

Article

Geothermal Heat Pumps and Their Impact on Building Energy Efficiency and Ecology

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Abstract

This article analyses the impact of ground-source heat pumps on the energy efficiency and environmental impact of a residential building, depending on the temperature of the ground source, the flow temperature of the heating system, and the domestic hot water temperature. In the section on heating, the best results were obtained for the 35/28 °C system at a ground temperature of 1 °C, for which the SCOP was 4.81, the system efficiency was 3.90, the final energy was 5.6 kWh/m²yr, and the primary energy was 13.9 kWh/m²yr. The least favourable heat pump heating option was recorded for the 55/48 °C system and a ground temperature of −1 °C, with a SCOP of 3.31 and a primary energy of 17.4 kWh/m²yr. For domestic hot water, the best results were achieved at a temperature of 47 °C and a ground temperature of 1 °C, for which the SCOP reached 3.88, and the primary energy was 23.6 kWh/m²yr, whereas the least favourable variant (55 °C/−1 °C) was characterised by a SCOP of 3.31 and primary energy of 27.5 kWh/m²yr. It was demonstrated that lowering the temperature on the upper-source side improves the system's energy performance to a greater extent than changes in ground temperature. At the same time, improvements in energy efficiency reduced pollutant emissions and lowered the equivalent emission ZrSO₂ index. The results confirm that the actual energy and environmental potential of ground-source heat pumps depend primarily on their integration with low-temperature systems.

Keywords: geothermal energy; ground-source heat pumps; energy efficiency; SCOP; primary energy; domestic hot water; environmental impact

1. Introduction

The compatibility of heat pump technology with the construction sector is not in doubt, demonstrating the market's maturity and its capacity to integrate geothermal technologies for heating and domestic hot water production. However, the operational efficiency of such solutions is particularly important, as it has a direct economic and environmental impact on investors. Whilst the economics of such investments are well understood within the energy sector, the environmental impacts still suffer from shortcomings in quantification and in-depth understanding.

The modern construction sector faces the challenge of simultaneously reducing energy consumption, cutting emissions, and increasing the share of renewable energy sources in buildings' energy balance. In this context, technologies that improve energy efficiency and reduce environmental impact are particularly important. The use of geothermal energy in residential construction, particularly in the form of geothermal (ground-source) heat pumps, is currently one of the most promising avenues for the energy transition of buildings. Ground-source heat pumps are recognised as among the most efficient technologies,



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as they utilise the relatively stable ground temperature and can achieve high seasonal efficiency in heating, cooling, and domestic hot water applications. Literature reviews indicate that systems of this type typically achieve COP values of 3–6, outperforming many conventional solutions and some air-source systems in terms of efficiency, particularly in temperate and cool climates [1–4]. At the same time, it is emphasised that their significance extends beyond energy consumption reduction, as this technology also supports the decarbonisation of the building sector and reduces dependence on fossil fuels [5,6]. An additional advantage is the possibility of integration with photovoltaic systems, which helps reduce the demand for grid-sourced electricity and lowers the non-renewable primary energy ratio. It should be borne in mind that useful, final, and primary energy indicators remain the fundamental metrics for the energy assessment of buildings in the European Union, and their interpretation is crucial for assessing a building's compliance with formal requirements and for comparing renovation options [6]. An important complement to the traditional energy assessment is the renewable energy share indicator, defined as the proportion of renewable energy in a building's total primary energy balance, which plays a significant role in assessing low-energy buildings [7].

From the perspective of the long-term energy transition, the 'energy efficiency first' principle is of particular importance; according to this principle, measures to reduce energy demand should precede or support the deployment of renewable energy sources, as lower and better-managed demand enhances the efficiency of the entire energy system [8,9]. However, the results of published studies clearly indicate that the efficiency of ground-source heat pumps is not constant but depends to a large extent on proper system selection for local conditions and the building's characteristics. Factors of significant importance include, amongst others, the thermal conductivity of the ground, the depth and configuration of the heat exchanger, groundwater flow, the building's load profile, and the required supply temperatures on the heat consumption side [10–12]. The literature also highlights the sensitivity of seasonal efficiency to the temperatures of the lower and upper sources, indicating that the actual energy performance is strongly dependent on the system design rather than solely on the choice of ground-source heat pump technology [3,13]. For this reason, comparative analyses that account for the different operating temperatures of the heating system and DHW preparation are of significant importance for both research and practical applications.

It is also increasingly recognised that the assessment of ground-source heat pumps should not be limited solely to energy performance indicators, but should also take into account environmental impacts throughout the system's entire life cycle [14]. Review studies and LCA analyses indicate that shallow geothermal technologies can significantly reduce greenhouse gas emissions and fossil fuel consumption; however, the scale of this benefit depends on the electricity mix powering the heat pump, as well as on the boundaries set for the environmental analysis [5,15–17]. This means that the same system may exhibit different environmental impacts depending on the country, region, and the degree of decarbonisation of the electricity sector. However, in this study, the environmental dimension is understood in a narrower, operational sense. The analysis is limited to emissions associated with electricity consumption during the use phase of the heat pump system, including CO₂ and the supplementary ZrSO₂ indicator. Therefore, the paper does not provide a full ecological or life-cycle assessment of the analysed variants. Its scope is restricted to a comparative evaluation of operational energy use and operation-related emissions under the adopted Polish boundary conditions.

In this context, it is appropriate to analyse final and primary energy alongside emission indicators, as only their combined consideration allows for a reliable assessment of the environmental impact of heat pump use. Despite clear environmental benefits, the literature

therefore calls for a cautious assessment of the risks associated with geothermal system operation, particularly in open-loop systems. Among the most frequently cited issues are the potential for changes in groundwater quality, local thermal effects in aquifers, and the need for the design to be closely adapted to hydrogeological conditions and regulatory requirements [5,18–20]. On the other hand, closed-loop systems are considered safer for the environment, though they still require proper sizing and long-term monitoring of operating parameters. This state of knowledge indicates that the development of ground-source heat pumps should be analysed not only through the prism of energy efficiency, but also through the prism of environmental safety and the quality of technical implementation.

Contemporary research into ground-source heat pumps increasingly encompasses issues relating to integration with automation, the Internet of Things (IoT), predictive methods, and hybrid systems, reflecting a shift in focus from the heat source itself towards the intelligent optimisation of the entire building system [1,21]. At the same time, the authors of numerous studies indicate that significant implementation barriers remain, relating to investment costs, the retrofitting of existing buildings, the heterogeneity of regulatory requirements, and the limited number of studies linking model results to actual operation under specific climatic and geological conditions [1,19,22]. This justifies the need for further research based on transparent comparisons of system operating variants, in which energy and environmental indicators are analysed in parallel, particularly for conditions corresponding to the realities of residential building operation.

The novelty of this study does not lie in demonstrating the already well-established thermodynamic principle that lower supply temperatures improve heat pump efficiency. Instead, its contribution consists of translating this known relationship into a building-level comparative framework that combines, within one consistent calculation procedure, (i) lower-source temperature, (ii) space-heating supply temperature, and (iii) domestic hot water temperature, and then traces their simultaneous effect on SCOP, total system efficiency, final energy, primary energy, electricity use, renewable energy share, and operational emissions. In this sense, the study goes beyond a simple parametric observation of heat pump behaviour and shows how changes in operating temperatures propagate into building energy performance indicators and environmental outcomes within a single regulatory and climatic context. The scientific motivation for combining these parameters is that, in practice, design and retrofit decisions are not made solely on the basis of SCOP, but on the combined effect of operating conditions on the overall energy and environmental performance of the building system. Therefore, the main contribution of the paper is methodological and application-oriented: it provides an integrated variant-based assessment for a real single-family house, separately for space heating and domestic hot water, and identifies which operating parameters have the strongest influence on the resulting building-level indicators.

2. Methodology

The study adopted a methodology based on assessing the energy efficiency and environmental impact of ground-source heat pumps. The aim of the analysis was to determine the final and primary energy values for selected configurations of heating and domestic hot water systems, and to estimate pollutant emissions into the atmosphere, enabling a parallel energy and environmental assessment of the variants under consideration.

