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Energy Potential of Existing Reversible Air-to-Air Heat Pumps for Residential Heating

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Abstract: Heat pumps can be considered one of the key technologies to meet the building stock decarbonization target set by Europe. Especially in warm locations, many households have already incurred costs for the installation of air-to-air heat pumps, but, in most cases, they only use them in summer for cooling, while heating is provided by fuel-fired boilers. For these households, the goal of reducing primary energy consumption could be achieved almost cost-free by using heat pumps, that were installed for summer cooling, also for winter heating. Based on this assumption, this research aimed to evaluate the energy savings and environmental benefits that can be achieved by using air-to-air heat pumps instead of gas boilers as the main heating system, without additional costs except for the installation of electric radiators in bathrooms. To quantify variations in energy, environmental, and economic savings compared to the baseline condition, detailed simulations were conducted with the dynamic hourly calculation method (EN ISO 52016) in six different European locations, considering heat pumps with different efficiencies and two different building types. The analysis showed positive impacts at all sites due to the use of heat pumps, which can lead to primary energy savings ranging from about 20% to about 60%. The results varied according to outdoor climate, coefficient of performance of heat pumps, building type, and, on the economic side, the cost of energy. This research provides useful results for outlining decarbonization scenarios, assuming that heat pumps are one of the technologies needed to meet the EU's climate neutrality goal.

Keywords: heat pump technology; fossil gas reduction; reversible air-to-air heat pumps; energy performance simulation; sustainable energy practices

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1. Introduction

As reported by Eurostat [1], about 50% of the EU's total gross energy consumption is used for heating and cooling, but, in 2021, renewable sources covered only 22.9% of this energy. Within the residential sector, about 80% [2] of the final energy consumption is allocated to space and water heating and is, for the most part, still related to the use of fossil fuels. These data point out that heat pumps are a key technology for achieving the EU's energy and climate targets for 2030 as they represent a viable alternative to the use of fuel-fired generators. For this reason, as part of the REPowerEU [3] initiative designed to reduce the EU's reliance on fossil fuel imports, the European Commission has proposed a plan to double the current deployment rate of individual heat pumps. The objective is to have a total of 10 million new units installed across EU member states by 2027 [4].

Heat pumps are increasingly recognized as a key technology for decarbonizing space heating. Nevertheless, according to the IEA [5], their current contribution addresses only approximately 10% of worldwide heating needs in buildings. To align with the Net Zero Emissions (NZE) Scenario by 2050, there is a need for a nearly threefold increase in the global heat pump stock by 2030 [5]. This growth is necessary to cover at least 20% of global heating energy needs and stay on track with the NZE Scenario objectives.

In the context of model-based decarbonization, according to the JRC's Potencia model [6], the number of individual heat pumps predominantly employed for heating purposes in the EU (13 million in 2020) is expected to increase by 2.5 times by 2030 and almost 10 times by 2050. The unit capacity is predicted to decrease by half by 2050 due to the improved thermal insulation of building envelopes. These projections confirm the objectives of the REPowerEU strategy, which aims to install 30 million or more heat pumps by 2030.

Toleikyte et al. [7] suggested that the adoption of heat pumps will entail replacing current gas and oil boilers, with specific structures incorporating both boiler replacement and building envelope renovation. The expected replacement of one-third of the existing gas and oil boilers is projected to lead to a notable 36% reduction in gas and oil consumption within the affected buildings. This reduction corresponds to a substantial energy saving of 348 TWh dedicated to residential space heating. When specifically considering gas consumption, replacing one-third of the current gas boilers in the residential buildings of the European Union could result in a total gas saving of 255 TWh.

P. Congedo et al. [8] examined the effect of future climate change with rising temperatures on the transition from fossil fuel-based heating to air-source heat pumps in winter. The outcomes varied widely depending on location, scenario, and climate change severity. The study showed reduced winter energy consumption under more severe climate scenarios but predicted an increase in cooling demand, potentially raising overall building energy use despite winter savings. By 2070, significant changes in energy consumption patterns are expected. These findings underscore the complex interaction between climate change and adopting air-source heat pumps, highlighting the need for adaptive strategies to mitigate future risks. Congedo P. et al. [8] underlined that the shift from fossil fuel-based heating systems to electric heat pumps is also partly facilitated by the ongoing effects of climate change, particularly concerning winter air conditioning requirements.

It is important to point out that heat pumps are only one of the technologies available for the energy transition.

A. Badakhsh and S. Mothilal Bhagavathy [9] identified two primary strategies to reduce CO_2 emissions: hydrogen boilers and heat pumps. Hydrogen boilers offer the benefit of reducing dependency on the electricity grid, thus compensating for the intermittency of electrical power from both renewable and conventional sources. On the other hand, heat pumps, despite their high energy conversion rate of up to 400%, present a significant challenge due to their substantial upfront costs [10]. Since many households are already connected to the natural gas grid and equipped with gas boilers, Badakhsh and Bhagavathy proposed leveraging this existing infrastructure for hydrogen to achieve carbon-neutral heating. In their conclusions, ref. [9] emphasized the importance of pursuing alternative heating solutions, such as heat pumps, alongside potential new disruptive technologies, both active and passive, to accelerate the transition and mitigate associated risks.

Hossein Ameli et al. [11] reviewed hydrogen's potential as a clean alternative for heating compared to fossil fuels. They discussed repurposing natural gas infrastructure for hydrogen as a sustainable, economical option. While hydrogen offers emission reduction and grid stability, challenges include production emissions and infrastructure needs.

In areas without gas networks, heat pumps are the preferred choice. Hybrid systems integrating hydrogen offer improved energy efficiency at costs comparable to net-zero strategies. However, significant challenges include managing the CO_2 emissions from steam methane reforming and enhancing the efficiency of green hydrogen production.

In the context of the Energiewende, the German government intends to install six million heat pumps by 2030. Von Döllen and Schlüter [12] estimated the costs and residual energy demand of a nationwide heat pump introduction, including the required power capacity and storage. They evaluated hydrogen, batteries, and carbon capture and storage as solutions for carbon-neutral electricity. They found solar power to be unsuitable for heat pumps due to its anticyclical annual period. Increasing the number of heat pumps replaced natural gas storage, complicating the inter-seasonal power supply. This either increased the need for additional fossil power capacity in winter or caused renewable overcapacity. According to the authors, an intelligent mix of hydrogen and fossil power with carbon capture and storage was identified as the most promising, cost-efficient solution for seasonal power structuring. Despite advancements in new hydrogen technologies, V. Shchegolkov et al. [13] emphasized the critical importance of developing next-generation waste management technologies.

There are different types of heat pumps, with the most popular being air-source (air-to-air and air-to-water). Several studies have addressed the efficiency of air-source heat pump systems compared with other technologies and have estimated the potential energy and economic savings that can be achieved in relation to different geographical contexts.

Ala et al. [14] investigated the energy and economic implications of employing air-to-air heat pump systems as an alternative to conventional gas boiler systems in response to changes in Italian government electricity tariffs for household heating. The study was conducted on three residential buildings in southern Italy. The analysis encompassed the installation expenses of the heating system, as well as electricity and/or gas expenditures, and the benefits associated with the existing tax credit program. The heat pumps offered greater economic benefits when integrated with gas boilers for domestic hot water production and gas-fired cookers, where fuel is directly burned to generate heat. When heat pumps were coupled with electric boilers and cookers, a superior advantage was offered over gas boiler systems, but only for a limited duration following installation.

Biao Xiao et al. [15] dealt with the environmental aspects of air-to-air heat pumps as an alternative to conventional coal-fired heating systems in residential buildings in the sites of Beijing and Tianjin. The study investigated the replacement of conventional systems with air-to-air heat pumps, considering environmental constraints often associated with their installation next to steel radiators. The fluid dynamic simulations showed that air-to-air heat pumps were superior to air-to-water heat pumps in terms of heating performance and comfort, especially at low temperatures. The outcomes indicated that air-to-air heat pumps are suitable for applications in the climatic conditions of northern China.

Kirsten Gram-Hanssen et al. [16] examined the role of individual air-to-air heat pumps in Danish homes and vacation houses, assessing their real impact on energy consumption savings. The results suggested that 20% of the expected reduction in electricity consumption was redirected into enhanced comfort, demonstrating a rebound effect.

O. Eguiarte et al. [17] explored the performance of heat pumps compared to non-electric heating systems in residential buildings across six European countries with diverse climate conditions and energy tariffs. A specific model for heat pumps using open data from various sources was developed. It included an assessment of primary energy and environmental impact to determine the comparative advantages of heat pumps over non-electric heating systems, considering the electric mix in each country. In countries heavily reliant on fossil fuels for electricity generation, non-electric heating systems may ensure lower primary energy consumption, despite the higher efficiency of heat pumps. Furthermore, current high electricity prices and the mix's fossil fuel dependency in certain countries hinder the widespread use of heat pumps, emphasizing the need for policies promoting energy efficiency and renewable sources to facilitate decarbonization.

