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Optimization of Heat Pump Systems in Buildings by Minimizing Costs and CO_2 Emissions

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Abstract: District heating systems are gaining global recognition as an essential tool for reducing greenhouse gas emissions and transitioning to a low-carbon-energy future. In this context, heat pumps are becoming an important technology, providing an effective solution for improving energy efficiency and reducing the reliance on fossil fuels in heating systems. Therefore, this study is focused on the optimal selection of heat pump systems for different types of buildings considering technical, economic, environmental, and social factors. This paper proposes a novel methodology based on mixed-integer nonlinear programming and multi-objective optimization that minimizes total costs and reduces CO_2 emissions for heat production and supply systems over a desired period. The methodology is applied to various building types, including renovated and unrenovated apartment buildings, schools, kindergartens, and a supermarket. The study analyzes various types of heat pumps and electric heaters for space heating and domestic hot water production. Optimization results showed that the optimal heating system includes air-to-water heat pumps and electric heaters. Furthermore, for schools and a supermarket, these systems are combined with hybrid heat pumps. The goal of making the heating system neutral in terms of CO_2 emissions was achieved for eight out of eleven buildings analyzed. The most profitable investments were in the heating systems of renovated five-story and unrenovated nine-story apartment buildings due to their low energy costs (0.0831 EUR/kWh), short payback periods, and high returns on investment.

Keywords: heating; heat pumps; electric heaters; optimization; CO_2 emissions; buildings; multi-objective optimization; nonlinear programming; MINLP

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1. Introduction

District heating (DH) plays a crucial role in smart energy systems and is regarded as a key tool for achieving a region's ambitious energy and climate goals to reduce greenhouse gas (GHG) emissions and transitioning to a low-carbon-energy future [1]. DH systems are gaining widespread adoption globally as countries strive to meet their energy and climate targets. Europe is rapidly recognizing its significance, especially in light of the European Green Deal's [2] goals to reduce net GHG emissions by at least 55% by 2030, compared to 1990 levels and to make Europe the world's first climate-neutral continent by 2050. To achieve these climate targets and fulfill the European Union's (EU) long-term strategy, it is imperative to decrease reliance on fossil fuels, increase the use of renewable energy sources (RES), and improve energy efficiency in heating systems. This is in line with national energy and climate action plans [3].

One of the most effective solutions to meet these goals is the use of heat pumps (HPs) in DH systems. Heat pumps are a highly energy-efficient and low-carbon technology that can be used for space and water heating in buildings by extracting heat from various sources such as air, ground, water bodies, industrial processes, waste heat or water, and geothermal sources such as geysers or hot springs. This not only reduces energy consumption but also helps to decrease reliance on fossil fuels and increase the use of RES. Large-scale electric HPs have been found to significantly reduce CO_2 emissions compared with traditional fossil fuel sources such as coal or oil [4,5]. Additionally, the use of HPs instead of traditional heating systems can help to reduce the burning of waste fuels, including biofuels. Although biofuels were initially considered to be a neutral or low-carbon fuel source, recent studies [6–8] have shown that the production and use of biofuels in terms of overall carbon footprint is less favorable than previously thought. Thus, HPs can have a significant impact on reducing the overall carbon footprint of buildings.

Integration of HPs in buildings can have a significant impact on the overall energy consumption of the building and associated CO_2 emissions. As such, there is a growing interest in optimizing the selection of HPs in order to reduce their environmental impact, lower heating costs, and improve heating system efficiency. In practice, these optimization problems can be approached through various mathematical optimization methods, including linear programming (LP), mixed-integer linear programming (MILP), genetic algorithms (GA), nonlinear optimization, and many others. These optimization methods can provide a systematic approach for decision makers to select the most suitable HP for a specific building and heating system, considering factors such as energy efficiency, initial costs, operating costs, and emissions.

The use of LP in heat pump design is aimed at finding the optimal solution that maximizes the performance and efficiency of the system while minimizing costs. Pieper et al. [9] utilized LP to minimize annual electricity consumption while determining optimum capacities for HPs using different heat sources. In this paper, the analyzed DH system consisted of HPs, an electric peak load boiler, and short-term storage. Arabzadeh et al. [10] proposed an LP model to define a cost-optimized 24-h schedule for HP operation in a residential building such that electricity demand and price would be at their lowest. Tosatto et al. [11] investigated the integration effects of an HP on large-scale thermal energy storage in district heating systems.

Another commonly used approach for designing an optimal heat pump system is MILP, which seamlessly integrates multiple variables and constraints into a mathematical optimization model. In the context of heating system design, MILP is used to optimize the performance, efficiency, and cost of the system by considering variables such as operating modes, equipment selection, and control strategies [12–16]. Krützfeldt et al. [17] used MILP for an optimization framework to find the economically optimal design for air-to-water HP systems in single-family houses. Their optimization framework considers both the design and operation of all components, taking into account system dynamics and interdependencies among them over a one-year period. The results of the optimization model include the optimal number and capacity of HPs and the use of thermal energy storage systems for domestic hot water (DHW) and space heating (SH).

However, designing an optimal heating system often requires accounting for multiple objectives, which is why multi-objective optimization techniques are frequently utilized in relevant research [18–22]. The study by Murray et al. [23] proposed a multi-objective optimization approach based on MILP to determine the most effective level of decentralization for reducing CO_2 emissions and achieving high levels of self-sustainability. The model aims to minimize both total annual costs and operational carbon emissions through simulation using the epsilon-constraint method. The analysis involves 225 unique mixed-use buildings, including single-family homes, multi-family homes, offices, a grocery store, and a sports facility located in the Swiss Alps. Miglani et al. [24] aimed to select an optimal energy system for a single-family building using bi-level multi-objective optimization to minimize total costs and CO_2 emissions for the optimal design and operation over a long-term period. Their proposed approach combined a GA at the design level and a MILP at the operational level. They analyzed various technologies such as ground source heat pumps (GSHPs), solar thermal collectors, solar photovoltaic (PV) panels, gas boilers, electric heaters (EHs), and thermal energy storage.

A multi-objective genetic algorithm (MOGA) with similar objectives was also applied in research by Vering et al. [25]. They used MOGA within the HPS eOD design framework (a simulation-based optimization approach) to optimize annualized costs and emissions of HP systems considering operational behavior already during the design phase. This method was coupled with the TEASER software [26] for automatic generation of the building, thus allowing for use in various types of buildings located globally. The optimization variables in the framework correspond to components of HP systems such as compressor type, heat exchanger size, number of fans, and operational parameters. Niemelä et al. [27] conducted an analysis to find the most cost-effective renovation solutions for large-panel apartment buildings located in cold climates over a 30-year life cycle period. In this study, various main heating systems were analyzed, and the cost-optimal solutions were determined from over 220 million renovation combinations by utilizing a simulation-based multi-objective optimization approach using the Pareto-Archive NSGA-II algorithm. The main objective of this research was to determine the cost-effective renovation concepts that provide both energy efficiency and reduction in total CO_2 emissions. The study by Kiptoo et al. [28] investigated the potential of integrating short-term flexibility into long-term capacity planning for microgrids with a high proportion of renewable energy. To achieve this, they used a multi-objective optimization model to minimize the loss of power supply probability index and total life cycle costs, evaluating the most cost-effective approach for microgrid planning. The researchers employed the multi-objective particle swarm optimization algorithm, implemented in MATLAB R software, to solve the optimization problems.

Additionally, nonlinear models have also been utilized in some studies to solve more complex optimization problems. One such model is the mixed-integer nonlinear programming (MINLP) model, which was analyzed in research by Hu et al. [29]. The MINLP model in this study considers various factors such as the quantity and quality of heat sources, heat sink requirements, feasible integration technologies, and economic performance to optimally design low-grade heat utilization systems and HP-integrated low-grade heat utilization systems. The objective of the MINLP model is to minimize total annual cost while ensuring that other parameters such as heat sources, heat sink requirements, and integration technologies are met. To solve this optimization problem, the MINLP model was solved using the BARON solver in the General Algebraic Modeling System (GAMS) software. Akulker and Aydin [30] analyzed the MINLP model for optimal equipment selection to design and schedule a multi-energy microgrid, with the goal of minimizing the total annualized cost of the system. The equipment considered in their study included wind turbine farms, solar panels, batteries, and combined heat and power plants. Ghorab et al. [31] used a combination of nonlinear programming and multi-objective optimization techniques to investigate the potential of a multi-module hybrid renewable energy system to reduce costs and GHG emissions over an annual period. The system consisted of a ground–air heat exchanger, photovoltaic thermal panels, and an air-to-water HP. The authors employed MILP techniques, evolutionary algorithms, and dynamic simulation to optimize the system design and performance parameters. These methods allowed the authors to optimize key performance parameters, such as module sizes, and to minimize both cost and environmental impact. The results of the study showed that the system could self-generate nearly 29.4% of the total HVAC electricity needs. The use of nonlinear programming and multi-objective optimization techniques was crucial in achieving these results. In a study by Vering et al. [32], a methodology called SPRINT was presented, which optimizes the design and operation of air-source HP systems for residential buildings. This approach involves a two-stage optimization process using MINLP and multiple objectives such as costs and emission minimization over a one-year period. In the first stage, an annual dynamic building performance simulation is used to optimize system design using surrogate-based optimization. The second stage uses GA with the same dynamic simulation models to optimize system controller settings. By considering both stages together through the intensification of the process, costs can be reduced by up to 36%, and emissions can be reduced by up 51% compared with standard procedures.

