the methodology currently in force in Poland, as specified in Journal of Laws 2023, item 697. The procedure is based on the annual energy balance of the building under standardized operating conditions and includes the determination of useful energy (EU), final energy (EK), and non-renewable primary energy (EP). In addition, one of the key indicators considered in this study is the associated CO_2 emission level.

The calculation of energy performance indicators requires the determination of annual energy demands. Among these, the annual useful energy demand for domestic hot water preparation, denoted as $Q_{W.nd}$, constitutes one of the fundamental components (Equation 1).

$$Q_{W.nd} = \frac{V_{Wi} \cdot A_f \cdot c_w \cdot \rho_w \cdot (\theta_w - \theta_0) \cdot k_R \cdot t_R}{3{,}600} \left[\frac{\text{kWh}}{\text{year}}\right] \tag{1}$$

where:

- V_{Wi} – specific daily demand for domestic hot water per unit of usable floor area [dm^3/m^2·day],
- $c_w = 4.19$ – specific heat capacity of water [kJ/(kg·K)],
- $\rho_w = 1000$ – water density [kg/m^3],
- $\theta_w = 55$ – temperature of the supplied domestic hot water [°C],
- $\theta_w = 10$ – temperature of incoming cold water [°C],
- k_R – correction coefficient accounting for intermittent building operation [–],
- t_R – annual number of days during which the domestic hot water system is in operation [day/year].

The result obtained from Equation (3.1) serves as the basis for determining the final annual useful energy demand for domestic hot water preparation, denoted as $Q_{K.HW}$ (Equation 2). These demand values directly influence both the total final energy consumption and the overall useful energy demand of the building.

$$Q_{K.HW} = \frac{Q_{W.nd}}{\eta_{w.DHW}} \left[\frac{\text{kWh}}{\text{year}}\right] \tag{2}$$

where:

- $Q_{W.nd}$ – annual heat demand for space heating and ventilation of the building [kWh/year],
- $\eta_{w.DHW}$ – average annual overall efficiency of the domestic hot water preparation system [–].

Another energy component required for the determination of energy performance indicators is the annual useful energy demand for space heating and ventilation, denoted as $Q_{H.nd}$. This value is calculated as the sum of the monthly useful energy demands $Q_{h.nd.s}$ over the entire year. Subsequently, the annual final energy demand of the heating system $Q_{K.HP}$ is determined analogously to Equation 2, applying the overall efficiency of the heating system. The corresponding relationships are presented in Equations 3 and 4.

$$Q_{h.nd.s} = Q_{h.ht.s} - Q_{h.gn.s} \cdot \eta_{h.gn.s} \left[\frac{\text{kWh}}{\text{month}} \right] \tag{3}$$

$$Q_{K.HP} = \frac{Q_{H.nd}}{\eta_{H.CO}} \left[\frac{\text{kWh}}{\text{year}} \right] \tag{4}$$

where:

- $Q_{H.nd}$ – annual heat demand for space heating and ventilation of the building [kWh/year],
- $\eta_{H.CO}$ – product of the average seasonal efficiencies of the subsystems constituting the overall heating system [–],
- $Q_{h.ht.s}$ – total heat transfer from the heated zone during a given month [kWh/month],
- $Q_{h.gn.s}$ – total heat gains within the heated zone in a given month [kWh/month],
- $\eta_{h.gn.s}$ – heat gain utilization factor for the heated zone in a specific month [–].

The above equations constitute the basis for determining the annual energy performance indicators. In each case, the calculated energy demand must be related to the conditioned floor area, i.e., the heated or cooled usable area of the building. Since the case study presented in this paper concerns the heating season, the analysis and the formulation of the following equations focus primarily on heating-related energy demand.

$$EP = \frac{Q_{P.H} + Q_{P.W} + Q_{P.L}}{A_f} \left[\frac{\text{kWh}}{\text{m}^2 \cdot \text{year}} \right] \tag{5}$$

$$EK = \frac{Q_{K.HP} + Q_{K.HW} + Q_{K.L} + E_{el.pom}}{A_f} \left[\frac{\text{kWh}}{\text{m}^2 \cdot \text{year}} \right] \tag{6}$$

$$EU = \frac{Q_{H.nd} + Q_{W.nd}}{A_f} \left[\frac{\text{kWh}}{\text{m}^2 \cdot \text{year}} \right] \tag{7}$$

where:

- EP – annual non-renewable primary energy demand per unit of conditioned floor area [kWh/(m^2·year)],
- EK – annual final energy demand per unit of conditioned floor area [kWh/(m^2·year)],

EU	–	annual useful energy demand per unit of conditioned floor area [kWh/(m^2·year)],
A_f	–	heated (conditioned) floor area [m^2],
$Q_{P.H}$	–	annual non-renewable primary energy demand for space heating [kWh/year],
$Q_{P.W}$	–	annual non-renewable primary energy demand for domestic hot water preparation [kWh/year],
$Q_{P.L}$	–	annual non-renewable primary energy demand for lighting [kWh/year],
$Q_{K.L}$	–	annual final energy demand for lighting [kWh/year],
$E_{el.pom}$	–	annual final auxiliary electricity demand for technical building systems [kWh/year].

The specific carbon dioxide emission indicator included in the energy performance certificate is determined on the basis of the annual final energy demand associated with individual energy carriers used in the building. The calculation procedure consists of applying appropriate CO_2 emission factors to the quantities of final energy consumed by the building's technical systems.

The total annual CO_2 emission is obtained as the sum of partial emissions resulting from space heating, ventilation, domestic hot water preparation, cooling and built-in lighting. The resulting value is subsequently related to the conditioned usable floor area, enabling the determination of the specific emission indicator expressed in t CO_2//(m^2·year).

$$E_{CO_2} = \frac{E_{CO_2.H} + E_{CO_2.W} + E_{CO_2.H} + E_{CO_2.L} + E_{CO_2.pom}}{A_f} \left[\frac{\text{t CO}_2}{\text{rok}}\right] \tag{8}$$

where:

$E_{CO_2.H}$	–	annual E_{CO_2} emissions generated from fuel combustion for space heating purposes [t CO_2/year],
$E_{CO_2.W}$	–	annual E_{CO_2} emissions resulting from fuel combustion for domestic hot water preparation [t CO_2/year],
$E_{CO_2.L}$	–	annual E_{CO_2} emissions associated with energy use for lighting systems [t CO_2/year],
$E_{CO_2.pom}$	–	annual E_{CO_2} emissions related to auxiliary energy consumption within technical building systems [t CO_2/year].

4. Evaluation of the performance of renewable energy sources integrated with a heat pump

For the purpose of analyzing the efficiency of final, primary, and auxiliary energy consumption, a typical single-family building with a floor area of 120 m^2, located in the Podkarpackie Voivodeship, was adopted. The demand for final energy for the heating system, natural ventilation, and domestic hot water (DHW) was determined based on the methodology consistent with that applied in the preparation of a building energy performance certificate.

Four variants of heat pump cooperation with alternative heat sources were compared. The analysis considered four configurations of heat pump operation in conjunction with renewable heat sources. The examined variants included the following systems: atmospheric air – AHP (air-source heat pump); ground – GHPH (ground-source heat pump with a horizontal heat exchanger); ground – GHPV (ground-source heat pump with a vertical heat exchanger); and water – WHP (system utilizing an extraction and absorption well). The variants were compared for the heating season, with the outdoor air temperature ranging from +12°C to –18°C, based on data obtained from the Rzeszów–Jasionka meteorological station. An identical internal installation was assumed for all analyzed variants.

Based on the calculated heat demand for space heating and domestic hot water (DHW) preparation, appropriate heat pump capacities were selected, and the coefficient of performance (COP) was determined for each system. Assuming a household of four occupants, the reduced heat demand for DHW preparation was set at Q_{HW} = 3.84 kW, with a storage tank capacity of V_{HW} = 120 liters. The heat demand for space heating and ventilation was determined as Q_H = 12.2 kW. For ground-source heat pumps and the system cooperating with extraction and absorption wells, the total heat pump capacity was determined by considering both space heating and DHW demand, assuming a 6-hour regeneration period required to restore the thermal properties of the ground. Consequently, the heat pump capacity was established at Q_{HP} = 16.5 kW.