Jankovic et al. [18] underscored the importance of evaluating the preparedness of residential buildings within the European Union, with a particular focus on their building envelopes, for the potential installation of heat pumps. Introducing the Heat Pump Readiness Indicator, the study assessed the degree to which a heat pump could meet a building's heating requirements based on its envelope characteristics and the prevailing climate. The readiness of a building for heat pump installation was significantly influenced by factors such as building thermal insulation and climate zone. The study also addressed the risk of interruptions in heating supply, emphasizing the central role of thermal insulation levels in mitigating such risks. The authors proposed that thorough renovation efforts could improve both heat pump readiness and comfort levels, especially during energy disruptions. It was emphasized that effective communication, facilitated through Energy Performance

Certificates, is crucial for conveying information about heat pump readiness to building owners and stakeholders.

The rising energy costs are putting a significant strain on low-income families or those experiencing energy poverty. As reported by [19], energy bills, which continue to increase regardless of the type of heating used, are projected to rise by 65–90% (from EUR 1429 to 2403/year) for gas boilers and by 20–40% (from EUR 1360 to 1849/year) for heat pumps by 2030. In this regard, Savage et al. [20] explored the impact of transitioning from natural gas to air-source heat pumps for domestic heating on fuel poverty and social inequality in the UK. The research focused on assessing regional variations in this impact. The analysis included an estimation of the coefficient of performance of air-source heat pumps, associated CO_2 savings, and the effects on fuel cost and fuel poverty. The results indicated that warmer, urbanized areas experienced relatively modest reductions in emissions, with areas such as London or Manchester showing a decrease of 700–1200 $kgCO_2eq$/year/household, while, in less densely populated areas, the potential for significant emissions reduction was higher, reaching up to 2200 $kgCO_2eq$/year/household. The study also highlighted the risk that emission reductions could lead to an increase in fuel costs, which would fall on the weaker strata of society, increasing social inequality. This demonstrates the importance of economic support measures to protect families affected by energy poverty.

Zhou et al. [21] argued that heat pumps offer economic advantages for households, businesses, and public organizations by reducing energy costs and stabilizing them. This impact is particularly important in addressing energy poverty and social inequality. They also emphasized the potential benefits of integrating self-generation technologies like solar photovoltaics and home energy management systems or incorporating heat pumps into district heating.

Regarding costs, Zhou et al. [21] pointed out that heat pumps have low operating costs but require substantial initial investment, which may necessitate government subsidies. They recommended enhancing economic benefits by integrating local renewable energy sources such as solar or wind power generation. Private electricity generation can also help offset electricity costs and consequently reduce heating expenses. Adopting heat pumps can provide long-term benefits, especially in preparing for potential future energy crises.

N.J. Kelly and J. Cockroft [22] utilized monitored data and simulations to assess the performance of an air-source heat pump system retrofitted into an existing residential building in Scotland. This involved developing and calibrating a model for the heat pump system and integrating it into a dynamic whole-building simulation tool. The predictions of the complete building model were compared with field trial data, suggesting that it provided a suitable foundation for energy performance assessment. The energy simulations indicated that the air-source heat pump system generated 12% less carbon compared to an equivalent condensing gas boiler system.

Other authors [23–25] have produced literature reviews of field studies on air-to-air heat pumps. P. Carroll et al. [23] examined the thematic focus, the design of the field studies, and the methods used in the data analysis for 34 academic articles. Three main areas emerged: defrost management, the monitoring of air-to-air heat pump systems, and the integration of these systems as components in smart grid demand response systems. The review also provided an overview of publicly available data on air-to-air heat pumps to assist researchers in creating, validating, and analyzing efficiency models.

Chua et al. [24] provided up-to-date insights into the latest developments in heat pump systems and showed a collection of proven practical solutions. Staffell et al. [25] explored the available technologies, their practical functioning, and their longevity. Also, economic aspects, including capital, installation, and operational costs, were discussed in detail.

N. Serey et al. [26] highlighted that air-to-air heat pump systems provide diverse applications such as space heating and hot water production, potentially decreasing utility expenses and environmental impact. Nevertheless, challenges like high initial costs and the scarcity of compatible components and refrigerants underscored existing barriers to widespread adoption.

Dill et al. [27] examined the environmental and financial impact of a reduction in greenhouse gas emissions in the state of New York through different pathways: air-source heat pumps, hydrogen blended into renewable natural gas, and renewable natural gas. In residential space heating, the lowest net present value was achieved by the pathway utilizing air-source heat pumps, coupled with a 10% financial discount rate and a 2% discount rate for the social cost of greenhouse gas.

The studies mentioned above highlight the energy savings and environmental benefits that can be achieved by installing heat pumps to replace fossil fuel-fired generation systems and point out the critical issues. The level of benefits is linked to climatic conditions, the cost of energy in each country, the energy mix used for power generation, and the cost of installing the systems.

In this regard, the IEA report [28] emphasizes the financial barrier that the upfront costs pose, despite potential lifetime savings. The report [28] highlights that in most European and non-European markets, heat pumps have a higher upfront cost than conventional gas boilers. Market maturity affects these costs, with variations observed globally. For example, in markets like Denmark and Japan, ductless air-to-air heat pumps have become cost-competitive, especially for smaller residences that need only one unit. Other countries have managed to make the initial costs of air-to-air heat pumps lower than those of gas boilers through the introduction of financial subsidies, as in France and the United States. The same does not apply to air-to-water heat pumps, which are more expensive not only compared to air-to-air heat pumps but also to gas boilers in all major markets, except for Sweden. The Joint Research Centre of the European Commission [7] also pointed out that air-to-air heat pumps have a significantly lower upfront cost compared to air-to-water heat pumps. Despite this, they are typically employed as an integrative solution rather than for heating a whole building unit.

Looking at the Italian situation, it can be observed that air-to-air heat pump systems are installed in many homes, but they are mainly used only in summer for cooling, while heating is provided by fuel boilers. According to the ISTAT report on household energy consumption for the year 2021 [29], about half of all households in Italy (48.8%) have a cooling system; the spread is high in all areas of the country: 51.2% in the south, 49.1% in the north, and 44.2% in the center. It is also reported that 32.6% of households have systems capable of producing both hot and cold air, mainly due to the growing popularity of heat pumps.

Directive (EU) 2024/1275 [30] mandates that member states gradually phase out standalone boilers powered by fossil fuels. Beginning in 2025, financial incentives for installing these boilers will no longer be available, except for investments made before that date. Clear legal frameworks are required to support national policies that ban heat generators based on high greenhouse gas emissions, the use of fossil fuels, or the insufficient use of renewable energy sources. Based on this premise, the aim of the research presented in this article was to investigate the economic and environmental benefits of using high-efficiency air-to-air heat pumps (reversible air-to-air units), which are typically employed in summer for cooling, during the winter period. For this purpose, energy simulation models were developed based on representative existing buildings. This study assumed that all rooms, except for the bathroom, were equipped with indoor units and that the installed power was adequate to cover the heating needs. For the bathroom, the addition of an electric radiator was planned.

Detailed simulations were conducted in six different European locations to quantify variations in energy, environmental, and economic savings concerning the baseline condition. In fact, the environmental impact of the intervention depended on the performance of the heat pump, strongly influenced by climatic conditions. Regarding economic advantages, they depended on the costs of energy, which differed in each country.

The simulations were carried out considering locations with different climates, from the warmest (Athens) to the coldest (Berlin). In fact, in order to obtain a complete overview, it was considered worthwhile to run the simulations not only in locations with warm climates, where the use of air-to-air heat pumps for cooling is widespread, but also in locations with colder climates, even though the number of air-to-air heat pumps already installed to satisfy cooling needs is much lower.

The simulations demonstrated positive impacts, diversified depending on the coefficient of performance of heat pumps, across all sites. The assessments were limited to operational energy characteristics and did not account for embodied energy. Moreover, the evaluations were carried out by comparing only heating consumption, without taking into account consumption related to the production of domestic hot water.

2. Main Typology of Heat Pumps

Heat pumps operate by utilizing ambient heat sources such as the air, water, or ground. The predominant type in buildings is the electrically driven vapor compression heat pump. However, there are diverse heat pump variations available, categorized by their ambient heat source (air, ground, water) and their method of heat distribution (e.g., warm air via ducts, hot water through radiators, or hydronic underfloor systems).

Air-to-air heat pumps are commonly found in commercial environments, such as offices and hospitals. In homes, these systems typically consist of an outdoor unit paired with an indoor unit and are known as split units. Ground-source heat pumps, on the other hand, are frequently employed in larger buildings due to their cost-efficiency and versatility in providing heating, cooling, and hot water [31,32].

In Table 1, a summary of the main characteristics of heat pumps is presented.

Table 1. Summary information on the main typology of heat pump systems used for space heating. Source: [7].

Type of Heat Pump	**Market Share for Space Heating in 2021 [33]**	**Max. Supply Temp**	**SCOP**		**Note**
			Minimum Requirement [34]	**Highest [7,35]**	
Air-to-water	48%	35 °C	3.2	5.75	(1)
Ground-to-water	7%	35 °C	3.2	6.00	(2)
Air-to-water high-temperature	Limited	55 °C	2.8	4.75	(3)
Air-to-air	44%	-	3.8	6.20	(4)

Note (1) Lower efficiency compared to low-temperature variants. Regulatory restrictions due to propane flammability. Note (2) Similar issues with efficiency and propane regulation. Note (3) Lower efficiency; regulatory hurdles due to propane flammability, shifting towards natural refrigerants. Note (4) Generally combined with other heat sources in northern Europe; predominant in southern Europe for both heating and cooling.