Despite the advancements in the relevant research, there is still a gap in the available literature that requires attention regarding the selection of optimal heat pump heating systems for various buildings, including apartment buildings, commercial buildings, and public buildings. Currently, there is limited research in this area that specifically analyzes the best heating system from the available options taking into account cost and emission minimization over a long-term period. This makes it imperative to conduct a study on the optimal selection of HPs for different types of buildings to address this gap in the literature.

The main objective of the study presented in this paper is to propose a novel methodology aimed at the selection of optimal heat production and supply systems for different types of buildings by minimizing total costs and reducing CO_2 emissions. The optimization problem takes into account various technical, economic, environmental, and social factors and analyzes various types of HPs, EHs, and their combination in a heat production and supply system. The methodology is applied to a range of building types, including renovated and unrenovated apartment buildings, schools, kindergartens, and a supermarket. The scientific novelty of this paper lies in providing an innovative and practical approach to selecting optimal heat production and supply systems for different types of buildings, which could lead to significant energy savings and environmental benefits.

This paper is structured as follows: Section 2 describes in detail the proposed methodology for the analysis including the developed mathematical model. Section 3 introduces the main assumptions and data used in the case study. Application of the proposed model as well as the main results are presented in Section 4. Implications of the main findings are discussed, and future research directions are highlighted in Section 5. Finally, in Section 6, the study's concluding remarks are presented.

2. Methodology

The paper examined the selection of the optimal heat production and supply system for different types of buildings. The main objective of the analysis was to select a heat production and supply system in such way that the total costs of the system and its operation are minimized over the period analyzed while also meeting the requirements of reducing CO_2 emissions. The model could cover various types of buildings, such as renovated and unrenovated buildings, apartment buildings, public buildings, supermarkets, etc. The optimization is performed taking into account various technical, economic, environmental, and social factors.

In order to construct a mathematical optimization model, various types of heat pumps, electric heaters, and their combinations in a heat production and supply system had to be analyzed. The optimization model included constraints to ensure that the capacity of the heating system selected for each building was sufficient to meet the actual monthly and the peak hourly heat demand. The monthly variable operating modes of the selected technologies were taken into account depending on the heat demand of the analyzed buildings and the maximum capacity of the heating system in different months. Variables reflecting the operating modes of the analyzed technologies each month show the time span across which the analyzed technology has to operate in order to meet the total monthly heat demand. The model also considered the degradation of heating technologies and their decreasing efficiency in the long term.

The problem of selecting the optimal heating system was solved using MINLP [33] and multi-objective optimization methods. The solutions for the optimization problem include the optimal number of HPs and EHs as well as the optimal operating modes of these technologies for each month during the analyzed period. The solutions were obtained using the branch and reduce algorithm. The MINLP problem was solved using the Python programming language, the Pyomo library, and the BARON solver [34], which is a popular optimization software known for finding globally optimal solutions for complex nonlinear problems. The formulation of the optimization problem and the solution process are presented in Figure 1.

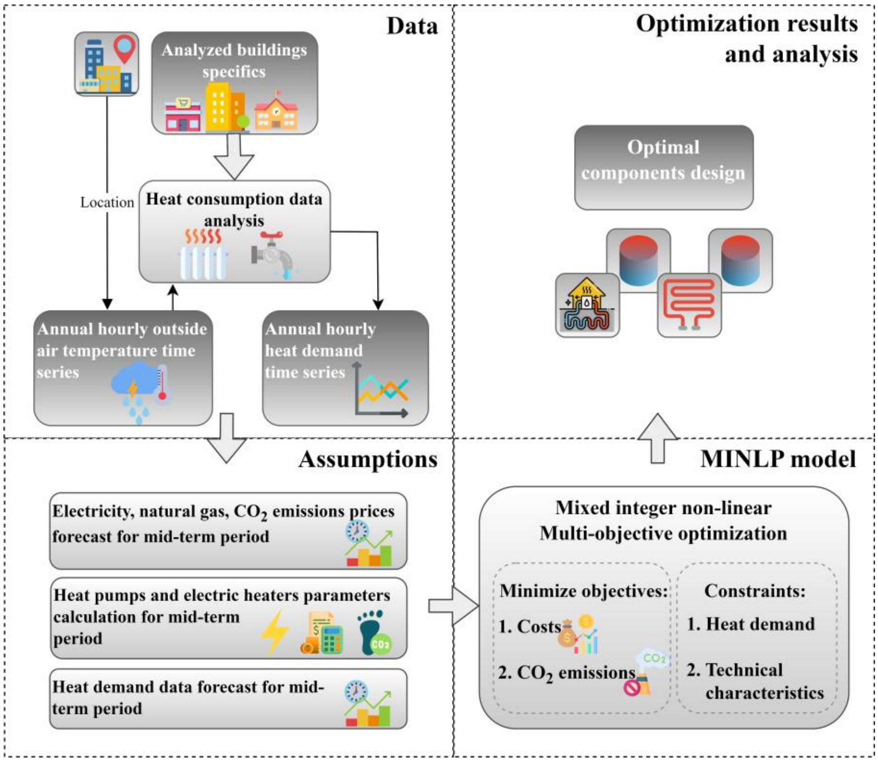

Figure 1. The scheme of the methodology framework for the optimization problem.

The methodology framework for the optimization problem, illustrated in Figure 1, was divided into four main parts: data, assumptions, optimization, and results. The workflow begins by collecting and analyzing data on the building's specific characteristics and heat consumption as well as forecasting heat demand for a mid-term period. Assumptions are then made about prices for electricity, natural gas, and CO_2 emissions, and the main parameters for HPs and EHs are calculated. A MINLP multi-objective optimization problem is then formulated [35–37] and solved for the selected buildings. The results are further analyzed through post-optimization analysis by presenting the performance of various technical and financial indicators.

The objectives of the analysis were to minimize the total heating costs (Equation (1)) and GHG emissions of the installed heating system (Equation (2)). The total heating costs consist of the price of HPs and EHs as well as their installation, the maintenance costs of the selected technologies, the price of the electricity needed for the operation of HPs and EHs, and the price of the natural gas consumed during the operation of hybrid HPs. The mathematical optimization model was constructed taking into account these two objectives and various constraints:

$$\min f(x,y) = \sum_{i=1}^{n}\sum_{j=1}^{t}\sum_{k=1}^{m} c_{ijk}y_{ijk}x_i + \sum_{i=1}^{n}(\widetilde{c}_i + \hat{c}_i + m\dot{c}_i)x_i, \tag{1}$$

$$\min g(x,y) = \sum_{i=1}^{n}\sum_{j=1}^{t}\sum_{k=1}^{m} \overline{c}_{ijk}y_{ijk}x_i, \tag{2}$$

subject to

$$\sum_{i=1}^{n} q_{ijk}y_{ijk}x_i \geq Q_{jk}, \tag{3}$$

$$\sum_{i=1}^{n} x_i q_{ij1} \geq Q_{max_j}, \tag{4}$$

$$\sum_{i=1}^{s} x_i q_{ij1} \geq pQ_{max_j}, \tag{5}$$

$$\sum_{i=1}^{s} x_i s_i \geq S_{hp}, \tag{6}$$

$$x_i \in \mathbb{Z},\ x_i \geq 0, 0 \leq y_{ijk} \leq h_j, y_{ijk} \in \mathbb{R}^+,\ i = 1, \ldots, n,\ j = 1, \ldots, t, k = 1, \ldots, m,$$

here, n is the number of analyzed technologies consisting of the number of ground source and air-to-water HPs, the number of hybrid HPs, and the number of EHs; t is the number of months; and m is the number of years. The variables x_i of the optimization model represent the number of HPs/EHs of type i in units, and y_{ijk} is the number of operating hours of HP/EH of type i in month j of year k, which cannot exceed the total number of hours (h_j) in month j.

Coefficients c_{ijk} of the objective function (1) denote the operating costs per hour for technology i in month j of year k, which are calculated by multiplying the electricity consumption per hour (kWh) for each technology by the corresponding electricity price c_{el_k} (EUR/kWh) for year k. The electricity consumption of ground source and air-to-water HPs per hour is calculated by dividing the heating capacity (q_{ijk}) by the coefficient of performance (COP_{ijk}) of HP i in month j of year k and then multiplying the result by the annually varying electricity price $\left(c_{el_k}\right)$. The operating costs of hybrid HPs per hour consist of the costs for electricity and natural gas when the electricity (kWh) and natural gas (m^3) consumption values (el_i and g_i) of the hybrid HPs, which are indicated in the specifications of the HPs, are multiplied by the electricity $\left(c_{el_k}\right)$ and natural gas $\left(c_{gas_k}\right)$ tariffs, respectively. The electricity consumption of EHs per hour is calculated by multiplying the values of their heating capacity (q_{ijk}) and the electricity consumption coefficient (t_{ik}). Multiplication of the electricity consumption and the electricity tariff $\left(c_{el_k}\right)$ provides the operating costs per hour. The calculation of the coefficients c_{ijk} of the objective function (1), which depends on the analyzed heating technology, is presented as follows:

$$c_{ijk} = \begin{cases} \frac{q_{ijk}}{COP_{ijk}} c_{el_k}, & \text{for geothermal and air-to-water HPs,} \\ g_i c_{gas_k} + el_i c_{el_k}, & \text{for hybrid HPs,} \\ q_{ijk} t_{ik} c_{el_k}, & \text{for EHs,} \end{cases} \tag{7}$$

$i = 1, \ldots, l, j = 1, \ldots, t, k = 1, \ldots, m.$

The coefficients c_{ijk} depend on the changes in heating capacities, efficiency and electricity (gas) utilization coefficients, and electricity and gas tariffs over m years.

