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Towards Sustainable Heating: An Energy–Economic–Environmental (3E) Analysis of an Air-to-Water Heat Pump System Integrated with Grid-Connected Photovoltaics for the Southern Romanian Climate

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Abstract

The electrification of residential heating through heat pumps represents one of the central directions of the European energy transition; however, evaluating these systems requires moving beyond classical approaches limited to purely energy-based indicators. This paper proposes an integrated 3E analysis (Energy–Economy–Environment) of a hybrid system composed of a split-type air-to-water heat pump (nominal heating capacity of 8 kW, R410A refrigerant) and an on-grid photovoltaic installation with a peak power of 6.02 kWp, installed in a single-family house with a usable floor area of 122.3 m², located in climatic zone II with a conventional winter design outdoor temperature of $t_{\text{ext}} = -15$ °C. Operational data, collected over two consecutive heating seasons (2024–2025 and 2025–2026) at daily resolution and aggregated monthly, were processed to determine the seasonal performance factor (SPF), the specific heat demand, the operating costs compared with a conventional natural-gas solution, and the climatic impact through the TEWI (Total Equivalent Warming Impact) indicator. The results show SPF values of 3.30–3.51 ($\pm 7\%$, standard uncertainty), a strong correlation between outdoor temperature and COP (at both the monthly and daily levels), average annual savings of approximately 2834 RON compared with the natural-gas solution, and a payback period of 15–16 years. The cumulative climatic impact over the equipment's lifetime (TEWI ≈ 35.1 t CO₂-eq over 15 years) is offset to a large extent ($\approx 83\%$) by the emissions avoided through photovoltaic production (≈ 29.25 t CO₂-eq). The results indicated a higher LCCP (Life Cycle Climate Performance) compared with TEWI, by approximately 4.0%, for the system presented in this paper. The study also identifies limitations associated with the local electricity grid infrastructure, which reduce the exploitation of photovoltaic production during periods of high solar potential, and proposes optimization directions such as battery storage and improvements to the building envelope. The results support the need for multicriteria, 3E/4E-type assessments to underpin decisions on the decarbonization of the residential building sector.

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1. Introduction

1.1. Current Context of the Heat Pump Market

In the context of the accelerating decarbonization of the energy sector and the intensification of policies aimed at reducing fossil fuel consumption, heat pumps have become one of the central technologies of the European and global energy transition. Their ability to use low-grade renewable heat sources while simultaneously providing space heating, cooling, and domestic hot water preparation is driving a continuous expansion of their application domains in both the residential and the commercial or industrial sectors.

Following the record growth recorded in 2021–2022, the European market entered an adjustment phase. In 2024, heat pump sales fell by approximately 20–23% compared with the previous year [1], amid the reduction of support schemes, falling natural gas prices, and a slowdown in the construction sector. However, the market partially recovered in 2025, when sales increased again in several European countries, and the total number of units installed in Europe exceeded approximately 28 million systems [2].

Total greenhouse gas (GHG) emissions from the EU building sector, including both direct and indirect emissions, decreased by 43% between 2005 and 2023. This reduction can largely be attributed to the EU's decarbonization strategy, which has been implemented through a range of legislative measures. The strategy promotes a combination of improved energy efficiency in buildings, including enhancements to building envelopes and technical systems, increased electrification of residential end uses, and the decarbonization of electricity as well as heating and cooling systems [3].

Estimates for 2024 indicate a further slight decrease in direct emissions from fossil fuel use in buildings compared with 2023, reflecting ongoing improvements in energy efficiency and the decarbonization of heating systems. Although emissions associated with fossil fuel use in buildings declined across the EU between 2005 and 2023, both historical trends and future projections vary considerably among Member States. Over this period, emissions from the building sector in Romania decreased by approximately 4%, indicating a relatively modest reduction compared with the EU-wide trend [4,5].

From a technological standpoint, air-source heat pumps continue to hold the dominant share of the market, owing to their relatively low investment costs and high implementation flexibility. Within this category, air-to-water systems show an accelerated rate of adoption, particularly in Europe, due to their compatibility with existing hydronic systems and the ease with which they can be integrated into energy renovation projects. Technological progress over the past decade—variable-speed compressors, optimized control algorithms, and more efficient refrigeration cycles—has extended the operational range of these systems, progressively reducing the traditional limitations on the use of heat pumps in regions with low outdoor temperatures.

Geothermal and water-to-water systems continue to offer significant advantages in terms of heat-source stability and higher coefficients of performance; however, their rate of adoption remains limited by high initial investment, the complexity of installation works, and site-specific geological or hydrological constraints. In parallel, the market is showing a growing orientation toward energetically integrated solutions, in which heat pumps are combined with photovoltaic systems, energy management systems, and storage solutions—a trend that reflects the transition from traditional thermal-energy production toward the concept of the energy-active, passive building.

Heat pumps (HPs) can be used for building heating and cooling and for heating domestic water, making them a versatile technology that has the potential to significantly reduce greenhouse gas emissions. For space heating, replacing gas furnaces with air-to-water HPs can reduce greenhouse gas emissions. Switching to heat pumps cuts greenhouse gas emissions and helps improve air quality. Accelerated deployment of heat pumps, in line with national climate targets, could reduce global CO₂ emissions by half a gigatonne already by 2030 [6].

While already meeting 10% of global space-heating needs in 2021, HPs have the potential to reduce global carbon dioxide emissions by at least 500 million tonnes by 2030, equivalent to the annual emissions of all cars currently in operation in Europe [7].

In Europe, the application of this technology is essential for achieving the global Net-Zero target proposed by the European Commission, aimed at decarbonization and a consequent reduction in building energy bills by 2030, in line with the European Green Deal's target of net-zero greenhouse gas emissions by 2050 [8,9].

In addition to using thermal energy storage (TES), the building's thermal mass can also be exploited. Heinz et al. [10] examined the energy-saving potential of coupling an air-source HP with a PV system and a TES to supply heat to renovated buildings with radiator heating systems, comparing this potential with that obtained using a floor-heating system. Simulations were performed in TRNSYS for a single-family house in Zurich with a gross floor area of 185 m². Assuming typical Austrian electricity prices and feed-in tariffs, the shortest payback time, 17.1 years, was achieved with 5 kWp of PV combined with a storage volume of 1 m³.

For example, the application of a solar-assisted air-water heat pump (AWHP) could balance photovoltaic (PV) power generation and consumption by using the power produced directly during periods of high demand and charging storage systems when little or no heating demand is required, for later use. ASHPs are sensitive to ambient climatic conditions, so climate-change factors must be taken into account when planning their long-term operation or when assessing building energy systems in the future [11].

Over the past decade, numerous studies on the seasonal performance of air-to-water heat pumps (AWHPs) have been published for Greek locations, showing that seasonal efficiency is influenced by several factors, including local climatic conditions, compressor technology, heat pump sizing relative to the building's thermal load, and heating-system control strategies [12,13].

Using PVT instead of ST collectors can increase the share of renewable energy in domestic solar-assisted heat pump systems and ensure good performance and reliability [14].

Ołtarzewska et al. [15] conducted a TRNSYS-based simulation to assess the performance of a PV-assisted air-source heat pump (PV-ASHP) system in a service building across different climatic zones in Poland. The results showed that modifying the heat pump control strategy led to a 36–62% increase in energy consumption, depending on location and the variant considered. Furthermore, changing the position of the PV panels on the roof slope resulted in a 16–22% reduction in electricity generation. Overall, the integration of PV panels with an ASHP in a service building was found to be a potentially cost-effective solution.

Although previous studies have compared PV, ST, and hybrid PV/ST systems, reference [16] investigated the relative benefits of solar thermal (ST) and photovoltaic (PV) systems integrated with air-source heat pumps for domestic hot water production in newly built residential buildings. The results show that the ST system provides 964.6 kWh of thermal energy annually, increasing to 1528 kWh under enhanced hot-water demand, while a similarly sized PV system generates 532.5 kWh of electricity [16].

Other studies have focused on the technical and economic aspects of grid-connected PV systems in Romania, in Bacău. This work investigated the feasibility of using a resi-

dential photovoltaic system in the absence of financial support for the implementation of such systems [17].

In ref. [18], Coman et al. conducted an energy, economic, and environmental assessment of a PV-assisted ground-source heat pump located in southeastern Romania. This study shows that a 5 kW PV system combined with a 5 kWh battery cannot cover the full heat demand of a medium-to-large house during winter and that full energy independence would require a larger PV array paired with a higher-capacity battery.

An air-to-water heat pump was installed in a school located in a rural area near Galați, Romania, and its performance was monitored over a two-year period. The heat pump was implemented because the village has no access to a district-heating or natural-gas network. This study presents an experimental thermo-economic assessment of the system, based on measurements collected during the cold season [19].

1.2. Regulatory Framework at the European Union Level

The most concrete action on heat pumps in Europe was launched in April 2023, through the EU Heat Pump Action Plan [20], with the objective of installing at least 10 million additional units by 2027. The initiative envisages four areas of action: partnership between the Commission, Member States, and industry; communication to all stakeholder groups and a skills partnership for implementation; legislation; and accessible financing.

This plan is consistent with earlier European Commission initiatives. In March 2022, following Russia's invasion of Ukraine and the need to decouple European heating systems from fossil fuels, the REPowerEU plan was published [21], announcing the intention to promote the electrification of heating systems, with an additional 10 million heat pumps installed between 2022 and 2027 and 30 million hydronic heat pumps by 2030—a target aligned with the 30-million-unit goal set out in the 'Fit for 55' package [22], published in 2021, which aims to reduce net greenhouse gas emissions by at least 55% by 2030.

Among the measures included in the 'Fit for 55' package is the revision of several key directives—the Energy Performance of Buildings Directive (EPBD) [23], the Renewable Energy Directive (RED) [24], and the Energy Efficiency Directive (EED) [25]—as well as comprehensive changes to the EU Emissions Trading System (EU ETS), which aims to put a price on CO₂ emitted from fossil-fuel-based heating, with the resulting revenues directed toward climate-action measures, which should stimulate investment in green technologies such as heat pumps.

All these initiatives fall within the framework of the European Green Deal [26], whose purpose is to transform the EU into a modern, resource-efficient, and competitive economy with net-zero greenhouse gas emissions by 2050. The European Commission also presented a Green Deal Industrial Plan in 2023, whose main pillars are the Critical Raw Materials Act and the Net-Zero Industry Act (NZIA) [27], which entered into force in 2024 and under which heat pumps were classified as strategic technologies for the European energy transition, aiming to develop domestic manufacturing capacity, reduce external dependencies, and accelerate industrial investment.

The recent geopolitical context, marked among other things by the regional conflict involving Iran, highlights the strategic nature of European energy security, since disruptions to hydrocarbon supply chains have direct effects on energy prices and economic competitiveness. In this context, investments in electrification, renewable sources, and high-efficiency heating systems are increasingly perceived not only as climate tools but also as measures to reduce exposure to geopolitical risk.

1.3. International Legislative Framework on Climate Change

The first international agreement on climate change, the Kyoto Protocol, successor to the United Nations Framework Convention on Climate Change, established binding

commitments for heavily industrialized countries to reduce greenhouse gas emissions (carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride), requiring a reduction of at least 5% over 2008–2012 compared with 1990 levels. The European Union adopted the protocol on 31 May 2002, which entered into force on 16 February 2005.

The international community set out a new climate agreement in December 2015 in Paris, at the COP21 Conference, where 195 countries ratified the first legally binding global agreement on climate change. The Paris Agreement entered into force on 4 November 2016, with Member States agreeing to keep global warming below 2 °C, with an additional effort to limit it to 1.5 °C. With the launch of the European Green Deal in 2019, the EU committed to reducing net greenhouse gas emissions by at least 55% by 2030 compared with 1990, a target transposed into legislation through the European Climate Law, adopted in 2021, which also establishes the target of climate neutrality by 2050.

The 2023 United Nations Climate Change Conference (COP28), held in Dubai, included the first Global Stocktake under the Paris Agreement, highlighting the need for global emissions to peak before 2025 and to be reduced by 43% by 2030 and 60% by 2035, relative to 2019 levels, in order to limit warming to 1.5 °C—the stocktake also finding that some countries are lagging behind in meeting their commitments.

A regulatory element with a direct impact on heat pump technology is the management of refrigerants. Their climatic impact is expressed through the Global Warming Potential (GWP), and hydrofluorocarbons (HFCs), widely used in air-conditioning and refrigeration equipment, have a high GWP. To reduce this impact, the new European F-gas Regulation, Regulation (EU) 2024/573 [28], which entered into force in 2024, accelerates the phase-down of high-GWP refrigerants and introduces additional restrictions on the use of HFCs, favoring natural refrigerants (such as propane, R290) and hydrofluoroolefins (HFOs), which have a low climatic impact. These requirements directly influence equipment design and selection, steering the market toward more energy-efficient and less polluting solutions.

1.4. National Legislative Framework

In Romania, the legislative framework on the energy performance of buildings has been developed to transpose European requirements on energy efficiency and the reduction of greenhouse gas emissions in the construction sector. The main regulation in this field is Law No. 372/2005 on the energy performance of buildings [29], republished and subsequently amended to align with European legislation. The law establishes requirements for the calculation of energy performance, the energy certification of buildings, and the promotion of high-efficiency technical systems.