3. Methods

3.1. Research Procedure

Two representative building typologies were analyzed: a single apartment in a multi-unit building and a single-family house. Both buildings' envelopes were characterized by thermal characteristics typical of existing structures built before the first energy-saving regulations came into force in Europe and by heating systems with atmospheric B-type gas boilers and radiators.

Two configurations were examined: (1) *ante-operam (baseline)*, a building unit with a gas boiler, and (2) *post-operam*, a building unit with air-to-air heat pumps and electric radiators (towel warmers) for the bathrooms. For the second configuration, three models of air-to-air heat pumps, characterized by increasing levels of energy efficiency, were analyzed. Consequently, operational CO_2 emissions, non-renewable primary energy consumption, operational costs, and the average seasonal performance factor of the air-to-air heat pumps were determined for each case study. Figure 1 reports the research procedure adopted in this study.

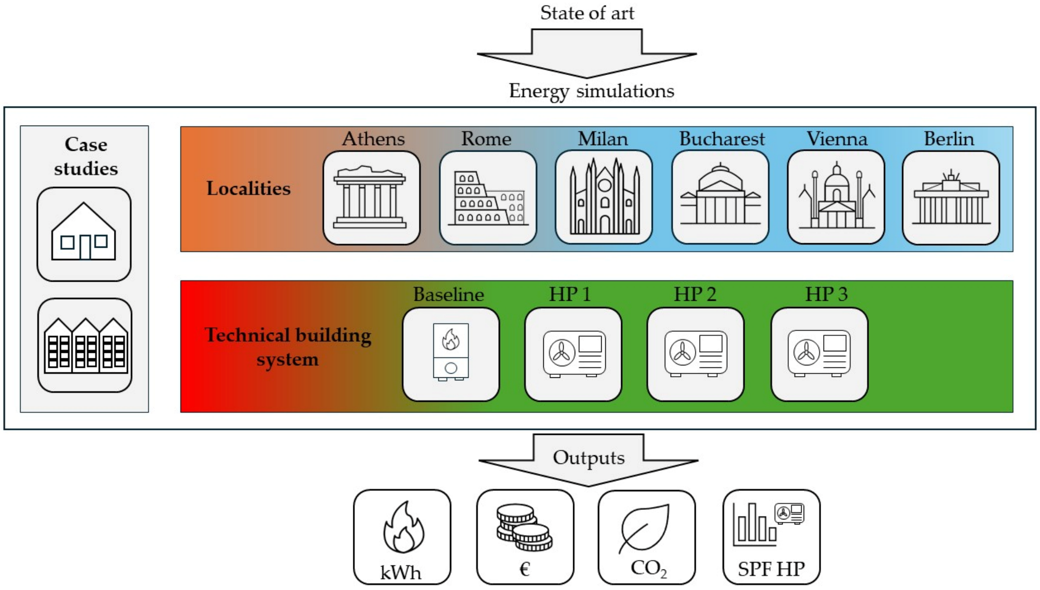

Figure 1. Research procedure employed in the analysis of air-to-air heat pumps.

3.2. Estimation of Energy Needs for Heating

The energy analyses were based on an hourly calculation method, as outlined in the EN ISO 52016-1 standard [36]. The analysis employed for the case studies relied on an RC (resistance–capacitance)-concentrated parameter model, wherein each dissipative element was represented by its equivalent circuit.

On an hourly basis, the energy balance of the building envelope was computed, taking into consideration boundary conditions and varying usage profiles.

The determination of primary energy demand and efficiencies for space heating was conducted by the methodologies specified in the Italian technical standards UNI/TS 11300-2 [37] and UNI/TS 11300-4 [38]. These standards offer comprehensive guidelines for assessing the energy performance of buildings and space heating systems in compliance with international technical regulations.

3.3. Climatic Characteristics of the Localities

The climatic data utilized in this research were sourced from Climate.OneBuilding.Org [39], a repository that provides freely accessible climate data tailored for building performance simulations. This platform was developed by the creators of the EPW (EnergyPlus Weather) file format. The dataset employed in this study is known as the TMYx dataset. TMYx files include typical meteorological data derived from hourly weather information up to the year 2021, utilizing the EN ISO 15927-4 [40] methodologies. For the analysis of solar data, the solar radiation information for each location was extracted from the ERA5 reanalysis dataset. The ERA5 dataset, offered by Oikolab [41], constitutes a comprehensive, globally gridded solar radiation dataset based on satellite data. This dataset is a valuable resource for researchers seeking precise solar radiation information across diverse geographical locations.

- GRC_AT_Athinai-Hellinikon.Olympic.Complex.167160_TMYx.2007-2021
- DEU_BE_Berlin-Tegel.AP.103820_TMYx.2007-2021
- ROU_B_Bucharest.154220_TMYx.2007-2021
- ITA_LM_Milan-Malpensa.AP.160660_TMYx.2007-2021
- ITA_LZ_Rome-Fiumicino-da.Vinci.AP.162420_TMYx.2007-2021
- AUT_WI_Wien-Innere.Stadt.110340_TMYx.2007-2021

Table 2 presents synthesized climatic data for each investigated location, derived from typical meteorological years. Table 2 includes heating degree days (HDDs) calculated with a base air temperature of 20 °C, annual average air temperature, and annual global solar irradiation on the horizontal plane. Additionally, air temperature percentiles at 1%, 2%, and

5% are provided for comprehensive analysis. These percentile values served as indicative measures for defining extreme climatic conditions, particularly during the winter period, in the studied locations.

Table 2. Main climatic indicators of the analyzed locations.

Location	Latitude	Longitude	$HDDs_{20}$	AVT	AGSIH	$T_{h,1\%}$ °C	$T_{h,2\%}$ °C	$T_{h,5\%}$ °C
Athens	37.88970	23.74170	1326	19.0	1775	4.1	5.4	7.7
Rome	41.80030	12.23890	1607	17.0	1608	5.4	6.5	8.0
Milan	45.63000	8.72310	2728	13.7	1352	−5.0	−2.2	1.3
Bucharest	44.41190	26.09390	3040	13.2	1412	−7.1	−3.8	−0.8
Vienna	48.19830	16.36690	3017	12.2	1244	−3.5	−1.6	0.2
Berlin	52.36667	13.51667	3536	10.7	1085	−5.0	−4.0	−2.0

$HDDs_{20}$: heating degree days calculated with T_{base} = 20 °C, AVT: annual average air temperature °C, AGSIH: annual global solar irradiation on the horizontal plane in $kWh \cdot m^{-2}$.

3.4. Characteristics of the Reference Buildings

Two representative residential building units—a city apartment and a single-family house—were selected for energy performance analysis. The choice of these cases aimed to capture different building typologies typical of the residential sector. The apartment, reflecting a common urban dwelling with shared walls in a multi-unit building, stands in contrast to the single-family house, which serves as an archetype of suburban residential construction. These cases were strategically simulated in various locations, including Athens, Rome, Milan, Bucharest, Vienna, and Berlin, accounting for different climatic conditions (with increasing heating degree days, see Table 2). Table 3 provides the key geometric characteristics for both case studies, facilitating a quantitative understanding of their respective structures.

Table 3. Main geometric features of the case studies, along with thermal properties of the building envelope.

Parameter	Unit of Measure	APA	SFH	Parameter	Unit of Measure	APA	SFH
V_g	m^3	409.6	659.5	WWR_W	-	0.06	0.09
V_n	m^3	304.8	493.8	A_{env}/V_g	m^{-1}	0.37	0.69
A_f	m^2	101.6	162.0	U_{wall}	$W \cdot m^{-2} \cdot K^{-1}$	1.10	1.48
A_{env}	m^2	153.3	452.0	$\kappa_{i,wall}$	$kJ \cdot m^{-2} \cdot K^{-1}$	60.22	63.10
A_w	m^2	24.1	21.6	U_{win}	$W \cdot m^{-2} \cdot K^{-1}$	3.47	4.90
WWR_S	-	0.35	0.15	$g_{gl,n}$	-	0.75	0.85
WWR_E	-	0.05	0.09	U_{avg}	$W \cdot m^{-2} \cdot K^{-1}$	1.71	1.84
WWR_N	-	0.30	0.00				

APA: apartment, SFH: single-family house, V_g: gross conditioned volume, V_n: net conditioned volume, A_f: net conditioned floor area, A_{env}: envelope area, A_w: windows area, WWR: windows-to-wall ratio, U_{wall}: thermal transmittance of the most common external wall, $\kappa_{i,wall}$: internal thermal capacity of the most common external wall, U_{win}: average thermal transmittance per windows, $g_{gl,n}$: total solar energy transmittance of the window glass, U_{avg}: overall average thermal transmittance.