The coefficients $\widetilde{c}_i$ in Equation (1) represent the price (EUR) of HP/EH i, and $\hat{c}_i$ denotes the installation costs (EUR). The maintenance costs of HPs/EHs are calculated by multiplying the maintenance costs of HP/EH of type i per year $(\dot{c}_i)$ by the number of years (m).

The coefficients $\overline{c}_{ijk}$ in Equation (2) denote the costs of CO_2 emissions of HP i in month j of year k per hour. These coefficients $\overline{c}_{ijk}$ are calculated by multiplying the amount of CO_2 emissions em_{ijk} (t/h) due to gas use of HP i in month j of year k by the price (EUR/t) of CO_2 emissions ($c_{co_{2_k}}$):

$$\overline{c}_{ijk} = em_{ijk} c_{co_{2_k}}. \tag{8}$$

Here, CO_2 emissions em_{ijk} are based on the gas consumption (kWh) of HP i per hour as given in the technical specifications of the hybrid HPs.

The heating system must satisfy the monthly heat demand of the analyzed buildings for each year, i.e., the total amount of heat (kWh) produced by the selected heating system should not be less than the actual heat demand Q_{jk} (kWh) in month j of year k. This condition is ensured by the system of inequalities (1).

The total amount of heat produced is determined by the capacity (q_{ijk}), the number of operating hours (y_{ijk}), and the quantity (x_i) of the selected HP/EH i in month j of year k.

The selected heating system must not only satisfy the actual monthly heat demand but also the maximum heat demand per hour. Constrains (2) ensure that the total capacity of the selected heating system is not less than the maximum heat demand per hour (Q_{max_j}) for each month in the heating season of the first year.

In this case, the total system capacity for each analyzed month is calculated using the heating capacities (q_{ij1}) of technology i in each analyzed month j of the first year. Free terms (Q_{max_j}) of the constraints are the maximum heat demand per hour for each month j or the maximum required heating system capacity, which is also calculated only for the first year when the heat demand is the highest.

The problem constraint, which states that the HPs must satisfy the majority of the maximum heat demand per hour (Q_{max_j}), is implemented by Equation (3). In the inequality (3), s is the number of HPs included in the analysis, and p is the coefficient indicating the proportion of the maximum heat demand per hour that must be covered by the heat pumps ($0 \leq p \leq 1$).

Additionally, the designed HP heating system cannot exceed the area of the heating substation (Equation (4)). In the constraint (4), s_i denotes the area of HP i (m^2), and S_{hp} is the area of the heating substation (m^2).

The multi-objective optimization problem (Equations (1)–(6)) is solved using a goal-programming and weighting coefficients method. The goal-programming method transforms a problem with two objective functions (Equations (1) and (2)) into a problem with one objective function:

$$\text{minimize } \alpha_1 d_1^+ + \alpha_2 d_2^+, \tag{9}$$

by introducing additional non-negative variables, called deviations ($d_1^-, d_1^+, d_2^-, d_2^+$), in objectives demonstrated in Equations (1) and (2):

$$\sum_{i=1}^{n}\sum_{j=1}^{t}\sum_{k=1}^{m} c_{ijk} y_{ijk} x_i + \sum_{i=1}^{n} \left(\tilde{c}_i + \hat{c}_i + m\dot{c}_i\right) x_i + d_1^- - d_1^+ = 0, \tag{10}$$

$$\sum_{i=1}^{n}\sum_{j=1}^{t}\sum_{k=1}^{m} \bar{c}_{ijk} y_{ijk} x_i + d_2^- - d_2^+ = 0, \tag{11}$$

here, α_1, α_2 are positive weights, which reflect the importance of the individual objectives.

3. Case Study

3.1. Analysis of Heat Consumption

In order to select the optimal heating system, the first step is to perform a detailed analysis of hourly heat consumption data, taking into account heat demand of the analyzed buildings, consumption trends, efficiency, and heat consumption peaks. Hourly heat consumption data of different buildings and hourly outdoor air temperatures were used for the statistical analysis. The analysis covered the period from 2021 to 2022 (hourly data for one full year). In total, data from 11 different buildings were analyzed, including renovated and unrenovated apartment buildings, schools, kindergartens, and a supermarket, to cover a wide spectrum of typical buildings. The general information of the selected buildings for the analysis is presented in Table 1.

Table 1. The main information of the analyzed buildings.

Building No.	Building Type	Number of Stories	Renovation	Area, m^2	Volume, m^3	Annual Heat Demand, MWh	Maximum Heat Demand per Hour, kWh
1.	Apartment building	5	Renovated	2452	7357	221.16	65.03
2.	Apartment building	5	Unrenovated	2510	7530	397.28	123.03
3.	Apartment building	5	Renovated	4520	13,561	551.27	185.25
4.	Apartment building	9	Unrenovated	5866	17,598	658.96	199.23
5.	Apartment building	2	Unrenovated	460	1381	85.73	26.00
6.	Apartment building	3	Renovated	531	1594	59.21	20.58
7.	Kindergarten	2	Renovated	2146	6438	197.28	86.75
8.	Kindergarten	2	Unrenovated	2189	6567	255.49	109.00
9.	School	3	Renovated	6288	18,864	276.00	147.40
10.	School	2	Unrenovated	8495	25,485	644.17	243.00
11.	Supermarket	1	Renovated	7405	29,619	569.05	309.00

Among the constraints of the analyzed optimization problem is the requirement to meet the actual heat demands of each month during the analyzed period. To achieve this, the total monthly heat demand for SH and DHW preparation for the analyzed buildings were calculated from the hourly values. In addition, monthly values were summed to determine the total annual heat demand for each building, which is shown in Table 1. The actual heat consumption depends heavily on the area, volume, and whether the analyzed building is renovated or not.

In order to eliminate the influence of building volume on heat consumption, the hourly relative heat demand (kWh/m^3) was further analyzed. The highest heat demand for both renovated and unrenovated buildings was observed in December 2021, during which the average outdoor air temperature was the lowest (−3 °C). The differences in relative heat consumption between renovated and unrenovated apartment buildings are presented in Figure 2.

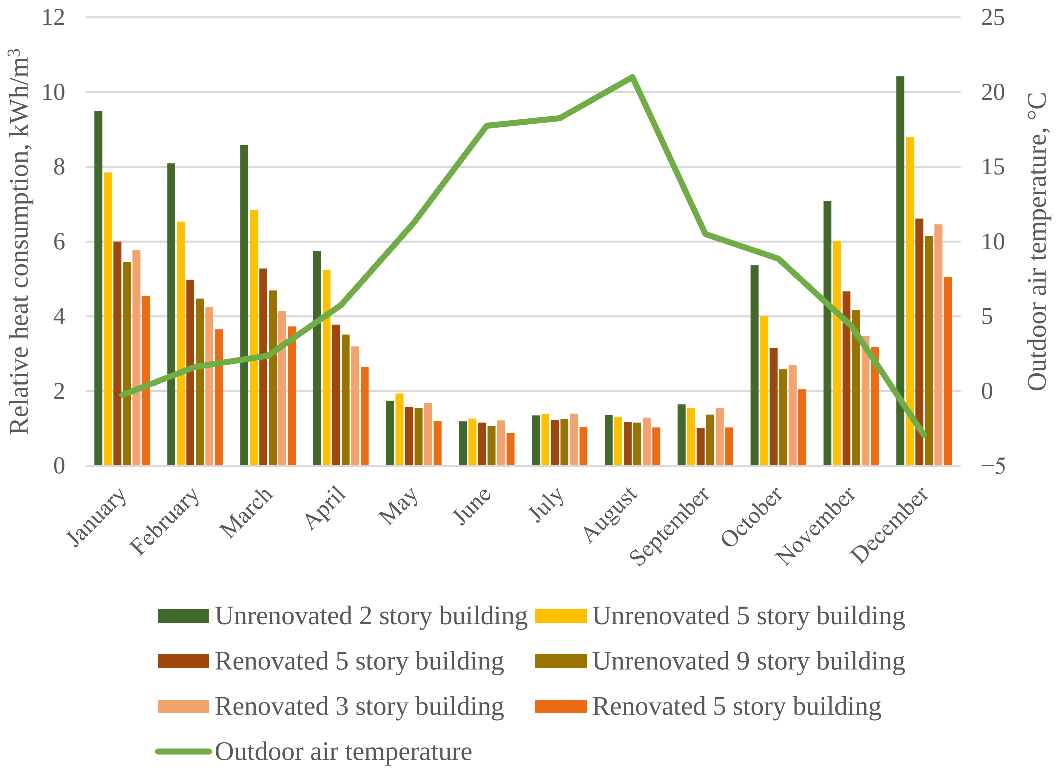

Figure 2. Comparison of relative heat consumption in renovated and unrenovated apartment buildings.