In applying this law, the energy performance of buildings is assessed according to the Methodology for Calculating the Energy Performance of Buildings (Mc 001) [30], periodically updated to reflect technological developments and European requirements, including the assessment of technical systems for heating, cooling, ventilation, and domestic hot water preparation, including those based on renewable energy sources. Heat pumps are recognized in this framework as high-energy-efficiency technical systems that contribute to reducing primary energy consumption and CO₂ emissions in buildings, representing one of the solutions promoted for achieving national and European decarbonization targets for the building sector.

1.5. The Need to Redefine the Evaluation Criteria for Modern Energy Systems

The building sector occupies a central position in the energy transition, being responsible for a significant share of final energy consumption and of emissions associated with fossil fuels. Over the past decades, the approach to building energy systems has

evolved from maximizing energy efficiency toward the simultaneous optimization of technical, economic, and environmental performance—a paradigm shift driven by three main factors: the intensification of climate change, the volatility of energy markets, and changes in the international and European legislative framework. Consequently, the evaluation of technological solutions can no longer be carried out solely through energy or economic indicators, requiring the adoption of multicriteria methodologies capable of capturing the complexity of current energy systems.

Heat pumps are considered key technologies of the electrification process, as they enable the transfer of thermal energy from low-grade heat sources to useful temperature levels, using a relatively small amount of electrical energy. Their main advantage lies in the multiplication of useful energy obtained relative to the electrical energy absorbed, which leads to coefficients of performance superior to those of conventional systems based on the direct conversion of primary energy. The accelerated development of these systems is explained by the convergence of several factors: the need to reduce fossil fuel consumption, the electrification of energy-consuming sectors, the increasing share of renewable energy in the energy mix, growing legislative requirements on the energy performance of buildings, and increasing concerns about energy security. At the same time, recent studies show that a simple energy assessment of heat pumps is insufficient, since real performance depends on the interaction between the heat source, the control strategy, climatic conditions, and the electricity supply.

The overall performance of heat pumps is directly influenced by the electrical energy required for their operation, so their association with photovoltaic systems becomes a natural solution for reducing grid dependence and mitigating indirect climatic impact. The integration of photovoltaic systems produces simultaneous effects at several functional levels: reducing net grid energy consumption, lowering operating costs, reducing indirect carbon emissions, improving energy flexibility, and increasing energy autonomy. However, the benefits of hybrid heat pump–photovoltaic (HP–PV) systems cannot be quantified solely through COP or energy-consumption analysis, since the interactions between solar production, user behavior, control strategies, and climatic conditions significantly affect the overall performance of the system. Therefore, the pairing of heat pumps with photovoltaic systems must be regarded as a complex energy integration, and not merely as a sum of independent pieces of equipment.

1.6. From 2E Analysis to 3E and 4E Analysis

Traditional approaches used to evaluate energy systems have long relied on 2E analysis—Energy–Environment—which allows the identification of solutions that combine energy efficiency with reduced emissions and negative environmental effects, offering a more complete perspective than traditional energy analysis alone. However, 2E analysis has significant limitations: it does not assess the economic viability of the analyzed solutions, does not quantify investment, operating, and maintenance costs, does not allow for payback-period analysis, does not highlight the trade-offs between environmental performance and implementation costs, and does not provide sufficient information to underpin long-term investment decisions. In practice, the solution with the lowest environmental impact is not always the most advantageous economically, and some technologies can generate significant environmental benefits under conditions of high initial costs or long payback periods.

To overcome these limitations, the evaluation of energy systems is increasingly carried out through 3E analysis—Energy–Economy–Environment—which allows the simultaneous evaluation of energy performance, economic sustainability, and environmental impact, providing a multidimensional framework capable of capturing the interdependencies between energy consumption, associated costs, and environmental effects,

thereby contributing to better-informed technical and investment decisions aligned with current sustainable-development objectives.

The evolution of complex energy systems shows, however, that even 3E analysis is not always sufficient for a complete characterization of performance. Energy quantifies only the amount transferred or consumed, without capturing its quality, so two processes with the same energy consumption can display completely different levels of efficient resource use. Exergy analysis introduces the concept of energy quality and allows the quantification of the irreversibilities of thermodynamic processes, making it possible to identify the components that generate the largest losses. Recent research on hybrid systems based on heat pumps and photovoltaic sources indicates a clear orientation toward 4E analysis methodologies—Energy, Exergy, Economy, Environment—in which exergy analysis complements energy, economic, and environmental assessments, being particularly relevant for integrated systems and for advanced control and optimization strategies. Thus, the conceptual evolution from 2E to 3E and, subsequently, to 4E does not merely represent a methodological extension but reflects the fundamental transformation in the way modern energy systems are designed, evaluated, and optimized.

1.7. Objectives of the Paper

In this context, the present paper aims to carry out a 3E analysis applied to a hybrid air-to-water heat pump–photovoltaic system installed in a single-family house, based on operational data collected over two consecutive heating seasons. Specifically, the study pursues: (i) the evaluation of the system’s real energy performance through the seasonal performance factor (SPF) and specific consumption indicators, as well as the analysis of the correlation between COP and outdoor temperature, at both the monthly and daily levels; (ii) the economic analysis of the investment, by comparing operating costs with a conventional natural-gas solution and determining the payback period; and (iii) the assessment of environmental impact through the TEWI (Total Equivalent Warming Impact) and LCCP (Life Cycle Climate Performance) indicators, including the quantification of CO₂ emissions avoided through photovoltaic production. The results obtained are discussed comparatively with recent studies on similar hybrid systems in order to identify optimization directions applicable at the residential scale. Despite the growing number of studies on heat pump–photovoltaic systems, several gaps remain. First, most 3E assessments of such systems are based on simulations or short-term monitoring, while studies using measured data from several consecutive heating seasons are still limited, particularly for air-to-water heat pumps operating with radiators in existing, moderately insulated houses. Second, the energy, economic and environmental performance are usually assessed separately or on different datasets, so that the effect of the real operating performance on the economic and climatic indicators is rarely quantified for the same system. Third, field data from South-Eastern Europe, and from Romania in particular, remain scarce; the few available Romanian studies address ground-source heat pumps, public buildings or PV systems alone. Finally, the influence of local low-voltage grid constraints on the use of residential PV generation is mainly discussed from the grid operator’s perspective, with little evidence from the end-user side. The present study addresses these gaps by providing an integrated 3E assessment of an air-to-water heat pump–PV system in a single-family house in southern Romania, based on measured data from two consecutive heating seasons.

2. Current State of Research in the Field

The specialized literature of recent years confirms the increasingly pronounced orientation toward multicriteria (3E/4E) evaluation of heat-pump-based heating systems, as well as the growing interest in hybrid configurations that combine heat pumps with

photovoltaic or solar-thermal sources. The following sections review the main research directions relevant to the present study: (i) 3E/4E analyses applied to hybrid heat pump–photovoltaic systems; (ii) monitoring studies of the real performance (COP/SCOP) of air-to-water heat pumps; (iii) the methodology and applications of the TEWI and LCCP indicators; and (iv) the limitations imposed by electricity grid infrastructure on the exploitation of photovoltaic production.

2.1. 3E/4E Analyses of Hybrid Heat Pump–Photovoltaic Systems

The number of studies applying the 3E (Energy–Economy–Environment) methodology to hybrid heating systems has grown significantly in recent years, as assessments based solely on energy indicators have proven insufficient for underpinning investment decisions. Zhang et al. [31] applied a 3E analysis to residential buildings equipped with photovoltaic and energy-storage systems in a case study from Shenzhen, China, demonstrating that the integration of storage improves the self-consumption rate and the economic indicators of the investment, but at the cost of a longer payback period. In a similar vein, Rashvand et al. [32] carried out a 3E and climatic analysis of a hybrid solar–ground-source heat pump system, applicable throughout the year, emphasizing the importance of correlating performance with the local climatic regime in order to identify an optimal operating point.

Studies on photovoltaic-thermal (PV/T) systems coupled with heat pumps also show significant efficiency benefits: an eight-month monitoring campaign of a solar-assisted PV/T system for residential buildings [33] revealed a 21.6% improvement in the coefficient of performance and a reduction in greenhouse gas emissions compared with a conventional air-source heat pump. In a recent study on a solar-assisted ejector-compression hybrid system coupled with PV/T collectors, the authors [34] used a 3E approach based on the entropy-weighted TOPSIS method to evaluate the sustainability of several heat pump technology variants associated with different electricity-generation technologies (photovoltaic, wind, hydro, nuclear, hydrogen fuel cells), obtaining improvements in COP and exergetic efficiency of up to 38.2% and 16.9%, respectively, compared with a standard air-source heat pump.

At the level of a complex energy system, other authors [35] carried out a dynamic 3E assessment of a combined heat, cooling, and power generation system based on photovoltaic-thermal panels coupled with a Stirling engine, applied to a building in Tehran, highlighting reduced emissions across all analyzed scenarios and a satisfactory payback period; related studies on sizing micro-CCHP systems for residential buildings in different climates reported significant fuel savings and a payback period of approximately six years. In turn, studies on the energy retrofit of buildings using water-source heat pumps coupled with PV/T panels, applied to social-housing blocks built in the 1980s [36], demonstrated significant reductions in consumption through the combination of the two technologies, validated experimentally and through annual dynamic simulations.

From a comparative economic perspective, a study based on real data on the thermal retrofit of residential buildings through the installation of heat pumps [37] showed that the solution combining a heat pump with a photovoltaic installation represents, for most of the analyzed buildings, the most advantageous option in terms of the balance between costs and emission reduction, confirming the direction also pursued in the present study. Likewise, a recent study on the energy efficiency of eco-friendly housing equipped with heat pumps and photovoltaic panels [38] highlighted the role of this technological combination as a key solution for achieving sustainable-development objectives at the residential level, offering practical recommendations for designers and engineers.

2.2. Real Performance (COP/SCOP) of Air-to-Water Heat Pumps

An essential aspect highlighted by recent literature is the existence of a ‘performance gap’ between the SCOP values declared by manufacturers, obtained under standardized testing conditions (in accordance with EN 14825/EN 14511) [39,40], and the actual performance measured in operation. A systematic analysis of monitoring data for 30 air-source heat pumps showed an average SCOP value of 4.25 for low-temperature heating applications (35 °C) and only 3.26 for medium-temperature applications (55 °C), with the authors concluding that an SCOP value of approximately 3.0 is more representative of real-world performance than the values reported in technical datasheets. The largest field study conducted to date, published in *Nature Communications* [41], used real operating data from more than 1000 heat pumps installed in residential buildings (87% of which were air-to-water systems), monitored for up to 777 days, providing a solid basis for estimating energy efficiency under real operating conditions, at a significantly larger scale than individual case studies.

Studies specifically dedicated to air-to-water heat pumps [42] have developed regression models for predicting SCOP based on short-term dynamic monitoring, using daily data on outdoor temperature, flow/return temperatures, and electricity consumption, demonstrating that linear models based on daily outdoor temperature provide a reliable prediction of seasonal performance—a methodological approach similar to the one applied in the present study for analyzing the daily correlation between COP and outdoor temperature. These results confirm, overall, that the SPF values obtained in the present case study (3.30–3.51) are comparable to, or even slightly higher than, the average resulting from large-scale field studies, suggesting a correctly sized and operated system, even under conditions of using radiators as heat-emission terminals.

For example, a study presented highlights how climatic conditions and energy price scenarios impact the performance and feasibility of air-water heat pumps. Results indicate that SCOP is highly sensitive to climatic variability, with efficiency decreasing by 40–50% in colder regions during cold years, while remaining stable in warmer climates such as Spain [43].

2.3. TEWI and LCCP Indicators and the Assessment of the Climatic Impact of Refrigerants

The TEWI (Total Equivalent Warming Impact) methodology, originally developed by Oak Ridge National Laboratory to compare residential and commercial air-conditioning systems in North America, Europe, and Japan equipped with different types of refrigerants (R-22, R-407C, R-410A, R-290) [44], remains one of the reference methods for quantifying the cumulative climatic impact of refrigeration equipment and heat pumps. Recent studies on two-stage vapor-injection heat pumps designed for cold climates [45] compared the performance and TEWI of several ultra-low-GWP refrigerants (R-290, R-152a, R-161, R-1234yf, R-1234ze(E)), identifying R-152a and R-290 as high-potential solutions that combine a higher COP with a lower TEWI value, in line with the requirements of the Kigali Amendment on the phase-down of high-global-warming-potential refrigerants.

Other comparative studies, applied both to residential air-conditioning installations [46] and to commercial refrigeration systems [28], confirm that replacing high-GWP refrigerants (such as R-22) with low-GWP alternatives can reduce TEWI values by up to 55%, even with a slight reduction in the coefficient of performance. A methodological analysis dedicated to comparing climate-impact assessment methods (SCOP, TEWI, LCCP, and life-cycle assessment—LCA) [47] showed that the differences between the results obtained through SCOP, TEWI, and LCCP are generally minor, the main reason being the dominant share of indirect emissions (associated with electricity generation) in the total impact—a conclusion also confirmed by the results of the present study, where

the indirect component represents approximately 76% of the total TEWI value. However, the classical TEWI method does not include the effects associated with equipment manufacturing, transport, and recycling, which is why some studies propose supplementing it with LCCP-type assessments or additional corrections, such as those accounting for system degradation through corrosion [48].