2.1. Building's Model

The calculations were based on an existing single-family house located in southern Poland, in the Lesser Poland Voivodeship. An outdoor design temperature of $-20.0\text{ }^{\circ}\text{C}$ and an average annual outdoor air temperature of $7.6\text{ }^{\circ}\text{C}$ were assumed for the building.

The heated floor area of the building is 191.31 m², and the heated volume is 477.4 m³. In terms of construction materials and technical solutions, this is a typical single-family house built in accordance with current technical regulations. Outside temperatures are typical for the climate zone, which covers the largest area and is therefore the most representative of Poland as a whole. The building's energy performance accounts for design heat losses of 3284.0 kWh/yr through thermal transmittance and 1268.5 kWh/yr through ventilation, for a total of 4552.5 kWh/yr. The useful energy demand for heating and ventilation was assumed to be 2321.6 kWh/yr, whilst that for domestic hot water production was 4820.6 kWh/yr. The building model and basic structural information are shown in Figure 1.

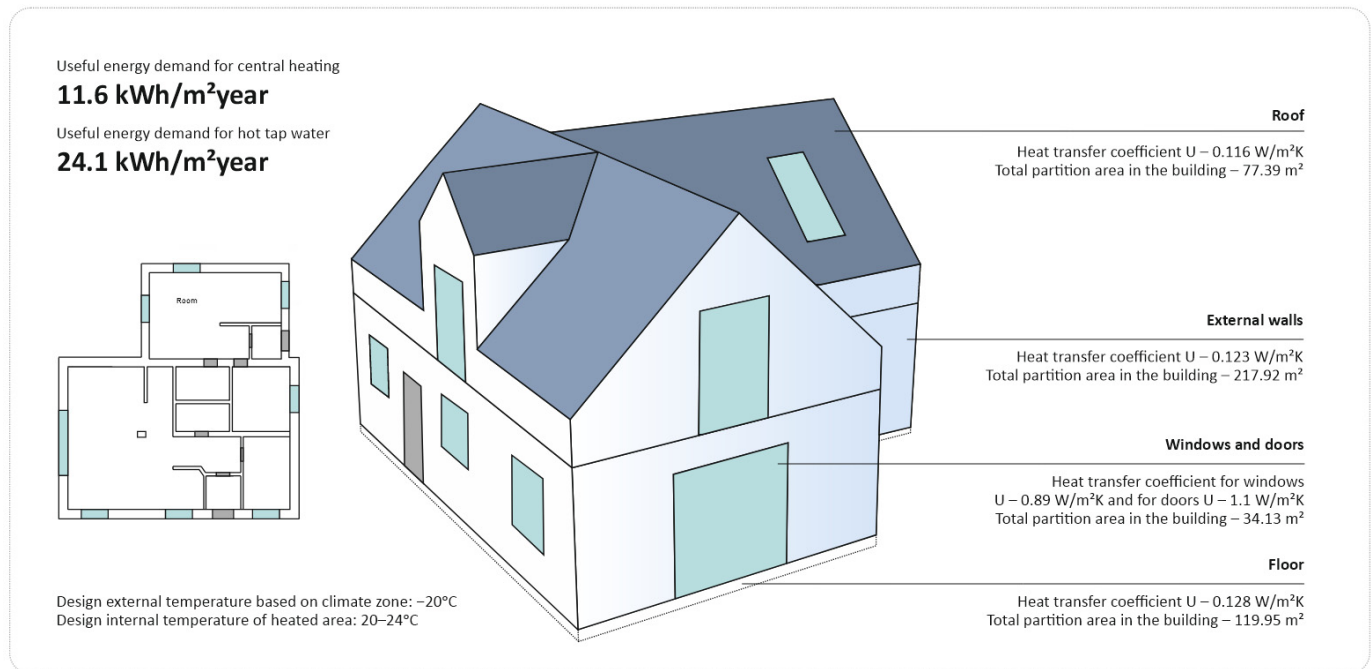


Figure 1. A model of the building under analysis, including the parameters of its building partitions.

The single-case-study design is a further limitation of the present work. Its main advantage is the methodological consistency of comparing all variants within a single, unchanged building and a fixed set of boundary conditions; however, this also limits the broader applicability of the results. The reported absolute values depend on the characteristics of the analysed house and should therefore be interpreted as case-specific rather than directly transferable to other building types, climates, or technical configurations. The main value of the study lies in identifying comparative trends within the analysed case, not in providing universally valid quantitative predictions.

The calculations were carried out in accordance with the applicable national regulations and standards relating to the energy performance of buildings. The methodological basis was primarily the Regulation of the Minister of Infrastructure and Development of 27 February 2015 on the methodology for determining the energy performance of a building or part of a building and energy performance certificates (Journal of Laws 2023, item 697) [23]. In addition, the standards ISO 6946 [24], ISO 12831:2006 [25], and ISO 13790 [26] were used, respectively, for the calculation of thermal resistance and heat transfer coefficients of building elements, the design heat load of a building, and thermal properties.

2.2. Assumptions and Variants Description

The most important variables in the analysed scenarios are the flow temperatures of the central heating system and the setpoint temperature for the domestic hot water tank.

The flow and return temperatures of the heating system, as parameters of the upper heat source, were varied between 35 and 55 °C, whilst those for domestic hot water were varied between 47 and 55 °C. In addition, the ground temperature, as a parameter of the lower heat source, was varied: 1 °C, 0 °C, and −1 °C. This stems from a desire to present a broader context than just the 0 °C temperature to which heat pump manufacturers refer when stating their SCOP. On this basis, the SCOP values of the heat pumps were determined from publicly available manufacturer data sheets for brine/water units with capacities up to 10 kW. The reference value adopted for the calculations was $SCOP_{B0/W35} = 4.72$. The SCOP values for higher load-side temperatures were then estimated using a temperature correction coefficient $k = 0.02$ according to Equation (1):

$$SCOP_{B0/Wx} = \frac{SCOP_{B0/W35}}{1 + k(x - 35)} \quad (1)$$

where x is the supply temperature for space heating or the domestic hot water setpoint temperature °C. Using this relationship, the values for 40, 45, 50, and 55 °C were obtained for the heating analysis, and the values for 47, 50, and 55 °C were obtained for the domestic hot water analysis.

The lower-source temperature was introduced in a separate step. Here, the case $B0$ was treated as the reference condition, and the SCOP values obtained from Equation (1) were corrected by assuming a 2% change in SCOP per 1 °C change in lower-source temperature:

$$SCOP_{Bt/Wx} = SCOP_{B0/Wx} \times (1 + k \times t) \quad (2)$$

where t is the lower-source temperature relative to the reference case $B0$.

For domestic hot water, the SCOP values for 50 and 47 °C were determined using Equation (1), with the hot-water setpoint temperature used instead of the space-heating supply temperature. In addition, the useful energy demand for domestic hot water was corrected because the energy required to heat water depends directly on the temperature increase above the cold-water temperature. Assuming $T_{cold} = 10$ °C and taking 55 °C as the reference case, the correction coefficient was calculated from Equation (3):

$$s = \frac{T_{DHW} - T_{cold}}{55 - T_{cold}} \quad (3)$$

This yielded $s = 1.00$ for 55 °C, $s = 0.89$ for 50 °C, and $s = 0.82$ for 47 °C.

Two reference scenarios were included in the analysis. In the first of these (REF_1), the efficiency of the heating and domestic hot water systems is disregarded. Unfortunately, neglecting the efficiency losses of the distribution, storage, control, and auxiliary components is a relatively common simplification in non-detailed assessments of heat pump systems. Such an approach may lead to an overestimation of the installation's actual performance and, consequently, to an underestimation of final energy use, operating costs, and operational environmental impacts. For this reason, the REF_1 scenario was deliberately introduced as a theoretical, idealised case in which only the heat pump SCOP is considered, while the remaining system losses are omitted. Its purpose is not to represent a realistic operating configuration, but to illustrate the scale of deviation that may arise when the heat pump is assessed in isolation from the rest of the technical system. In this way, REF_1 serves as a methodological benchmark showing how strongly the overall building-level results depend on whether auxiliary consumption and subsystem efficiencies are included in the calculation procedure. The second variant (REF_2) is a reference system for a heating device other than a heat pump, namely an electric boiler. An electrically powered device was deliberately chosen to avoid demagoguery in assessing energy performance. For the

same reason, hybrid systems with PV installations and energy storage, as well as economic effects, are not analysed. All energy performance values, with the exception of SCOP, were adopted on the basis of the values recommended in the Regulation of the Minister of Infrastructure and Development of 27 February 2015 on the methodology for determining the energy performance of a building or part of a building and energy performance certificates (Journal of Laws 2023, item 697) [23]. The variants for central heating are presented in Table 1 below.