In contrast, for the air-to-water heat pump, regeneration of the lower heat source is not required. Therefore, its nominal capacity was selected based solely on the design space-heating demand Q_{HP} = 12.2 kW, in accordance with the manufacturer's sizing guidelines (Dimplex 2025). The DHW demand in this case was included in the annual energy balance but did not determine the nominal capacity of the unit in order to avoid oversizing under design conditions.

All heat pumps were selected in accordance with the manufacturer's guidelines provided by Dimplex. The following models were applied:

- Type SI 18 TU B0W35 – for horizontal and vertical ground collectors,
- Type WI TU W10W35 – for systems utilizing groundwater from extraction and absorption wells,
- Type LA 17 TU A20W35 – for the air–to–water heat pump configuration (Dimplex 2025).

4.1. Energy efficiency coefficient

The ground temperature below a depth of 15 meters, where the vertical collector is installed, remains practically constant throughout the year at approximately 7°C. For this reason, the coefficient of performance (COP) for the ground-source heat pump remains stable at a level of 5.4. A similar situation occurs in systems utilizing groundwater, where the temperature in the well is also nearly constant year-round, averaging around 10°C. Consequently, the COP for the heat pump operating with a well remains comparable throughout the entire heating season, reaching 5.8.

In contrast, for a heat pump cooperating with a horizontal ground collector, the COP values are strongly dependent on outdoor air temperature. The air–source heat pump exhibits even greater fluctuations in COP as a function of outdoor temperature than systems using horizontal ground collectors (Chwieduk 2025; Rubik 2006). Figure 2 presents the variation of the COP depending on the applied configuration.

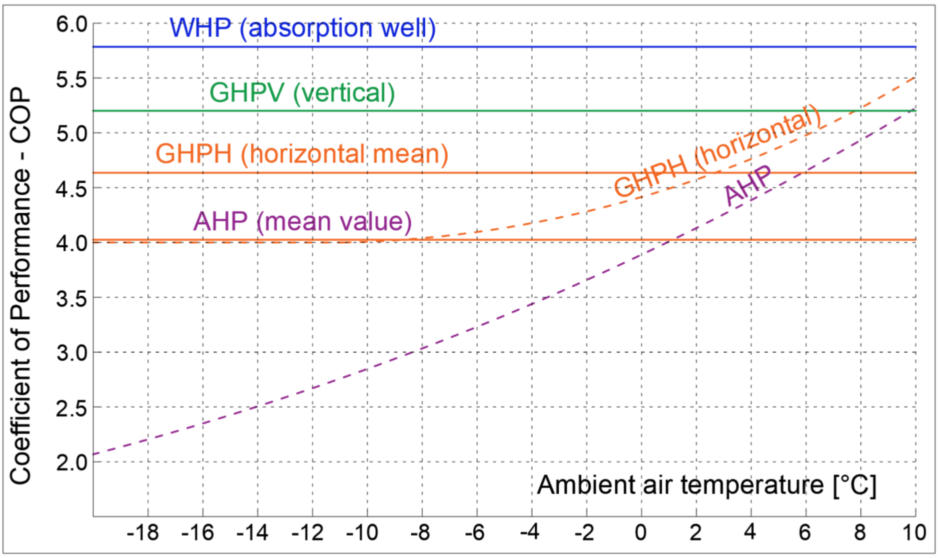

Fig. 2. Effect of ambient air temperature on COP values for various lower heat sources in heat pumps (own elaboration)

Rys. 2. Wpływ temperatury otoczenia na COP dla wybranych rodzajów dolnych źródeł ciepła

Since the procedure for calculating the final energy demand requires the adoption of a single representative value of the COP, an averaged value was used. A weighted average was applied, which is essential for heat pumps operating with ground-based (horizontal collector) or air-based heat sources. The calculations were performed based on the number of hours corresponding to individual COP values, which depend on the outdoor air temperature. Data on the frequency of specific temperature occurrences were obtained from statistical reports of the Rzeszów–Jasionka meteorological station (Rabczak and Proszak-Miąsik 2016; Kim et al. 2022). The results of these calculations are illustrated in Figure 2.

