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Evaluating the Energy Efficiency of Combining Heat Pumps and Photovoltaic Panels in Eco-Friendly Housing

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Abstract: This article aims to analyze the energy efficiency of combining heat pumps with photovoltaic (PV) panels in energy-efficient homes. The research methodology involved a detailed energy balance analysis, assessment of the impact of mechanical ventilation, location, heat loss, and the choice and operation of heat sources, with a particular focus on heat pumps in synergy with PV installations. The results demonstrate that integrating heat pumps with PV panels can significantly reduce the demand for external energy sources and lower the operating costs of buildings, while contributing to their energy self-sufficiency. This study highlights that such a combination of technologies is key to promoting sustainable development and achieving energy efficiency goals in the residential sector. The results of this analysis expand knowledge about the effectiveness of such systems and provide practical recommendations for designers and engineers interested in implementing renewable energy technologies in modern energy-efficient buildings, taking into account the impact of these solutions on reducing CO_2 emissions as well.

Keywords: heat pump; photovoltaic panel; energy efficiency; CO_2 emissions

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1. Introduction

In the face of global challenges related to climate change, such as global warming and increased carbon dioxide concentration in the atmosphere, sustainable management of energy resources has become an indispensable priority in designing modern residential homes [1–6]. Growing ecological awareness and pressures to reduce carbon footprints necessitate rethinking the use of available technologies and shaping living spaces sustainably. Studies and analyses conducted in various parts of the world confirm that integrating modern technological solutions with appropriate design can significantly contribute to reducing emissions of harmful substances and improving the energy efficiency of buildings [7–11].

Modern technologies, such as heat pumps and photovoltaic (PV) installations, play a significant role in achieving ecological goals, such as reducing CO_2 emissions and decreasing energy consumption from non-renewable sources [10,12–17]. Heat pumps, by utilizing thermal energy from the environment (air, water, or earth), can efficiently heat and cool buildings while consuming significantly less electrical energy than traditional systems [10,14,18]. Meanwhile, photovoltaic installations, by converting solar radiation into electrical energy, are becoming an increasingly popular solution, enabling the production of green energy directly at the point of consumption [15,16]. Combining these technologies not only reduces the use of traditional energy sources but also lowers the operational costs of buildings, which is particularly important from a long-term economic perspective [19,20].

Moreover, the goal set out in the article is consistent with the 2030 Agenda for Sustainable Development, which in paragraph 31 "calls for the broadest possible international cooperation aimed at accelerating the reduction of global greenhouse gas emissions and addressing the issue of adaptation to the adverse effects of climate change" [21].

2. Review of the Literature

Integrated systems, combining heat pumps with photovoltaic installations, are becoming a key element of sustainable development strategies in modern ecological construction. The introduction of such systems not only allows for the energy self-sufficiency of buildings but also significantly reduces their impact on the natural environment [7,9,22]. For instance, studies [7] have demonstrated that in appropriately designed buildings utilizing both heat pumps and photovoltaic panels, it is possible to achieve up to an 80% reduction in carbon dioxide emissions compared to using traditional heating methods. Such integrated approaches to energy management in residential buildings are becoming a model to follow in designing future architectural projects, promoting technologies that are both economically viable and environmentally friendly.

The integration of heat pumps and photovoltaic panels into building systems represents a forward-looking direction that is already gaining importance today due to its potential benefits for both users and the planet. By utilizing renewable energy sources and maximizing operational efficiency, it is possible to significantly reduce maintenance costs and substantially limit the negative impact of human activities on climate change.

Research conducted in various climatic regions, such as the northern United States and Canada, shows that the combination of PV systems with heat pumps can be economically viable, offering returns on investment of up to 2.7%, while also increasing the energy self-sufficiency of residential buildings [13,23]. In study [13], it was noted that integrating these systems into cooler climates not only improves energy efficiency but also provides economically beneficial solutions that can significantly exceed initial investment expectations.

Analyses [19] have highlighted the possibilities of optimizing energy consumption through the smart control of thermal systems combined with PV installations. A developed heuristic model for planning the operation of heat pump systems integrated with PV installations allows for a significant increase in the efficiency of using energy produced by solar panels, thereby reducing dependence on the power grid and operational costs [19]. The results of these studies indicate that properly programmed systems can automatically adjust their operation to current energy demand and weather conditions, thereby increasing the level of energy self-sufficiency.

Additionally, research [20] has shown that hybridization of various energy-generation technologies, including heat pumps and PV panels, can lead to even greater optimization and energy efficiency. Technical-economic assessments of various hybrid schemes for solar and gas power plants have demonstrated that such an approach can significantly reduce CO_2 emissions and other associated operational costs, while simultaneously increasing the reliability of the energy system.