Table 1. Types of central heating systems.

Variant	Ground Temperature [°C]	Heating System Description [Supply/Return Temp. °C]	System Description
1.A	1	55/48 classic plate heaters	- Location of the heat source: water-based central heating, from a local heat source situated within the heated building, with insulated pipes, fittings, and equipment within the heated space (efficiency 0.96); - Type of installation—sectional/panel radiators with central and local control (efficiency 0.88); - Buffer tank parameters and location—buffer tank within the heated space (efficiency 0.95)
1.B	0		
1.C	−1		
2.A	1	50/43 classic plate heaters	- Central heating system circulation pumps, heating limit 15 °C—0.30 W/m², 3116 h/yr; - Buffer tank charging pump in the heating system—0.20 W/m², 1500 h/yr; - Auxiliary drive for the glycol/water heat pump—0.45 W/m², 1600 h/yr.
2.B	0		
2.C	−1		
3.A	1	45/38 classic plate heaters	As with options 1–3, except for the type of installation—underfloor heating with central and local control (efficiency 0.89).
3.B	0		
3.C	−1		
4.A	1	40/33 underfloor heating	As with options 1–5, except for efficiency. This has been omitted, with only the heat pump’s SCOP being included in the calculations.
4.B	0		
4.C	−1		
5.A	1	35/28 underfloor heating	As with options 1–5, except for the efficiency of the heating appliance. An electric boiler with an efficiency of 0.99 has been assumed.
5.B	0		
5.C	−1		
REF_1	0	35/28 underfloor heating	As with options 1–5, except for efficiency. This has been omitted, with only the heat pump’s SCOP being included in the calculations.
REF_2	0	35/28 underfloor heating	As with options 1–5, except for the efficiency of the heating appliance. An electric boiler with an efficiency of 0.99 has been assumed.

The analysis is based on the following indicators: the heat pump’s SCOP, total system efficiency, useful energy, final energy, primary energy, the share of renewable energy sources, and electricity consumption. Useful energy for heating is constant across all variants and amounts to 11.6 kWh/m²yr, indicating that the variants being compared relate to the same building and the same useful heat demand. It is therefore not the building’s heat demand that changes, but the efficiency with which the technical system meets that demand.

The same assumptions were applied to the domestic hot water analysis, except for the temperature to be maintained in the domestic hot water tank: 47–55 °C. As in the previous analysis for heating, the useful energy remains constant for all variants and amounts to 24.1 kWh/m²yr, which means that the actual useful energy demand for domestic hot water preparation does not change, and the differences between the variants result solely from the varying efficiency and performance of the technical system. The variants are described in Table 2.

Table 2. Domestic hot water options.

Variant	Ground Temperature [°C]	Hot Water Temperature [°C]	Description of the Hot Water System Specifications
11.A	1	55	- Heat source location—insulated circuits, limited operating time, small installations with up to 30 outlets (heat transfer efficiency 0.80); - Storage tank in the DHW system (storage efficiency 0.86); - Circulation pumps, intermittent operation up to 8 h/day—0.04 W/m², 5840 h/yr; - Hot water storage tank charging pump—0.25 W/m², 270 h/yr.
11.B	0		
11.C	−1		
12.A	1	50	- Daily hot water demand per unit—1.4 dm³/m²day; - Correction factor due to periods of non-use 0.9; - Water temperature before heating 10 °C.
12.B	0		
12.C	−1		
13.A	1	47	
13.B	0		
13.C	−1		
REF_1	0	55	As with options 1–5, except for efficiency. This has been omitted, with only the heat pump’s SCOP being included in the calculations.
REF_2	0	55	As with options 1–5, except for the efficiency of the heating appliance. An electric boiler with an efficiency of 0.99 has been assumed.

2.3. Energetic Calculations

The methodology adopts the standard classification of energy indicators into useful, final, and primary energy [23]. Useful energy is the amount of energy required to maintain the desired thermal conditions within the building under specified external conditions. This value depends primarily on the building’s geometric and thermal characteristics, including the properties of external partitions, joinery, the roof, the ground floor, and ventilation parameters. Final energy also accounts for the efficiency of technical equipment and the properties of the energy carrier used to meet the building’s thermal needs. Primary energy, on the other hand, also includes the inputs associated with the extraction, processing, and delivery of the energy carrier to the point of use. From the perspective of the research objectives presented in this article, the final energy indicators are significant; these were determined according to the following formula:

$$EK_{co} = Q_{H,nd} / A_f \times \eta_{co} + E_{add_co} \quad (4)$$

$$EK_{cwu} = Q_{W,nd} / A_f \times \eta_{cwu} + E_{add_cwu} \quad (5)$$

EK_{co} denotes the final energy for central heating expressed in kWh/m²yr, and similarly EK_{cwu} for domestic hot water; $Q_{H,nd}$ is the annual demand for useful energy for heating and ventilation in kWh/m²yr, $Q_{W,nd}$ is the annual demand for useful energy for the preparation of domestic hot water in kWh/m²yr, A_f is the floor area of rooms with controlled air temperature expressed in m², whilst η_{co} and η_{cwu} are the efficiency of the central heating and domestic hot water systems. E_{add_co} and E_{add_cwu} are the auxiliary energy requirements to drive the circulation and feed pumps supporting system operation. Primary energy was calculated using the formula:

$$EP = EK \times w_i \quad (6)$$

EP denotes primary energy in kWh/m²yr, whilst w_i is a dimensionless indicator of non-renewable primary energy input, which equals 2.50 for electricity generated in the Polish energy mix. The use of this coefficient enabled assessment of the impact of the energy carrier not only on final consumption but also on the overall balance of non-renewable primary energy.

The adopted calculation procedure is a simplified quasi-steady-state approach intended for a consistent comparison of the analysed variants rather than for dynamic simulation of the installation. In all cases, the same building geometry, thermal characteristics, indoor design temperature, climatic boundary conditions, and useful energy demand were assumed; therefore, the differences between the variants result exclusively from the adopted SCOP values, subsystem efficiencies, auxiliary electricity use, and the temperature levels of the lower and upper heat sources. The method assumes fixed annual conversion factors for electricity, including the primary energy input factor used to convert final energy into primary energy and the emission factors used to calculate operational emissions from electricity consumption. Consequently, the adopted approach does not account for transient operation, part-load effects, hourly weather variability, control dynamics, seasonal regeneration of the ground source, or variability in domestic hot water draw-off, and the absolute values of primary energy demand and operational emissions should be interpreted as specific to the adopted Polish boundary conditions.