The presented data demonstrate that the consumption of renovated residential apartment buildings is, on average, 30% lower than that of unrenovated buildings. It was also observed that the relative heat consumption in unrenovated apartment buildings also depends on the number of stories; consumption was the highest in an unrenovated two-story building and the lowest in an unrenovated nine-story building (Figure 2).

Heat consumption is not only dependent on whether the building is renovated or not but also on the type and purpose of the building and user habits. In commercial buildings and public institutions, heat consumption can be affected by the working hours in these buildings. When making technical decisions to update the heating system, it is crucial to take into account the energy needs of a specific building, which is why public institutions (e.g., schools and kindergartens) and a supermarket were included in the analysis. A comparison of the average relative heat consumption of different types of buildings analyzed in the paper is illustrated in Figure 3.

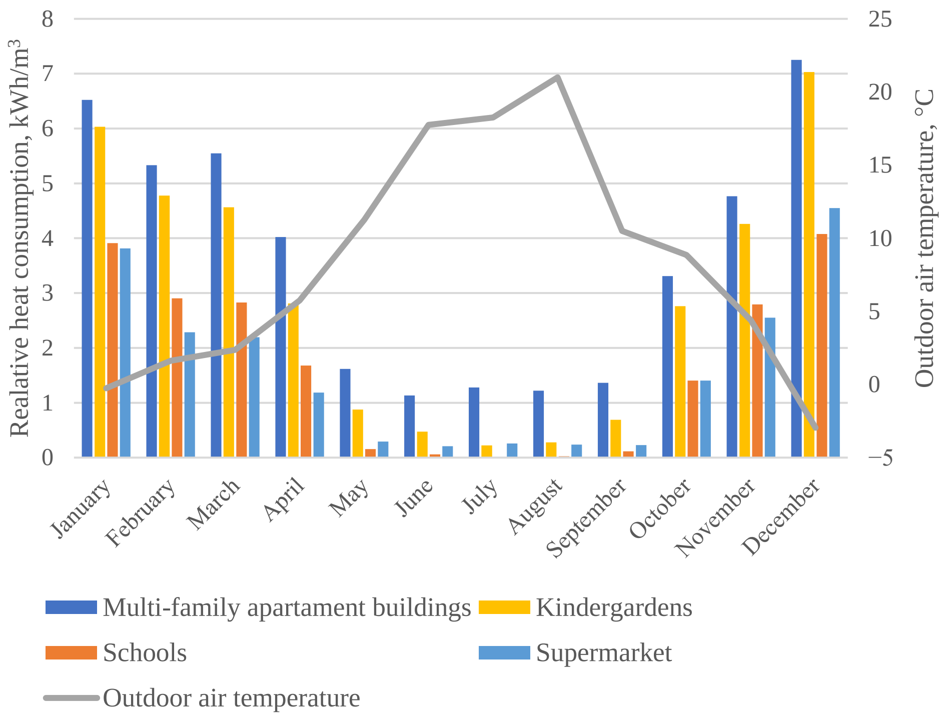

Figure 3. Average relative heat consumption for space heating and hot water preparation in different types of buildings.

As shown in Figure 3, the lowest heat consumption each month was in schools and a supermarket, while the highest was in residential apartment buildings. The average consumption of kindergartens was slightly lower than that of apartment buildings, but the differences were not significant.

Figure 4 illustrates a comparison of the relative heat consumption for each month of the analyzed public institutions along with the average outdoor air temperatures.

The highest relative heat consumption was observed in kindergartens, while the lowest was in the renovated school. Distance learning, non-working hours, weekends, or school holidays may have influenced the lower heat consumption in schools. Additionally, as shown in Figure 4, the highest heat consumption in all buildings was in December 2022, when the average outdoor air temperature was the lowest.

The capacity of the heating system must be sufficient to meet the maximum hourly heat demand. In order to fulfill this condition, the maximum (kWh) heat demand per hour (Q_{max_j}) for each month (j) was estimated for the analyzed buildings and used as a background for selecting the optimal heating system capacity.

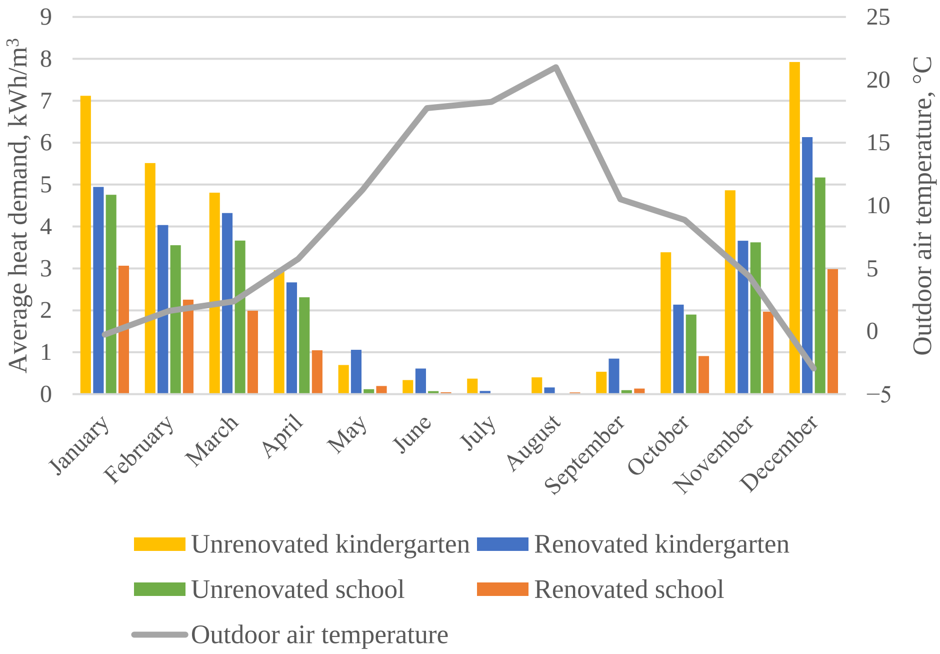

Figure 4. Relative average monthly heat consumption in renovated and unrenovated schools and kindergartens.

When analyzing the 10-year period, it is important to take into account the increasing energy efficiency of buildings over time and changes in outdoor air temperatures. These factors lead to a lower energy demand for SH, which was considered in this analysis. The assumptions for heat demand forecasts are based on the forecasts of annual relative heat consumption of residential buildings in the Baltic States for SH presented in the report [38]. Based on the report data, it was assumed that the heat demand for SH from 2022 to 2031 would decrease by 9.3% in this case study. On the other hand, the degradation of the energy efficiency of isolation as well as energy supply technologies increases the energy demand factor.

3.2. Assumptions for Heat Pumps and Electric Heaters

3.2.1. Types of Heat Pumps and Electric Heaters

In this study, the buildings under analysis had high heat demands and were situated in an area without proximity to open water bodies and with limited land plots. To address these factors, larger capacity GSHPs with a vertical earth probe system, hybrid HPs, and air-to-water type HPs were selected. A total of 25 different HPs models were analyzed, including 17 GSHPs from the "Viessmann Group" manufacturer [39], 4 hybrid HPs from the "Robur" manufacturer [40], and 5 air-to-water HPs from the "Hitachi" manufacturer [41].

To meet peak heat demands or produce domestic hot water, auxiliary EHs are often utilized in heating systems. This analysis included seven different electric heater models [42]. It is worth noting that these EHs should only be used as an auxiliary source that produce no more than 40% of the hourly heat demand. The optimization model being studied took into account the combination of various HPs and EHs in the general heating system, assuming that the HPs should meet at least 60% of the maximum heat demand per hour and ensuring that EHs are only utilized during hours of peak demand.

3.2.2. Costs of Installed Heating System

The costs associated with all components of a heating system as well as their installation and maintenance costs were evaluated over the period analyzed. The prices of HPs were determined based on commercial offers, taking into account the capacity and type of heat pump. The prices of EHs were sourced from the website [42]. It is important to note that various types of HPs have different lifetimes. Ground source heat pumps are generally considered more reliable and durable compared to air-to-water and hybrid HPs, with warranty periods of up to 20 years. On the other hand, air-to-water and hybrid HPs usually come with a 10-year warranty. This means that in the long term, air-to-water and hybrid HPs will require more frequent repairs or replacements. In the case of a heat pump replacement, the installation cost will be significantly lower than for the first installation. Thus, due to their durability and reliability, GSHPs result in lower long-term investment costs and a 30% reduction in the cost of GSHPs, and their installation was assumed in the analysis. When determining the installation and maintenance costs, it was assumed that the installation costs of GSHPs would not exceed 15% of the heat pump's price, with an annual maintenance cost of EUR 950. The installation costs of air-to-water and hybrid HPs were assumed to be 10% and 20% of the heat pump's price, respectively, and annual maintenance costs were assumed to be 2% of the heat pump's price. The installation cost of EHs was assumed to be 7% of the electric heater's price, and the annual maintenance costs was assumed to be 1% of the electric heater's price.