These results, illustrating the synergistic combination of modern technologies, emphasize the importance of integrating heat pump systems with photovoltaics as a key component in designing sustainable, energy-independent, and economically viable residential homes. Focusing on these aspects could lead to a revolution in residential construction, where every home is capable of independently managing its energy needs, thereby minimizing its impact on the natural environment.

In Eastern Europe, where renewable energy is gaining importance in the context of energy independence and the implementation of the Paris Agreement objectives [19,24], systems combining heat pumps and PV installations also demonstrate significant potential for increasing energy efficiency. The role of renewable energy sources in shaping the energy policies of the region is becoming increasingly important, and investments in green energy bring tangible benefits, both ecological and economic. Studies conducted in Krakow show how managing the operating time of heat pumps can significantly increase the energy self-sufficiency of homes, achieving up to 18% in monthly savings [14,25]. This analysis proves that intelligent energy-management systems can effectively adjust the operation of devices to the current needs of users and weather conditions, resulting in reduced demand for energy from external sources.

Across the European Union, with political support and subsidies, PV installations and heat pump systems are increasingly used in new construction projects, supporting the achievement of ambitious goals to reduce greenhouse gas emissions by 55% by 2030, compared to 1990 levels [26,27]. This reflects a broader trend towards increasing energy efficiency and sustainable development. The dynamic development of PV technology in Europe, supported by favorable regulatory and financial frameworks, favors the faster adaptation of these technologies in residential and commercial projects [26]. Additionally, the increased availability and economic attractiveness of heat pumps, as well as advancements in photovoltaic technologies, open new possibilities for designers and engineers who are looking for effective ways to integrate these systems to maximize energy self-sufficiency while minimizing the negative impact on the environment.

Simultaneously, the engagement of European institutions in promoting and supporting energy-sustainable solutions indicates a growing awareness of the importance of green energy in achieving not only climate goals but also in improving the quality of life of residents. Through appropriate policies and investments, it becomes possible to shape a future where sustainable construction and energy management become the standard, not the exception.

According to 2023 data [28], 2.64 million heat pumps were sold in Europe. This increase in sales indicates a growing market interest in solutions that enhance the energy efficiency of buildings. Additionally, there is a steady decrease in the prices of photovoltaic panels, which results from both technological progress and increased production scale. These changes are supported by the development of new technologies that allow for the production of higher efficiency panels at lower material costs [29].

This trend is crucial because lower investment costs can contribute to faster development and broader implementation of these technologies in residential homes. This paradigm shift aims not only to increase energy efficiency but also to improve the energy self-sufficiency of residential buildings, which is significant in the context of increasing energy price volatility. The reduction in initial costs allows for faster investment payback, making such installations more accessible to a wider range of consumers.

Moreover, the increased efficiency of these systems contributes to lower energy bills for end-users, which further motivates their adoption. In response to these trends, the energy policies of many European countries are increasingly focusing on supporting renewable energy initiatives, which include not only subsidies and tax incentives but also educational programs aimed at raising awareness about the benefits of using modern heating and energy production systems [29].

These market and regulatory changes demonstrate how dynamically the renewable energy sector is developing, adapting to new economic and environmental challenges. This represents an important step towards building a sustainable energy future on the European continent. These initiatives, by increasing the accessibility of eco-friendly technologies, have the potential to significantly contribute to achieving global climate goals, reducing dependency on fossil fuels, and minimizing the adverse effects of climate change.

The aim of this paper is to examine the energy efficiency of combining heat pumps and photovoltaic panels in environmentally friendly buildings. These systems, increasingly used in modern construction, offer the possibility of significantly reducing dependency on conventional energy sources and reducing carbon footprints. A variant analysis of the energy balance of a heat pump operating in a monoenergetic system with an electric heater and in a bivalent system with a gas boiler will be conducted. Both cases will be considered as systems powered by electricity from the power grid, or optionally powered by a photovoltaic installation.

This analysis will include a detailed examination of the energy efficiency of both systems under various climatic and operational conditions, with particular attention paid to their ability to integrate with local power networks, as well as the potential benefits of energy autonomy. The results of this analysis aim not only to increase knowledge about the efficiency of such systems but also to provide practical guidance for designers and engineers interested in implementing renewable technologies in modern energy-efficient construction. Particular emphasis will be placed on identifying best practices in energy consumption management, which can contribute to the optimization of operational costs and increase the durability of systems.