2.4. Environmental Impact Methodology

The environmental component of the methodology involved calculating the pollutants emitted by the systems under analysis during operation. The assessment covered emissions of PM10 and PM2.5 particulate matter, sulphur dioxide (SO₂), nitrogen oxides (NO_x), carbon monoxide (CO), and carbon dioxide (CO₂). The determination of specific emissions was based on emission factors published by KOBiZE (2025) [27] for electricity, which for end users are as follows: 553 kg/MWh for carbon dioxide, 0.352 kg/MWh for sulphur oxides and sulphur dioxide, 0.362 kg/MWh for nitrogen oxides and nitrogen dioxide, 0.219 kg/MWh for carbon monoxide, and 0.013 kg/MWh for particulate matter PM10 and PM2.5.

$$\text{Emission} = \text{electricity used} \times \text{pollution coefficient (w)} \quad (7)$$

In addition, an SO₂-equivalent emission, denoted ZrSO₂, was established as a synthetic indicator of emission impact. This indicator was calculated as the sum of SO₂ and other pollutant emissions, multiplied by the relevant toxicity factors for SO₂. This approach enabled reducing diverse emissions into a single, comparable synthetic measure [28].

$$Z_rSO_2 = ZSO_2 + ZNO_x \times eSO_2/eNO_x + ZPM10 \times eSO_2/ePM10 + ZPM2.5 \times eSO_2/ePM2.5 \quad (8)$$

where Z_rSO_x is equivalent emission per SO_x ; Z_i is emission of i -th pollutant, where “ i ” denotes SO_x , NO_x , $PM10$, $PM2.5$; eSO_x/e_i is toxicity coefficient of the i -th pollutant with respect per SO_x , where “ i ” means NO_x (assumed value 0.8), $PM10$ (0.5), $PM2.5$ (0.8).

The ZrSO₂ indicator was used in this study as a complementary operational indicator that aggregates selected air pollutants into a single comparative value based on relative toxicity coefficients. Its role is different from that of CO₂: while CO₂ describes climate-related operational impact, ZrSO₂ reflects the combined burden of local air pollutants associated with individual heating. At the same time, the indicator does not represent a life-cycle metric and should not be interpreted as an alternative to LCA. It is limited to the operational phase and was adopted to maintain consistency with the author’s previous building-level energy–environmental assessment framework [6,28].

The methodology ultimately adopted enabled a simultaneous energy and environmental assessment of the technical solutions under consideration. On the one hand, it enabled determining the impact of the type of heat source on final and primary energy values, and, on the other, on the share of energy from renewable sources and the level of pollutant emissions. This made it possible to carry out a multi-criteria comparative analysis in which geothermal systems, particularly those combined with a photovoltaic installation, could

be assessed not only in terms of energy efficiency but also in terms of their environmental impact and the quality of the building's energy performance.

3. Results and Discussion

3.1. Heating System

The most general conclusion that can be drawn from the data presented is that the efficiency of a ground-source heat pump depends to a very large extent on the supply temperature of the load system. The lower the heating water temperature at the upper source, the more favourable the values of all analysed indicators: SCOP, total system efficiency, final energy, primary energy, and electricity consumption. This relationship is consistent with the principle of heat pump operation, which states that efficiency increases as the temperature difference between the lower and upper sources decreases. In practice, this means that a heat pump works best with low-temperature systems, primarily underfloor heating, whereas it performs significantly worse with systems that require a high supply temperature, such as traditional radiators.

The least favourable results among the heat pump variants analysed were obtained for the 55/48 °C system, corresponding to conventional panel radiators (Table 3). For this group of variants, SCOP values range from 3.31 to 3.44, and the total system efficiency ranges from 2.65 to 2.76. Final energy consumption here ranges from 6.8 to 7.0 kWh/m²yr, primary energy consumption from 17.0 to 17.4 kWh/m²yr, and annual electricity consumption from 1297.3 to 1330.6 kWh. These are the worst values among all the analysed working variants with a heat pump, clearly showing that a high supply temperature limits the benefits of geothermal technology. Such a system forces the compressor to work harder and increases the energy required to achieve the required temperature of the heating medium.

A marked improvement is already evident when the system's operating parameters are reduced to 50/43 °C. In this group of variants, the SCOP ranges from 3.56 to 3.70, whilst the system's overall efficiency ranges from 2.86 to 2.97. Final energy consumption falls to 6.5–6.6 kWh/m²yr, primary energy consumption to 16.2–16.6 kWh/m²yr, whilst electricity consumption decreases to 1240.4–1269.1 kWh/yr. This indicates that even a moderate reduction in the supply temperature can bring about a noticeable increase in energy efficiency, without the need for a complete overhaul of the consumer installation. Even more favourable results are achieved at 45/38 °C, which also corresponds to a radiator system but is already much better suited to working with a heat pump. In this case, the SCOP ranges from 3.86 to 4.01, the overall efficiency from 3.10 to 3.22, the final energy consumption from 6.2 to 6.3 kWh/m²yr, the primary energy consumption from 15.5 to 15.8 kWh/m²yr, and the electricity consumption from 1182.4 to 1209.1 kWh/yr. This means that even in a radiator-based system, relatively high efficiency can be achieved, provided the operating parameters are correctly selected.

However, the best results are achieved by low-temperature systems, namely underfloor heating. For operating parameters of 40/33 °C, SCOP values range from 4.21 to 4.37, and the system's overall efficiency ranges from 3.42 to 3.55. Final energy consumption falls to 5.8–6.0 kWh/m²yr, primary energy to 14.6–14.9 kWh/m²yr, and electricity consumption ranges from 1118.3 to 1142.1 kWh/yr. Even better results were achieved for the 35/28 °C variants, which should be considered the most favourable among all the heat pump systems analysed. In this group, the SCOP ranges from 4.63 to 4.81, the total system efficiency ranges from 3.76 to 3.90, the final energy consumption remains at 5.6–5.7 kWh/m²yr, the primary energy consumption is 13.9–14.2 kWh/m²yr, and the annual electricity consumption is 1062.2–1083.4 kWh. These results clearly confirm that the energy potential of a ground-source heat pump is best realised when the unit is combined with low-temperature surface

heating. In design practice, selecting the appropriate heat distribution system is one of the most important factors in achieving high seasonal efficiency.

Table 3. Results of energy calculations for central heating.

Variant	Ground Temperature [°C]	Heating System Description [Supply/Return Temp. °C]	Heat Pump SCOP [–]	Total System Efficiency [–]	Useful Energy [kWh/m ² yr]	Final Energy [kWh/m ² yr]	Primary Energy [kWh/m ² yr]	RES Share [–]	Electricity Used [kWh/yr]
1.A	1	55/48 classic plate heaters	3.44	2.76	11.6	6.8	17.0	0.58	1297.3
1.B	0		3.39	2.71	11.6	6.9	17.1	0.59	1312.1
1.C	–1		3.31	2.65	11.6	7.0	17.4	0.60	1330.6
2.A	1	50/43 classic plate heaters	3.70	2.97	11.6	6.5	16.2	0.56	1240.4
2.B	0		3.63	2.91	11.6	6.6	16.4	0.57	1255.8
2.C	–1		3.56	2.86	11.6	6.6	16.6	0.57	1269.1
3.A	1	45/38 classic plate heaters	4.01	3.22	11.6	6.2	15.5	0.53	1182.4
3.B	0		3.93	3.16	11.6	6.2	15.6	0.54	1195.5
3.C	–1		3.86	3.10	11.6	6.3	15.8	0.54	1209.1
4.A	1	40/33 underfloor heating	4.37	3.55	11.6	5.8	14.6	0.50	1118.3
4.B	0		4.29	3.48	11.6	5.9	14.8	0.51	1130.9
4.C	–1		4.21	3.42	11.6	6.0	14.9	0.51	1142.1
5.A	1	35/28 underfloor heating	4.81	3.90	11.6	5.6	13.9	0.48	1062.2
5.B	0		4.72	3.83	11.6	5.6	14.0	0.48	1072.6
5.C	–1		4.63	3.76	11.6	5.7	14.2	0.49	1083.4
REF_1	0	35/28 underfloor heating	4.72	4.72	11.6	5.0	12.6	0.43	963.4
REF_2	0	35/28 underfloor heating	0.99	0.79	11.6	17.2	42.9	0.0	3286.3

The second key factor affecting performance is ground temperature, i.e., the operating conditions of the ground source. The same trend is observed across all groups analysed: a decrease in ground temperature from 1 °C to –1 °C results in deterioration across all key performance indicators. In the 55/48 °C group, the SCOP decreases from 3.44 to 3.31; in the 50/43 °C group from 3.70 to 3.56; in the 45/38 °C group from 4.01 to 3.86; in the 40/33 °C group from 4.37 to 4.21, and in the 35/28 °C group from 4.81 to 4.63. This is accompanied by a systematic increase in final energy, primary energy, and electricity consumption. These changes are not as significant as those resulting from a reduction in the consumer system's supply temperature, but they remain clear and substantial. This means that more favourable geothermal conditions improve the system's operating parameters, but their significance is secondary to the heating system's operating temperature. In other words, a well-designed low-temperature heating system can yield a greater energy benefit than a slight improvement in the operating conditions of the ground source. On the other hand, the data confirm that the thermal stability of the ground and the proper selection of the ground heat exchanger remain important factors in determining the heat pump's final seasonal efficiency.