Table 4 shows the annual energy needs and methane gas consumption for both the apartment and the single-family house, utilizing the methane gas and radiator-based generation system. The calculation of energy consumption was carried out in relation to year-round energy needs, considering heating system activation for a maximum of 16 h for all locations.

Table 4. Sensible energy needs for heating and estimated annual methane gas consumption for space heating.

	Apartment		Single-Family House	
Location	**$EP_{H,nd}$**	**Methane Gas**	**$EP_{H,nd}$**	**Methane Gas**
	$kWh \cdot m^{-2}$	**m^3**	**$kWh \cdot m^{-2}$**	**m^3**
Athens	27.41	401	64.25	1871
Rome	39.46	580	79.68	2321
Milan	105.75	1503	190.62	5610
Bucharest	125.36	1775	221.85	6529
Vienna	134.81	1904	240.32	7073
Berlin	150.79	2165	274.29	8072

3.5. Estimates of Economic Savings

Figure 2 shows the trend of average prices in EUR/kWh, including taxes, in the member states of the European Union from 2008 to 2023 for both electricity and natural gas. The analysis of electricity and natural gas price data [42,43] in the European Union from 2008 to 2023 revealed that until 2015, electricity prices remained relatively stable, with minor fluctuations. Starting from 2016, there has been a gradual increase, which has become more pronounced from 2021 onwards due to the COVID-19 pandemic and the growing international demand. The Russian invasion of Ukraine and climatic conditions have had an exacerbating effect. In the early years, natural gas prices exhibited greater variability, but without a clear directional trend. Nevertheless, from 2020 onwards, a significant uptick in natural gas prices was observed, indicating a substantial shift in energy market dynamics. In 2022, the Russian war against Ukraine and its unilateral decision to suspend gas supplies to some EU member states pushed up gas prices, in turn causing a record increase in electricity prices in the EU [44]. Additionally, the ratio between the prices of electricity and gas is also presented. High ratios between electricity and gas costs discourage consumers from choosing more environmentally friendly heating options powered by electricity, such as heat pumps, as opposed to gas.

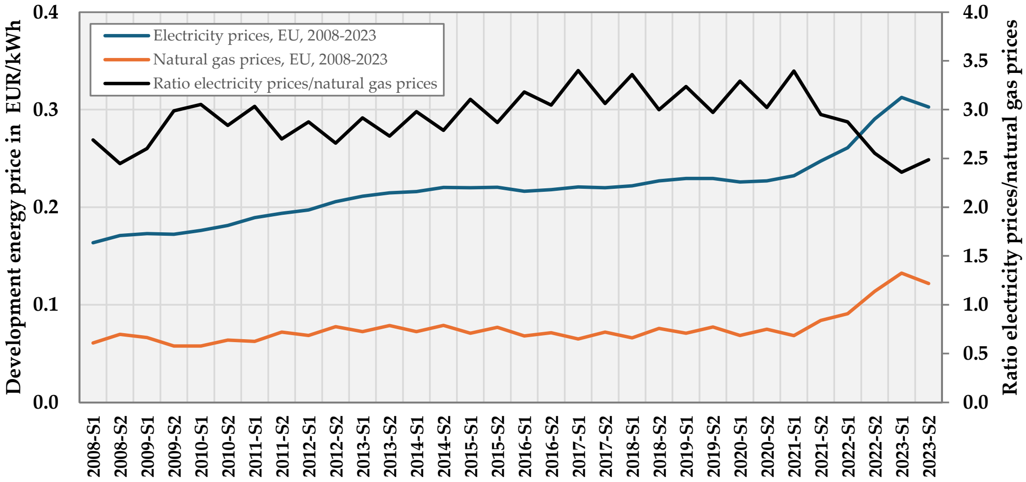

Figure 2. Development of electricity and natural gas prices for household consumers (prices including taxes), EU area, 2008–2023. Source: [42,43].

The IEA [28] highlights that, even before the current energy crisis, heat pump operational expenses were notably lower than those of gas boilers in key heating markets. In the European context, this advantage has further expanded in recent months, resulting in an annual saving of over USD 900 for the average European household. This trend is attributed to the relatively slower increase in electricity tariffs compared to gas tariffs, a phenomenon influenced in part by governmental interventions aimed at mitigating price escalations. The economic savings projections are informed by data extracted from Eurostat [42,43]. The tabulated information in Table 5 details the prices of energy carriers (electricity and methane gas) during the second half of 2023. These prices encompass taxes, levies, and VAT applicable to household consumers while excluding refundable taxes, levies, and VAT for non-household consumers. The ratios of electricity price/gas price for the different sites reveal significant differences in electricity and gas prices. Austria exhibited a relative balance in costs, with a moderate ratio of 1.86, indicating an economic advantage for electricity. In contrast, Germany displayed a notable discrepancy, with a high ratio of 3.51, highlighting an economic challenge for electric heating options. Italy presented an intermediate scenario, with a ratio of 2.48.

Table 5. Prices of energy carriers for household consumers in the second half of 2023 (including taxes). Source: Eurostat [42,43].

Location	Country	Electricity Price	Gas Price	Ratio
		EUR/kWh	EUR/kWh	Electricity Price/Gas Price
Athens	Greece	0.2309	0.0926	2.49
Milan/Rome	Italy	0.3347	0.1347	2.48
Bucharest	Romania	0.1910	0.0558	3.42
Vienna	Austria	0.2748	0.1477	1.86
Berlin	Germany	0.4020	0.1145	3.51

3.6. Technical Characteristics of Air-to-Air Heat Pumps

The analysis was carried out considering the use of three heat pumps in the apartments and six heat pumps in the single-family house. Tables 6–8 show the heating capacity for the investigated air-to-air heat pumps, detailing performance metrics across different indoor and outdoor temperature scenarios. The tables show data on total capacity (TC), power input (PI), and coefficient of performance (COP) for various outdoor wet-bulb air temperature and indoor air temperature conditions. In the tables, the grey cells indicate the rated capacity, rated power input coefficient, and rated COP under reference conditions.

Figure 3 illustrates a comparison of the coefficient of performance (COP) for the three investigated heat pumps at an indoor temperature of 20 °C. The third examined model exhibited significant variations in energy performances in response to operational conditions. Heat pump 3 stood out as the most efficient, showcasing a progressive increase in the COP compared to the other two. From Figure 3, it is also evident how air-to-air heat pump 3 maintained consistent performance from −5 to 0 degrees Celsius, and performance was degraded less rapidly as the outdoor wet-bulb air temperatures decreased.

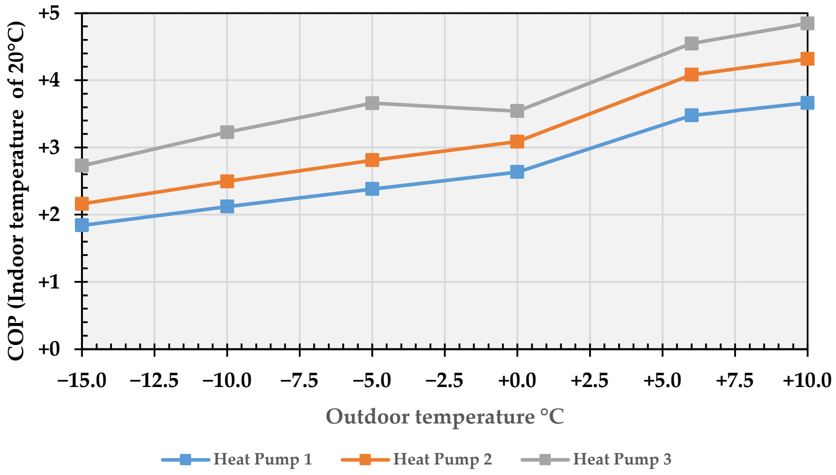

Figure 3. COP of the three air-to-air heat pump models examined at an indoor temperature of 20 °C.

Table 6. Performance characteristics of the heating building system adopted for the energy simulations. Air-to-air heat pump, first model examined.

Indoor Temperature	**Outdoor Wet-Bulb Temperature °C**																	
		−15			**−10**			**−5**			**0**			**6**			**10**	
°C	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**
15	1.86	0.92	2.02	2.23	0.97	2.30	2.61	1.02	2.56	2.98	1.07	2.79	4.14	1.12	3.70	4.50	1.16	3.88
20	1.75	0.95	1.84	2.12	1.00	2.12	2.50	1.05	2.38	2.87	1.09	2.63	4.00	1.15	3.48	4.36	1.19	3.66
22	1.70	0.96	1.77	2.07	1.01	2.05	2.45	1.06	2.31	2.82	1.10	2.56	3.94	1.16	3.40	4.31	1.20	3.59
24	1.65	0.97	1.70	2.03	1.02	1.99	2.40	1.07	2.24	2.78	1.11	2.50	3.89	1.17	3.32	4.25	1.21	3.51
25	1.63	0.98	1.66	2.01	1.02	1.97	2.38	1.07	2.22	2.76	1.12	2.46	3.86	1.18	3.27	4.22	1.21	3.49
27	1.59	0.99	1.61	1.96	1.03	1.90	2.33	1.08	2.16	2.71	1.13	2.40	3.81	1.19	3.20	4.02	1.21	3.32

Table 7. Performance characteristics of the heating building system adopted for the energy simulations. Air-to-air heat pump, second model examined.