Additionally, this work aims to highlight the impact of these solutions on reducing CO_2 emissions, analyzing data from actual installations and simulation modeling. By comparing emissions associated with traditional heating methods with those achievable using a combination of heat pumps and photovoltaic panels, this paper will contribute to the discussion on the best strategies for achieving goals related to green energy transformation.

Considering the detailed discussion presented in the article, the structure of the work is as follows: Section 3 provides a comprehensive description of the experimental setup and methodologies used to assess the synergy between heat pumps and photovoltaic panels, focusing on a single-family building located in a temperate climate zone in Eastern Europe. Section 4 analyzes the outcomes of the extensive analysis of the building's energy demand over the year, including monthly and annual heat demand values, variations in the heat pump system's coefficient of performance relative to external temperatures, the economic implications of operating the system, and an assessment of CO_2 emissions from various heating system configurations. Potential reductions achievable through the integration of PV panels are also discussed. Section 5 synthesizes findings from the empirical data, offering conclusions about the practical and environmental benefits of integrating heat pumps with photovoltaic panels in residential buildings, and discusses implications for energy policy, emphasizing the need for ongoing investments in renewable technologies and the integration of more efficient heating solutions to effectively combat climate change.

3. Materials and Methods

The analysis focused on a single-family building located in a climate zone with a temperate climate in Eastern Europe. Characteristic of this zone are cold winters and warm summers, which directly affect the energy demand for heating and cooling. The building is designed for four occupants, equipped with a domestic hot water system (DWS) featuring a storage tank with a capacity of 150 L. Water in the tank is heated from 10 °C to 60 °C. The total hourly heat demand for DWS purposes, considering water heating in the tank over 8 nighttime hours, is 1.1 kW. Additionally, the central heating system (CHS) is designed to operate in external temperatures down to −20 °C, with an hourly heat demand of 8 kW. The total heat demand of the building is 10.2 kW.

The mechanical ventilation system (MVS) in the analyzed building, equipped with a rotary heat exchanger with a capacity of 300 m^3/h, is crucial for maintaining high indoor air quality and energy efficiency. The heat recovery efficiency in the analyzed system is 73%, which corresponds to an energy demand for heating ventilation air at the level of 1.1 kW. Energy requirements for cooling during the summer period were not analyzed.

Figure 1 illustrates the schematic of the analyzed baseline system. It is assumed that the air source heat pump (AHP) will operate with an electric heater in a monoenergetic system to ensure continuous heat supply for the building. The electric heater activates when the coefficient of performance (COP) for heating drops below 2.8. This value was selected as the minimum due to the economic efficiency of the AHP operation, given current electricity prices.

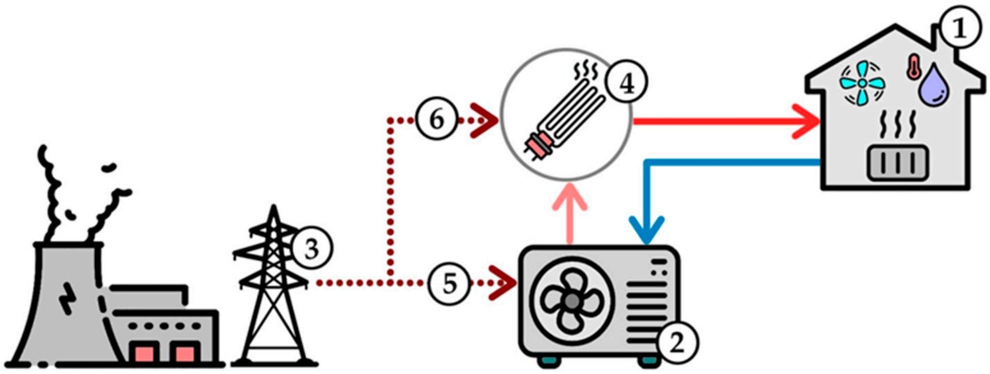

Figure 1. Diagram of the cooperative system involving an air source heat pump (AHP) with an electric heater in a monoenergetic system. The components are labeled as follows: 1—building installations; 2—air source heat pump (AHP); 3—electrical grid; 4—electric heater (EH); 5—electric power for the heat pump (NAPH); 6—electric power for the electric heater (EHM). This layout illustrates the flow of energy and the integration of components necessary to maintain efficient heating within the building.

To perform the calculations, it was necessary to determine the parameters of the air source heat pump (AHP). For this purpose, data from the existing market model HPA-O 10 Premium by Stiebel Eltron was used. Table 1 shows the technical data of the heat pump.

Table 1. Technical data of the heat pump.