2.4. Limitations Imposed by Electricity Grid Infrastructure on Residential Photovoltaic Systems

A research direction relevant to the results of the present study concerns the limitations imposed by the low-voltage electricity grid on the exploitation of distributed photovoltaic production. The increasing penetration of residential photovoltaic installations causes, under certain conditions, reverse power flows and voltage rise at the low-voltage grid level, which can trigger inverter protection mechanisms—automatic reduction of the injected active power or even temporary disconnection. Studies based on real data collected from more than 1300 homes equipped with photovoltaic installations and storage systems [49] confirmed the existence of significant production losses caused by these protection mechanisms, particularly for installations located at the end of long distribution circuits or affected by undersized grid connections.

To mitigate this phenomenon, the literature mainly proposes two directions of intervention: the use of smart inverters, capable of regulating voltage through reactive power absorption [50], and the integration of battery storage systems, which reduce the power flow injected into the grid [51] by locally storing surplus photovoltaic energy. Studies dedicated to the optimal sizing of residential storage systems [52] have demonstrated significant reductions in the financial losses associated with photovoltaic curtailment, confirming that the integration of a storage system—a solution also proposed in the conclusions of the present study—can represent an effective measure for mitigating the grid limitations observed in the analyzed case.

2.5. Market Context and Positioning of the Present Study

According to the most recent report of the European Heat Pump Association (EHPA), the European market recorded sales declines of 5% in 2023 and 21% in 2024, driven mainly by the gap between electricity and natural-gas prices, as well as by the instability of support schemes, followed by a 10.3% recovery in 2025, reaching 2.62 million units sold across the 16 monitored European countries—an evolution consistent with the trends described in Section 1.1 of this paper. Across the 19 countries included in the EHPA report, the more than 25.5 million installed heat pumps annually avoid the import of approximately 21 billion cubic meters of natural gas, and Romania is among the emerging markets for this technology, with sales estimated at approximately 10,000 units in 2023.

The report of the European Clean Energy Technology Observatory (European Commission, 2025) [53] also confirms that heat pumps remain a strategic technology for the decarbonization of the EU building sector, supported by sustained demand driven by the regulatory framework described in Section 1.2 but also by the need to reduce the gap between declared and actual equipment performance through performance-based commissioning.

The main studies reviewed in this section are summarized in Table 1. The synthesis of the specialized literature thus reveals three important observations for positioning the present study. First, although 3E/4E analyses of hybrid heat pump–photovoltaic systems are becoming increasingly frequent, most of them rely on simulations or short-term monitoring, with a relatively limited number of studies based on real operational data collected over several consecutive heating seasons, as is the case in the present paper. Second, although the gap between declared and actual heat pump performance is widely documented, few studies correlate this gap with a complete economic and environmental analysis applied to the same system and the same field data. Third, the influence of local

electricity grid constraints on the exploitation of photovoltaic production is investigated in the literature mainly from the perspective of grid operators, with few studies documenting this phenomenon from the perspective of the end user of a hybrid heat pump–photovoltaic system, as is the case here. The present study therefore contributes to filling these gaps through an integrated 3E analysis based on real operating data collected over two consecutive heating seasons.

Table 1. Summary of the main studies reviewed in Section 2.

Ref.	System/Topic	Approach	Main Findings
[31]	Residential buildings with PV and energy storage	3E analysis	Storage increases self-consumption and improves economic indicators, but lengthens the payback period
[32]	Hybrid solar–ground-source HP	3E and climatic analysis	Performance must be correlated with the local climate to identify the optimal operating point
[33]	Solar-assisted PV/T HP, residential	Field monitoring (8 months)	COP improved by 21.6% and GHG emissions reduced compared with a conventional ASHP
[34]	Solar-assisted ejector–compression HP with PV/T	3E, entropy-weighted TOP-SIS	COP and exergy efficiency improved by up to 38.2% and 16.9%. vs. a standard ASHP
[35]	PV/T–Stirling CCHP system	Dynamic 3E assessment	Reduced emissions in all scenarios; satisfactory payback period
[36]	Water-source HP with PV/T, retrofit of 1980s social housing	Experimental + dynamic simulation	Significant reduction in energy consumption
[37]	HP retrofit of residential buildings	Economic analysis on real data	HP + PV is the most advantageous option in terms of cost and emission reduction
[38]	Eco-friendly housing with HP and PV	Energy efficiency analysis	HP + PV is a key solution for sustainable residential buildings
[41]	>1000 residential HPs (87% air-to-water)	Field monitoring (up to 777 days)	Large-scale basis for real-world efficiency; performance gap vs. rated values
[42]	Air-to-water HP	Short-term monitoring, regression models	Linear models based on daily outdoor temperature reliably predict seasonal performance
[43]	Air-to-water HP, several climates	Climate and energy-price scenarios	Seasonal performance decreases by 40–50% in cold regions during cold years; stable in warm climates
[44]	Residential/commercial AC and HPs (R-22, R-407C, R-410A, R-290)	TEWI (ORNL methodology)	Reference method for the cumulative climate impact of refrigerants
[45]	Two-stage vapor-injection HP, cold climate	Performance and TEWI comparison	R-152a and R-290 combine higher COP with lower TEWI
[46]	Residential split AC (R-22 replacement)	TEWI	Low-GWP alternatives reduce TEWI by up to 55%
[47]	Comparison of SCOP, TEWI, LCCP and LCA	Methodological analysis	Differences between methods are minor; indirect emissions dominate
[48]	TEWI methodology	TEWI with corrosion correction	Classical TEWI should be supplemented to account for system degradation
[49]	>1300 homes with PV and storage	Analysis of real data	Significant PV losses due to inverter protection at voltage rise
[50]	Smart inverters	Voltage regulation	Reactive power absorption mitigates voltage rise
[51]	Residential battery storage	Grid-injection analysis	Storage reduces power injected into the grid
[52]	Residential storage sizing	Optimization	Optimal storage reduces financial losses due to PV curtailment
–	Present study	Field monitoring (2 heating seasons), 3E (SPF, economics, TEWI/LCCP)	Integrated 3E assessment of an air-to-water HP–PV system with radiators in an existing house

3. Materials and Methods

3.1. Building Characteristics and Location

The building under analysis is a single-family house located in the southeastern part of Romania, in climatic zone II, with an average winter design temperature of $-15\text{ }^{\circ}\text{C}$.

The analyzed system serves a single-family, single-story house with a usable floor area of 122.3 m^2 , built in 1998 and located in Băjani, Buzău County. Prior to the implementation of the project, in December 2023, the building was heated using three wood-burning stoves, a solution that was fully replaced by the electrified system described below (Figure 1).



Figure 1. Site map of Băjani, Buzău County [54].

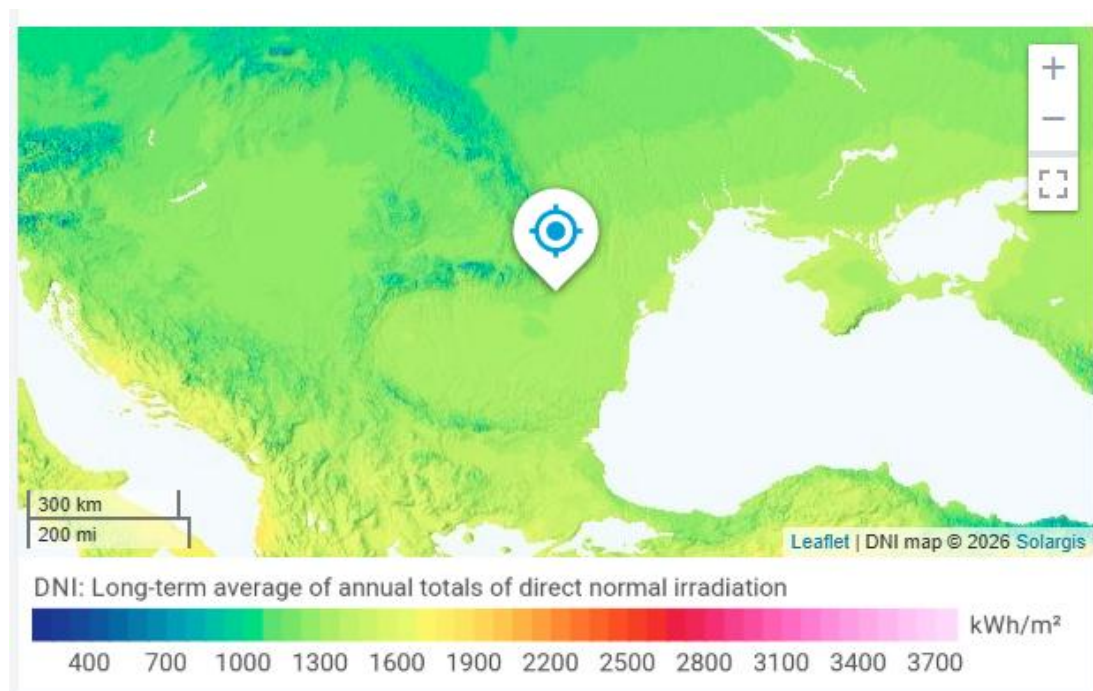
As shown in Figure 2, the site has high solar potential, with a direct normal irradiation of 1301 kWh/m^2 and climate data indicating roughly 230 sunshine days per year.

From a structural standpoint, the building features a reinforced-concrete frame consisting of beams and columns, with both the exterior and interior walls constructed from autoclaved aerated concrete (AAC) blocks. The windows and external doors are fitted with PVC frames incorporating four air chambers and double-glazed insulating glass units. The exterior walls are thermally insulated with a 50 mm layer of expanded polystyrene (EPS). The attic roof is insulated with 200 mm of mineral wool and incorporates a vapor barrier, as illustrated in Figure 3. The thermal properties of the building's main structural elements are detailed in Table 2.

The building was occupied by four people; the indoor temperature during the heating season was set at $23\text{ }^{\circ}\text{C}$ for the main rooms, $22\text{ }^{\circ}\text{C}$ for the kitchen, and $24\text{ }^{\circ}\text{C}$ for the bathroom.

Table 2. Thermal properties of the building envelope.

Construction Element	Area [m ²]	Overall Heat Transfer Coefficient [W/m ² ·K]
Exterior walls	78.04	0.44
Windows	11.97	1.07
Floor	91.71	0.40
Doors	4.03	1.07
Roof	119.2	0.69

**Figure 2.** Direct normal irradiation for the climate zone (Global Solar Atlas [55]). Available online: <https://globalsolaratlas.info/detail?c=45.149600,26.833420,11> (accessed on 13 August 2026).**Figure 3.** General view of the building.

3.2. Description of the Heat Pump Installation

The heating installation was sized taking into account the climatic zone, the building's height regime, and its usable floor area, in accordance with the national technical regulations in force [56–62]. The air-to-water, split-type heat pump heating system, manufactured by Mitsubishi Electric (Mitsubishi Electric Corporation, Tokyo, Japan; Zubadan system, Hydrobox model PUHZ-SHW80VAA) [63], is used to prepare the hot water required for heating, the building being fitted with radiator-type heat-emission terminals (Figure 4).

The indoor unit is installed in the technical room on the ground floor, with a footprint of only 530 × 360 mm. It contains a plate-type refrigerant/water heat exchanger, a circulation pump, a 10 L expansion vessel, a safety valve, a backup electric heating element, and a Y-filter. A reversible model was selected, even though, for the time being, the heat pump is used solely for heating, thereby retaining the possibility of adding cooling in the event of a future renovation and the installation of indoor air-conditioning units.

The outdoor unit is installed next to the exterior wall of the technical room, as close as possible to the indoor unit in order to avoid a long refrigerant line, on special supports that ensure both stability and a sufficient distance from the ground to allow condensate drainage without the risk of clogging at sub-zero temperatures. The unit has a nominal heating capacity of 8 kW and uses R410A as the refrigerant. The system is equipped with an intelligent monitoring interface (the Ecodan system), which provides energy-monitoring functions, two-zone control (cooling and heating), and operation scheduling, allowing the extraction of the operating data required for the energy analysis.



Figure 4. Front view of the air-to-water heat pump: (left) indoor unit; (right) outdoor unit.

3.3. Description of the Photovoltaic Installation

The electrical energy produced by the photovoltaic panels is used to partially supply the heat pump, creating an integrated system that maximizes the use of renewable resources and minimizes dependence on fossil fuels. The project implemented an on-grid photovoltaic system with a peak power of 6.02 kWp, consisting of 14 monocrystalline photovoltaic modules of 430 W each, arranged in two rows of 7 panels (Figure 5),

mounted on the roof using an aluminum K2 mounting system, which ensures sufficient clearance between the roof and the panels for ventilation [64]. The conversion component is provided by a single-phase solar inverter with a peak power of 5 kW, installed in the technical room.



Figure 5. Front view of the PV system.

Being an on-grid system connected to the national electricity network, the surplus solar energy not consumed by the user is fed into the grid, while during periods when the panels do not produce enough energy, the deficit is covered from the national grid. This type of system does not require batteries for energy storage, since the energy produced is either used immediately or exported to the grid. Bidirectional energy metering is ensured by a smart meter, and the installation is protected by dedicated electrical panels on both the DC and AC sides.

The general system configuration is shown in Figure 6.