Indoor Temperature	**Outdoor Wet-Bulb Temperature °C**																	
		−15			**−10**			**−5**			**0**			**6**			**10**	
°C	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**
15	1.86	0.79	2.35	2.23	0.83	2.69	2.61	0.87	3.00	2.98	0.91	3.27	4.14	0.96	4.31	4.50	0.99	4.55
20	1.75	0.81	2.16	2.12	0.85	2.49	2.50	0.89	2.81	2.87	0.93	3.09	4.00	0.98	4.08	4.36	1.01	4.32
22	1.70	0.82	2.07	2.07	0.86	2.41	2.45	0.90	2.72	2.82	0.94	3.00	3.94	0.99	3.98	4.31	1.02	4.23
24	1.65	0.83	1.99	2.03	0.87	2.33	2.40	0.91	2.64	2.78	0.95	2.93	3.89	1.00	3.89	4.25	1.03	4.13
25	1.63	0.83	1.96	2.01	0.87	2.31	2.38	0.91	2.62	2.76	0.95	2.91	3.86	1.00	3.86	4.22	1.03	4.10
27	1.59	0.84	1.89	1.96	0.88	2.23	2.33	0.92	2.53	2.71	0.96	2.82	3.81	1.01	3.77	4.02	1.04	3.87

Table 8. Performance characteristics of the heating building system adopted for the energy simulations. Air-to-air heat pump, third model examined.

Indoor Temperature	**Outdoor Wet-Bulb Temperature °C**																	
		−15			**−10**			**−5**			**0**			**6**			**10**	
°C	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**	**TC**	**PI**	**COP**
15	2.18	0.69	3.16	2.63	0.72	3.65	3.08	0.74	4.16	3.08	0.77	4.00	4.08	0.80	5.10	4.44	0.83	5.35
20	2.10	0.77	2.73	2.55	0.79	3.23	3.00	0.82	3.66	3.01	0.85	3.54	4.00	0.88	4.55	4.36	0.90	4.84
22	2.07	0.80	2.59	2.52	0.82	3.07	2.97	0.85	3.49	2.99	0.88	3.40	3.97	0.91	4.36	4.33	0.93	4.66
24	2.04	0.83	2.46	2.49	0.85	2.93	2.94	0.88	3.34	2.96	0.91	3.25	3.94	0.94	4.19	4.30	0.96	4.48
25	2.02	0.84	2.40	2.47	0.87	2.84	2.92	0.89	3.28	2.94	0.92	3.20	3.92	0.95	4.13	4.28	0.98	4.37
27	1.99	0.87	2.29	2.44	0.90	2.71	2.89	0.92	3.14	2.92	0.95	3.07	3.89	0.98	3.97	4.25	1.01	4.21

All the air-to-air heat pumps investigated employed a type of refrigerant R-32 characterized by a GWP (Global Warming Potential) of 675, with a charge of 0.76 kg and a TCO_2eq (CO_2 equivalent) charge of 0.52.

In all configurations with heat pumps, electric radiators (towel warmers) were provided in the bathrooms. For warm locations (Athens and Rome), a 500 W electric radiator was simulated, while, for cold locations, a 700 W radiator was simulated. In the apartment, there was one bathroom with one towel warmer, while in the single-family house, there were two bathrooms, each equipped with a towel warmer. The analyses therefore considered the additional energy consumption resulting from these systems.

3.7. Assessing Primary Energy Consumption

To evaluate the primary energy consumption in the different locations, bibliographic research was carried out to determine the weighting factors for primary energy defined at the member state level, as shown in Table 9. In Greece, the weighting factors for the conversion of primary energy and pollutants released per unit of energy are defined by the Ministry of Environment and Energy [45]. In Italy, these weighting factors are defined in an Interministerial Decree of the Ministry of Economic Development, in agreement with the Ministry of the Environment, Land and Sea Protection and the Ministry of Infrastructure and Transport [46]. In Romania, the weighting factors are described in the approved technical regulation published in an official document [47] of the Ministry of Development, Public Works, and Administration in the Official Monitor of Romania. In Austria, the primary energy conversion factors are defined by the guidelines of the Austrian Institute for Building Technology [48]. In Germany, the determination of primary energy weighting factors for calculations in accordance with the Energy Saving Ordinance in the Federal Republic of Germany is described in Annex 1 of the Energy Saving Ordinance 2016 [49], partly in conjunction with DIN V 18599-1:2011-12 [50]. Table 8 provides a comparative framework of the different reference values, including weighting factors for primary energy and equivalent CO_2 emissions. The analysis did not consider the CO_2 equivalent emissions related to refrigerant losses from refrigeration/air conditioning systems. In some countries, such as Romania, quantification was required [47]. In the case of Greece, only the total primary energy factor was available.

As Table 9 shows, electricity weighting factors differed considerably from one country to another. They should be linked to the electricity mix and the efficiency of power generation plants, but the different criteria used by countries to define them make comparison difficult. Moreover, in many cases, they are outdated factors that were established when the national guidelines for energy certification were published. For these reasons, Table 9 also includes the indicative reference weighting factors specified in the EN ISO 52000-1 standard [51]. These data were used for comparison between the different locations; considering the same weighting factors, primary energy consumption and greenhouse gas emissions only depended on the different climatic conditions of the locations.

Table 9. Primary energy conversion factors and equivalent CO_2 emissions conversion factors (kg/kWh).

Country	Location	Gas			Electricity			References	Gas	Electricity	References
		$f_{P,nren}$	$f_{P,ren}$	$f_{P,tot}$	$f_{P,nren}$	$f_{P,ren}$	$f_{P,tot}$		f_{CO2}	f_{CO2}	
GR	Athens	1.05	0.00	1.05	-	-	2.90	[45]	0.196	0.989	[45,52]
IT	Milan/Rome	1.05	0.00	1.05	1.95	0.47	2.42	[46]	0.210	0.460	[53]
RO	Bucharest	1.17	0.00	1.17	2.00	0.50	2.50	[47]	0.202	0.107	[47]
AT	Vienna	1.10	0.00	1.10	1.02	0.61	1.63	[48]	0.247	0.227	[48]
DE	Berlin	1.10	0.00	1.10	1.80	1.00	2.80	[49,54]	0.240	0.550	[50]
Standard	EN ISO 52000-1	1.10	0.00	1.10	2.30	0.20	2.50	[51]	0.220	0.420	[51]

$f_{P,nren}$: non-renewable primary energy factor, $f_{P,ren}$: renewable primary energy factor, $f_{P,tot}$: total primary energy factor, f_{CO2}: equivalent CO_2 emissions conversion factors.

Regarding the conversion of electricity consumption into CO_2 equivalent emissions, Table 10 shows additional factors, which were updated to 2021 and calculated according to the IPCC Guidelines for national greenhouse gas inventories [55]. These factors were useful for comparing avoided emissions in the different locations, considering the national energy mix in each country in the most recent year available (2021). For natural gas, Table 10 shows the IPCC standard default emission factor [56].

Table 10. Emission factors for natural gas (kgCO_2eq./kWh) and national electricity consumption for EU member states (kgCO_2eq./kWh), year 2021.

Country	Location	Gas	References	Electricity	References
		f_{CO2}		f_{CO2}	
GR	Athens	0.202	[56]	0.412	[55]
IT	Milan/Rome	0.202	[56]	0.285	[55]
RO	Bucharest	0.202	[56]	0.378	[55]
AT	Vienna	0.202	[56]	0.244	[55]
DE	Berlin	0.202	[56]	0.383	[55]

4. Results and Discussion

4.1. Evaluation of Heat Pump Energy Consumption

Using energy simulation models, the consumption due to the use of heat pumps instead of gas boilers was estimated. Tables 11 and 12 show the electricity consumption associated with the three heat pump models analyzed for the apartment and single-family house, respectively. It is evident that the consumption of heat pumps decreased with more efficient systems. For each option, the additional consumption due to the electric radiators needed to heat the bathrooms is also shown (one for the apartment and two for the single-family house).

Table 11. Annual electricity consumption due to the use of heat pumps in the apartment (APA).

Location	APA—Option 1 Annual Electricity Consumption (kWh)			APA—Option 2 Annual Electricity Consumption (kWh)			APA—Option 3 Annual Electricity Consumption (kWh)		
	HP_1 (3 Units)	ER (n.1)	Total	HP_2 (3 Units)	ER (n.1)	Total	HP_3 (3 Units)	ER (n.1)	Total
Athens	906	282	1188	769	282	1051	686	282	968
Rome	1354	436	1790	1149	436	1585	1027	436	1463
Milan	4246	893	5138	3613	893	4505	3203	893	4095
Bucharest	5099	921	6020	4340	921	5261	3819	921	4740
Vienna	5473	1007	6480	4656	1007	5662	4091	1007	5098
Berlin	6222	1060	7282	5297	1060	6356	4691	1060	5751

HP: heat pump, ER: electric radiator.

Table 12. Annual electricity consumption due to the use of heat pumps in single-family house (SFH).