Energy efficiency class of the heat pump W35	A+++
Heating power at A7/W35 (EN 14511 [30])	7.84 kW
Heating power at A2/W35 (EN 14511 [30])	8.33 kW
Heating power at A-7/W35 (EN 14511 [30])	9.54 kW
Coefficient of Performance at A7/W35 (EN 14511 [30])	5.09
Coefficient of Performance at A2/W35 (EN 14511 [30])	4.14
Coefficient of Performance at A-7/W35 (EN 14511 [30])	3.26
SCOP 35 °C (EN 14825 [31])	4.70
Sound power level (EN 12102 [32])	55 dB (A)
Limit of use of lower source min./max.	−20/40 °C
Limit of use on the heating side max.	65 °C
Refrigerant	R410A

The Coefficient of Performance (*COP*) at the working point A2/W35 is 3.26, whereas at A7/W35 it is 4.14. Based on this information, interpolation of the *COP* values depending on the external temperature was conducted using a linear equation:

$$COP = A \cdot T_Z + B \quad (1)$$

where:
A—constant of the equation, *A* = 0.176,
B—constant of the equation, *B* = 2.908,
T_z—value of the external temperature, °C.
The bivalent temperature, at which the additional electric heater in the heat pump is activated, is −0.6 °C. Below this temperature, the *COP* value drops below 2.8. In such a situation, the AHP begins to operate in a parallel system with the electric heater until a *COP* of 2.0 is reached, below which operation is limited only to the electric heater.

4. Results

The calculation results have been divided into three groups for better visualization of the problem. The annual heat demand for the various systems in the building was determined based on statistical data on the occurrence of temperature values at different hours throughout the year. The data were obtained from a meteorological station located in Poland in Jasionka, near the main city of the Podkarpackie region, Rzeszów. Such data are available on a government website [33]. It is assumed that the CHS system will not operate during the summer period due to high external air temperatures. It should be noted that similar calculations can be made by entering data into a spreadsheet created by the authors for any location in the world.

4.1. Heat Demand

Table 2 presents the monthly heat demand values for various systems in the building. As the data show, the highest heat demand occurs in the winter months (January, February, December), which is typical for a continental temperate climate characterized by cold winters.

Table 2. Monthly heat demand values for the building.

Month	Q_{CHS}	Q_{DWS}	Q_{MVS}	Q_{total}
	kWh/month	kWh/month	kWh/month	kWh/month
1	3656	271	503	4430
2	2644	245	364	3253
3	2834	271	390	3495
4	1708	263	235	2206
5	0	271	149	420
6	0	263	75	338
7	0	271	62	333
8	0	271	59	330
9	0	263	111	373
10	1953	271	269	2493
11	2588	263	356	3206
12	3159	271	435	3865
Q_{annual}, kWh/a	18,541	3194	3009	24,743
Q_{annual}, GJ/a	66.8	11.5	10.8	89.1

The total annual heat demand for the analyzed building, Q_{total}, is 24,743 kWh. The seasonal coefficient of performance for heating, SCOP, in this case, is 4.19.

4.2. Coefficient of Performance (COP)

Figure 2 shows the variation of the *COP* (Coefficient of Performance) with external temperature over the analyzed statistical year. The highest values are achieved during the summer months, when the external temperature reaches its peak for the year.

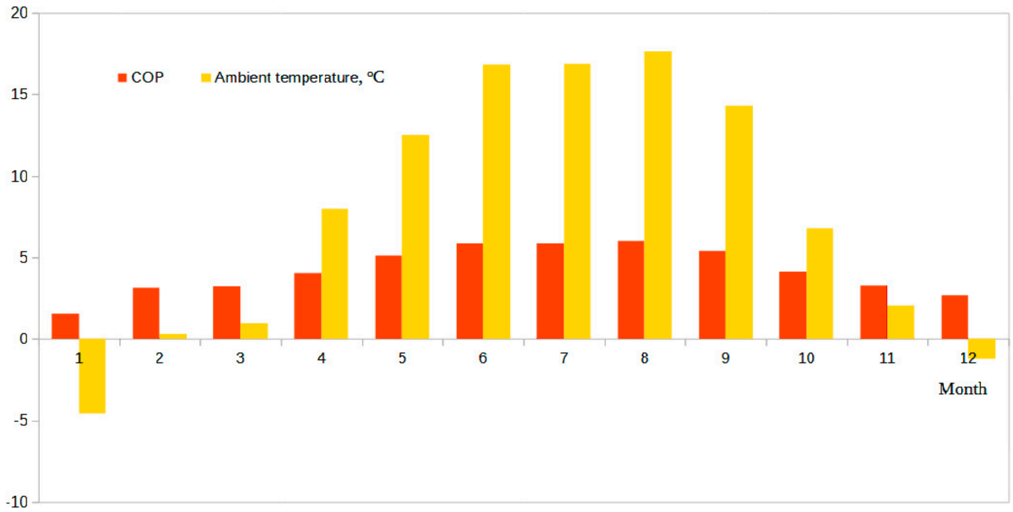

Figure 2. Change in the heat pump's COP (Coefficient of Performance) value depending on the external temperature.