3.2.3. Capacity of Heat Pumps and Electric Heaters

The maximum power of a heat pump is not constant and is based on the primary source temperature and the temperature of the heating water. In this analysis, it was assumed that the temperature of the heating water was constant at 55 °C. The primary heat source for GSHPs is the earth's ground, while air-to-water HPs use outdoor air, and hybrid HPs are a combination of a gas boiler and a heat pump, with the primary source being either the earth's ground or outdoor air. The majority of the HPs analyzed were ground source. Thus, the temperature of the earth's ground was required to calculate the change in power of these pumps. This temperature is influenced by factors such as the depth of the borehole, the temperature of the outdoor air, and the operating mode of the heat pump.

In Lithuania, the temperature of the ground deeper than 7–10 m is relatively constant and reaches 7–9 °C, while the surface ground temperature without the effect of a heat pump collector can drop to 0 °C during the coldest months [43]. Due to limited land area in urban areas near apartment buildings, this study examined a vertical collector with a radial borehole consisting of 10 radial boreholes of 75 m each, with a total borehole length of 750 m. As a result, it was assumed that the temperature of the earth's ground depends solely on the operation of the heat pump. The temperatures of the earth's ground in different months, along with the average outdoor air temperatures for each month, are illustrated in Figure 5.

The analysis of various types of heat pumps was conducted to evaluate their maximum heating capacity. Factors such as the average monthly temperatures and the heat pump's specifications [44–47] for heating capacity dependency on the heating water temperature and primary source temperature were taken into account. For GSHPs, the maximum heating power was evaluated by using the average monthly ground temperature and assuming a constant heating water temperature of 55 °C. This enabled the determination of varying powers of the HPs for each month. In the case of air-to-water HPs, the maximum power change was determined by using data on average monthly outdoor air temperatures and specifications provided by the manufacture [44] for the heat pump's heating power dependency on the primary source temperature (outdoor air temperature) and the set indoor temperature (heating water temperature). This enabled the evaluation of varying powers of the HPs for each month, depending on the outdoor air temperature, in order to ensure a temperature of 20 °C in the buildings. On the other hand, the power of the analyzed hybrid HPs was found to be constant. The amount of heating energy produced by the HPs per month was calculated by multiplying the heating power of the heat pump by its working hours during the analyzed month.

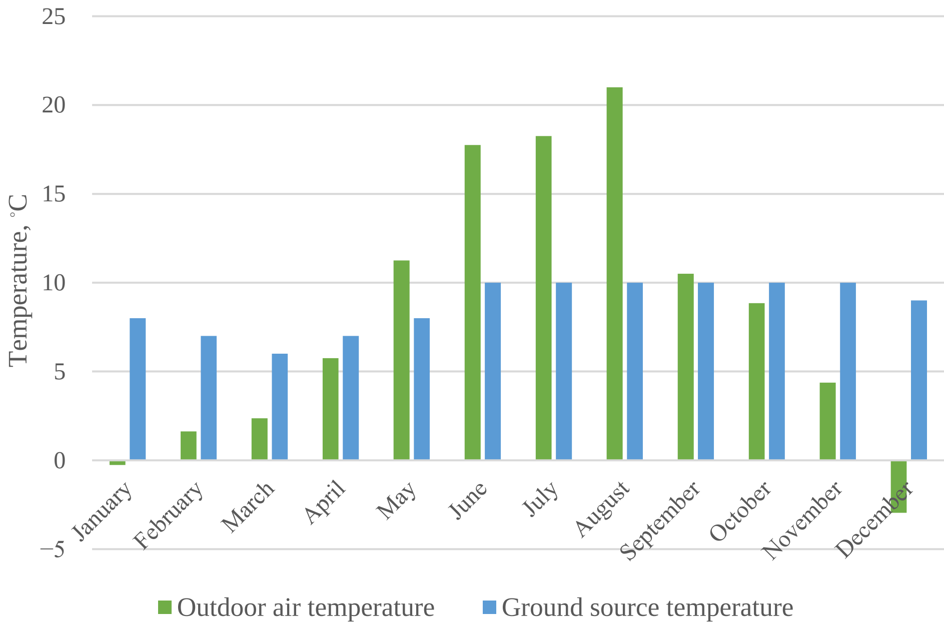

Figure 5. Average monthly temperatures of the primary heat sources.

3.2.4. Coefficient of Performance of Heat Pumps

The energy transformation coefficient, also known as the coefficient of performance (COP), is a metric used to measure the efficiency of HPs. It is calculated as the ratio of the amount of heat obtained to the amount of electricity used by the heat pump. The COP of HPs is calculated by the manufacturer under certain standardized field and indoor air conditions. However, it can vary depending on the unique system of each user. Factors such as primary source temperature and heating water temperature that is fed into the heating system greatly affect COP. In this analysis, COP values for GSHPs were evaluated for each month by using tables and graphs provided in the specifications [45–47] of the HPs and considering varying primary source (ground soil) temperatures and a constant heating water temperature of 55 °C.

Similarly, COP values for air-to-water HPs were determined by dividing the maximum heat pump power by the input power, taking into account the varying average outdoor air temperatures and a constant indoor temperature of 20 °C. These COP values were then used to calculate the hourly electricity consumption for heating. The electricity consumption for heating of hybrid HPs was calculated using the parameters provided in the specifications [40] of HPs. Additionally, over a 10-year period, the COP values of ground source and air-to-water HPs were assumed to decrease by 0.5% annually, while the energy consumption parameters of hybrid pumps may increase due to factors such as deterioration and natural degradation of the components over time. Therefore, it is crucial to consider the long-term COP values in the selection and maintenance of HPs to ensure that they remain energy efficient over time.

3.2.5. CO_2 Emissions of Hybrid Heat Pumps

The use of hybrid heat pumps in apartment buildings presents an efficient and cost-effective heating solution, but one of the biggest drawbacks of these systems is their carbon footprint. During the combustion process, carbon dioxide is released into the atmosphere, contributing to the greenhouse effect and global warming. As the problem of climate change becomes increasingly pressing, governments and organizations worldwide, particularly in the EU, are implementing various restrictions, penalties, and requirements aimed at reducing CO_2 emissions [48]. Despite these efforts, pollution continues to rise [49], resulting in increased taxes on CO_2 emissions. As the concern for the environment continues to grow, it can be expected that in the future, CO_2 emission restrictions will become even stricter, and taxes on emissions will be imposed not only on companies but also on residential buildings.

As this study aims to reduce the amount of emissions by minimizing the cost of CO_2 emissions, a fee for each ton of CO_2 emissions is included in the analysis. By using the gas energy power (kW) parameters provided in the specifications of hybrid HPs and the "household CO_2" calculator [50], the CO_2 emissions of the analyzed hybrid HPs were evaluated in tons per hour. Additionally, the gas consumption per hour (m^3/h) of hybrid HPs was also determined from the specifications [40], and it was assumed that over a 10-year period, this value would increase by 0.25% per year.

3.3. Assumptions for Prices of Electricity, Natural Gas, and CO_2 Emissions

The cost of energy and the environmental impact are critical considerations when assessing the performance of a heating system over a mid-term period. In this subsection, the paper focuses on the assumptions and forecasts of electricity, natural gas and CO_2 prices, and their impact on the operating costs of heat pumps and electric heaters over a 10-year period.

When evaluating the operating costs of HPs and EHs, it is essential to take into account the prices of both electricity and natural gas. According to the tariffs offered by UAB "Ignitis", valid from 1 July 2022 to 31 December 2022, the cost of electricity is 0.24 EUR/kWh [51], and the cost of natural gas is 0.77 EUR/m^3 [52]. However, when analyzing a 10-year period, it is important to consider the potential for energy price fluctuations due to various environmental factors.

In this study, the trend of electricity prices for the period of 2023–2031 was based on a long-term forecast presented in the report in [38], using the 2022 electricity price as a reference point. The prices of natural gas for the same 10-year period were also analyzed. According to the data from [53], gas prices in Europe are predicted to increase from 2021 to 2035, with the gas price in 2035 being approximately 18% higher compared to 2021. Based on this forecast and the 2022 natural gas price in Lithuania, the natural gas prices for the period of 2023–2031 were assessed. The assumptions of electricity and natural gas prices for the 10-year period are illustrated in Figure 6.

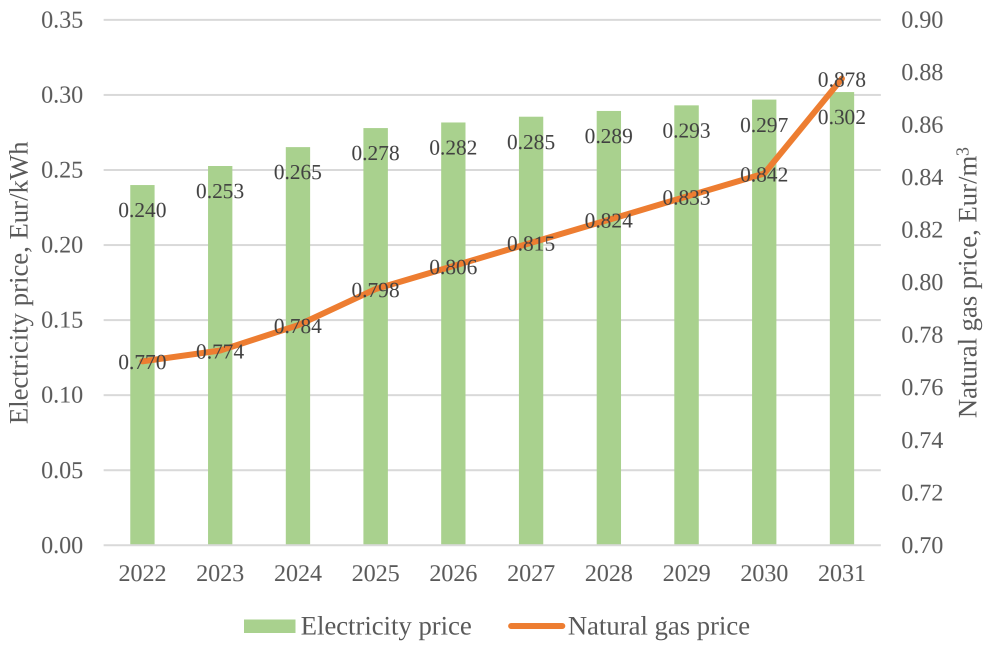

Figure 6. Forecasted trend of natural gas and electricity prices in Lithuania for the period of 2022–2031.