It is particularly interesting to compare the extreme scenarios. The worst of the heat pump scenarios analysed is scenario 1.C, which corresponds to a ground temperature of –1 °C and a radiator system operating at 55/48 °C. This variant is characterised by a SCOP of 3.31, a total efficiency of 2.65, a final energy of 7.0 kWh/m²yr, a primary energy of

17.4 kWh/m²yr, and an electricity consumption of 1330.6 kWh/yr. The best of the basic operating variants is variant 5.A, i.e., a ground temperature of 1 °C and underfloor heating at 35/28 °C. Here, the SCOP reaches 4.81, the overall efficiency 3.90, the final energy drops to 5.6 kWh/m²yr, the primary energy to 13.9 kWh/m²yr, and the electricity consumption to 1062.2 kWh/yr. A comparison of these two variants demonstrates the scale of the benefits resulting from system optimisation. The SCOP increases by approximately 45%, the total system efficiency by approximately 47%, whilst final energy, primary energy, and electricity consumption decrease by approximately 20%. This is a very clear difference, indicating that the decision to use a heat pump alone does not guarantee maximum system efficiency. The final outcome depends on how the unit is integrated into the building's system.

The renewable energy share indicator is also worth noting. It ranges from around 0.60 for high-temperature variants to around 0.48–0.49 for the most efficient variants, and stands at 0.43 and 0.0 for the reference variants. At first glance, it might seem that a higher RES share should occur in the most efficient systems; however, the data presented suggest that interpreting this indicator must take into account the adopted calculation methodology. In practice, the variants with the highest SCOP and lowest final energy consumption—and thus the most energy-efficient—do not have the highest RES share values. This means that the RES share indicator alone should not be interpreted in isolation from the system's other parameters. From the perspective of actual energy efficiency and environmental impact, SCOP, final and primary energy, and electricity consumption remain more reliable indicators.

An important element of the comparison is the two reference scenarios. Scenario REF_1 achieves very favourable results with a SCOP of 4.72, as the efficiency of all other components is disregarded. This is a deliberate approach, driven by the need to highlight the assessment errors that occur when the efficiency of the entire heating system is not taken into account. The total efficiency of the system is also 4.72, the final energy consumption is 5.0 kWh/m²yr, the primary energy consumption is 12.6 kWh/m²yr, and the electricity consumption is 963.4 kWh/yr. REF_2, on the other hand, represents a system with an electric boiler instead of a heat pump. The efficiency here is 0.99, which is objectively very high compared to conventional heating systems. The overall efficiency is 0.79, the final energy is 17.2 kWh/m²yr, the primary energy is 42.9 kWh/m²yr, the annual electricity consumption is as high as 3286.3 kWh, and the RES share, as is obvious, is 0.0. This variant serves as a very clear benchmark, demonstrating the advantage of all the systems under consideration with a ground-source heat pump. A system with a primary energy carrier analogous to that of heat pumps was deliberately chosen, as it results directly from the energy transition towards electrification. The best variant, 5.A, consumes approximately three times less electricity than REF_2 and has approximately three times lower primary energy consumption. This difference clearly shows that using a ground-source heat pump can significantly improve a building's energy performance compared to an inefficient or conventional system.

The analysis also has a significant environmental dimension (Table 4). Lower final energy consumption and lower primary energy consumption mean reduced demand for externally supplied energy and, consequently, a reduced environmental impact. In the context of an electricity system that is not fully decarbonised, this directly translates into a reduction in emissions associated with the building's operation. For this reason, the options with the highest seasonal efficiency, namely 5.A, 5.B and 5.C, followed by 4.A, 4.B and 4.C. These results confirm that the environmental advantage of ground-source heat pumps does not stem solely from the use of renewable ground heat, but primarily from the very high efficiency of energy conversion within a well-configured technical system. In other words, the mere presence of a heat pump in a building is not yet sufficient to achieve the maximum environmental benefit. Only by combining this technology with a suitably

low-temperature heat distribution system can its energy and environmental potential be fully exploited.

Table 4. Results of environmental calculations for the central heating system.

Variant	Ground Temperature [°C]	Heating System Description [Supply/Return Temp. °C]	PM10 [g/yr]	PM2.5 [g/yr]	SO _x [g/yr]	NO _x [g/yr]	CO [g/yr]	CO ₂ [g/yr]	ZrSO ₂ [g/yr]
1.A	1	55/48 classic plate heaters	16.9	16.9	456.6	469.6	284.1	717,381	854.2
1.B	0		17.1	17.1	461.9	475.0	287.3	725,585	864.0
1.C	−1		17.3	17.3	468.4	481.7	291.4	735,838	876.2
2.A	1	50/43 classic plate heaters	16.1	16.1	436.6	449.0	271.6	685,942	816.8
2.B	0		16.3	16.3	442.0	454.6	275.0	694,462	826.9
2.C	−1		16.5	16.5	446.7	459.4	277.9	701,834	835.7
3.A	1	45/38 classic plate heaters	15.4	15.4	416.2	428.0	258.9	653,861	778.6
3.B	0		15.5	15.5	420.8	432.8	261.8	661,097	787.2
3.C	−1		15.7	15.7	425.6	437.7	264.8	668,614	796.2
4.A	1	40/33 underfloor heating	14.5	14.5	393.6	404.8	244.9	618,433	736.4
4.B	0		14.7	14.7	398.1	409.4	247.7	625,386	744.7
4.C	−1		14.8	14.8	402.0	413.4	250.1	631,573	752.1
5.A	1	35/28 underfloor heating	13.8	13.8	373.9	384.5	232.6	587,409	699.5
5.B	0		13.9	13.9	377.6	388.3	234.9	593,160	706.3
5.C	−1		14.1	14.1	381.4	392.2	237.3	599,125	713.4
REF_1	0	35/28 underfloor heating	12.5	12.5	339.1	348.7	211.0	532,741	634.4
REF_2	0	35/28 underfloor heating	42.7	42.7	1156.8	1189.6	719.7	1,817,310	2164.0

Figure 2 summarises the conclusions drawn from the tabular analysis and clearly illustrates the relationships between the system's operating parameters, the heat pump's efficiency, and energy demand. The summary covers three basic groups of indicators: useful energy (EU), final energy (EK), and primary energy (EP), as well as the seasonal coefficient of performance (SCOP), the total system efficiency, and the environmental indicator, ZrSO₂ emissions. It is immediately apparent that the useful energy remains constant for all analysed variants, confirming that it is not the building's heat demand itself that changes, but only the efficiency with which it is met by different heating system configurations. Consequently, the graph allows one to focus solely on the impact of the lower and upper-source temperatures on the operation of the ground-source heat pump system.

The reference levels defined by the reference variants REF_1 and REF_2 are also a key element in interpreting the diagram. The REF_2 variant represents by far the least favourable configuration, with the highest primary energy consumption and the lowest efficiency, whilst REF_1 sets a significantly more energy-efficient standard. All analysed variants with a ground-source heat pump exhibit significantly better performance than REF_2, whilst low-temperature variants, particularly those in group 5, approach the level of REF_1 for selected indicators. This indicates that a properly configured system with a ground-source heat pump can achieve very high energy efficiency, comparable to the most favourable reference variants.

