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How the Energy Price Variability in Italy Affects the Cost of Building Heating: A Trnsys-Guided Comparison between Air-Source Heat Pumps and Gas Boilers

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Abstract: The paper investigates the variation in building thermal energy demand for different indoor air set-point temperature and presents an economic analysis comparing the cost of a heating generation system based on an air-to-water heat pump and a gas boiler. Dynamic simulations were performed considering three different residential building characteristics of the Italian building stock placed in different Italian municipalities: Milan, Rome and Naples. An economic analysis was carried out considering the gas and electricity prices related to the years 2019–2022 provided by Italian Regulatory Authority for Energy, Networks and Environment (ARERA). The analysis showed the competitiveness of the heat pump compared with the gas boiler as a heating generation system in terms of annual costs for heating in almost all the scenarios considered and also showed an important reduction in building thermal energy demand if the set-point temperature was reduced, even by 1 °C.

Keywords: heat pump; energy price; economic analysis; dynamic simulation; energy crisis

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1. Introduction

The 2018/844/EU directive [1] reports that 50% of the Union's final energy consumption is employed for heating and cooling, of which 80% is used in buildings. Moreover, the directive promotes renovation strategies to reach the 2050 EU climate targets. In the European Union, in fact, buildings are responsible for approximately 36% of carbon dioxide emissions. Several studies propose different energy retrofitting strategies and the estimation of considered investments [2,3], mostly considering heat pumps as generation systems for heating and cooling buildings.

Wang et al. [4] proposed a systematic literature review of heat pumps applied in the residential sector and their roles in achieving the nearly Zero Energy Buildings (nZEB) target and decarbonizing the energy sector. For cost savings and increased photovoltaic self-consumption, they also analyzed heat pumps paired with thermal storage systems and heat pumps integrated with solar PV systems. With the aim of reducing carbon dioxide emissions by deciding the utilization strategies of a heat pump for heating a building, a recent study by Valdiserri et al. [5,6] proposed a method to evaluate the CO_2 emissions generated when a common electric device is connected to the grid. In the context of reducing carbon dioxide emissions, it is also important to consider that the energy price has risen since 2021, and for this reason, European countries impose measures to reduce primary energy consumption. For instance, in Italy, the minister of ecological transition recently signed a new decree [7] that imposes (i) the reduction of 1 °C in buildings and (ii) a reduction in the period when heating systems can be switched on. As mentioned, most studies on this topic focus on the primary energy saving in buildings using ground- or air-source heat pumps as generation systems, replacing old boilers or employing hybrid systems. Beccali et al. [8] reviewed hybrid systems using electrical heat pumps assisted by gas boilers for heating and domestic hot water production. Their comprehensive review focused on the importance of control strategies; different studies showed that hybrid systems could be very advantageous if the integration or switch of the two generators is well managed. In this context, a recent case study in southern Italy [9], where a rule-based control algorithm was applied, showed energy flexibility's importance in the building design and retrofit process. Moreover, Beccali et al. [8] remarked that climate can influence the performance of a heat pump. As demonstrated by many researchers [10–12], the climatic and installation conditions affect the entire system's performance. Carrol et al. [10] found three main areas of focus within this framework: defrosting management, ASHP system management and ASHPs as smart grid demand response components. Rossi di Schio et al. [13] performed a Trnsys analysis of three different Italian municipalities to evaluate how experimental climate data affect defrosting cycles in air-source heat pumps. Their study showed that neglecting the effect of defrosting yields the tendency to underestimate the electric energy consumption of heat pumps by up to 10%.

In the literature, some works focus mainly on the economic relevance of a heat pump as an alternative to a gas boiler for residential building heating. The study by Ruffino et al. [14] showed that heat pumps are competitive against gas boilers, but also that they are heavily dependent on refurbishment incentives and penalized by the high electricity prices in Italy. Ala et al., in [15], presented an energetic and economic analysis of using heat pumps instead of gas boilers in the south of Italy; the results showed that the competitiveness of the heat pump with respect to a gas boiler is mainly influenced by the amount of thermal energy demand of the building. In 2020, Barnes and Bhagavathy [16] asserted that in the UK scene, there is weak economic competitiveness of the heat pump compared with the gas boiler due to the taxes and levies that are heavily applied to domestic electricity bills compared with gas bills. As discussed in [4], heat pumps associated with a photovoltaic system could be an interesting alternative in nZEBs. Moreover, as highlighted in [17], a step-by-step approach to achieving nZEB status must be carried out with a perspective on the cost to identify a better energy solution.