The price of CO_2 emissions and its potential fluctuations during the analyzed period are important considerations in the analysis, as the presented methodology aims to minimize the costs associated with such emissions. The study uses the average price of CO_2 emissions in 2022, which was 83 EUR/t, as a reference point, based on the latest data of [54]. It is important to note that the price of CO_2 emissions is subject to change and may fluctuate due to various factors, such as economic conditions, energy policies, and technological advancements.

The CO_2 emission price forecast in this study is based on the report in [55], which predicts that it will significantly increase by 2050 (more than six times) as a result of increased energy efficiency and the promotion of less CO_2-emitting energy sources. The trend of CO_2 emission prices for each year during the analyzed period, assuming that the price for CO_2 emissions was 83 EUR/t in 2022, is presented in Figure 7.

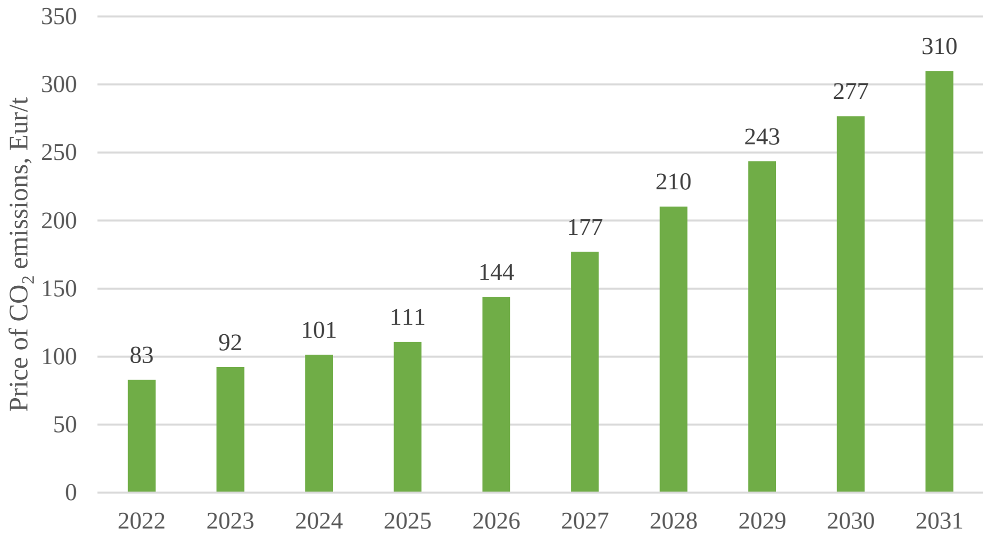

Figure 7. Forecasted trend of CO_2 emission prices in Lithuania for the period of 2022–2031.

4. Results

The selection of the optimal heating system for different types of buildings was performed using a MINLP multi-objective optimization model described in Section 2 and data and assumptions outlined in Section 3. The main findings and results obtained are presented in the following subsections.

4.1. Optimal Heating Systems for Different Buildings

The optimization model simulations enabled us to determine the optimal heating systems for each building in terms of the type, number, and capacity of heat pumps and electric heaters needed to meet the heat demand for SH and DHW preparation. The results of the optimization include the optimal number of HPs and auxiliary EHs as well as the operating mode for each technology in hours per month over a 10-year period for each case analyzed. By minimizing the objective function of the problem analyzed, the dual objectives of lowest total costs of the selected heating system and lowest CO_2 emissions were achieved.

The total costs include the cost of the installed technologies of the heating system, emission costs (if applicable), and maintenance and operation costs over a 10-year period. The main results of the optimized heating systems for different buildings are presented in Table 2, which includes the optimal heating system components, their heating capacity in December, and the proportion of heat produced by HPs and EHs in the first year for each analyzed building.

Table 2. Results for the optimal heating systems in different buildings.

Building No.	Selected Types of Heat Pumps	Number of Selected Heat Pumps	Number of Selected Electric Heaters	Capacity of Heat Pumps in December, kW	Capacity of Electric Heaters, kW	Total Capacity of the Heating System, kW	Heat Pump Contribution to Total Heat Production per Year, %	Electric Heater Contribution to Total Heat Production per Year, %
1.	Air-to-water	1	1	58.61	7.5	66.11	99.7	0.3
2.	Air-to-water	2	3	78.58	39	117.58	94.9	5.1
3.	Air-to-water	2	4	117.22	60	177.22	96.2	3.8
4.	Air-to-water	3	5	137.19	63	200.19	97.7	2.3
5.	Air-to-water	1	1	19.97	7.5	27.47	98.6	1.4
6.	Air-to-water	1	1	19.97	3	22.97	99.8	0.2
7.	Air-to-water	1	1	58.61	30	88.61	95.8	4.2
8.	Air-to-water	2	3	78.58	31.5	110.08	96.9	3.1
9.	Air-to-water, hybrid	1 1	4	96.91	46.5	143.41	95.1	4.9
10.	Air-to-water, hybrid	3 1	5	175.49	69	244.49	97.0	3.0
11.	Air-to-water, hybrid	2 2	9	193.82	117	310.82	96.2	3.8

Table 2 shows that, in all cases analyzed, the optimal heat production and supply system included air-to-water HPs as one of its components. Furthermore, for schools and a supermarket (buildings no. 9, 10, and 11), these HPs were combined with hybrid HPs. Therefore, the results of the problem showed that the goal of making the heating system neutral in terms of CO_2 emissions was achieved for eight of the eleven buildings analyzed. However, the buildings for which hybrid HPs were selected will still slightly contribute to environmental pollution due to the burning of gas. Based on the results of CO_2 emissions, the highest CO_2 emissions during the analyzed period were in the supermarket for which two hybrid HPs were selected. Over a 10-year period, the use of hybrid HPs in the analyzed supermarket is expected to result in the emission of approximately 73 tons of CO_2, which corresponds to a cost of approximately 12k EUR. During the analyzed period, CO_2 emissions were measured in both the renovated and unrenovated schools; the renovated school produced 24 tons of CO_2 emissions, while the unrenovated school produced 39 tons. This indicates that while hybrid HPs may be a cost-effective heating solution, their use may have environmental implications in terms of GHG emissions. However, utilizing an HP system instead of relying on DH significantly reduces CO_2 emissions, especially when the DH supply is based on fossil fuels. Additionally, EHs of various capacities are selected for all buildings to meet the peak heat demand. The capacity of these EHs depends on the building's energy efficiency and the building's actual heat demand.

The percentage of heat produced by EHs indicates that they covered the largest share of the total heat demand in the unrenovated five-story apartment building (no. 2). In this building, EHs produced approximately 5% of the total heat demand for the first year. Electric heaters made up the smallest proportion of the total heat needs in the most energy-efficient buildings, the five-story renovated apartment building (no. 1), as well as in two other buildings with low heat needs: the unrenovated two-story apartment building (no. 5) and the renovated three-story apartment building (no. 6).

The capacity of the heat production and supply system depends on the actual heat needs in the buildings. The supermarket (building no. 9) had the highest actual heat demand and, as a result, had the highest total capacity of 310.82 kW. The renovated three-story and unrenovated two-story apartment buildings (no. 6 and 5, respectively), which had the lowest actual heat demands, had the smallest heating system capacities of 27.47 kW and 22.97 kW, respectively.

The optimal modes of operation for the selected heat production and supply systems were also determined for the entire analyzed period. After analyzing the optimal modes of operation for each month of the first year, it was found that HPs were used to meet most of the heat demand. Electric heaters were only used during peak demand hours when the capacity required to meet the demand exceeded the maximum capacity of the HP systems. Figure 8 illustrates the amount of heat produced by the selected EHs and HPs in the five-story and nine-story apartment buildings during the first year of the analyzed period.