Location	SFH—Option 1 Annual Electricity Consumption (kWh)			SFH—Option 2 Annual Electricity Consumption (kWh)			SFH—Option 3 Annual Electricity Consumption (kWh)		
	HP_1 (6 Units)	ER (n.2)	Total	HP_2 (6 Units)	ER (n.2)	Total	HP_3 (6 Units)	ER (n.2)	Total
Athens	3167	834	4001	2687	834	3520	2400	834	3233
Rome	4121	1058	5178	3497	1058	4554	3124	1058	4182
Milan	11,691	2069	13,759	9946	2069	12,014	8784	2069	10,852
Bucharest	13,716	2077	15,792	11,672	2077	13,749	10,309	2077	12,386
Vienna	14,690	2325	17,016	12,505	2325	14,830	11,124	2325	13,449
Berlin	16,699	2526	19,225	14,213	2526	16,738	12,622	2526	15,148

HP: heat pump, ER: electric radiator.

4.2. Non-Renewable Primary Energy Reduction

As stated in the previous paragraphs, the primary energy saving related to the use of heat pumps instead of gas boilers was calculated by considering the same conversion factors for all locations (provided by the EN ISO 52000-1 standard [51]), so that the results obtained were comparable and consumption only depended on climatic conditions. The energy consumption associated with the use of the gas boiler served as a benchmark to illustrate the primary energy impact of using heat pumps for space heating. A comparison was made between the non-renewable primary energy data associated with the gas boiler system and the three air-to-air heat pump models (more towel warmers in the bathrooms), both for the apartment and the single-family house in the different locations. Figure 4 shows the results obtained.

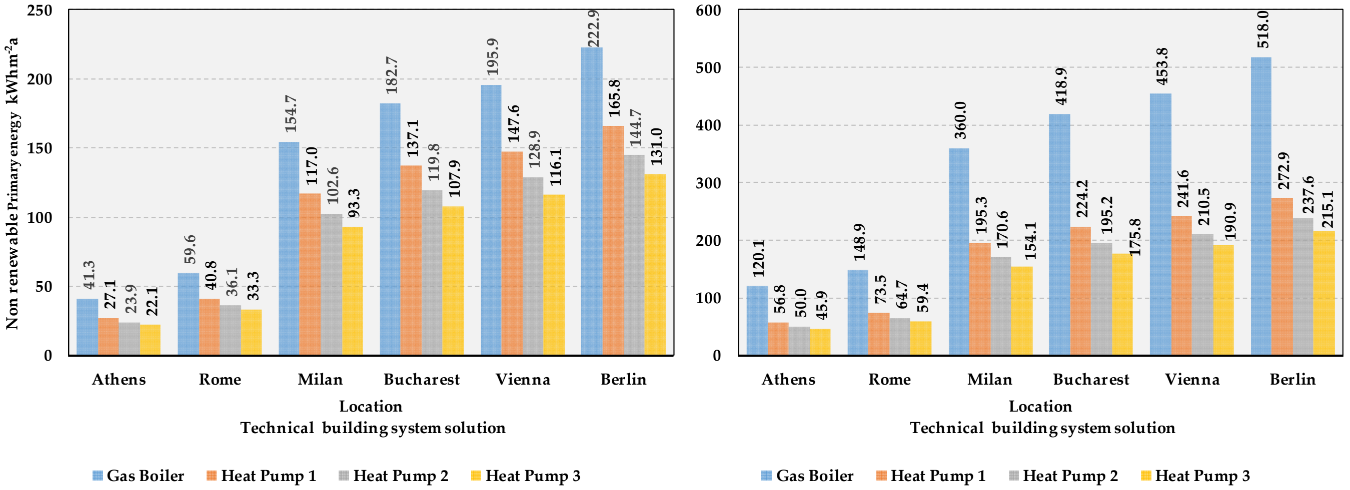

Figure 4. Non-renewable primary energy normalized per unit of floor area. Apartment (**left**) and single-family house (**right**). Conversion factors used: EN ISO 52000-1 [51].

The use of air-to-air heat pumps (more towel warmers in the bathrooms) proved to be extremely advantageous for achieving considerable savings in non-renewable primary energy in all cases. The analysis of the apartment provided the following results:

- Athens showcased an energy savings rate of 34–47% per year.
- Rome exhibited an energy savings rate of 32–44% per year.
- Milan demonstrated an energy savings rate of 24–40% per year.
- Bucharest reported an energy savings rate of 25–41% per year.
- Vienna showed an energy savings rate of 25–41% per year.
- Berlin displayed an energy savings rate of 26–41% per year.

This energy consumption trend was mirrored in single-family houses, where the use of air-to-air heat pumps (more towel warmers in the bathrooms) delivered even more tangible results:

- Athens showcased energy savings ranging from 53% to 62% per year.
- Rome exhibited energy savings between 51% and 60% per year.
- Milan demonstrated energy savings between 46% and 57% per year.
- Bucharest reported energy savings of 46% to 58% per year.
- Vienna showed energy savings between 47% and 58% per year.
- Berlin displayed energy savings between 47% and 58% per year.

The percentage difference in the reduction of non-renewable primary energy between the least efficient air-to-air heat pump (heat pump 1) and the most efficient (heat pump 3) was remarkable and lay between 12% and 16% for the apartment and between 9% and 12% for the single-family house.

The analysis of the data confirmed the effectiveness of air-to-air heat pumps in achieving substantial savings in non-renewable primary energy across various European locations. Although air-to-air heat pumps performed better in milder climates—the coefficient of performance (COP) decreased as outdoor air temperatures fell—the opportunities for energy savings were significant in cold locations due to higher energy demand. These results, in addition to reinforcing the guidelines of the REPowerEU [3] initiative, provide a solid foundation for guiding targeted energy policies and promoting the adoption of more efficient technical system solutions.

4.3. Greenhouse Gas Emission Reduction

For the calculation of the carbon dioxide emissions, as for the calculation of primary energy, the reference factors established by the EN ISO 52000-1 standard [51] were used. The results are shown in Figure 5.

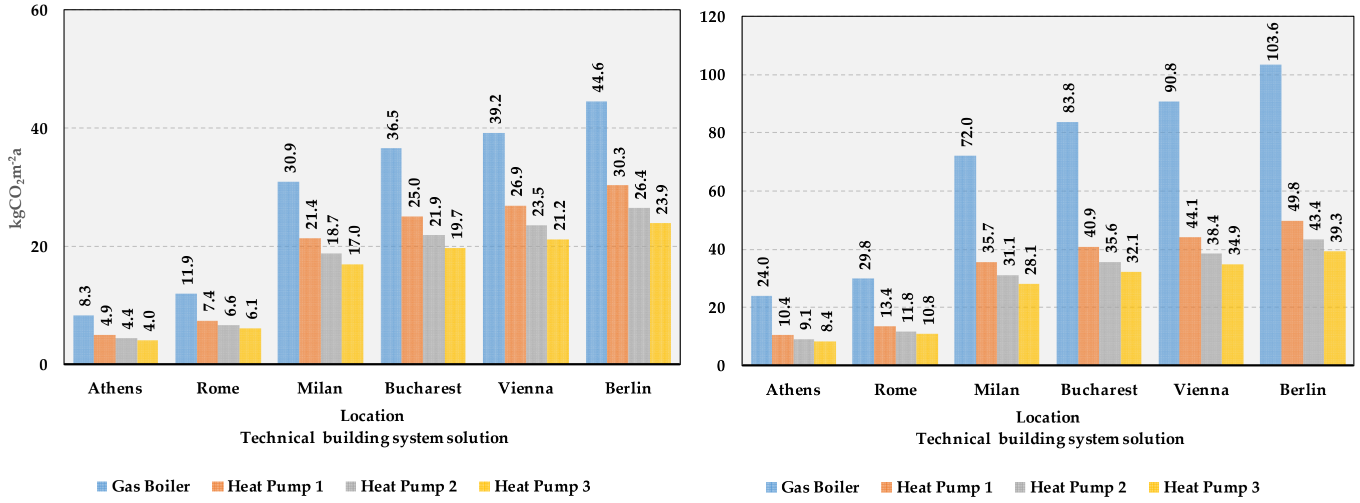

Figure 5. CO_2 emissions normalized per unit of floor area. Apartment (**left**) and single-family house (**right**). Emission factors used: EN ISO 52000-1 [51].

Below are the results obtained for the apartment in the various locations:

- In Athens, the reduction in CO_2 emissions was between 40% and 51% per year.
- In Rome, the reduction in CO_2 emissions was between 38% and 49% per year.
- In Milan, the reduction in CO_2 emissions was between 31% and 45% per year.
- In Bucharest, the reduction in CO_2 emissions was between 31% and 46% per year.
- In Vienna, the reduction in CO_2 emissions was between 31% and 46% per year.
- In Berlin, the reduction in CO_2 emissions was between 32% and 46% per year.