In a few papers, attention is paid to the analysis of costs [18–20]. In particular, in [18], two cost estimation methods, i.e., the Levelized Cost of Energy (LCOE) and the Energy System Analysis (ESA) methods, were introduced and were compared for electricity, decentralized heating and district heating technologies, with reference to two system configurations of the German energy system. Fakhri et al. [19] referred to Sweden, and Busato et al., to Italy [20].

In the authors' opinion, it can be useful to characterize the effectiveness of the two different heating generation systems, determining the cost-effective management of heat pumps compared with gas boilers, in a situation globally characterized by an energy crisis and an increase in energy prices. In the present paper, indeed, a comparison is presented, referring to the Italian scenario and considering the gas and electricity prices related to the years 2019–2022 provided by Italian Regulatory Authority for Energy, Networks and Environment (ARERA). In detail, a single-family house was investigated, with three different envelope components and placed in three different municipalities, i.e., climatic conditions. The energy requirement was numerically evaluated, for all the considered cases, using a dynamic simulation performed with Trnsys. For all the considered cases, a comparison between an air-to-water heat pump and a gas boiler was conducted with special regard to the costs of energy consumption, evaluated using the official prices provided by ARERA.

2. Energy Analysis

This paper investigated the behavior of a single-family house with three different building envelope components, in three different climates. The choice of three different envelope components corresponded to three different building typologies, referring to different construction period habits. Moreover, in order to present general results that can be applied to approximately the entire Italian territory, the building's behavior modeled in three different climates was investigated.

2.1. Building

In Figure 1, the layout of the considered residential building is shown. We investigated a single-family house characterized by a floor area of 80 m^2 and a volume of 240 m^3. The building considered displays six different thermal zones: two rooms (R1 and R2), a living room (LR), a kitchen (K), a bathroom (BA) and a corridor (CO). The total window surfaces are reported in Table 1. Three different sets of building envelope components, reported in Tables 2 and 3, were investigated to better fit the real characteristics of an important part of buildings built in Italy in the last decades. The envelope elements of building B1 in Tables 2 and 3 are typical of Italian buildings built in years 1970–1990; conversely, the envelope components of buildings B2 and B3 are characteristics of more recent Italian residential constructions.

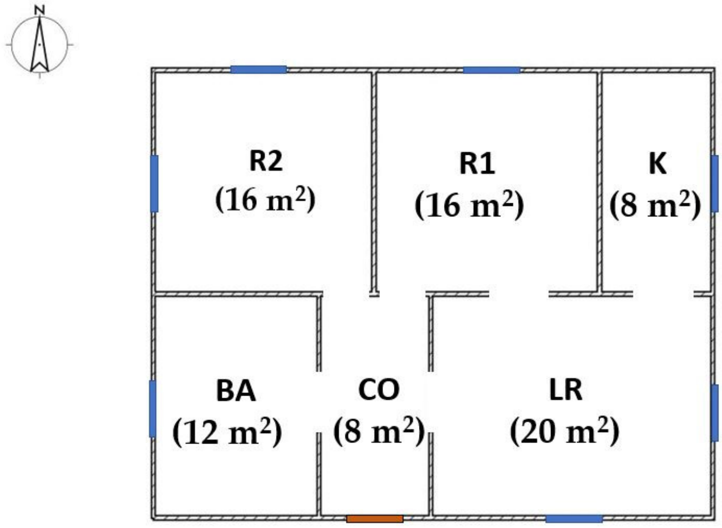

Figure 1. Layout of the single-family house analyzed.

Table 1. Window area by exposition for the single-family house.

Exposition	Window Area (m^2)
North	4.08
East	4.08
South	2.04
West	4.08

Table 2. Stratigraphy of most important building envelope components for the three buildings considered.

		Layer	Thickness (m)	Conductivity (W/(mK))
B1	External walls	Plaster	0.015	0.70
		Brick	0.120	0.50
		Air layer	0.080	-
		Brick	0.120	0.50
		Plaster	0.015	0.70
	Roof	Plaster	0.015	0.70
		Concrete	0.150	0.47
		Air layer	0.080	-
		Tiles	0.050	1
	Floor	Paving	0.020	0.17
		Light concrete	0.100	0.32
		Concrete	0.100	0.47

Table 2. *Cont.*

		Layer	Thickness (m)	Conductivity (W/(mK))
B2 (B3)	External walls	Plaster	0.015	0.70
		Brick	0.120	0.50
		Insulant	0.040 (0.120)	0.04
		Brick	0.120	0.50
		Plaster	0.015	0.70
	Roof	Plaster	0.015	0.70
		Concrete	0.150	0.47
		Insulant	0.050 (0.120)	0.04
		Tiles	0.050	1.00
	Floor	Paving	0.020	0.17
		Light concrete	0.100	0.32
		Insulant	0.040 (0.120)	0.04
		Concrete	0.100	0.47

Table 3. Transmittance values of building envelope components for the three different buildings considered.