4.3. Cost Analysis

Based on the data provided, the costs associated with the heat demand for the building were calculated using an average price of 0.25 Euro per kWh of electricity. Table 3 lists the monthly operating costs of the heat pump related to the electricity demand for the heat pump compressor (NAHP) and the costs associated with activating the electric heater (EHM) during periods when the heat pump achieves low *COP* values.

Table 3. Monthly electricity demand for the NAHP compressor and the EHM electric heater, and the percentage of electricity demand covered by the EHP electric heater.

Month	NAHP	EHM	EHM + NAHP	EHP
	kWh/m	kWh/m	Euro/m	%
1	633	3163	949	83.3
2	1030	34	266	3.2
3	1082	19	275	1.8
4	570	0	142	0.0
5	414	0	104	0.0
6	222	0	55	0.0
7	186	0	47	0.0
8	174	0	44	0.0
9	303	0	76	0.0
10	754	0	189	0.0
11	959	76	259	7.4
12	1001	1169	542	53.9
Total	7328 (26.4) *	4462 (16.1) *	1947	149.6

* GJ/a.

EHP represents the percentage of the electric heater's demand in the total electricity demand. For the entire year, the power of the electric heater accounts for 12.5% of the total electricity demand for the discussed system. The annual costs associated with providing heat for the building for the aforementioned purposes amount to 2947 Euro/a. This is a relatively high cost due to the low external air temperatures from October to January, and the high price of electricity. Therefore, it was decided that an alternative bivalent system where the AHP works in conjunction with a gas boiler (GB) would be analyzed. Figure 3 shows the diagram of the aforementioned system.

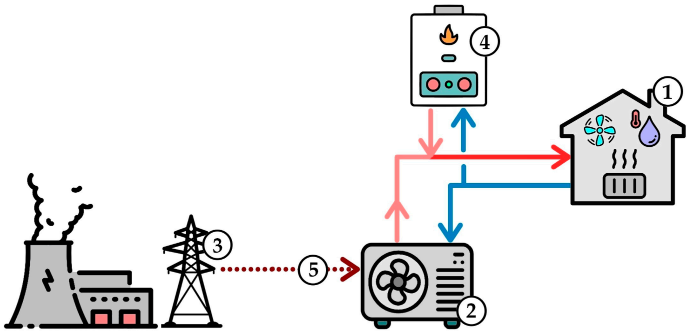

Figure 3. Diagram of the cooperative system between the heat pump (AHP) and the gas boiler (GB) in a bivalent system, where: 1—building installations; 2—heat pump (AHP); 3—electrical grid; 4—gas boiler (GB); 5—electric power for the heat pump (NAPH).

The price of 1 kWh of gas is assumed to be 0.11 Euro in Poland, but in Ukraine for example, only 0.065 Euro. This seems to be a more favorable solution compared to the monoenergetic variant operating in a parallel system due to the lower price per kWh of gas compared to electricity. Table 4 presents the calculation results, where the heat demand obtained from the AHP and the gas boiler GB is determined. The AHP operates up to a *COP* of 2.8; below a COP of 2.8, the system provides heat solely from the GB due to the lower cost of gas compared to the price of electricity needed for the NAHP compressor.

Table 4. Summary of monthly heat demand supplied by the gas fuel (GB), electricity demand for the heat pump compressor (NAHP), the cost of electricity for the heat pump (NAHPM), and the cost of gas fuel (GBM).

Month	Q_{total}	NAHP	GB	NAHPM	GBM	NAHPM + GBM
	kWh/m	kWh/m	kWh/m	Euro/m	Euro/m	Euro/m
1	4430	633	3163	158	348	506
2	3253	1030	34	257	4	261
3	3495	1082	19	271	0	271
4	2206	570	0	142	0	142
5	420	414	0	104	0	104
6	338	222	0	55	0	55
7	333	186	0	47	0	47
8	330	174	0	44	0	44
9	373	303	0	76	0	76
10	2493	754	0	189	0	189
11	3206	959	76	240	8	248
12	3865	1001	1169	250	129	379
Total	24,743 (89.1) *	7328 (26.4) *	4462 (16.1) *	1832	489	2 321

* GJ/a.