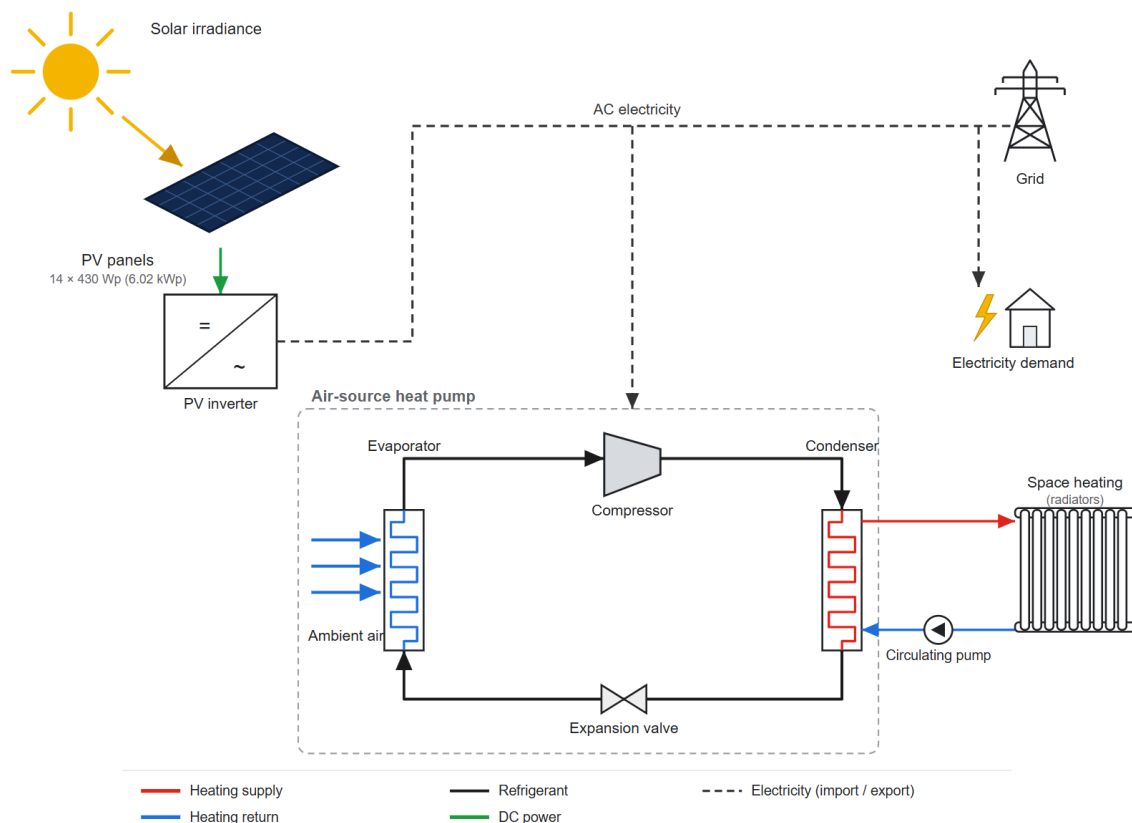


Figure 6. Schematic of the existing hybrid heat pump–photovoltaic system.

3.4. Data Collection and Processing

Data on electricity consumption and thermal energy delivered by the heat pump were extracted from the equipment's SD memory, and could be read both on the heat pump interface and using the dedicated software produced by Mitsubishi (eco-dan_SD_TOOL_FTC6_Ver1.01_basic_20200320). To enable a correlated analysis between heat pump performance and outdoor climatic conditions, meteorological data corresponding to the analyzed period were used, including the daily average, minimum, and maximum outdoor temperatures.

Data were recorded in a network of automatic weather stations connected to a system that measures all the basic meteorological parameters.

To evaluate the contribution of the renewable energy source within the analyzed system, data on the electrical energy produced by the photovoltaic installation, as well as the self-consumed energy and the energy injected into the grid, were extracted from the dedicated photovoltaic system application, FusionSolar (v26.1.1.013, Huawei Technologies Co., Ltd., Shenzhen, China). The collected daily data were processed into monthly series for the two analyzed heating seasons (2024–2025 and 2025–2026), reducing the influence of short-term point variations and highlighting the system's energy behavior over representative time intervals. This approach allowed the evaluation of system performance under different seasonal conditions, as well as the analysis of the interdependencies between climatic conditions, the building's energy demand, and the contribution of renewable energy sources.

3.5. Energy Performance Indicators

The energy performance of the heat pump over a given time interval (day or month) was evaluated through the coefficient of performance (COP), defined as the ratio of the useful thermal energy delivered (E_{thermal}) to the electrical energy consumed by the

heat pump ($E_{\text{electrical}}$) over the same interval. As it is calculated from energy totals rather than instantaneous power values, this indicator represents an interval performance factor rather than an instantaneous COP:

$$COP = E_{\text{thermal power}}/E_{\text{electrical}} [-] \quad (1)$$

To characterize system performance over the entire heating season, the seasonal performance factor (SPF) was used, calculated as the ratio of the total thermal energy supplied during the season (Q_{heating}) to the total electrical energy consumed by the heat pump over the same period ($E_{\text{electrical,HP}}$). Since it is determined from field measurements, the SPF is not directly equivalent to the SCOP determined under standardized test conditions according to EN 14825:

$$SPF = Q_{\text{heating}}/E_{\text{electrical,HP}} [-] \quad (2)$$

The electrical energy consumption recorded by the Ecodan system includes the outdoor unit (compressor, fan and control electronics), the circulation pump of the indoor unit and the backup electric heater; the SPF therefore corresponds to a system boundary that includes auxiliary and backup energy. The consistency of the recorded data was verified as described in Section 3.6.

The building's specific heat demand was determined by dividing the total thermal energy delivered during the season (Q_{heating}) by the heated usable floor area ($A = 122.3 \text{ m}^2$):

$$Q_{\text{spec}} = Q_{\text{heating}}/A [\text{kWh/m}^2] \quad (3)$$

Similarly, the seasonal specific electricity consumption of the heat pump was determined by dividing the electrical energy consumed by the heat pump ($E_{\text{electrical,HP}}$) by the heated usable floor area:

$$E_{\text{specific,HP}} = E_{\text{electrical,HP}}/A [\text{kWh/m}^2] \quad (4)$$

In addition, the correlation between COP and mean outdoor temperature was analyzed, both at the monthly level (for both analyzed seasons) and at the daily level, for two representative months—December 2025 (a typical cold-season month) and March 2026 (a transition month toward the warm season)—in order to highlight the thermodynamic behavior specific to air-to-water heat pumps under different operating conditions.

3.6. Measurement Uncertainty

The thermal energy is determined by the Ecodan FTC6 controller from the water flow rate, measured by the built-in vortex flow sensor (SIKA VVX20, SIKA Dr. Siebert & Kühn GmbH & Co. KG, Kaufungen, Germany; range 5–80 L/min) [65], and the flow/return water temperatures, measured by the built-in thermistors, while the electrical energy is determined from the operating data of the unit. The accuracy limits of the measured quantities were converted into standard uncertainties assuming a rectangular distribution ($u = a/\sqrt{3}$), and the combined standard uncertainty of the performance indicators was determined according to the GUM [66]:

$$u(SPF)/SPF = [(u(Q)/Q)^2 + (u(E)/E)^2]^{0.5} \quad (5)$$

The input values and the resulting uncertainties are summarized in Table 3; the detailed calculation was performed according to the GUM [66]. The combined standard uncertainty of the SPF is approximately $\pm 7\%$ ($k = 1$), corresponding to $SPF = 3.51 \pm 0.25$ (2024–2025) and 3.30 ± 0.23 (2025–2026). As the same sensors were used throughout the monitoring period, systematic errors largely cancel out when comparing the two seasons or analyzing the correlation between COP and outdoor temperature; the uncertainty therefore mainly affects the absolute SPF values rather than the observed trends. As a consistency check, the heat pump electricity consumption represented 84–93% of the to-

tal household consumption during the main heating months (Tables 4 and 5), in agreement with the operating regime of the building.

Table 3. Measurement uncertainties.

Quantity	Sensor/Source	Accuracy (Limits)	Relative Standard Uncertainty ($k = 1$)
Water flow rate	SIKA VVX20 (5–80 L/min) [65]	$\pm 2\%$ of range	$\pm 4.0\%$
Flow/return temperature difference	Built-in thermistors	± 0.3 K	$\pm 4.9\%$
Thermal energy, Q	Ecodan FTC6	–	$\pm 6.3\%$
Electrical energy, E	Ecodan FTC6	$\pm 5\%$	$\pm 2.9\%$
Outdoor temperature	Weather station	± 0.3 K	± 0.17 K
PV energy	FusionSolar	$\pm 1\%$	$\pm 0.6\%$
SPF	–	–	$\pm 7.0\%$

Table 4. Monthly total values for climate, HP, and PV parameters (2024–2025 season).

Month	Tmean Ext [°C]	Tmin Ext [°C]	Tmax Ext [°C]	Total Energy Cons. [kWh]	HP Energy Cons. [kWh]	Thermal Energy [kWh]	COP [-]	PV Out-put [kWh]	PV Self-Cons. [kWh]	PV Grid Inj. [kWh]
October 2024	10.32	4.92	16.05	159	0	0	–	482	59	424
November 2024	9.65	–2.6	10.26	1063	901	3505	3.89	373	193	179
December 2024	6.43	–2.9	8.37	1386	1221	4262	3.49	184	117	68
January 2025	3.59	–5.84	15.22	1193	1081	3341	3.09	412	192	219
February 2025	3.95	–3.92	15.15	1531	1430	4477	3.13	459	269	190
March 2025	7.95	–1.98	20.02	704	592	2245	3.79	558	182	376
April 2025	11.95	–0.28	25.71	511	403	1793	4.45	576	197	379
May 2025	15.18	3.94	31.27	311	135	635	4.7	617	157	459
SEASON 2024–2025	8.63	–1.08	17.76	6858	5764	20,258	3.51	3661	1366	2295

Table 5. Monthly total values for climate, HP, and PV parameters (2025–2026 season).

Month	Tmean Ext [°C]	Tmin Ext [°C]	Tmax Ext [°C]	Total Energy Cons. [kWh]	HP Energy Cons. [kWh]	Thermal Energy [kWh]	COP [-]	PV Out-put [kWh]	PV Self-Cons. [kWh]	PV Grid Inj. [kWh]
October 2025	11.16	2.97	20.54	524	412	1698	4.12	355	190	165
November 2025	6.18	–5.84	19.41	655	547	1891	3.46	208	128	80
December 2025	3.92	–7.17	14.46	1366	1254	3676	2.93	220	167	53
January 2026	1.74	–9.03	12.84	1235	1111	3245	2.92	254	123	131

February 2026	6.71	−1.73	21.06	1465	1353	4095	3.03	279	202	77
March 2026	7.46	−3.66	17.84	953	827	3069	3.71	506	292	213
April 2026	12.18	−0.02	23.57	564	404	1803	4.46	613	292	321
SEASON 2025–2026	6.2	−4.08	17.69	6761	5908	19,478	3.3	2435	1395	1040

3.7. Economic Analysis Methodology

The economic analysis compared the operating costs of the hybrid heat pump–photovoltaic system with the estimated costs of an alternative natural-gas heating solution, for each of the two analyzed heating seasons, taking into account the actual recorded consumption and the unit prices of electricity and natural gas applicable during the analyzed period. Based on the resulting savings and the total investment cost of the system (equipment, installation, and photovoltaic system), the simple payback period of the investment was determined.

3.8. Environmental Impact Assessment Methodology

3.8.1. Total Equivalent Warming Impact (TEWI)

To quantify the climatic impact associated with the operation of the installation, the TEWI (Total Equivalent Warming Impact) indicator was used, a method widely applied in the refrigeration and HVAC field for estimating the total contribution to global warming. This indicator integrates both the direct-emissions component, associated with potential refrigerant losses during operation and at the end of the installation's service life, and the indirect component, determined by the electrical energy required for the installation's operation. The TEWI indicator was developed in the context of the need to reduce the climatic impact of refrigeration installations, subsequently becoming one of the standard methods for evaluating the environmental performance of systems based on synthetic or natural refrigerants, with the advantage that the total impact of an installation does not depend exclusively on the properties of the refrigerant but also on the overall energy efficiency of the equipment.

According to the Oak Ridge National Laboratory (O.R.N.L.) methodology [44,67], the total equivalent warming impact (TEWI) is calculated using the relation:

$$TEWI = \text{direct emissions} + \text{indirect emissions} = \{(GWP \cdot ALR \cdot m_{\text{refrigerant}} \cdot n) + [GWP \cdot m_{\text{refrigerant}} \cdot (1 - \alpha REC)]\} + (n \cdot AEC \cdot \beta) \text{ [kg CO}_2\text{-eq]} \quad (6)$$

where

GWP—Global Warming Potential (kg CO₂-eq/kg)

$m_{\text{refrigerant}}$ —Refrigerant Charge [kg]

ALR—Annual Leakage Rate [% of the refrigerant charge lost per year]

n —Average Lifetime of Equipment [yr]

AEC—Annual Energy Consumption [kWh]

αREC —recovery/recycling factor for refrigerant

β —indirect emission factor for Romania in 2024/2025 [68]

The relation can be written synthetically as $TEWI = a + b + c$, where a represents the contribution of direct emissions caused by the annual refrigerant losses into the atmosphere, b represents the contribution of emissions associated with refrigerant losses at the end of the installation's service life, and c represents the contribution of indirect emissions resulting from the generation of the electrical energy required for the installation's operation.