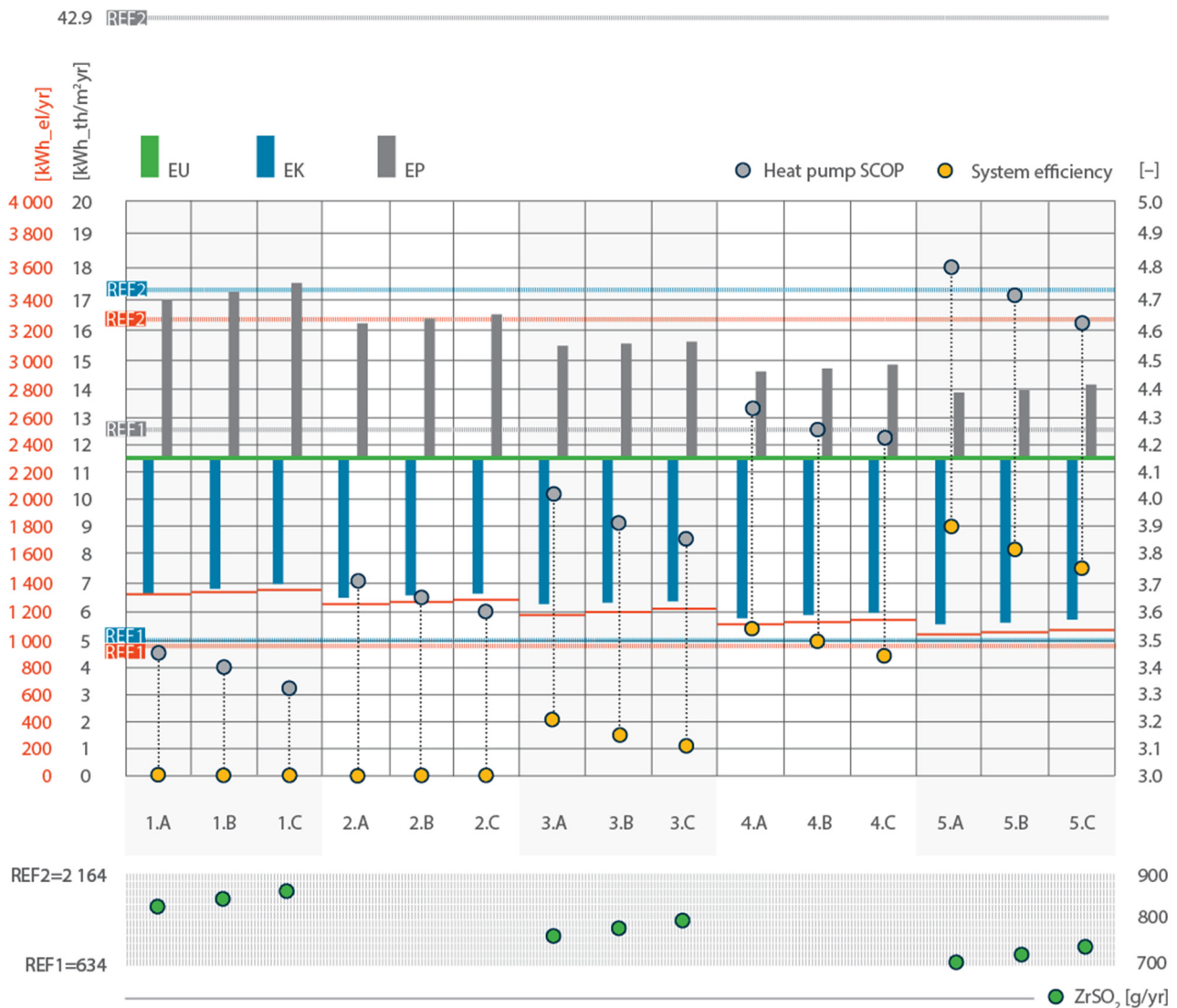


Figure 2. A summary interpretation of the energy and environmental performance of central heating systems.

A more analytical interpretation of the results shows that, within the analysed range, the dominant influencing parameter was the temperature level on the heat-demand side rather than the lower-source temperature itself. At the reference ground temperature of 0°C , reducing the heating-system temperature from $55/48^\circ\text{C}$ to $35/28^\circ\text{C}$ increased the SCOP from 3.39 to 4.72, i.e., by approximately 39%, while primary energy decreased from 17.1 to $14.0 \text{ kWh}/\text{m}^2\cdot\text{yr}$ and electricity consumption from 1312.1 to $1072.6 \text{ kWh}/\text{yr}$, corresponding in both cases to a reduction of about 18%. By contrast, for a fixed low-temperature system of $35/28^\circ\text{C}$, changing the ground temperature from -1°C to 1°C increased the SCOP only from 4.63 to 4.81, i.e., by about 4%, while primary energy changed from 14.2 to $13.9 \text{ kWh}/\text{m}^2\cdot\text{yr}$, i.e., by about 2%. This indicates that, for the analysed building, the design of the heat emission system was the first-order determinant of seasonal performance, whereas the lower-source temperature acted mainly as a secondary modifying factor. Such a hierarchy is consistent with earlier studies showing that the seasonal efficiency of geothermal heat pumps is strongly dependent on supply temperature and improves markedly when low-temperature heating systems are used [10,13]. At the same time, the present results extend those findings to building-level indicators by showing that the thermodynamically expected SCOP improvement is directly translated into lower final

energy, lower primary energy, and lower operational emissions within a single consistent calculation framework.

3.2. Domestic Hot Water

The key conclusion from the data presented is that, in the case of domestic hot water production, the required temperature at the upstream source is also crucial. As the domestic hot water temperature is reduced from 55 °C to 50 °C, and then to 47 °C, a systematic improvement in all key energy performance indicators is observed. The seasonal coefficient of performance of the heat pump increases, the overall efficiency of the system rises, whilst final energy, primary energy, and electricity consumption decrease. This relationship is consistent with the principle of heat pump operation: the smaller the temperature difference between the lower and upper sources, the less energy is required to achieve the desired temperature level. In the case of domestic hot water, lowering the required water-heating temperature results in a significant increase in the system's efficiency.

From a practical perspective, the energy benefits of lowering the DHW setpoint temperature must be weighed against hygienic constraints related to *Legionella* control. This issue is particularly important because *Legionella* can proliferate in water systems within the temperature range of approximately 20–50 °C, i.e., in the range partly overlapping with the analysed low-temperature DHW variants. In temperature-based control strategies, hot water is commonly stored at or above 60 °C, while the circulating or distributed hot water temperature is generally maintained at or above 50 °C. Therefore, the 47 and 50 °C variants analysed in this study should be interpreted primarily as comparative efficiency scenarios rather than as universally recommended operating temperatures for real installations. In practice, the minimum acceptable DHW temperature depends not only on heat pump efficiency, but also on the storage concept, circulation regime, stagnation risk, frequency of draw-off, hydraulic design, and the adopted risk-control measures, including flushing procedures, thermal disinfection, or the use of thermostatic mixing valves at points of use. For this reason, any practical reduction in DHW temperature should be assessed alongside the system's sanitary safety strategy, rather than based solely on energy performance.

The least favourable results are corresponding to a domestic hot water temperature of 55 °C. In this variant, SCOP values range from 3.31 to 3.44, and the total system efficiency ranges from 2.25 to 2.34. Final energy consumption ranges from 10.6 to 11.0 kWh/m²yr, primary energy consumption from 26.5 to 27.5 kWh/m²yr, and electricity consumption from 2027.9 to 2106.7 kWh/yr. These are the poorest results among all the operating variants analysed, indicating that heating DHW to 55 °C represents the most demanding operating condition for the heat pump. The high domestic hot water temperature increases the compressor load and reduces the system's seasonal efficiency, thereby increasing final and primary energy consumption (Table 5).

A marked improvement is observed when the domestic hot water temperature is reduced to 50 °C. SCOP values rise to 3.56–3.70, and the system's overall efficiency reaches 2.42–2.52. Final energy consumption falls to 9.9–10.3 kWh/m²yr, primary energy consumption to 24.7–25.6 kWh/m²yr, and electricity consumption decreases to 1887.2–1962.8 kWh/yr. These results show that even a 5 K reduction in the DHW preparation temperature leads to a noticeable improvement in the system's energy efficiency. Even more favourable results were obtained for temperature of 47 °C. In this case, the SCOP ranges from 3.73 to 3.88, the overall system efficiency from 2.54 to 2.64, the final energy consumption falls to 9.4–9.8 kWh/m²yr, the primary energy consumption to 23.6–24.5 kWh/m²yr, and the electricity consumption to 1804.0–1872.8 kWh/yr. This means that the lowest analysed DHW temperature ensures the best operating conditions for the ground-source heat pump and leads to the most favourable energy performance indicators.