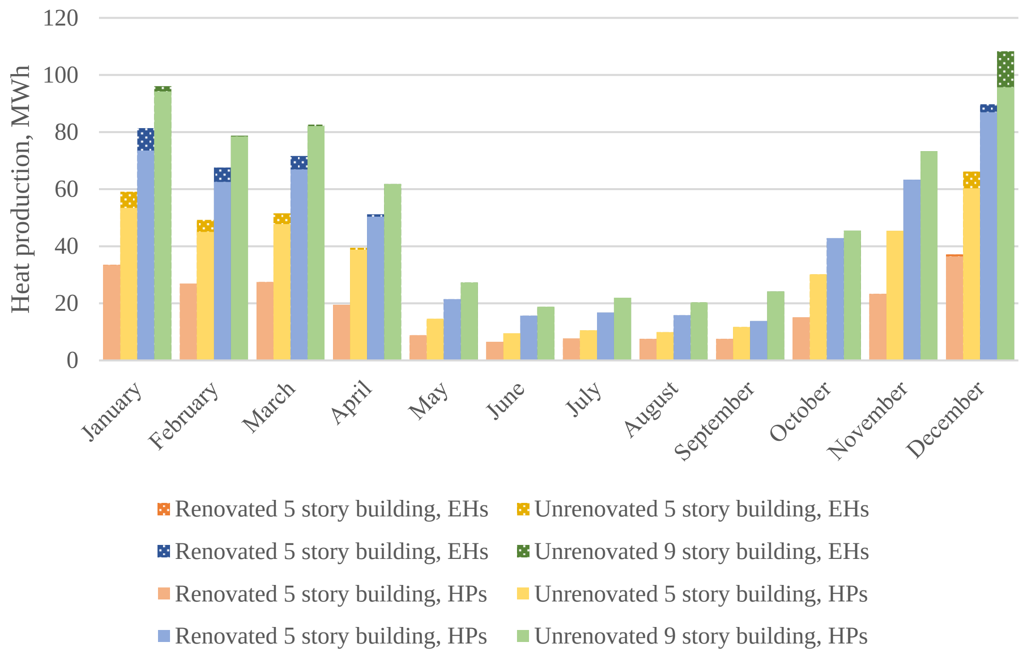

Figure 8. Comparison of heat production in renovated and unrenovated apartment buildings.

Figure 8 shows that in the analyzed apartment buildings, the highest heat demand occurred in December and January. During these months, EHs also contributed to heat production by covering peaks in heat demand. In contrast, during the warmer months of the year (May–October), HPs were sufficient to meet the heat demand, and EHs were not used. Furthermore, EHs produced the most heat in the unrenovated nine-story building in December (approx. 11.4%), when the heat demand in this building was also at its highest. EHs made a minor contribution to heat production in two-story and three-story apartment buildings, which had the lowest heat demand.

After adjusting for the effect of building volume and comparing relative heat demand, the results of the analysis revealed some notable changes. Specifically, the buildings with the highest relative heat demands were the unrenovated five-story and two-story apartment buildings. Furthermore, in the unrenovated five-story building, EHs produced the most heat per m^3, they contributed to approximately 5% of the annual relative heat demand, and during January, they produced over 9% of the monthly heat demand. Additionally, it was found that during the first year of the analyzed period, the use of EHs in this apartment building accounted for the largest portion of electricity consumption. Specifically, the EHs accounted for 20% of the total electricity consumption per year. The most energy-efficient was the renovated five-story apartment building, with the lowest monthly relative heat consumption. Additionally, in this building, EHs relatively produced the least amount of heat energy compared to other buildings, and the amount of electricity consumed by EHs accounted for less than 1.5% of the total electricity consumption per year. The other efficient building was a renovated three-story apartment building where EHs were used minimally, and the electricity consumption attributable to the use of EHs constituted slightly less than one percent of the total annual electricity consumption for SH and DHW preparation. Figure 9 presents a comparison of the selected systems' heat production in schools, kindergartens, and a supermarket. In this case, the heat production of HPs and EHs had a similar trend as the production in apartment buildings, which was presented in Figure 8.

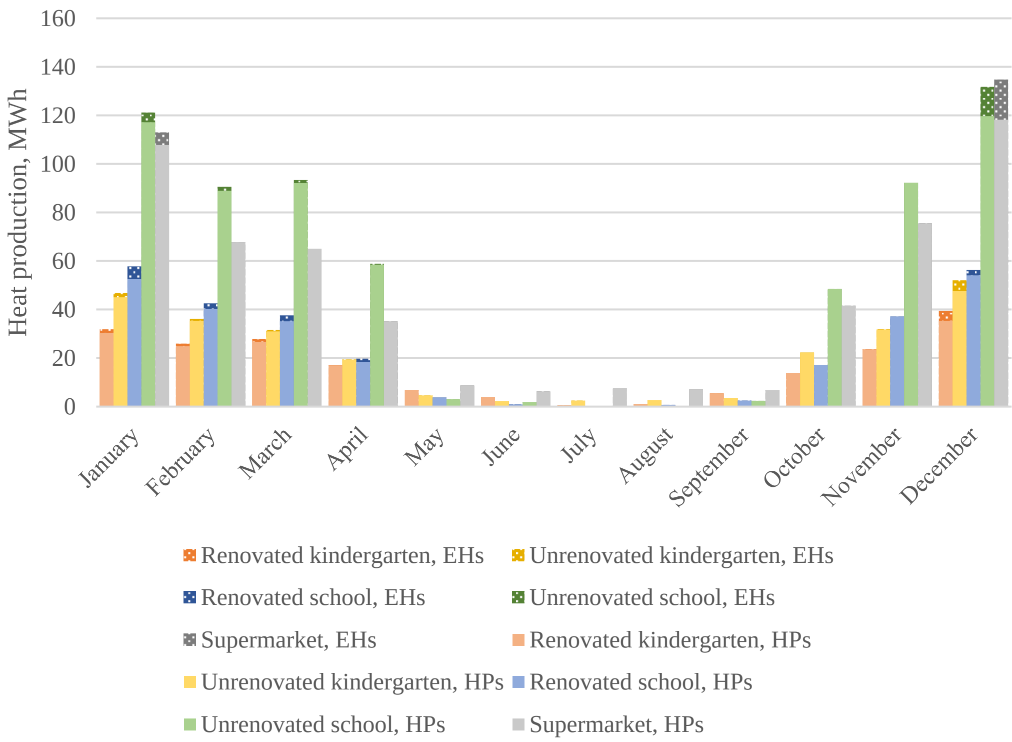

Figure 9. Comparison of heat production in renovated and unrenovated schools, kindergartens, and supermarket.

Electric heaters produce heat mostly in December and are not utilized during the warmer months of the year (May–October). During this time, the capacity of HPs was sufficient to meet the heat demand in all analyzed buildings. The largest amount of heat produced by EHs was found in the supermarket and the unrenovated school in December.

After comparing the relative heat demands in public buildings, the results showed that the smallest relative heat demand was in the renovated school, and the highest demand was in the unrenovated kindergarten. EHs produced the most relative heat energy in the renovated school (about 4.9% per year). Additionally, it was determined that the amount of electricity consumed by EHs made up 19% of the total electricity demand for SH and DHW preparation in this building. In the supermarket, EHs covered the highest monthly relative heat demand, which was about 12% and occurred in December. In this building, the electricity consumption for the operation of EHs made up 15% of the total electricity consumption during the first year of the analyzed period.

4.2. Performance of Economic and Financial Indicators

The economic performance of heat production and supply systems for different buildings was evaluated by analyzing key financial indicators, such as investment costs, operating costs, and the levelized cost of heat (LCOH). Additionally, the internal rate of return (IRR), net present value (NPV), and payback period (PB) for each heating system were determined using a 5% discount rate. The monthly heat prices of heat suppliers in Lithuania for 2022 were used for the calculations of these financial indicators [56]. The change in heat prices over a 10-year period was projected by assuming that the trend of heat price change is similar to that of electricity prices as presented in Section 3.3. The main results of the economic analysis for each analyzed case are presented in Table 3.

Table 3. Results of economic and financial analysis for analyzed heat systems.

Building No.	Initial Capital Expenditure (ICE) (k EUR)	Total Operating Costs (TOC) over 10 Years (k EUR)	Total Costs (TC) for Heating over 10 Years (k EUR)	Levelized Cost of Heat (LCOH) (EUR/kWh)	Payback Period (PB) (Year)	Operating Cost Savings in 1 Year (EUR)	Internal Rate of Return (IRR) (%)	Net Present Value (NPV) (k EUR)
1.	39.54	146.68	186.22	0.0866	11.63	4290	2.74	−4.24
2.	56.45	269.67	326.12	0.0847	9.23	7009	6.35	3.86
3.	81.02	363.61	444.63	0.0831	8.55	10,854	7.61	10.72
4.	96.81	435.67	532.49	0.0831	8.89	12,373	6.98	9.78
5.	15.90	56.15	72.05	0.0870	10.82	1824	3.80	−0.92
6.	15.84	39.34	55.18	0.0956	21.73	1126	−4.52	−6.48
7.	40.51	133.59	174.09	0.0915	13.39	3998	0.84	−7.80
8.	56.26	172.05	228.31	0.0931	13.91	5415	0.36	−12.00
9.	61.53	192.65	254.18	0.0961	17.86	5265	−2.29	−19.59
10.	116.74	439.88	556.62	0.0905	11.06	13,314	3.50	−8.31
11.	123.64	397.69	521.33	0.0954	16.02	11,481	−1.02	−32.88

According to the results of indicators presented in Table 3, the most profitable investments for the analyzed period were in the heating systems of the renovated five-story (no. 3) and unrenovated nine-story (no. 4) apartment buildings, as shown by their low energy costs, short payback periods, and high returns on investment. These buildings had the lowest average heat prices per kWh, with an average of approximately 0.0831 EUR/kWh. These buildings also had the shortest payback periods of 8.55 and 8.89 years, respectively. The internal rate of return (IRR) for these buildings was the highest, indicating a high potential return on investment. Their net present value (NPV) was also highest, meaning the present value of projected cash flows exceeded the cost of investment. The heat production and supply systems in these buildings were determined to be the most economically attractive due to their large volume and resulted in the lowest payback and average heat price.