The application of the TEWI method has the advantage of a relatively simple implementation and allows the simultaneous evaluation of the main components that contribute to the climatic impact of the analyzed system.

In addition, the amount of CO₂ emissions avoided through the use of photovoltaic energy was estimated by relating the produced/exploited energy (EPV, energy output) to the emission factor of the electricity grid (β), for an operating period of 15 years:

$$\text{Green emission}_{PV} = (EPV, \text{energy output} \cdot \beta) / 1000 \text{ [t CO}_2\text{-eq]} \quad (7)$$

3.8.2. Life-Cycle Climate Performance (LCCP)

The TEWI metric provides a more comprehensive assessment than GWP alone; however, it does not account for all indirect emissions associated with the refrigerant life cycle, such as those arising from the manufacturing and transportation of the refrigeration system and refrigerant. To address these limitations, the Life Cycle Climate Performance (LCCP) indicator is used. LCCP accounts for the overall greenhouse gas emissions associated with the operation and life cycle of a refrigeration system, including the environmental impacts resulting from emissions generated during refrigerant production and transportation. These impacts, combined with those already considered in the TEWI assessment, provide a more holistic evaluation of the climate impact of different refrigerants.

In practice, however, LCCP calculations are considerably more complex than TEWI assessments, and the additional contribution captured by LCCP beyond TEWI is generally considered negligible. The LCCP methodology is a very flexible tool that can be tailored for use with any type of heat pump system using a vapor-compression cycle powered by electricity from the electricity grid.

The LCCP equation is split into two parts: direct and indirect emissions (Figure 7).

$$\begin{aligned} \text{LCCP} = \text{Direct Emissions} + \text{Indirect Emissions} = \{m_{\text{refrigerant}} \cdot (n \cdot \text{ALR} + \\ \text{EOL}) \cdot (\text{GWP} + \text{Adp.GWP})\} + \{n \cdot \text{AEC} \cdot \text{EM} + \Sigma(m \cdot \text{MM}) + \Sigma(mr \cdot \text{RM}) + C \cdot (1 + \\ n \cdot \text{ALR}) \cdot \text{RFM} + m_{\text{refrigerant}} \cdot (1 - \text{EOL}) \cdot \text{RFD}\} \end{aligned} \quad (8)$$

where

$m_{\text{refrigerant}}$ = Refrigerant Charge [kg]

n = Average Lifetime of Equipment [yr]

ALR = Annual Leakage Rate [% of the refrigerant charge lost per year]

EOL = End-of-Life Refrigerant Leakage [% of Refrigerant Charge]

Adp.GWP = GWP of the Atmospheric Degradation Product of the Refrigerant [kg CO₂e/kg]

AEC = Annual Energy Consumption [kWh]

EM = CO₂ Produced/kWh [kg CO₂e/kWh]

m = Mass of Unit [kg]

MM = CO₂e Produced/Material [kg CO₂e/kg]

mr = Mass of Recycled Material [kg]

RM = CO₂e Produced/Recycled Material [kg CO₂e/kg]

RFM = Refrigerant Manufacturing Emissions [kg CO₂e/kg]

RFD = Refrigerant Disposal Emissions [kg CO₂e/kg]

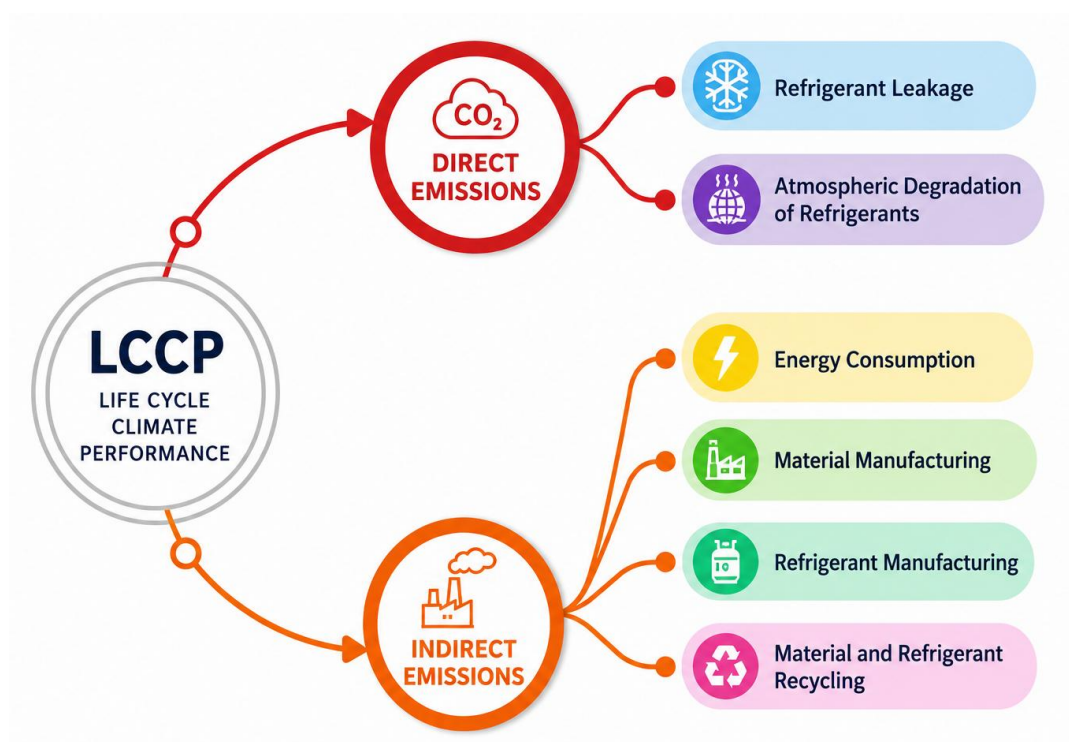


Figure 7. Life-cycle performance components [69].

4. Results and Discussion

4.1. Energy Performance—2024–2025 Heating Season

The results of the monthly processing of the climatic and energy parameters for the 2024–2025 heating season are presented in Table 4.

A progressive increase in energy demand is observed as outdoor temperatures decrease, with maximum values recorded in December 2024 and February 2025, periods characterized by more severe climatic conditions. The heat pump's electricity consumption follows the same trend as the thermal energy delivered, confirming the direct correlation between heating demand and the energy absorbed by the system: the maximum value of delivered thermal energy was recorded in February 2025, reaching 4477 kWh, corresponding to an electricity consumption of 1430 kWh. Starting in March, a marked reduction in energy demand is observed, driven by rising outdoor temperatures and decreasing heating demand, a trend that continues until the end of the analyzed season (Figure 8).

4.2. Energy Performance—2025–2026 Heating Season

The results of the monthly processing of the parameters analyzed for the 2025–2026 heating season are presented in Table 5.

The comparative analysis of the 2025–2026 season highlights important differences from the previous season, both in terms of energy consumption and heat pump performance. Although the maximum values of electricity consumption and delivered thermal energy remain within similar ranges, the monthly distribution of energy demand indicates an extended period of operation under demanding conditions (Figure 9). The system's energy performance in the 2025–2026 season shows COP values slightly lower than in the previous season, particularly in the months characterized by lower outdoor temperatures, suggesting a more pronounced influence of climatic conditions on heat pump operation.

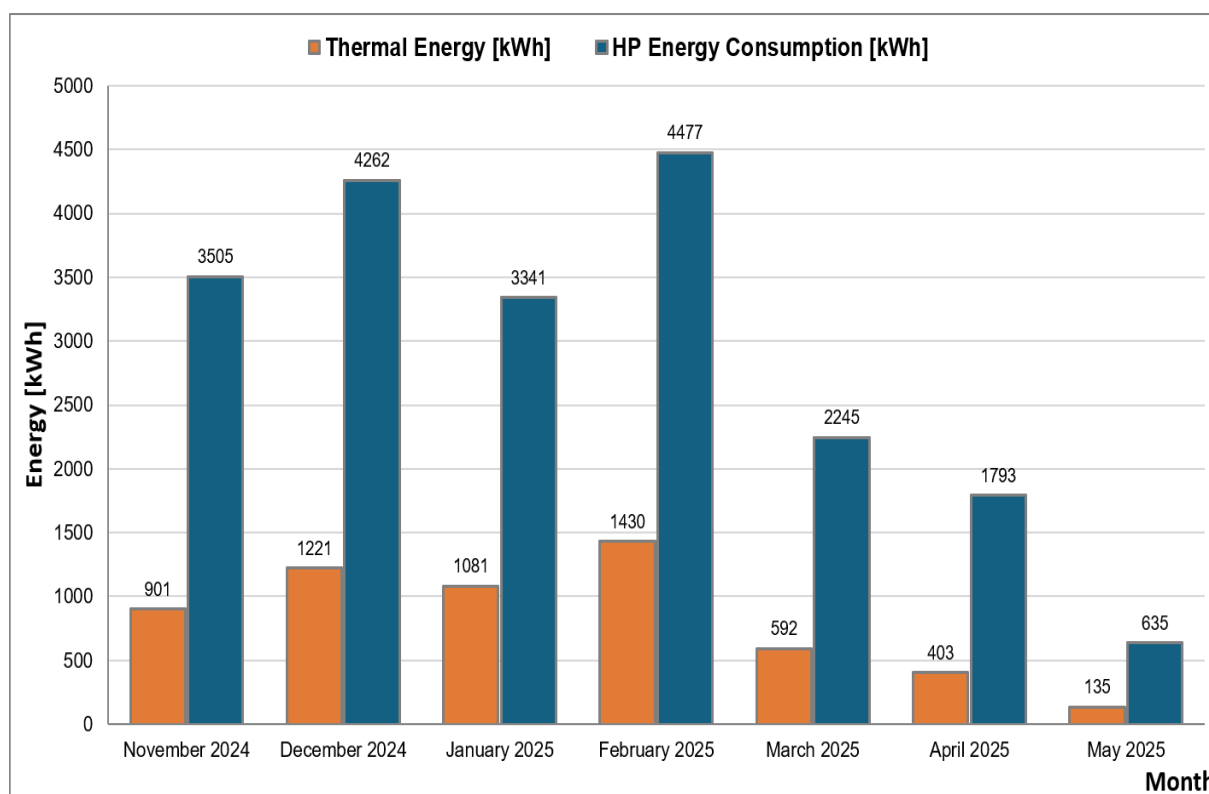


Figure 8. Monthly evolution of the heat pump's electricity consumption and the thermal energy delivered for the 2024–2025 season.

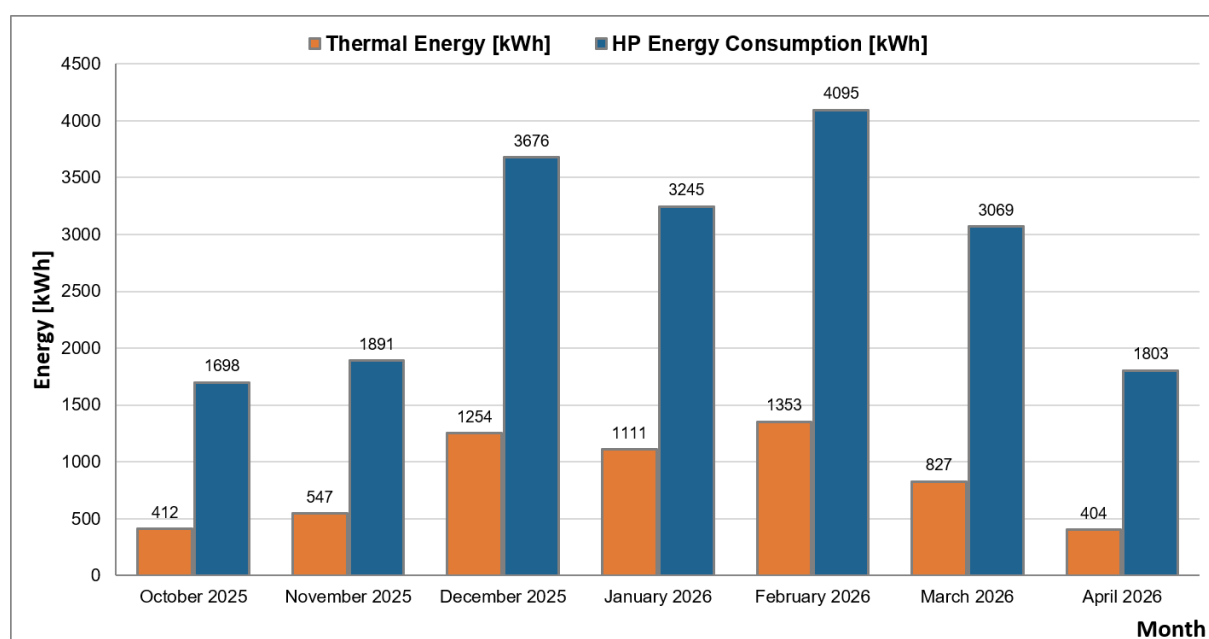


Figure 9. Monthly evolution of the heat pump's electricity consumption and the thermal energy delivered for the 2025–2026 seasons.