Even for the single-family house, using the heat pumps (more towel warmers in the bathrooms) always brought environmental advantages:

- In Athens, the reduction in CO_2 emissions was between 57% and 65% per year.
- In Rome, the reduction in CO_2 emissions was between 55% and 64% per year.
- In Milan, the reduction in CO_2 emissions was between 50% and 61% per year.
- In Bucharest, the reduction in CO_2 emissions was between 51% and 62% per year.
- In Vienna, the reduction in CO_2 emissions was between 51% and 62% per year.
- In Berlin, the reduction in CO_2 emissions was between 52% and 62% per year.

It is worth noting that the consistent use of air-to-air heat pumps resulted in lower operational emissions compared to gas boilers in all cities, underlining the environmental benefits of switching to more sustainable heating solutions. The percentages of CO_2 emissions avoided, calculated in relation to the data achieved for apartments and single-family houses, showed significant environmental benefits. The percentage difference in the reduction of CO_2 emissions between the least efficient heat pump (heat pump 1) and the most efficient (heat pump 3) was remarkable and lay between 11% (Athens and Rome) and 15% (Bucharest and Vienna) for the apartment and between 8% (Athens) and 11% (Bucharest) for the single-family house. These percentage variations highlight the importance of choosing efficient solutions with a high COP to ensure the maximum environmental benefit.

To evaluate the impact of the national electricity generation mix on the environmental benefits of using heat pumps instead of gas boilers, emissions were recalculated, taking into account emission factors updated to 2021 (Table 10). The reductions in emissions in the different locations are shown in Figure 6.

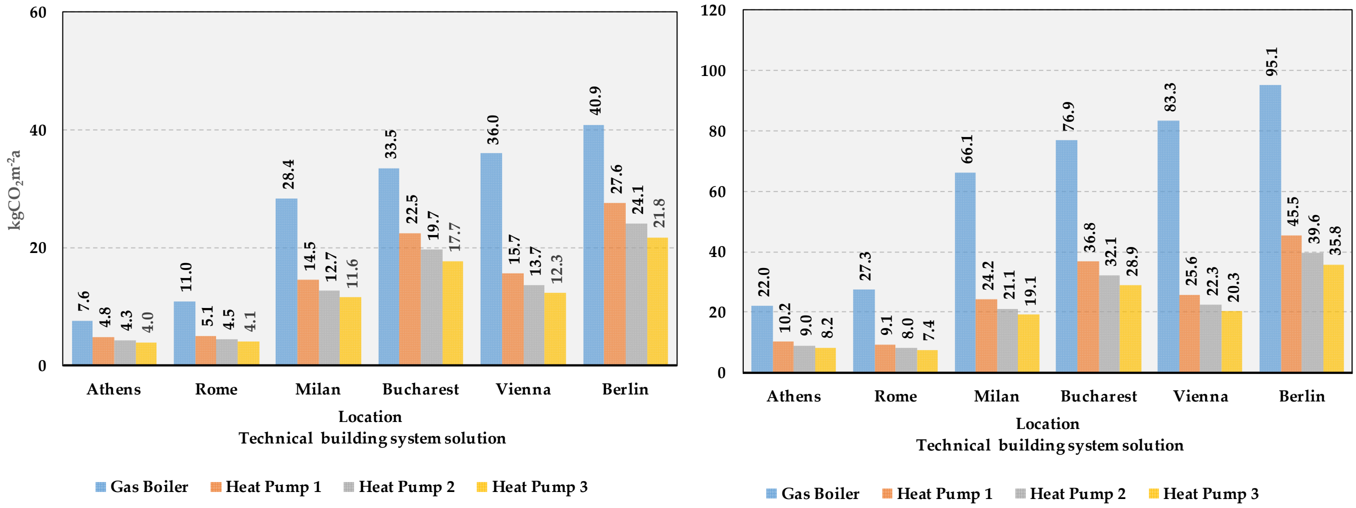

Figure 6. CO$_2$ emissions normalized per unit of floor area. Apartment (**left**) and single-family house (**right**). Emission factors used: IPCC standard. Reference year for emission factors for national electricity consumption: 2021 [55].

For the apartment, the results in terms of percentage reduction were as follows:

- In Athens, the reduction in CO$_2$ emissions was between 36% and 48% per year.
- In Rome, the reduction in CO$_2$ emissions was between 54% and 62% per year.
- In Milan, the reduction in CO$_2$ emissions was between 49% and 59% per year.
- In Bucharest, the reduction in CO$_2$ emissions was between 33% and 47% per year.
- In Vienna, the reduction in CO$_2$ emissions was between 56% and 66% per year.
- In Berlin, the reduction in CO$_2$ emissions was between 33% and 47% per year.

The following results were obtained for the single-family house:

- In Athens, the reduction in CO$_2$ emissions was between 54% and 63% per year.
- In Rome, the reduction in CO$_2$ emissions was between 67% and 73% per year.
- In Milan, the reduction in CO$_2$ emissions was between 63% and 71% per year.
- In Bucharest, the reduction in CO$_2$ emissions was between 52% and 62% per year.
- In Vienna, the reduction in CO$_2$ emissions was between 69% and 76% per year.
- In Berlin, the reduction in CO$_2$ emissions was between 52% and 62% per year.

The new calculations showed slightly different results from those previously reported. Using the emission factors in Table 10, the highest percentage of savings was achieved in Vienna, as the equivalent CO$_2$ emission factor was the lowest among the locations considered.

Such values are consistent with those estimated by the EU publications [19], which state that heat pumps can reduce heating emissions for households by around 70%.

4.4. Operative Cost Reduction

Figure 7 shows the operating costs of a gas boiler compared to various air-to-air heat pump solutions (reference energy prices for 2023 [42,43]). The analysis revealed a consistent pattern of decreasing costs for the different heat pump configurations in all the studied cases. In only two cases (apartments in Bucharest and Berlin), heat pump 1 and heat pump 2 were less economically advantageous than the gas boiler due to the high electricity costs compared to gas (Table 5). This situation arose because, as shown in Table 5, the ratio between the cost of electricity and the cost of gas was very high, at 3.42 and 3.51, respectively. Heat pump 3 enabled the maximum economic savings for heating during the operational phase, with figures of 36% for Athens, 34% for Rome, 28% for Milan, 3% for Bucharest, 47% for Vienna, and 2% for Berlin.

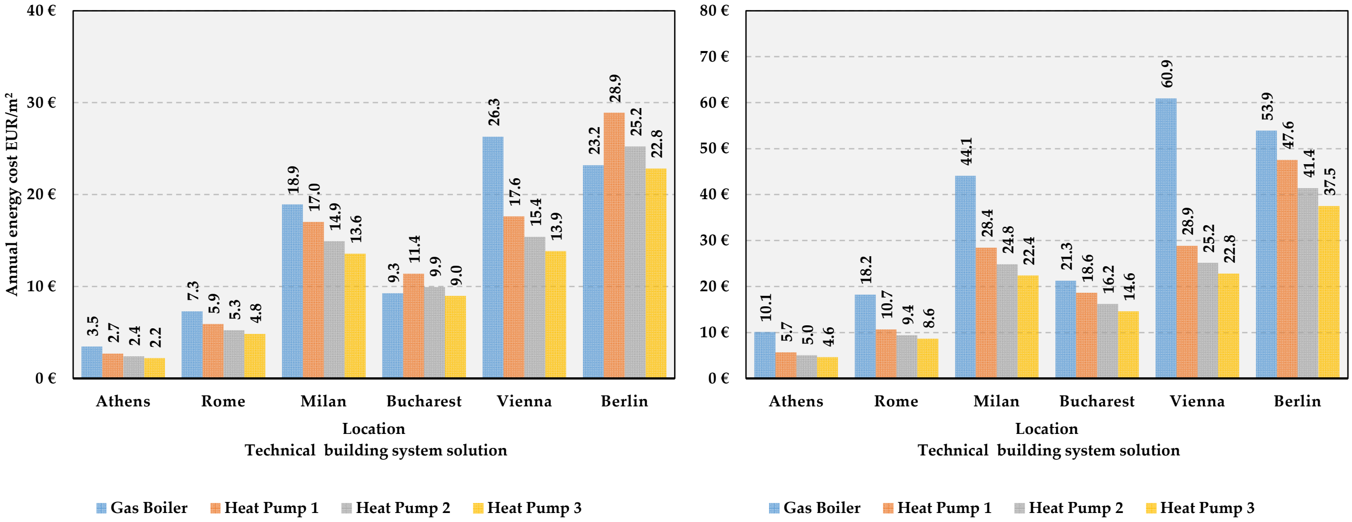

Figure 7. Annual energy cost normalized per unit of floor area. Apartment (**left**) and single-family house (**right**).

For single-family houses, the economic savings during the operational phase were even more significant in Athens (from 44% for heat pump 1 to 54% for heat pump 3), Rome (from 41% for heat pump 1 to 53% for heat pump 3), Milan (from 36% for heat pump 1 to 49% for heat pump 3), Bucharest (from 12% for heat pump 1 to 31% for heat pump 3), Vienna (from 53% for heat pump 1 to 63% for heat pump 3), and Berlin (from 12% for heat pump 1 to 30% for heat pump 3).

The reduced operational expenses of heat pumps make them an attractive technological choice, providing a strong justification for their use instead of fuel boilers. These considerations, however, are particularly linked to variations in energy costs.