4.2. Final, primary and auxiliary energy

The overall system performance of the analyzed heat pump configurations was determined as the product of the efficiencies of control and utilization, distribution, storage, and the generation stage performance. It should be emphasized that the generation parameter is represented by the weighted average coefficient of performance (COP) and is not interpreted as thermodynamic efficiency.

Unlike efficiency, which is defined as the ratio of total energy output to total energy input, the COP expresses the ratio of useful heat delivered to the driving energy supplied to the compressor. Since the environmental heat extracted from air, ground, or water is not included in the denominator of the COP definition, COP values may exceed unity and therefore must not be treated as efficiency in the strict thermodynamic sense.

For the air-to-water heat pump, the storage efficiency was assumed to be equal to 1, which results from its continuous daily operation and the absence of thermal energy storage in the system. (Chwieduk 2025; PN-EN ISO 52016-1:2017).

Table 1. Types of heat pump configurations

Tabela 1. Rodzaje konfiguracji pomp ciepła

Efficiency component / Renewable source	Control system	Distribution	Storage	Generation	Seasonal performance factor
AHP	0.94	0.80	1.00	4.10	3.05
GHPH	0.94	0.80	0.97	4.60	3.35
GHPV	0.94	0.80	0.97	5.40	3.94
WHP	0.94	0.80	0.97	5.80	4.23

The term final energy refers to the amount of energy consumed during the heating season for space heating, ventilation, and domestic hot water preparation. This value was determined by dividing the useful energy by the overall system efficiency corresponding to the given type of heat source.

The values of auxiliary energy result from the operation of supporting devices, such as circulation pumps and components of the electrical control systems of the heating installation. It should be emphasized that heat pumps are compressor-based devices, which means they require an electricity supply in an amount dependent on the annual heat production and the seasonal performance factor (SPF). In this study, the SPF was assumed as the weighted average value of the COP, according to the data presented in Figure 2. The presented values reflect the actual operating costs of the building. Primary energy, on the other hand, represents the amount of energy derived from non-renewable sources necessary for the generation and delivery of final energy. Although it does not directly affect the operating costs borne by the end user, it serves as a key indicator in assessing carbon dioxide emissions associated with energy production and transmission processes. The comparison of final, primary, and auxiliary energy values is presented in Figure 3.

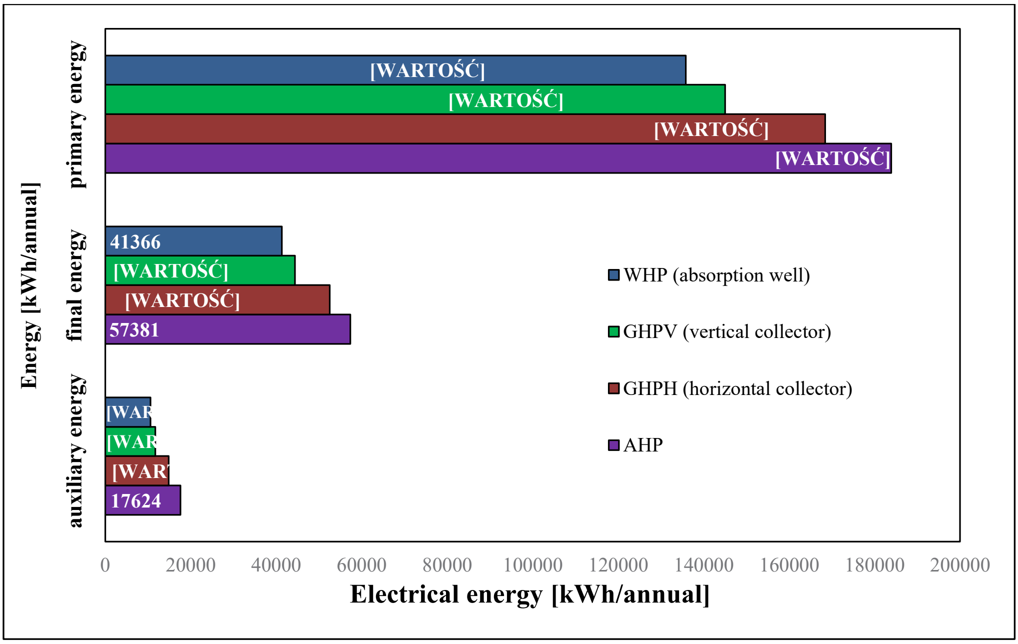

Fig. 3. Analysis of energy consumption in relations to the type of heat pump ground source (own elaboration)