To more clearly highlight the influence of climatic conditions on system performance at the daily scale, Figure 10 shows the daily variation in COP relative to the mean outdoor temperature for December 2025 and March 2026—a month typical of the cold season and a transition month toward the warm season, respectively. These two periods were chosen to highlight the behavior of the system under different operating conditions, while avoiding overloading the paper with a large volume of daily data. The analysis

confirms a strong correlation between outdoor temperature and heat pump energy performance: during periods of higher outdoor temperatures, the heat pump operates at lower condensing temperatures, which increases the efficiency of the thermodynamic cycle and, consequently, results in higher coefficient-of-performance values. A lower dispersion of data points is also observed for March 2026 compared with December 2025, suggesting more stable system operation during transition periods.

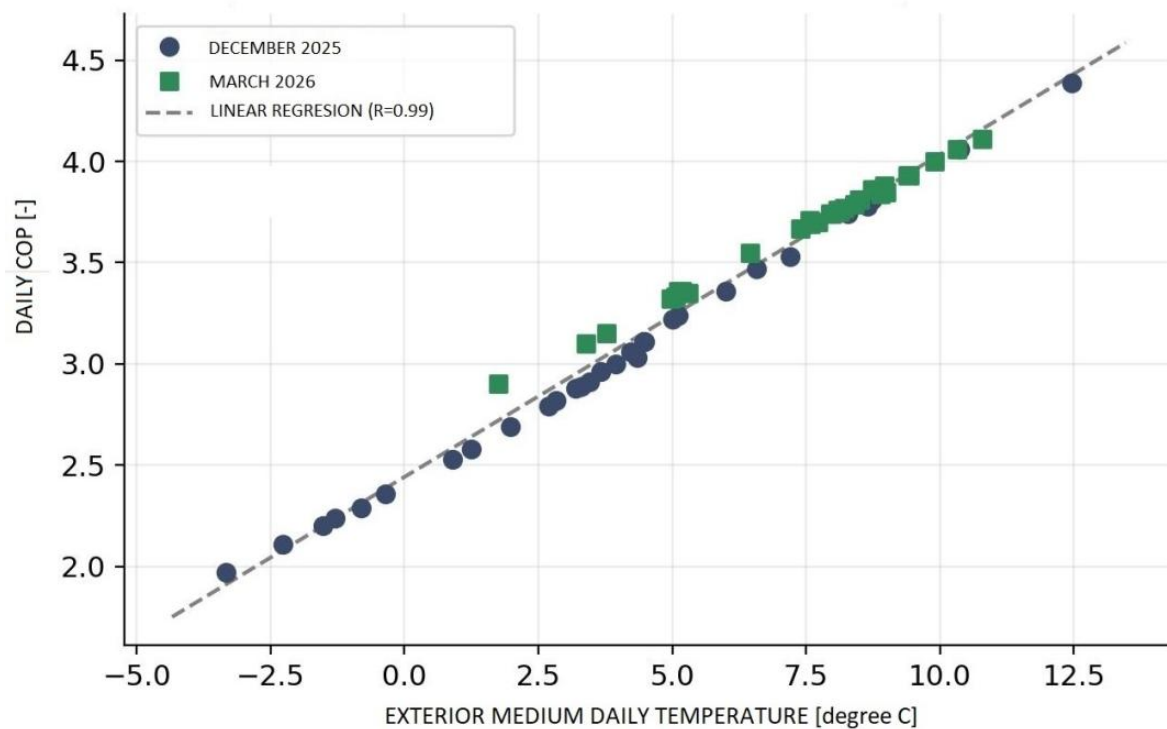


Figure 10. Daily variation in COP as a function of the mean daily outdoor temperature—December 2025 and March 2026.

The analysis of the relationship between COP and the mean monthly outdoor temperature (Figure 11) confirms the existence of a direct correlation: the lowest performance values were recorded in January and February 2025, when mean outdoor temperatures were around 3–4 °C, resulting in COP values of 3.09–3.13. During the transition months and toward the end of the heating season, as outdoor temperatures rise, system efficiency increases significantly, reaching a maximum of 4.70 in May 2025. This behavior confirms the characteristic performance pattern of air-to-water heat pumps, whose energy performance is strongly influenced by the temperature of the outdoor (cold) heat source.

4.3. Comparative Analysis of the Photovoltaic Contribution

Figure 12 shows the comparison between the electrical energy consumed by the heat pump and the monthly production of the photovoltaic system, for both analyzed seasons. In the winter months, photovoltaic production is insufficient to fully cover the heat pump's energy demand, with the difference being covered by grid consumption. Starting in March, the increase in photovoltaic production, combined with the reduction in heating demand, leads to a progressive convergence between energy produced and energy consumed, and in April and May photovoltaic production exceeds heat pump consumption, generating an energy surplus available for self-consumption or grid injection.

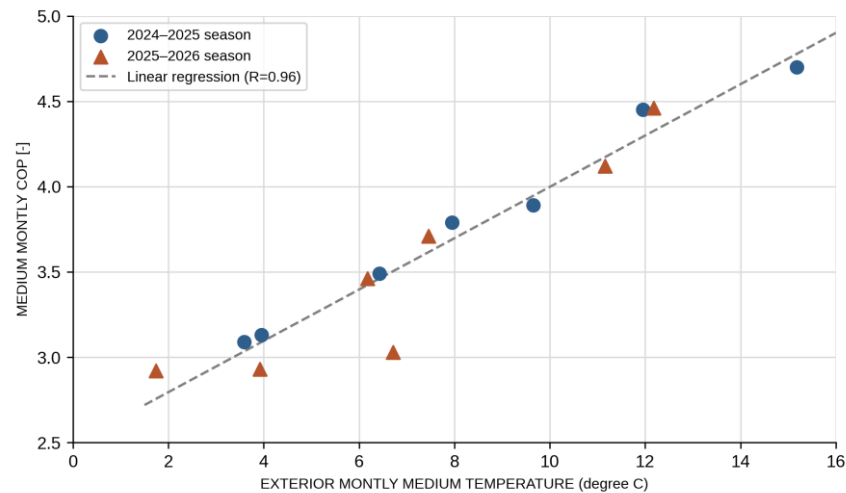


Figure 11. Variation in the coefficient of performance (COP) versus mean monthly outdoor temperature for both analyzed seasons.

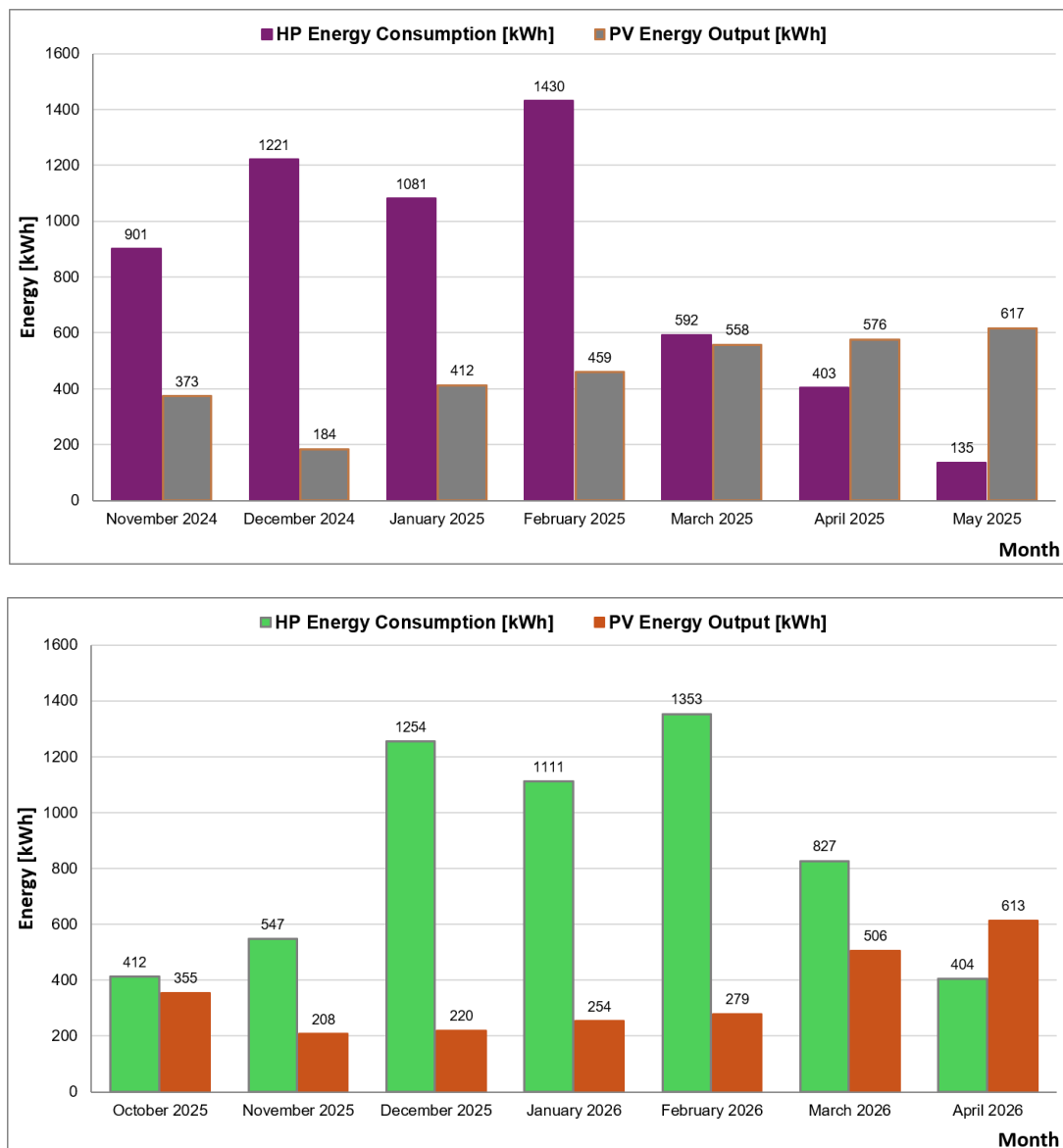
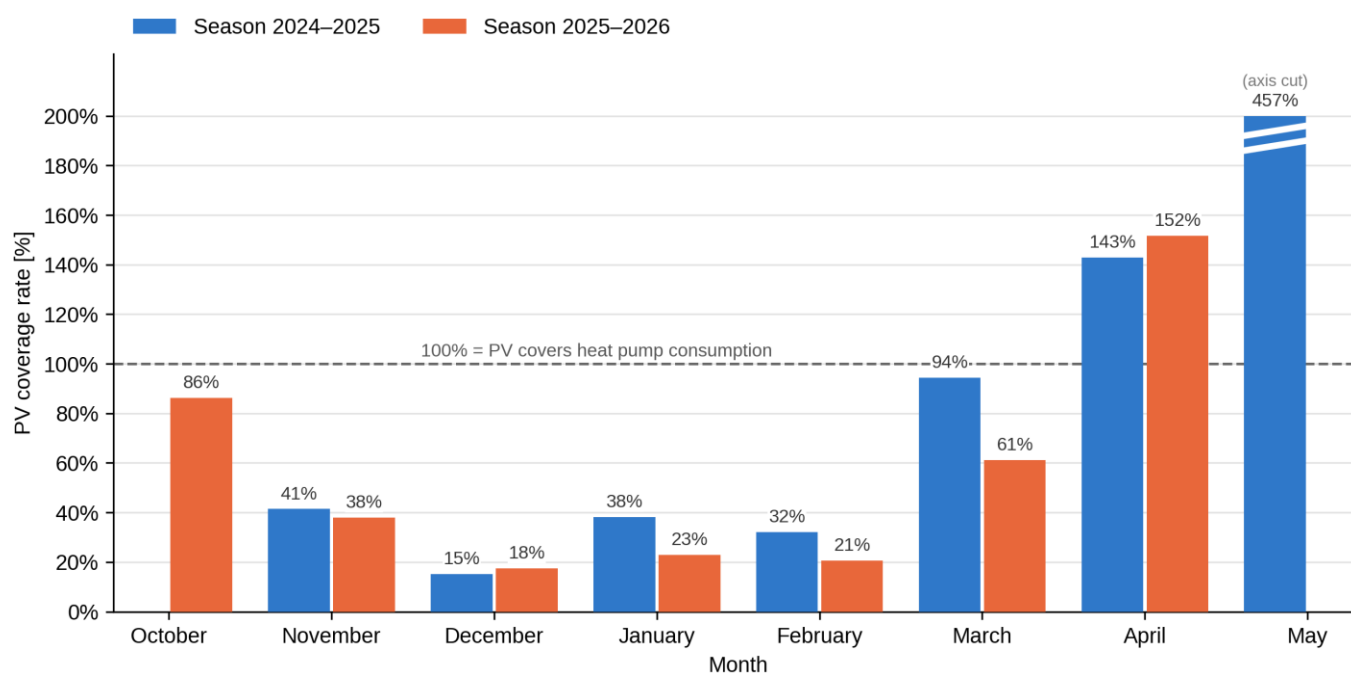


Figure 12. Monthly photovoltaic system production versus heat pump electricity consumption for the 2024–2025 and 2025–2026 seasons.