EU publications [19] have estimated that in the next decade, air-source heat pumps will be more cost-effective compared to high-efficiency gas boilers, with potential annual savings of around EUR 300–700 and a reduction in bills of 20–25% compared to gas. Switching from gas heating to heat pumps can annually save between 1200 and 2400 m^3 of gas per average household. To provide context, the gas saved by 1 million heat pumps in households amounts to approximately 1% of the Russian gas supply to the EU in 2021. The gas used to generate the additional electricity makes up less than 10% of the gas savings (100 m^3/year), based on the assumption of a 20% average share of gas in the electricity generation mix in 2019 [19].

As underlined by [7], the challenge persists in the relationship between the costs of electricity and gas. This ratio is central in assessing the competitiveness of heat pump operational expenses. If the price ratio surpasses the seasonal performance factor (SPF) of heat pumps, the operational costs for heat pumps become more expensive than those for gas boilers. With a presumed SCOP of three, the economic viability of operating a heat pump is sustained as long as the electricity cost does not surpass three times the cost of gas or oil. While the uptake of heat pumps is influenced by various factors, reducing electricity costs relative to gas is a crucial policy lever to encourage the adoption of electric-based systems like heat pumps over fossil fuel heating [57].

4.5. Seasonal Coefficient of Performance of Heat Pump Solutions

Figure 8 illustrates the assessment of the seasonal coefficient of performance (SCOP) of air-to-air heat pump solutions for the two case studies. The analysis of the SCOP revealed a clear correlation between the energy performance of heat pumps and climatic severity. In the temperate climates of Athens and Rome, all heat pumps exhibited higher SCOP values, indicating superior energy performance in milder weather conditions. The decline in the efficiency of air-to-air systems with low outdoor temperatures might suggest the installation of different types of heat pumps in locations with cold climates in order to achieve even higher energy savings and environmental benefits.

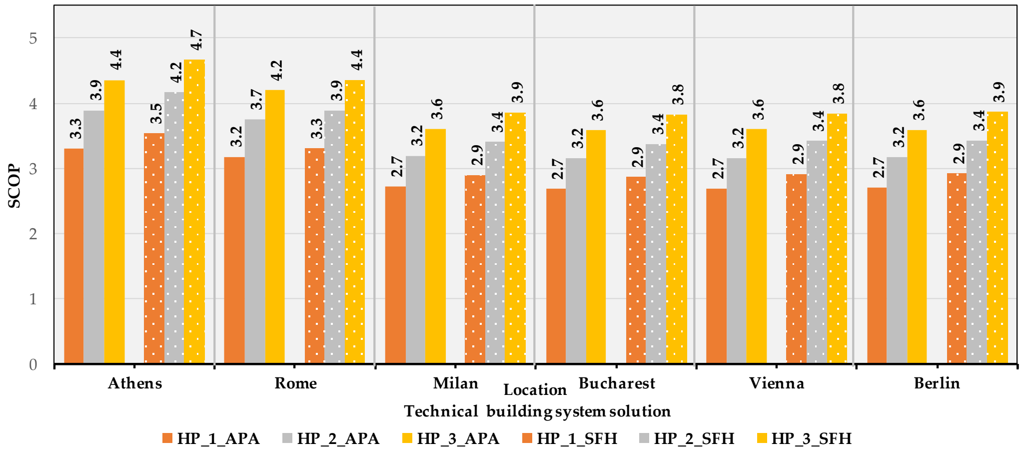

Figure 8. SCOP. Apartment (APA) and single-family house (SFH).

5. Limitations

The comparisons in this study were made by contrasting a baseline heating system that utilized atmospheric B-type gas boilers and radiators with various air-to-air heat pump systems of increasing energy efficiency. Energy savings, environmental impact, and economic costs can vary significantly depending on the specific performance characteristics of these reference systems.

The operational efficiency of heat pumps is notably affected by several factors including ambient conditions, installation specifics, and the unique characteristics of the buildings where they are installed [1,7]. For example, ref. [58] highlighted that maintaining consistent indoor setpoint temperatures improves the thermal efficiency of heat pumps, resulting in reduced energy consumption. Consequently, the real-world energy performance of air-to-air systems may deviate from the metrics observed in controlled laboratory settings or stated in manufacturers' technical specifications.

Our analysis was based on standard climatic data and typical building usage patterns, assuming the optimal functioning, proper installation, and regular maintenance of the air-to-air heat pump over time. It is also essential to consider factors such as user behavior, preferences, and comfort levels, which may involve setpoint temperatures different from the standard 20 °C. These variations can significantly influence the outcomes of the parameters studied.

Furthermore, this study did not consider the rebound effect, which, in the literature, primarily describes changes in households' energy consumption behavior following the adoption of energy-saving goods and services. This includes both the direct rebound effect, where households increase energy consumption after implementing energy-saving measures, and the indirect rebound effect [19,59], where energy cost savings can be used for other energy-intensive expenditures.

6. Conclusions

The comprehensive analysis of the consumption of non-renewable primary energy, operational environmental emissions, and economic operational costs in various European localities provides guidelines for the sustainability and energy efficiency of different heating systems. The evaluation considered the heating degree days and compared gas boilers and air-to-air heat pumps in apartments and single-family houses.

The choice of investigating the savings that can be achieved by using air-to-air heat pumps instead of natural gas boilers was based on the consideration that many homes, especially in warmer climates, are equipped with individual cooling appliances that can also be used as heat pumps for heating. The aim of the analysis was therefore to quantify the energy savings and environmental benefits of using heat pumps instead of fuel boilers, without the investment costs of installing new systems, apart from electric radiators in bathrooms. When adopting solutions with air-to-air heat pumps, it is important not to overlook the contribution to energy consumption of towel warmers installed in bathrooms, as they can reduce the economic and energy savings associated with these energy efficiency solutions. Furthermore, except for the bathroom, it was assumed that each room was equipped with an indoor unit so that the comfort of the home was close to that obtained with a gas boiler.

The environmental impact analysis showed that air-to-air heat pumps in all localities had consistently lower operating emissions per unit area compared to gas boilers, supporting the transition to more sustainable heating solutions. For apartments in locations with milder climates, the estimated annual CO_2 emissions were reduced by 40% to 51%. In sites with colder climates, the reduction ranged from 31% to 46% per year. For single-family houses in locations with milder climates, annual reductions in CO_2 emissions ranged from 57% to 65%. In cities with colder climates, reductions in CO_2 emissions ranged from 50% to 62% per year. The case study of the single-family house highlights a greater potential for environmental savings compared to apartments. The use of air-to-air heat pumps proves particularly convenient in locations with milder climates, where outdoor air temperatures ensure higher efficiencies. In terms of avoided CO_2 emissions, the analysis with emission factors differentiated for European countries highlighted the importance of renewable energy sources in the electricity generation mix.

However, in terms of the amount of energy saved, the potential is most evident in cold locations, where the starting consumption is very high, with high-efficiency heat pumps showing clear advantages over models with lower efficiencies.

Using air-to-air heat pumps combined with additional towel warmers in bathrooms proved highly effective in achieving significant savings in non-renewable primary energy across different locations. For apartments, this technology delivered substantial annual energy savings: in milder climates, savings ranged from 34% to 47%, while in colder climates, savings ranged between 24% and 41% annually. Similarly, in single-family houses, air-to-air heat pumps demonstrated even greater efficiency: locations with milder climates achieved energy savings between 53% and 62%, whereas locations with colder climates achieved savings between 46% and 58% per year.

Also, in economic terms, this study highlights the operational cost-effectiveness of air-to-air heat pumps. Heat pump 3, with a COP in standard conditions of 4.55 (technical data in Table 8), stood out as the most economically efficient option in all climates, offering substantial savings (which were more consistent for the case study relating to the single-family house). However, the economic viability was influenced by the electricity-to-gas cost ratio, emphasizing the need for strategic decision-making based on this crucial factor. Financial assistance programs should aim to reduce obstacles to investing in heat pumps and prioritize the adoption of highly efficient systems, considering building-specific factors that encompass cost, efficiency, and climate impact.

In conclusion, the use of air-to-air heat pumps proved to be cost-effective in all locations considered. No mention was made regarding the possibility of covering the needs of heat pumps with renewable energy production systems, such as solar photovoltaic systems, which would further increase convenience. Furthermore, this research did not address the aspects of comfort and the possibility of installing technologies other than air-to-air heat pumps (including air-to-water heat pumps or geothermal heat pumps) as part of an energy requalification of the building involving the replacement of the existing systems. In fact, this study only assessed the opportunity to use the heat pumps already installed for cooling as the main heating system, which included adding towel warmers for bathrooms.

It is obvious that achieving the challenging energy transition goals set by Europe to reach climate neutrality by 2050 will require a mix of technologies and that air-to-air heat pumps are only one of the possible solutions available.

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Nomenclature

APA:	Apartment
COP:	Coefficient of Performance
EU:	European Union
HP:	Heat Pump
PI:	Power Input in kW
SFH:	Single-Family House
TC:	Total Capacity in kW
SCOP:	Seasonal Coefficient of Performance

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