The total annual cost associated with the electricity for AHPM and the gas fuel for GBM amounts to 2321 Euro/a, which is 21.3% lower than the monovalent heat pump system (AHP) with an electric heater (EH). This indicates that the cooperation between

AHP and GB is more cost-effective. Further in the analysis, the CO_2 emissions resulting from the operation of the analyzed heat pump installation variants were determined.

4.4. CO_2 Emissions

Unit CO_2 emissions from gas combustion are set at 55.5 kgCO_2/GJ, while for the combustion of lignite coal, they are 110.0 kgCO_2/GJ, reflecting the production of electricity in power plants fueled by these sources [34]. The calculations were performed in accordance with the guidelines provided by the International Panel of Climate Change for statistical data for 2021 [35]. Two variants for electricity supply are considered: one produced in a gas-fired power plant, and the other in a coal-fired power plant, labeled respectively as "gas" and "coal" on Figure 4 for the heat pump systems with a gas boiler (AHP + EH), and a heat pump cooperating with a gas boiler (AHP + GB).

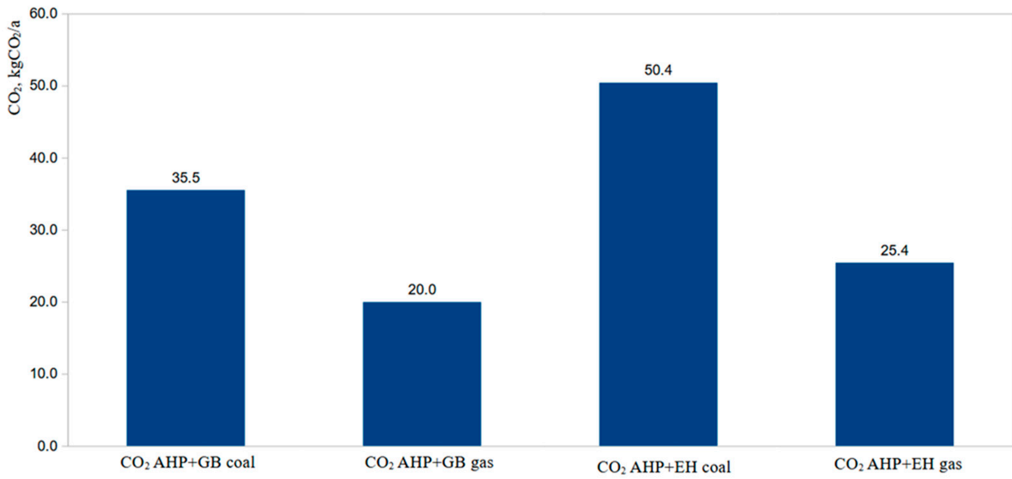

Figure 4. The annual CO_2 emissions for each installation variant.

For the AHP + EH system, all the electricity comes from the power plant, for which an energy input factor of 3.0 is assumed [34]. For the AHP + GB system, the energy input factor for electricity from the power plant is also 3.0, but for gas-generated energy locally produced in the gas boiler, an input factor of 1.3 is assumed [34]. The emission of gas is the product of energy consumption, the energy input factor, and the unit CO_2 emission.

Assuming electricity production solely from a coal-fired power plant, the AHP + GB installation shows about 32.9% lower CO_2 emissions compared to the installation with an electric heater (EH). When covering the electricity demand from a natural gas-fired power plant, the difference is not as significant, showing a 21.5% disadvantage for the installation with the electric heater. As can be seen, the installation with GB generates lower CO_2 emissions in every case.

4.5. System with PV Panels

The main issue concerning CO_2 emissions is the demand for electrical energy, which reaches 11,790 kWh annually for the installation with an electric heater (AHP + EH), while for the installation with a gas boiler (AHP + GB), this value is only 62.2% of the above value, i.e., 7328 kWh. Assuming that the demand for electrical energy would be covered by an additional photovoltaic (PV) installation designated solely for the purposes of the heat pump (excluding the demand for electrical energy for building-lighting and other purposes such as induction stoves, refrigerators, washing machines, dryers, etc.), the size of the PV installation can be roughly determined, assuming 1 kWp for every 1300 kWh of demand. Thus, the size of the PV installations for the respective systems can be estimated at about 15.5 kWp for the AHP + EH system, and about 9.5 kWp for the AHP + GB system. Figures 5 and 6 show the schematics of the analyzed systems.