The degree of coverage of the heat pump's electricity consumption by photovoltaic energy (Figure 13) varies significantly over the course of the heating season. During winter, the coverage rate is low, ranging between 15.1% and 41.4% in the 2024–2025 season, as a result of the combination of reduced photovoltaic production and high heating demand. Starting in March, a marked increase in the coverage rate is observed, reaching 94.3%, followed by exceeding the 100% threshold in April and May, with a maximum of 456.8% in May 2025—a value that highlights the major contribution of the photovoltaic source during periods of low heating demand and high solar radiation. Values above the 100% line do not mean that PV directly covered the heat pump's demand. The indicator compares total monthly PV generation with heat pump consumption, so it also counts the energy exported to the grid and ignores that generation and heating demand happen at different times.

The comparative analysis of photovoltaic production between the two seasons reveals a significant reduction in energy generated during the 2025–2026 season, particularly in November, January, and February, where the differences from the previous year exceed 35–40%. This decrease in photovoltaic contribution directly influences the coverage rate of the heat pump's electricity consumption and leads to greater dependence on grid-supplied energy. The monitoring data show that, during periods of high solar production, the inverter automatically reduces its active power when the voltage at the connection point exceeds 253 V and may temporarily interrupt production, in accordance with the operating requirements for grid-connected generators. An example is shown in Figure 14a (4 July 2025), where the output power decreases repeatedly as the grid voltage exceeds 253 V, whereas in Figure 14b the power variations are caused only by changes in solar irradiance, with the grid voltage remaining below 245 V. This behavior is favored by the limited hosting capacity of the local distribution grid, as the number of prosumers increases faster than the grid infrastructure is upgraded. During the heating season, however, the lower PV production is mainly associated with meteorological conditions.



PV coverage rate = total PV production / heat pump consumption. No heat pump operation in Oct 2024; no data for May 2026.

Figure 13. PV coverage rate of the heat pump's electricity consumption.

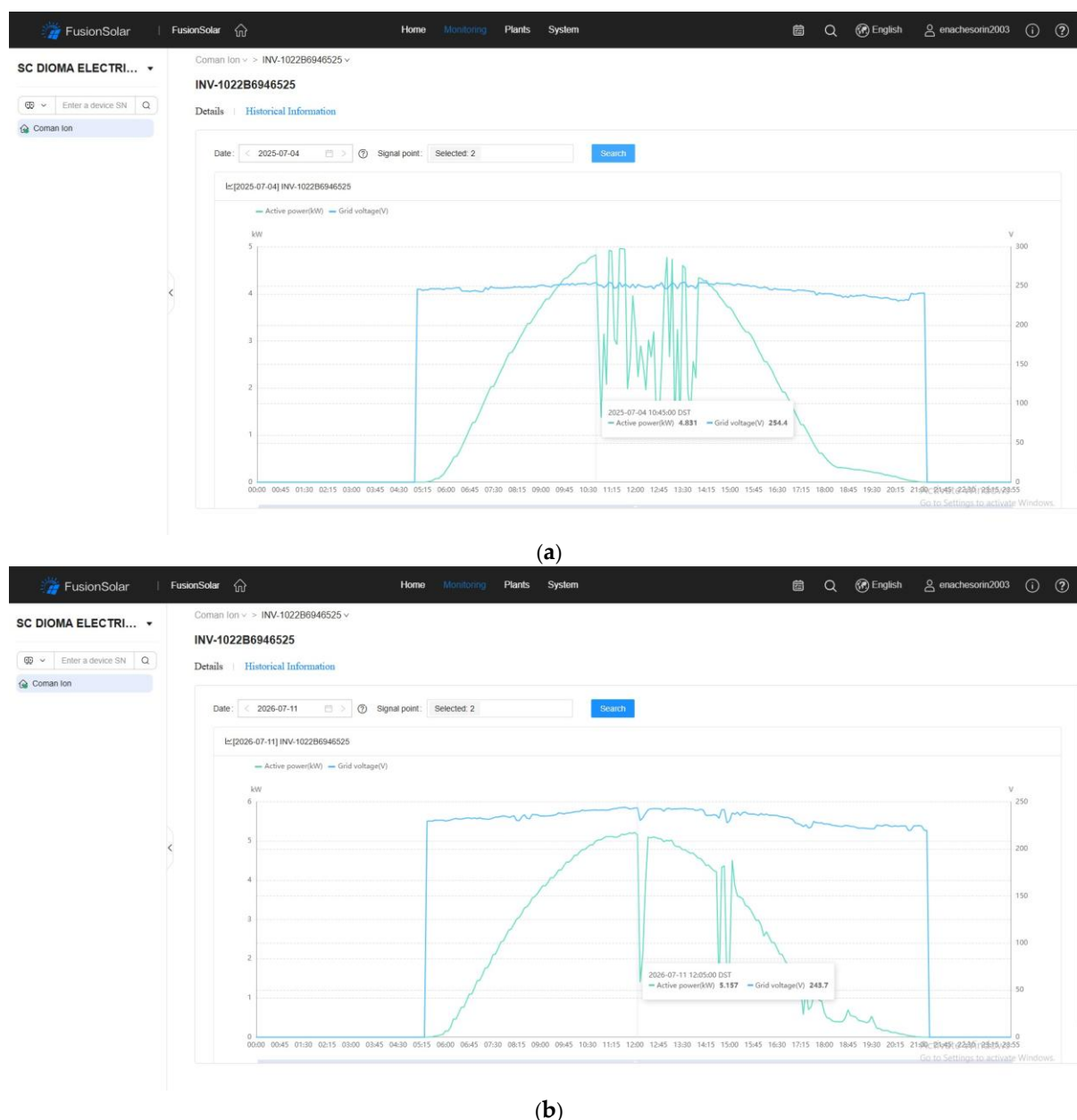


Figure 14. Inverter active power and grid voltage recorded by the monitoring platform: (a) power limitation when the grid voltage exceeds 253 V (4 July 2025); (b) normal operation, with power variations caused by solar irradiance and grid voltage below 245 V.

4.4. Seasonal Performance Indicators (SPF) and Specific Heat Demand

Applying Equations (2)–(4) to the data compiled in Tables 4 and 5, the seasonal indicator values presented in Table 6 were obtained.

Table 6. Seasonal energy performance indicators for the 2024–2025 and 2025–2026 heating seasons.

Indicator	Season 2024–2025	Season 2025–2026
Total heat pump electricity consumption [kWh]	5764	5908
Delivered thermal energy [kWh]	20,258	19,478
Seasonal performance factor, SPF [-]	3.51 ± 0.25	3.30 ± 0.23
Specific heat demand [kWh/m ²]	165.6	159.3
Specific HP electricity consumption [kWh/m ²]	47.1	48.3
Photovoltaic production [kWh]	3661	2435
	(October 2024–May 2025)	(October 2025–May 2026)

Total photovoltaic production [kWh]	7863	5149
Self-consumed photovoltaic energy [kWh]	1366	1395

The value of approximately 6500 kWh/year represents the arithmetic mean of the total PV production over the two analyzed seasons. The PV production data were extracted from the FusionSolar platform as both daily and monthly series.

The SPF values obtained (3.51 ± 0.25 for 2024–2025 and 3.30 ± 0.23 for 2025–2026) confirm the efficient operation of the air-to-water heat pump under real operating conditions, even in the context of using radiators as heat-emission terminals, which require higher flow temperatures compared with radiant systems. Comparing the specific indicators for the two seasons shows a slight reduction in the specific delivered thermal energy, from approximately 165.6 kWh/m² in the 2024–2025 season to 159.3 kWh/m² in the 2025–2026 season, while the specific heat pump consumption increases slightly, from 47.1 to 48.3 kWh/m². The results confirm that the actual performance of an air-to-water heat-pump-based system is simultaneously influenced by the level of thermal insulation of the building envelope, outdoor conditions, the operating regime, and the availability of integrated renewable sources. The relatively high specific heat demand of 159–166 kWh/m² suggests a significant thermal demand for the building, an aspect discussed further in the conclusions section from the perspective of complementary measures to reduce energy consumption.

4.5. Economic Analysis

The economic analysis of heat-pump-based systems is an important element in the evaluation of modern building-heating solutions, as it allows the correlation of the system's energy performance with the initial investment and the operating costs over the entire service life. In the current context, characterized by rising energy prices and intensifying measures to reduce carbon emissions, these systems are becoming increasingly attractive for residential applications, even though their implementation involves higher initial investment costs compared with conventional heating solutions.

The operating costs of the gas boiler were calculated for the same useful heat as that delivered by the heat pump, assuming a boiler efficiency of 93% and an average gas price of 0.31 RON/kWh; the gas consumption was converted from volume to energy using a gross calorific value of approximately 10.8 kWh/m³. The electricity price includes, in addition to the active energy, the regulated transmission and distribution components, excise duties, green certificates and VAT. The PV electricity exported to the grid was considered under the prosumer compensation scheme from Romania. During the analyzed period, household electricity and gas prices in Romania were subject to national price-cap mechanisms.

The comparative cost analysis shows that the integration of the photovoltaic system significantly reduces the heat pump's operating costs, with savings being more pronounced during periods characterized by high photovoltaic production and low heat demand. Comparing operating costs with those associated with natural-gas heating indicates that the heat pump and photovoltaic energy system can generate significant reductions in seasonal energy expenses. Depending on the analyzed season, the savings obtained compared with natural-gas heating range from approximately 1814 to 3853 RON/season, resulting in average annual savings of approximately 2834 RON (Table 7).

Table 7. Summary of the investment's economic indicators.

Economic Indicator	Value
Total investment cost of the system (HP + PV) [RON]	≈45,000
Total investment cost of gas boiler [RON]	≈5000
Gas connection [RON]	≈19,500
Savings compared with natural-gas heating [RON/season]	1814–3853
Average annual savings [RON/year]	≈2834
Estimated payback period [years]	15–16

Energy cost tariffs used in the calculations were 0.68 RON/kWh for electricity in 2024 and 1.11 RON/kWh in 2025 and 0.31 RON/kWh for natural gas.

Based on the total investment cost, estimated at approximately 45,000 RON, and the annual savings determined from the comparative analysis, the resulting payback period is approximately 15–16 years, indicating that the economic benefits are manifested predominantly over the long term, being significantly influenced by energy price trends and the contribution of the photovoltaic system.

Although the economic analysis reveals a relatively extended payback period for the integrated heat pump–photovoltaic system, the choice of technical solution must also be interpreted in the specific context of the analyzed site. In the studied area, there is no available natural-gas supply infrastructure, an aspect that limited the technological options and steered the choice toward a fully electrified system. At the same time, the economic evaluation must also be carried out in light of the stability and predictability of the energy sources used: electricity benefits from a diversified generation mix, originating from multiple sources (hydropower, wind, solar, nuclear, and thermal power), which reduces exposure to fluctuations associated with a single energy resource. By comparison, the price of natural gas is influenced to a greater extent by geopolitical factors, resource availability, and the volatility of international markets, aspects that can lead to significant variations in long-term operating costs. From this perspective, using a heat pump associated with local photovoltaic production can represent an advantageous solution not only from an energy and environmental standpoint but also through increased energy independence and reduced exposure to the risks associated with the evolution of conventional fuel prices.

4.6. Environmental Metrics—TEWI vs. LCCP

The assessment of the environmental impact associated with the use of heat pumps is an important step in evaluating the sustainability of modern building-heating solutions. Applying the TEWI methodology described in Section 3.8.1, the values of the calculation parameters extracted from the technical datasheet of the analyzed heat pump are presented in Table 8.

Table 8. TEWI calculation parameters and results for the heat pump.

Parameter	Value
Refrigerant	R410A
Condensing temperature [°C]	47
Cooling capacity [kW]	5.8
Refrigerant charge, mrefrigerant [kg]	4.6
Annual leakage rate, ALR [%/year]	6%
Recovery factor of refrigerant, α_{REC}	0.95
Average lifetime of equipment, n	15
Annual energy consumption, AEC [kWh]	5940
Indirect emission factor, β [kg/kWh]	0.3

a— Effect due to refrigerant losses in the atmosphere [kgCO ₂ -eq]	7961.2
b— Effect due to refrigerant losses when recovering refrigerant for recycling [kgCO ₂ -eq]	442.3
c— Effect due to CO ₂ emissions in the atmosphere from producing electrical energy [kgCO ₂ -eq]	26,730
TEWI = a + b + c [kgCO ₂ -eq]	35,134 (≈35.1 t CO ₂ -eq)

The TEWI value obtained, 35.1 t CO₂-eq, is reasonable for an air-to-water heat pump using R410A refrigerant over a 15-year service life, with the dominant share remaining the indirect component, associated with the electricity consumed (26,730 kgCO₂-eq, approximately 76.1% of the total impact). However, due to the high GWP of R410A and the estimated annual leakage rate of 6%, the direct contribution (components a and b, totaling approximately 8404 kgCO₂-eq) is significant (approximately 23.9% of the total), an aspect that supports the direction taken by recent European regulations (Regulation (EU) 2024/573) toward low-GWP refrigerants.

The amount of CO₂-equivalent emissions avoided through the use of the photovoltaic system was determined by applying Equation (7), based on an estimated average annual production of approximately 6500 kWh and a service life of 15 years:

$$CO_{2,avoided} = (6500 \cdot 15 \cdot 0.3) / 1000 = 29.25 \text{ t CO}_2\text{-eq}$$

The integration of the photovoltaic system thus reduces the climatic impact associated with heat pump operation by lowering the amount of electricity drawn from the grid, with the value of avoided emissions (≈29.25 t CO₂-eq) corresponding to approximately 83% of the total climatic impact estimated through the TEWI indicator (≈35.1 t CO₂-eq). These results highlight the synergy between the air-to-water heat pump and the photovoltaic system, with the combination of the two technologies leading to a significant reduction in environmental impact and an increase in the energy sustainability of the analyzed heating system. From the perspective of reducing greenhouse gas emissions, the use of locally produced renewable energy is a decisive factor in reducing the carbon footprint associated with system operation.