Table 5. Energy performance of the domestic hot water system.

Variant	Ground Temperature [°C]	Hot Water Temperature [°C]	Heat Pump SCOP [–]	Total System Efficiency [–]	Useful Energy [kWh/m ² yr]	Final Energy [kWh/m ² yr]	Primary Energy [kWh/m ² yr]	RES Share [–]	Electricity Used [kWh/yr]
11.A	1	55	3.44	2.34	24.1	10.6	26.5	0.44	2027.9
11.B	0		3.39	2.31	24.1	10.7	26.8	0.45	2053.5
11.C	–1		3.31	2.25	24.1	11.0	27.5	0.46	2106.7
12.A	1	50	3.70	2.52	24.1	9.9	24.7	0.41	1887.2
12.B	0		3.63	2.47	24.1	10.1	25.1	0.42	1924.2
12.C	–1		3.56	2.42	24.1	10.3	25.6	0.43	1962.8
13.A	1	47	3.88	2.64	24.1	9.4	23.6	0.39	1804.0
13.B	0		3.81	2.59	24.1	9.6	24.0	0.40	1837.7
13.C	–1		3.73	2.54	24.1	9.8	24.5	0.41	1872.8
REF_1	0	55	3.81	3.81	24.1	6.6	16.6	0.27	1267.7
REF_2	0	55	0.99	0.67	24.1	36.1	90.3	0.0	6906.3

Analysis of the results also shows a clear influence of the ground-source temperature. In each group of variants, a reduction in ground temperature from 1 °C to 0 °C, then to –1 °C, results in a systematic deterioration in the system’s performance parameters. For a DHW temperature of 55 °C, the SCOP drops from 3.44 to 3.31; for 50 °C, from 3.70 to 3.56; and for 47 °C, from 3.88 to 3.73. At the same time, the overall efficiency of the system decreases, whilst final energy, primary energy, and electricity consumption increase. This means that more favourable operating conditions for the ground source also improve the heat pump’s efficiency for DHW production. However, as in the analysis of heating, the influence of ground temperature is secondary to the temperature on the air-source side. A change in DHW temperature of a few degrees has a greater effect than small changes in ground temperature within the analysed range. In design practice, this means that although the correct selection of the ground source remains very important, it is particularly important to rationally determine the required DHW temperature, taking into account actual operational needs and hygiene requirements.

Two reference scenarios serve as key points of comparison. The REF_1 scenario achieves significantly better performance than all the working scenarios involving a heat pump, as—just as with central heating—efficiency factors other than the SCOP (3.81) are excluded. Final energy 6.6 kWh/m²yr, primary energy 16.6 kWh/m²yr, and electricity consumption 1267.7 kWh/yr. This result is significantly more favourable than for variants 11–13, suggesting that the reference variant was based on overly favourable calculations or technological assumptions, likely omitting some of the losses that occur in real operating variants. In contrast, REF_2 represents an extremely unfavourable variant. In this case, the SCOP is merely 0.99, the total system efficiency is 0.67, the final energy consumption reaches 36.1 kWh/m²yr, the primary energy consumption is 90.3 kWh/m²yr, and the electricity consumption is as high as 6906.3 kWh/yr. These values are often higher than for all the analysed variants with a ground-source heat pump, clearly demonstrating the advantage of this technology over inefficient or conventional systems.

Table 6, which sets out environmental indicators, confirms the trends observed in the energy analysis. As the system’s operating parameters deteriorate, the levels of all the emissions analysed increase: PM₁₀, PM_{2.5}, SO_x, NO_x, CO, CO₂ and ZrSO₂. For the variants in group 11 (at a DHW temperature of 55 °C), these values are the highest among all operating variants. For example, CO₂ emissions here rise from 1,121,447 to 1,165,031, and the ZrSO₂ index from 1335.4 to 1387.3 as the conditions of the lower source deteriorate.

For group 12, these values are lower: CO₂ emissions range from 1,043,619 to 1,085,427, and ZrSO₂ from 1242.7 to 1292.5. The lowest values occur in group 13, for which CO₂ emissions range from 997,630 to 1,035,652, and ZrSO₂ from 1188.0 to 1233.2. This trend clearly indicates that improving the energy efficiency of the DHW preparation system directly reduces environmental impact.

Table 6. Environmental performance of domestic hot water systems.

Variant	Ground Temperature [°C]	Hot Water Temperature [°C]	PM10 [g/yr]	PM2.5 [g/yr]	SO _x [g/yr]	NO _x [g/yr]	CO [g/yr]	CO ₂ [g/yr]	ZrSO ₂ [g/yr]
11.A	1	55	26.4	26.4	713.8	734.1	444.1	1,121,447	1335.4
11.B	0		26.7	26.7	722.8	743.4	449.7	1,135,597	1352.2
11.C	−1		27.4	27.4	741.6	762.6	461.4	1,165,031	1387.3
12.A	1	50	24.5	24.5	664.3	683.2	413.3	1,043,619	1242.7
12.B	0		25.0	25.0	677.3	696.6	421.4	1,064,100	1267.1
12.C	−1		25.5	25.5	690.9	710.5	429.9	1,085,427	1292.5
13.A	1	47	23.5	23.5	635.0	653.1	395.1	997,630	1188.0
13.B	0		23.9	23.9	646.9	665.3	402.5	1,016,274	1210.2
13.C	−1		24.3	24.3	659.2	677.9	410.1	1,035,652	1233.2
REF_1	0	55	16.5	16.5	446.2	458.9	277.6	701,053	834.8
REF_2	0	55	89.8	89.8	2431.0	2500.1	1512.5	3,819,207	4547.8

A comparison of the working variants with the reference variants in terms of emissions is particularly telling. REF_1 is characterised by significantly lower values for all the environmental indicators analysed than variants 11–13. For example, CO₂ emissions here amount to 701,053 g/yr, and the ZrSO₂ indicator is 834.8 g/yr. REF_2, on the other hand, achieves by far the highest values: PM10 and PM2.5 at 89.8 g/yr each, SO_x 2431.0 g/yr, NO_x 2500.1 g/yr, CO 1512.5 g/yr, CO₂ 3,819,207 g/yr, and ZrSO₂ 4547.8 g/yr. This means that using a ground-source heat pump for domestic hot water production not only reduces energy consumption but also significantly reduces pollutant emissions and environmental impact compared to the low-efficiency reference system.

Figure 3, which presents the results for domestic hot water production, highlights, above all, a different pattern of efficiency changes compared to the space heating system. In the analysed variants, the variation in SCOP and system efficiency values is significantly smaller, indicating that, in the DHW preparation process, the scope for improving efficiency is more limited by the technological process itself. This is due to the need to achieve relatively high temperatures on the supply side, regardless of the variant, meaning that even the most favourable configurations still operate under conditions less favourable than those of typical low-temperature surface heating systems. Consequently, the graph shows that the improvement in heat pump performance in the DHW sector is gradual and stable, but not as rapid as when reducing the heating system supply temperature.

The position of the reference variants is also significant. Against the backdrop of the preliminary results, the REF_2 level remains clearly distinct from the other data, which visually highlights the extent to which ground-source heat pump systems outperform a system with very low efficiency. In turn, REF_1 sets a more demanding benchmark, showing that, despite clear improvements in parameters in variants 13, domestic hot water production remains an area where achieving very low final and primary energy levels is more difficult than in reference solutions with exceptionally favourable assumptions. In scientific terms, the graph therefore illustrates not only the effectiveness of a ground-source heat pump but also its limits in applications requiring higher operating temperatures.