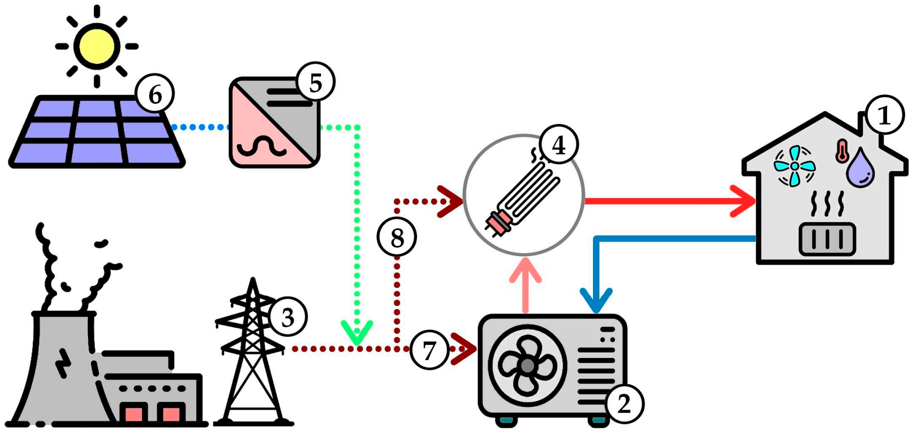

Figure 5. Diagram of the heat pump system (AHP) with an electric heater (EH) cooperating with a photovoltaic installation (PV), where: 1—building installations; 2—heat pump (AHP); 3—electrical grid; 4—electric heater (EH); 5—inverter; 6—photovoltaic panels (PV); 7—electric power for the heat pump (NAHP); 8—electric power for the electric heater (EHM).

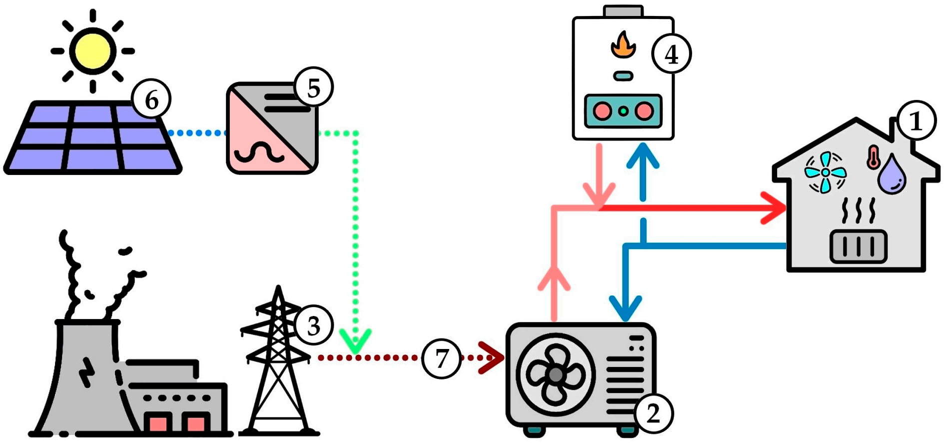

Figure 6. Diagram of the cooperative system between the heat pump (AHP) and the gas boiler (GB) in a bivalent system, where: 1—building installations; 2—heat pump (AHP); 3—electrical grid; 4—gas boiler (GB); 5—inverter; 6—photovoltaic panels (PV); 7—electric power for the heat pump (NAHP).

The estimated installation costs for these variants are 14,800 Euros for the AHP + EH system, and 9500 Euros for the AHP + GB system. The installation of a PV system would eliminate costs associated with electricity charges, which amount to 2947 Euros per year for the AHP + EH system, and 1832 Euros per year for the AHP + GB system. This means that the investment in PV panels would pay for itself after about 7.0 years for the variant with the electric heater. A similar payback period, estimated at about 6 years, is expected for the installation equipped with the GB gas boiler, as calculated from the cash flows (Table 5). This indicates that, in both cases, after approximately 6–7 years, the operating costs of the system will reduce to 0 Euros for the AHP + EH system, which represents a 100% reduction in annual bills, and to 489 Euros for the AHP + GB system, which represents a 79% reduction in annual bills (remaining costs are associated with the gas fuel needed for the gas boiler).

After an average operational period of about 15 years for this type of installation, it is estimated that the final savings amount to €23,516 for the AHP + EH installation, and €20,668 for the AHP + GB gas boiler installation.

Table 5. Comparison of cash flows in a system with PV panels.