According to the LCCP guideline, assumptions and restrictions were made for the variables used in the LCCP calculation. The annual leakage rate (ALR) is assumed to be 6%, as in the TEWI calculation, and the EOL leakage rate is 15%, based on the guideline [69] (Table 9). R410A has an RFM value of 10.7 kg CO₂-eq/kg. The shares of recycled materials and the corresponding recycling emissions are given in Table 10.

Table 9. LCCP calculation parameters for the heat pump—mass composition and manufacturing emissions of raw materials.

Material	% of Unit Mass Composition	Manufacturing Emissions – Mixed [kg CO ₂ -eq/kg]	Manufacturing Emissions – Virgin [kg CO ₂ -eq/kg]
Steel	46	1.43	1.8
Aluminum	12	4.5	12.6
Copper	19	2.78	3
Plastics	2.8	2.61	2.8

Table 10. Recycled material and recycling emissions.

Recycled Material	% of Recycled Material	Recycling Emissions [kg CO ₂ -eq/kg]
Metal	77	0.07
Plastics	23	0.01

The emissions from equipment and refrigerant manufacturing and disposal are very small, at less than 0.512 t CO₂-eq (1.4% of total lifetime emissions, Figure 15). Figure 16 shows the direct, indirect, and total emissions for the R410A refrigerant. The dominant term is power-consumption emissions, reaching a share of 73.17–76.1% of total emissions. Indirect emissions are much higher than direct emissions because of the large emissions from power consumption of the hybrid heating system, which in turn contribute to a leading share of both LCCP and TEWI.

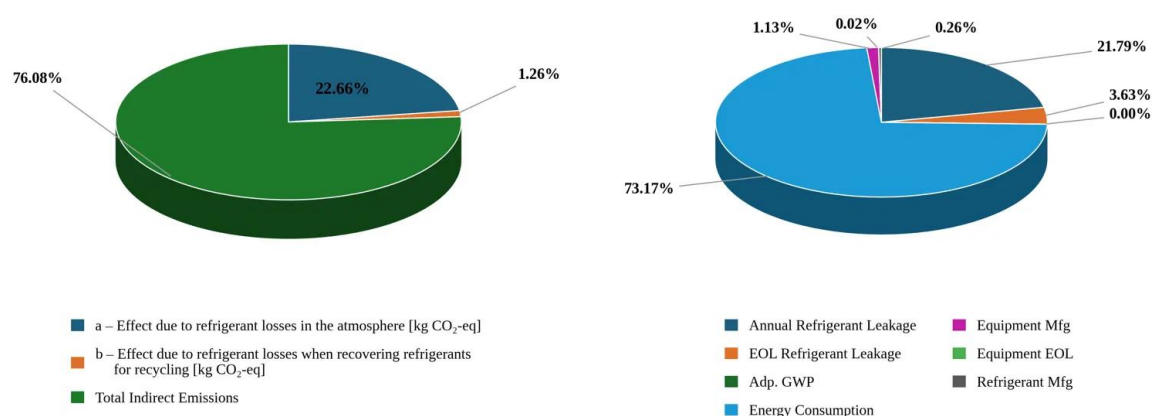


Figure 15. Percentage composition of LCCP and TEWI.

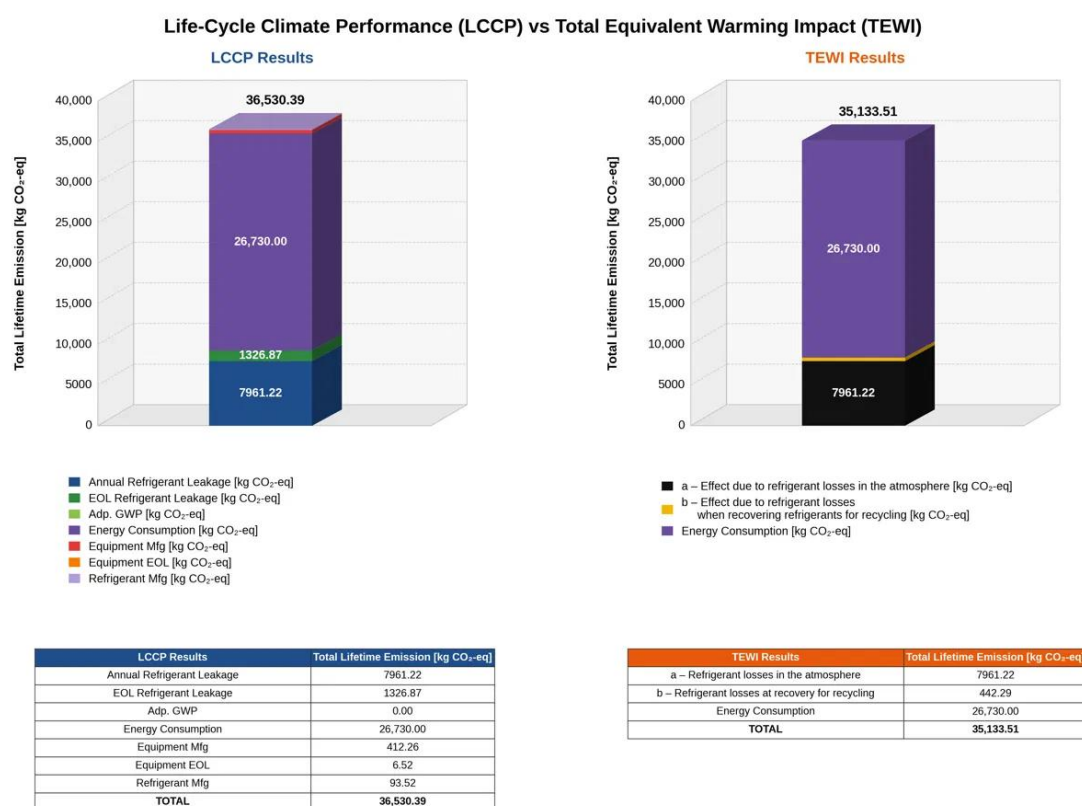


Figure 16. Total lifetime emissions, LCCP vs. TEWI.

In terms of LCCP, the total lifetime CO₂-eq emissions amount to 36.53 t CO₂-eq, a value approximately 4.0% higher than TEWI; the additional LCCP terms therefore make only a limited contribution, in agreement with [47] (Table 11).

Table 11. TEWI versus LCCP values for the heat pump.

Refrigerant	R410A
LCCP [t CO ₂ -eq]	36.53
TEWI [t CO ₂ -eq]	35.1
% relative to TEWI	+4.0%

4.7. Discussion in Relation to the Current State of Research

The results obtained in this study are generally consistent with the conclusions of other recent papers on hybrid heat pump–photovoltaic systems. 3E-type studies applied to residential buildings equipped with photovoltaic and energy-storage systems confirm that multicriteria assessments provide a more complete picture of the real benefits of these systems than analyses based solely on energy indicators, highlighting, similarly to the results presented in Section 4.5, the existence of extended payback periods, particularly in the absence of financial support schemes.

Likewise, research on 3E and climatic analysis of hybrid solar–ground-source heat pump systems [32] emphasizes the importance of correlating energy performance with local climatic conditions and system control strategy, an aspect also confirmed by the results of the present study through the strong correlation observed between COP and outdoor temperature, at both the monthly and daily scales. The main difference lies in the fact that the systems analyzed in the literature often benefit from more stable heat sources (ground or water), whereas the system studied here, based on an air source, shows more pronounced seasonal variability in performance, offset, however, by lower investment costs and the high implementation flexibility specific to this technology.

A specific aspect highlighted by the present study, less discussed in the specialized literature, is the influence of local electricity grid constraints (voltage rise at the connection point) on the exploitation of photovoltaic production, an aspect that can significantly limit the real benefits of on-grid photovoltaic systems in rural areas with less robust electrical infrastructure, underlining the need for complementary investments either at the level of the distribution grid or at the level of local storage systems.

5. Conclusions

The 3E analysis carried out on the hybrid air-to-water heat pump–photovoltaic system showed that the analyzed solution can ensure the efficient operation of a residential building using predominantly electricity and integrated renewable sources. The values obtained for the seasonal performance factor, SPF, ranging between 3.30 and 3.51, confirm the efficient operation of the system under real operating conditions, even when radiators are used as heat-emission terminals. Comparable Romanian studies have reported heating COP values ranging from 2.90 to 3.54 for an air-to-water heat pump operating in a single-family house under cold-climate conditions, which are broadly consistent with the SPF obtained in this study.

To the authors' knowledge, this study provides one of the first integrated 3E assessments in Romania of an air-to-water heat pump coupled with grid-connected photovoltaics, based on measured data from two consecutive heating seasons in an existing single-family house with radiators, thereby complementing previous Romanian studies that have focused on ground-source heat pumps, public buildings or stand-alone PV systems. The monitored data also contribute to building a much-needed database of real operating performance for heat pump–PV systems in southern Romania. Such a database can support designers, end users and policymakers in sizing, evaluating and promoting these systems under local climatic and grid conditions.

The analysis of the specific heating demand revealed relatively high values, of approximately 159–166 kWh/m² for the analyzed seasons, suggesting a significant thermal demand for the building. This result indicates that reducing energy consumption should not be achieved solely through optimizing the heating system but also through improving the building's constructive characteristics. In this regard, increasing the thermal-insulation performance of the building envelope and using exterior joinery with superior thermal characteristics (triple glazing) represent measures with high potential for reducing energy demand and improving the overall performance of the system.

The integration of the photovoltaic installation demonstrated a positive effect on reducing operating costs and on mitigating the climatic impact associated with heat pump operation. However, the analysis of photovoltaic production revealed important limitations associated with the operating conditions of the local electricity grid. During periods of high solar production, the monitoring data showed that the inverter automatically limits its output or temporarily disconnects when the grid voltage exceeds 253 V, due to the limited hosting capacity of the local distribution grid. In this context, the integration of a battery storage system can represent an effective solution for increasing the self-consumption rate, reducing the energy injected into the grid, and mitigating the losses associated with the limitations imposed by the existing electrical infrastructure.

From the perspective of renewable energy use, a further direction for optimization is the integration of solar-thermal panels dedicated to domestic hot water preparation. In the current configuration, domestic hot water is prepared using an existing electric boiler, a solution adopted to limit investment costs and make use of already available infrastructure.

The economic analysis showed that the profitability of the investment is significantly influenced by the contribution of the photovoltaic system, the evolution of energy prices, and local operating conditions. Even though the payback period is relatively long, the absence of natural-gas supply infrastructure in the analyzed area and the diversification of electricity generation sources support the use of a fully electrified solution, with high potential for reducing long-term energy dependence. The comparative cost analysis demonstrates that integrating the photovoltaic system significantly reduces heat-pump operating costs, particularly during periods of high photovoltaic production and low heat demand, generating seasonal savings of approximately 1814–3853 RON compared with natural-gas heating and average annual savings of approximately 2834 RON.

From an environmental impact perspective, the TEWI value obtained (≈ 35.1 t CO₂-eq over 15 years) is offset to a large extent ($\approx 83\%$) by the emissions avoided through photovoltaic production (≈ 29.25 t CO₂-eq), confirming the synergy between the two technologies and the decisive role of local renewable sources in reducing the carbon footprint of residential buildings.

TEWI, as an environmental metric, is easier to apply than LCCP and provides a more accurate basis than GWP for selecting environmentally friendly, low-GWP refrigerants. The manufacturing of the heat pump's materials has only a minor influence on the LCCP of a heat pump, amounting to 1.13% of total lifetime emissions. Additionally, the composition and weight of a heat pump have a negligible influence on LCCP, since this influence is already below 0.3% of total emissions.

Looking ahead, the simultaneous optimization of building-envelope performance, the expansion of energy-storage capacity, and the increased use of renewable sources can further improve the energy, economic, and environmental efficiency of the analyzed system, while also supporting the decarbonization objectives of the building sector at both the European and national levels.

6. Study Limitations and Future Research Directions

This study presents a number of limitations that must be considered when interpreting the results. First, the analysis is based on operational data from a single case study, which limits the generalization of the results to other constructive, climatic, or technological configurations. Second, the TEWI indicator used to assess environmental impact does not include the effects associated with the manufacturing, transport, installation, and recycling stages of the equipment, which is why the results obtained could be supplemented, in future research, with a full life-cycle assessment (LCA) of the system [47,48].

Third, the economic analysis was carried out using energy prices specific to the analyzed period, which may vary significantly over time; therefore, the results regarding the payback period should be interpreted as indicative, and it is recommended that the analysis be supplemented with a sensitivity study evaluating the influence of electricity and natural-gas price variation on the investment payback period. Finally, extending the analysis with an exergetic component (4E analysis) would allow a more complete characterization of the energy quality of the flows within the system and a more precise identification of the sources of thermodynamic irreversibility, a direction that remains open for future research, particularly for hybrid systems with advanced control strategies.

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