Rys. 3. Analiza zużycia energii w zależności od rodzaju dolnego źródła pompy ciepła

The analysis presented in the figure indicates that the heat pump system operating with an absorption well is characterized by the lowest energy consumption. The highest demand is observed for the air-source heat pump, which, in turn, requires the lowest investment costs. For this reason, in practical applications, intermediate solutions are often implemented – systems based on horizontal ground collectors, which ensure moderate energy consumption at relatively low investment costs, significantly lower than those associated with vertical borehole systems or configurations using absorption wells.

4.3. Operating costs of the installation

The summary of operating costs is presented in Table 2. These values were calculated assuming an electricity tariff typical for a single-family building and a unit energy price of 0.90 PLN/kWh (Eurostat 2025). The final energy consumption was included in the total operating costs. In the case of compressor-type heat pumps, this represents the only expense incurred by the user, covering the electricity consumption required for the operation of the entire system, including the annual operating costs of the heat pump.

Table 2. Annual running costs [PLN/year]

Tabela 2. Koszty funkcjonowania systemu w ciągu roku [zł/rok]

Heat pump	Cost [PLN]
Air-source heat pump (AHP)	16,484
Ground-source heat pump with a horizontal ground heat exchanger (GHPH)	15,005
Ground-source heat pump with a vertical ground heat exchanger (GHPV)	12,764
Water-source heat pump using an absorption well (WHP)	11,884

The relationships presented in Table 2 remain consistent with the energy consumption results shown in Figure 3. This is characteristic of compressor-type heat pumps, in which the total thermal demand is supplied exclusively by electricity. In contrast, systems based on gas boilers or district heating networks operate differently, as part of the energy is generated through combustion processes. The analysis indicates that the efficiency of the lower heat source is inversely proportional to its availability – both in geological and technical terms.

Easily accessible heat sources are characterized by lower investment costs and simple installation; however, their efficiency is limited, resulting in higher operating expenses. In such cases, it is necessary to conduct an investment profitability analysis using indicators such as SPBT – Simple Payback Time, LCC – Life Cycle Cost, and NPV – Net Present Value. This approach enables a comprehensive assessment of the economic efficiency of the investment, taking into account both construction and system operating costs.

4.4. Emission of pollutants in the form of carbon dioxide into the atmosphere

Based on the conducted analyses, carbon dioxide (CO_2) emissions to the atmosphere were determined for the considered heating systems as well as for a system based on a condensing gas boiler. It was assumed that the electricity used originates from power plants fueled by solid fuels – lignite or natural gas. The unit CO_2 emission factors were adopted according to the methodology for preparing building energy performance certificates and amount to: 109.48 kg CO_2/GJ for lignite and 55.73 kg CO_2/GJ for natural gas (Rabczak 2016; KOBiZE 2024).

The type of heat source used in the building's heating system significantly affects the level of pollutant emissions into the atmosphere. The combustion of hard coal and lignite is associated with very high CO_2 emissions, whereas natural gas produces less than half of that amount. Biomass, in turn, results in negligible emissions, and its combustion process can be considered part of the closed carbon cycle, thereby reducing the negative environmental impact. Based on the literature data (Park and Kim 2012; Rabczak 2016), the calculated emission values are presented in Table 3.

TABLE 3. Annual CO_2 output for different ground and conventional heat sources [t CO_2/year]

TABELA 3. Roczny poziom emisji ditlenku węgla dla wybranych źródeł ciepła w systemach pomp ciepła i konwencjonalnych układach grzewczych [t CO_2/rok]

Fuel type / Type of system	Gas	Lignite
Air-source heat pump (AHP)	15.00	29.59
Ground-source heat pump with a horizontal ground heat exchanger (GHPH)	13.41	26.45
Ground-source heat pump with a vertical ground heat exchanger (GHPV)	11.23	22.11
Water-source heat pump using an absorption well (WHP)	10.43	20.49
Local gas furnace	5.36	10.54
District heating system	7.10	13.98

The analysis of several heating system variants indicates that systems commonly regarded as environmentally friendly – such as those utilizing ground collectors – do not always ensure low CO_2 emissions. This is primarily due to the high demand for electricity required for heat pump operation and the dependence of the results on the energy source used for electricity generation.