	AHP + EH			AHP + GB		
Year	PV Installation Cost	Yearly Cost without PV	Cash Flow	PV Installation Cost	Yearly Cost with PV	Cash Flow
	Euro	Euro/a	Euro/a	Euro	Euro/a	Euro/a
1	14,800	2947	−17,747	9500	2321	−11,821
2	0	2947	−14,800	0	2321	−9500
3	0	2947	−11,853	0	2321	−7179
4	0	2947	−8905	0	2321	−4859
5	0	2947	−5958	0	2321	−2538
6	0	2947	−3010	0	2321	−218
7	0	2947	−63	0	2321	2103
8	0	2947	2884	0	2321	4424
9	0	2947	5832	0	2321	6744
10	0	2947	8779	0	2321	9065
11	0	2947	11,727	0	2321	11,385
12	0	2947	14,674	0	2321	13,706

5. Conclusions

The analysis conducted reveals a challenging decision regarding the application of a heat pump system operating in either a monovalent configuration with an electric heater or in a bivalent configuration with a gas boiler. On the one hand, considering the financial aspect, the solution with a gas boiler seems to be more favorable, being cheaper to operate. However, with the use of PV panels, the investment return in a dedicated PV installation is achieved in 6–7 years, but there still remains an annual fee for gas fuel, which is not the case with an electric heater installation. The electric heater solution also offers savings throughout the assumed 15-year lifespan of the installation, amounting to nearly €3000 more in favor of the EH installation. This is a significant aspect of the issue.

On the other hand, an equally important ecological aspect is the release of CO_2 emissions into the atmosphere, which is more favorable with the gas boiler installation, averaging a reduction of between 21.5 and 29.6% when there is no additional PV installation. With the implementation of PV panels, there is a reduction in emissions by approximately 88.3% for the AHP + GB installation powered by a coal-fired power plant, and by 79.1% for a natural gas-fired power plant. In the case of the AHP + EH installation, the use of PV panels results in a 100% reduction in CO_2 emissions, bringing them down to zero annually.

Taking into account that the total lifespan of the installation is approximately 15 years, we can estimate the total CO_2 emissions that will occur in the analyzed cases with the use of PV installations. Since the monovalent AHP + EH installation relies entirely on electricity, achieving a 100% reduction in CO_2 emissions allows for the elimination of 756 kg CO_2 from the environment over the 15-year period when powered by electricity produced in a coal-fired power plant. Similarly, for a gas-fired power plant, the avoidable emissions amount to 381 kg of CO_2.

This solution fully supports the goals of the 2030 Agenda, which is aimed at reducing greenhouse gas emissions into the atmosphere.

In general, the main conclusions from the analysis presented above can be condensed into:

1. Financial aspects:
   - The gas boiler solution is cheaper to operate;
   - PV panel investment return in 6–7 years;
   - Electric heater (EH) installation has no annual gas fuel fee;

- EH installation saves nearly €3000 more over a 15-year lifespan.

2. Ecological aspects:
   - Gas boiler installation reduces CO_2 emissions by 21.5–29.6% without PV panels;
   - PV panels reduce CO_2 emissions by 88.3% (coal-fired power) and 79.1% (natural gas-fired power) for AHP + EH.

Comparing these results with other studies, it is evident that the integration of heat pumps and photovoltaic systems is a widely supported approach for achieving energy efficiency and sustainability in residential buildings. For instance, studies in the northern climates of the U.S. and Canada demonstrated that combining PV systems with heat pumps can offer returns on investment, while also increasing energy self-sufficiency [13]. Similarly, other research [23] conducted highlights the optimal sizing of solar-assisted heat pump systems for residential buildings, emphasizing the significant reduction in CO_2 emissions and operational costs, further supporting our findings on the benefits of hybrid heat pump and PV systems.

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Nomenclature

A	constant of the equation (-)
AHP	air source heat pump
B	constant of the equation (-)
COP	coefficient of performance (-)
MVS	mechanical ventilation system
DWS	domestic hot water system
CHS	central heating system
EH	electric heater
EHM	electric power for the electric heater (kWh/month)
EHP	percentage of electricity demand covered by the electric heater (%)
GB	gas boiler
GBM	costs of gas fuel (Euro/month)
NAHP	electric power for the air heat pump (kWh/month)
NAHPM	costs of electricity for the heat pump (Euro/month)
PV	photovoltaic system
Q_{annual}	annual costs for heat demand (kWh/a)
Q_{DHS}	heat demand for district heating system (kWh/month)
Q_{DWS}	heat demand for district water system (kWh/month)
Q_{DVS}	heat demand for ventilation system (kWh/month)
Q_{total}	total annual heat demand (kWh/month)
SCOP	seasonal coefficient of performance for heating (-)
T_z	value of the external temperature (°C)

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