The results revealed that the heating system in the renovated three-story apartment building (no. 6) was not economically viable among the analyzed buildings, and it had the lowest actual heat demand during the analyzed period. The economic performance resulted in an LCOH of 0.0956 EUR/kWh and a payback period of 21.73 years, which was not reached within the modeling period. Negative values of IRR and NPV indicate that the investment in the heating system of this building was unprofitable. Similarly, the renovated school (no. 9) also had poor performance of economic indicators, with a payback period of 17.86 years, a negative IRR and NPV of −2.29% and −19.59k EUR, respectively, and an LCOH of 0.0961 EUR/kWh. In both these cases (buildings no. 6 and 9), the LCOH exceeded the average heat price of the heat supplier. This makes the selected heating systems unprofitable and not worth the investment.

The analysis of other buildings revealed varying values for economic indicators, with the LCOH ranging from 0.0847 to 0.0954 EUR/kWh, payback periods ranging from 9.23 to 16.02 years, and the IRR ranging from −1.02% to 6.35%. Most of the buildings had a negative NPV, indicating that the optimal heat production and supply systems were not profitable, and the investments were not returned during the analyzed period. However, some of the heating systems in the analyzed buildings demonstrated promising results in terms of economic performance. For example, a positive NPV was obtained for the unrenovated five-story apartment building (no. 2), and other economic indicators for this building also indicated better results. This suggests that the unrenovated five-story apartment building may be a good investment option for heat production and supply systems in addition to other buildings with the best economic indicators.

Additionally, the annual operating cost savings for SH and DHW preparation were calculated for the analyzed buildings. It is important to note that these savings were calculated only for operating costs and excluded costs of the heating system itself and its installation. The results show that the implementation of the optimal heating system provides significant cost savings in terms of operating expenses for both SH and DHW preparation. The calculations of the annual operating cost savings revealed the potential for significant financial benefits. The results showed that the cost savings in one year ranged from 1126 EUR to 13,314 EUR, depending on the analyzed building and its heat demand. These results suggest that the implementation of optimal heating systems of HPs and EHs can be a cost-effective alternative to traditional district heating systems, leading to significant operation cost savings and potential long-term financial benefits.

5. Discussion

The results of this study indicate that the optimal heating systems for various types of buildings can be determined using a MINLP multi-objective optimization model. By minimizing the objective function of the problem analyzed, the lowest total costs of the selected heating systems were achieved. The optimization model simulations enabled the determination of the optimal number, type, and capacity of HPs and EHs needed to meet the heat demand for SH and DHW preparation. The results of the optimization include the optimal heating system components, their heating capacity in December, and the proportion of heat produced by HPs and EHs in the first year for each analyzed building.

One of the key findings of this study is that in all cases analyzed, the optimal heat production and supply system includes air-to-water HPs as one of its components. Furthermore, for schools and a supermarket (buildings no. 9, 10, and 11), these HPs were combined with hybrid HPs. This implies that the use of air-to-water HPs is a cost-effective and energy-efficient solution for meeting the heating needs of various types of buildings. The use of hybrid HPs in certain buildings can also provide an additional source of energy and enhance the overall efficiency of the heating system. Additionally, EHs of various capacities were selected for all buildings to meet the peak heat demand.

The results of the economic and financial analysis show that the optimal heating systems for the buildings are cost-effective, as they have positive NPV and IRR indicators. However, it is important to note that not all systems have positive NPV and IRR indicators, which can be due to the fact that different buildings have different characteristics, and this leads to different optimal systems.

The results of this study align with previous research on the topic of heating systems for buildings, which has demonstrated the benefits of using HPs, particularly air-to-water HPs, for energy efficiency and environmental sustainability. Additionally, the findings of this study have practical implications for the design and operation of buildings, as they provide guidance on the selection of heating systems that can meet the heat demand while minimizing total costs.

However, it is important to acknowledge that this case study has some limitations. One limitation is that the data used in the simulation were based on assumptions, which may not accurately represent the real-world situation. Additionally, the study only considered a 10-year period. Therefore, it would be beneficial to extend the analysis to a longer time horizon to observe how the optimal heating systems evolve over time.

In terms of future research, there are several aspects that could be considered. First, it would be valuable to expand the scope of the study to consider other factors such as environmental sustainability and energy security. Additionally, the study could broaden its scope to include not only heating technologies but cooling technologies as well. This would provide a more complete picture of the energy demands and requirements of buildings and could lead to the development of more efficient and effective systems. Additionally, it would be useful to investigate the potential of using other RES such as solar or wind power in heating and cooling systems. This would not only enhance the overall cost-effectiveness and environmental impact of the systems but also would demonstrate the potential of using a mix of RES in the built environment. Another aspect that would be useful to consider is the use of HPs together with waste heat or water and their application in low-temperature heat networks. Finally, it would be important to apply the methodology of optimal system selection to a city block. By considering the heating and cooling demands of multiple buildings within a city block, the study can better understand the interconnections and synergies between buildings and help to optimize the energy systems at a neighborhood level. This would not only lead to more efficient and cost-effective heating and cooling systems but also would help to reduce the overall carbon footprint of the built environment and promote sustainability.

6. Conclusions

In this paper, a methodology for selecting the optimal heat production and supply systems for various building types, considering technical, economic, environmental, and social factors was presented. The methodology enables us to minimize total costs and reduce CO_2 emissions of the heating system consisting of various HPs and EHs over a 10-year period, taking into account changes in technical and economic parameters over that time frame. The optimization problem was addressed through a multi-objective approach and solved using MINLP, resulting in the optimal number of components and their optimal operating hours each month. The model was applied to various types of renovated and unrenovated buildings, including schools, kindergartens, apartment buildings, and supermarkets. The results provide a comparison of the heating system's dependence on building type, heat demand, and efficiency. Furthermore, the model can be easily expanded to include additional technologies of HPs or EHs and adapted to any specific building, making it a highly applicable tool.

The results of the performed case study demonstrated that the capacity of the optimal heat production and supply system is dependent on the building's heat demand and efficiency. The supermarket required the largest heating system with a capacity of 310.8 kW, with an annual heat demand of 569 MWh. On the other hand, the lowest capacity of heating system was required for the renovated three-story apartment building, with a capacity of 22.97 kW and an annual heat demand of 59.21 MWh.

The results of the analysis of various heating technologies, including air-to-water, ground source, hybrid HPs, and EHs, revealed that the optimal solution was a combination of air-to-water HPs and EHs. For the specific case of an unrenovated school and a supermarket, the combination of these technologies with hybrid HPs proved to be the most effective solution to meet their heat demand. This study emphasizes the importance of taking building characteristics, such as renovation status, into consideration when selecting heating technologies to ensure energy efficiency and cost-effectiveness.

Based on the results of CO_2 emissions, the highest CO_2 emissions during the analyzed period were in the supermarket, for which two hybrid HPs were selected. Over a 10-year period, the use of hybrid HPs in the analyzed supermarket was expected to result in the emission of approximately 73 tons of CO_2, which corresponds to a cost of approximately 12k EUR. Additionally, CO_2 emissions were measured in both the renovated and unrenovated schools, which produced 24 and 39 tons of CO_2 emissions, respectively. For the remaining analyzed buildings, the goal of making the heating system neutral in terms of CO_2 emissions was achieved.

The economic viability of various heating systems for buildings was assessed using financial indicators. The results showed that low production costs and high demand lead to high profits and positive financial performance. The heating systems in renovated five-story and unrenovated nine-story apartment buildings had the most favorable economic outcomes, with an LCOH of 0.0831 EUR/kWh, short payback periods of 8.55 and 8.89 years, a high IRR of 8% and 7%, and a high NPV of 10.7k EUR and 9.8k EUR, respectively. Conversely, the worst-case scenario featured high production costs and low demand, resulting in low profits and negative financial performance. The heating systems in renovated three-story apartment buildings and renovated schools had unfavorable outcomes, with an LCOH of 0.0956 EUR/kWh and 0.0961 EUR/kWh, long payback periods of 21.73 years and 17.86 years, a negative IRR of −5% and −2%, and a negative NPV of −6.5k EUR and −19.6k EUR, respectively. The study suggests that while some heating systems may not be economically feasible, others offer promising investment opportunities. Therefore, it is crucial to account for both scenarios when making business decisions and reducing risks.

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Abbreviations

COP	Coefficient of Performance
DH	District Heating
DHW	Domestic Hot Water
EH	Electric Heater
EU	European Union
GA	Genetic Algorithm
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
HP	Heat Pump
ICE	Initial Capital Expenditure
IRR	Internal Rate of Return
LCOH	Levelized Cost of Heat
LP	Linear Programming
MILP	Mixed-Integer Linear Programming
MINLP	Mixed-Integer Nonlinear Programming
NPV	Net Present Value
PB	Payback Period
PV	Photovoltaic
RES	Renewable Energy Sources
SH	Space Heating
TC	Total Costs
TOC	Total Operating Costs

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