Electricity generation in coal-fired power plants produces significant carbon dioxide emissions. Although a heat pump does not emit CO_2 directly, it constitutes an indirect source of emissions resulting from the type of energy used to power the compressor. Actual emission reduction is achievable only when the electricity consumed originates from renewable sources such as biomass, biogas, or other renewable energy systems (Rabczak 2012; Lee et al. 2006).

5. Summary

Based on the conducted analyses and calculations, it was determined that the highest final energy consumption during the heating season occurs in the case of the air-source heat pump, whereas the lowest is observed for the heat pump operating with a well, which results from its stable and high coefficient of performance (COP = 5.8). For the air-source heat pump, the COP value varies throughout the heating season, depending on the outdoor air temperature.

Ground-source heat pumps exhibit relatively small differences between final and auxiliary energy demand, with the vertical ground collector being considered a more advantageous solution due to the stable ground temperature and a high COP of 5.4. In contrast, the horizontal ground collector system generates higher energy consumption; however, it offers lower investment costs and widespread practical applicability.

Operating costs are directly proportional to final energy consumption. The highest operating costs were observed for the air-source heat pump, approximately 10% higher than those of the horizontal ground collector system.

The CO_2 emission analysis was performed assuming electricity generation predominantly based on fossil fuels, representing a conservative emission scenario for the Polish power system. This assumption reflects the high carbon intensity of electricity during the heating season, when renewable generation – particularly photovoltaic – is reduced. Although the annual share of renewable energy sources in Poland reached approximately 27% in 2024, the adopted approach allows for assessing heat pump performance under high-emission conditions. Even when considering an increasing share of renewable electricity, the relative differences in CO_2 emissions between heat pump systems and conventional heat sources remain significant.

The Authors have no conflicts of interest to declare.

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Analiza emisyjności CO_2 w kontekście zastosowania wybranych pomp ciepła w systemach elektroenergetycznych opartych na paliwach kopalnych

Streszczenie

W obliczu globalnego wzrostu zapotrzebowania na energię oraz postępującego wyczerpywania się zasobów paliw kopalnych obserwuje się intensyfikację działań ukierunkowanych na ograniczenie wykorzystania surowców nieodnawialnych na rzecz rozwoju i wdrażania technologii opartych na odnawialnych źródłach energii. W niniejszym opracowaniu zaprezentowano potencjał wykorzystania pomp ciepła jako efektywnego narzędzia do pozyskiwania energii termicznej w kontekście systemów grzewczych, wentylacyjnych oraz przygotowania ciepłej wody użytkowej. Przedmiotem analizy były dolne źródła ciepła, z uwzględnieniem ich charakterystyki energetycznej oraz dostępności w warunkach klimatyczno-geograficznych Polski. Rozpatrzono warianty współpracy pomp ciepła z wybranymi odnawialnymi nośnikami energii: powietrzem atmosferycznym, gruntem oraz wodami powierzchniowymi lub gruntowymi. Szczególną uwagę poświęcono dwóm konfiguracjom wymienników gruntowych: układom z sondami pionowymi oraz kolektorami poziomymi. Zastosowano znaną w literaturze metodykę obliczania sezonowego zapotrzebowania na energię użytkową, umożliwiającą wyznaczenie zużycia energii końcowej oraz pierwotnej dla każdego analizowanego scenariusza wraz z uwzględnieniem energii pomocniczej. W dalszej części dokonano oceny emisji ditlenku węgla generowanej przez każdy z rozpatrywanych wariantów i przeprowadzono porównanie względem emisji wynikających z eksploatacji tradycyjnych źródeł ciepła – kotła gazowego oraz ciepła sieciowego. Uzyskane wyniki umożliwiają identyfikację najbardziej efektywnych energetycznie i korzystnych dla środowiska konfiguracji, podkreślając przewagę systemów gruntowych nad systemami powietrznymi w warunkach klimatycznych Polski.

Słowa kluczowe: pompa ciepła, emisja ditlenku węgla, odnawialne źródła energii, wymiennik gruntowy