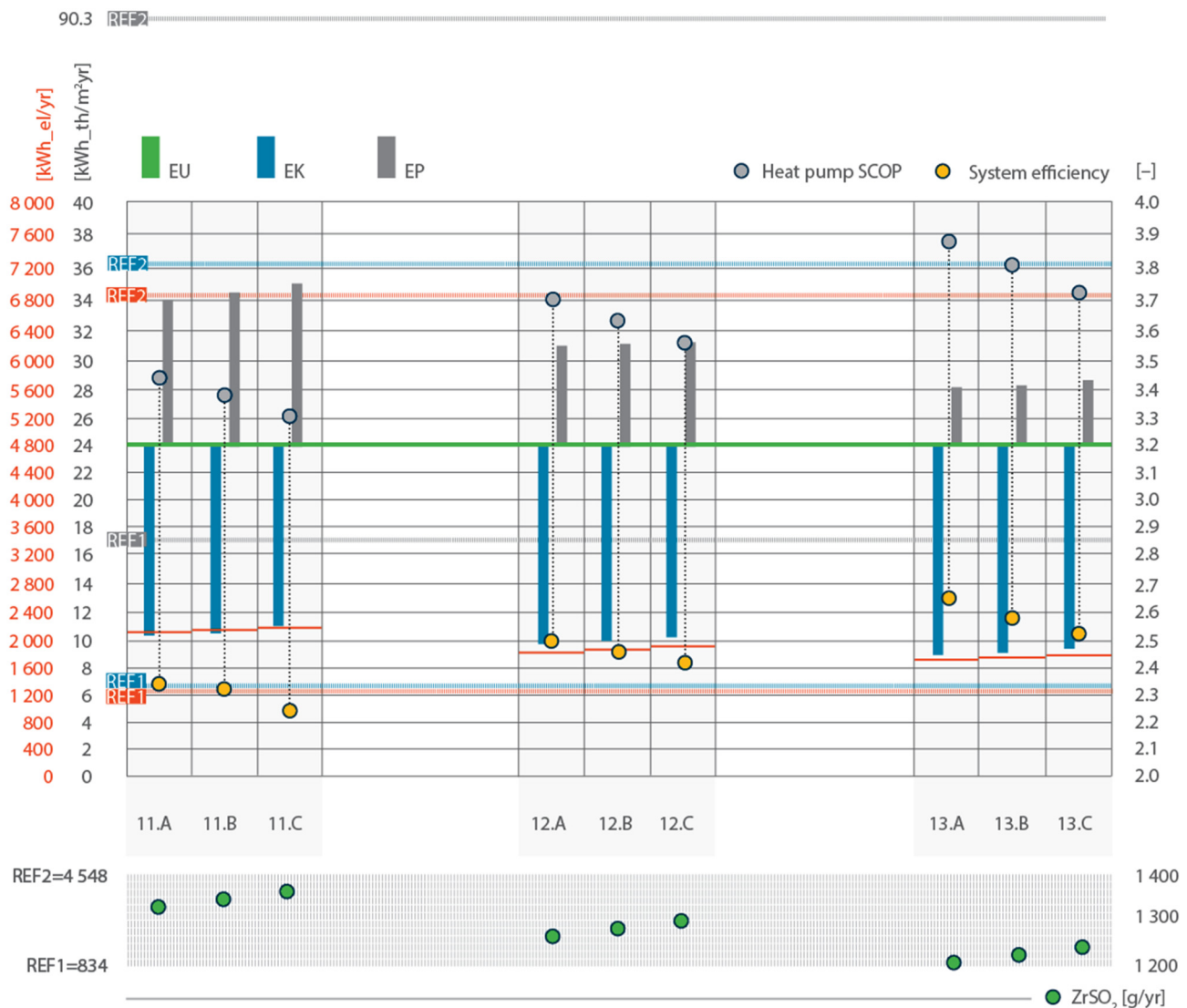


Figure 3. A summary interpretation of the energy and environmental performance of domestic hot water systems.

ZrSO₂ indicator deserves particular attention. Its distribution does not merely serve a supplementary function, but provides an important interpretative insight: reducing the energy intensity of the hot water preparation process leads, in parallel to a reduction in the cumulative environmental impact. Importantly, the trend of this indicator closely follows that of primary energy, suggesting a strong link between environmental impacts and electricity grid demand. From this perspective, the graph confirms that improving the efficiency of hot water production is significant not only for operational performance but also for emissions, and should therefore be analysed as part of a broader environmental assessment of the building.

The DHW results also indicate a clear hierarchy of influencing parameters, although the range of improvement is smaller than for space heating because all analysed variants still operate at relatively high supply temperatures. At a ground temperature of 0 °C, reducing the DHW temperature from 55 to 47 °C increased the SCOP from 3.39 to 3.81, i.e., by approximately 12%, while primary energy decreased from 26.8 to 24.0 kWh/m²/yr and electricity consumption from 2053.5 to 1837.7 kWh/yr, corresponding to reductions of about 10–11%. For a fixed DHW temperature of 55 °C, changing the ground temperature from −1 °C to 1 °C increased the SCOP from 3.31 to 3.44, i.e., by about 4%, while primary

energy decreased from 27.5 to 26.5 kWh/m²yr, i.e., by about 4%. Therefore, in the DHW analysis as well, the upper-source temperature remained the dominant parameter, while the lower-source temperature exerted a weaker but still systematic effect. This observation is consistent with the general thermodynamic trends reported in previous heat-pump studies, but the present paper provides an integrated comparison that shows how these effects propagate separately into DHW-related building energy and environmental indicators.

4. Summary and Conclusions

The analyses carried out confirmed that ground-source heat pumps can significantly improve a building's energy efficiency and reduce its environmental impact. The results showed that the most important factor influencing the system's efficiency is the surface-source temperature. In the case of space heating, the best results were achieved for low-temperature systems, particularly underfloor heating, for which the highest SCOP and overall system efficiency values were recorded, along with the lowest values for final energy, primary energy, and electricity consumption. At the same time, a deterioration in the ground-source conditions, reflected in a drop in ground temperature, led to a systematic reduction in efficiency; however, the impact of this factor was less significant than that of the consumer system's supply temperature.

Similar relationships were observed for domestic hot water production. Lowering the required DHW temperature improved the system's energy performance, whereas lowering the ground-source temperature worsened it. This means that the actual efficiency of a ground-source heat pump is determined not only by the geothermal technology itself, but above all by its integration into the building's overall technical system. The results also confirmed that improved energy performance is directly linked to reduced pollutant emissions and a lower synthetic environmental impact indicator.

The results of the study provide ample evidence of the high efficiency of ground-source heat pumps, as do the findings of previously published works, including Self et al. (2014) [10], Peřka et al. (2017) [13], and Menberg et al. (2025) [5]. However, the simultaneous analysis of the impact of system operating parameters on a building's energy performance indicators and on environmental impacts, considered in aggregate, is still relatively rare. This applies in particular to studies in which variations in the ground-source temperature, the heating system supply temperature, and the domestic hot water preparation temperature are considered collectively within a single calculation model. Yet it is precisely this approach that enables better integration of heat pump theory with design practice and with the environmental assessment of a building.

The results obtained and the conclusions drawn enable the establishment of a clear framework and objectives for future action, including, in particular, the following:

- Energy efficiency should be regarded as a prerequisite for the effective integration of renewable energy sources into a building, rather than as a separate objective of modernisation [8,9].
- Traditional building energy performance does not provide a complete picture of its environmental impact; therefore, there is an increasing call to supplement it with elements of emissions and resource analysis, including carbon and water footprints [29–31].
- The use of fixed annual emission factors and primary energy consumption figures may lead to oversimplifications in the assessment of the actual carbon footprint of buildings, particularly in the context of the ongoing decarbonisation of the electricity system [32,33].
- A more comprehensive environmental assessment of a building requires consideration not only of the operational phase, but also of the stages related to material production, construction, use, and end-of-life, which form the basis of the LCA approach [30,31].

The research carried out, therefore, suggests that ground-source heat pumps are a highly efficient solution, but their full potential is realised only in properly designed systems, particularly low-temperature ones. From a practical point of view, this means that optimisation should encompass not only the selection of the heat source itself, but also the heating system's operating temperature, the parameters for domestic hot water preparation, and an assessment of environmental impacts that goes beyond traditional energy indicators.

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