	B1 (W/m^{2}K)	B2 (W/m^{2}K)	B3 (W/m^{2}K)
External walls	1.160	0.620	0.277
Roof	1.370	0.552	0.281
Floor	1.230	0.552	0.262
Internal walls	1.950	1.950	1.950
Windows	1.620	1.620	0.500

Internal gains related to occupation and electric equipment according to IEA SHC Task 44 [21] were considered, and the hourly profiles (the same for each day of the simulation performed) are shown in Figure 2; task 44, in fact, provides common boundary conditions for the dynamic simulations of heating and cooling systems coupled with buildings.

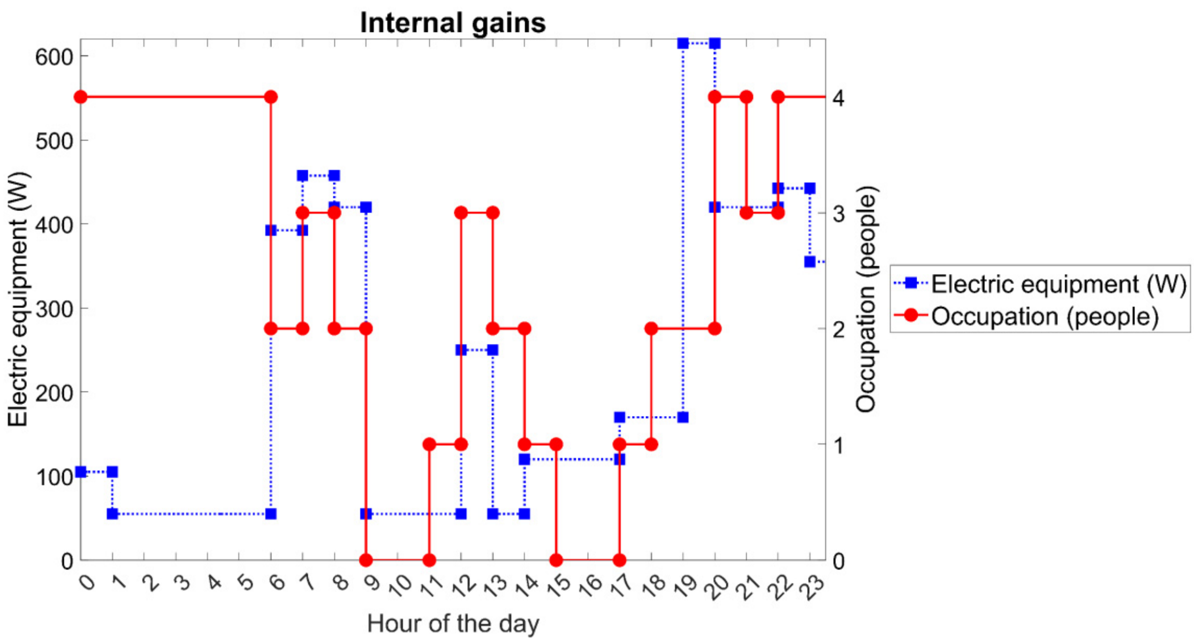

Figure 2. Internal gains related to occupation and electric equipment. The hourly profile was the same for all days of the heating season. A power of 60 W per person was considered, given by 40 W radiative and 20 W convective gains.

The behavior of the three buildings (B1, B2 and B3) was modeled by virtually placing them in three different Italian municipalities: Milan (45°28′ N, 9°11′ E), Rome (41°54′ N, 12°29′ E) and Naples (40°21′ N, 14°15′ E). The three municipalities are characterized by different climates; therefore, each of them presents different winter design temperatures (t_{des}), different heating degree days (*HDD*) and different standard periods for the operation of the heating system, as reported in Table 4. In Table 4, the thermal power requested by the three buildings ($P_{th,des}$) at the corresponding winter design temperature of the respective municipality is also reported.

Table 4. Winter design temperature, *HDD* and heating system operation period characteristics of the three municipalities considered.

City	t_{des} (°C)	*HDD*	Heating Period	$P_{th,des}$ (kW)		
				B1	B2	B3
Milan	−5	2404	15 October–15 April	10	6.6	4.5
Rome	0	1415	1 November–15 April	8.2	5.5	3.8
Naples	2	1034	15 November–31 March	7.5	5	3.6

2.2. Heating System

The building presented five fan-coils as emitters for the thermal abovementioned zones, LR, K, R1, R2 and BA, while the corridor (CO) had no terminal emitter. In Figure 3, the layout of the heating system is sketched; there was a thermal storage tank of 0.1 m^3 connected to the fan-coils and to the generator, which was an electric air-to-water inverter heat pump.

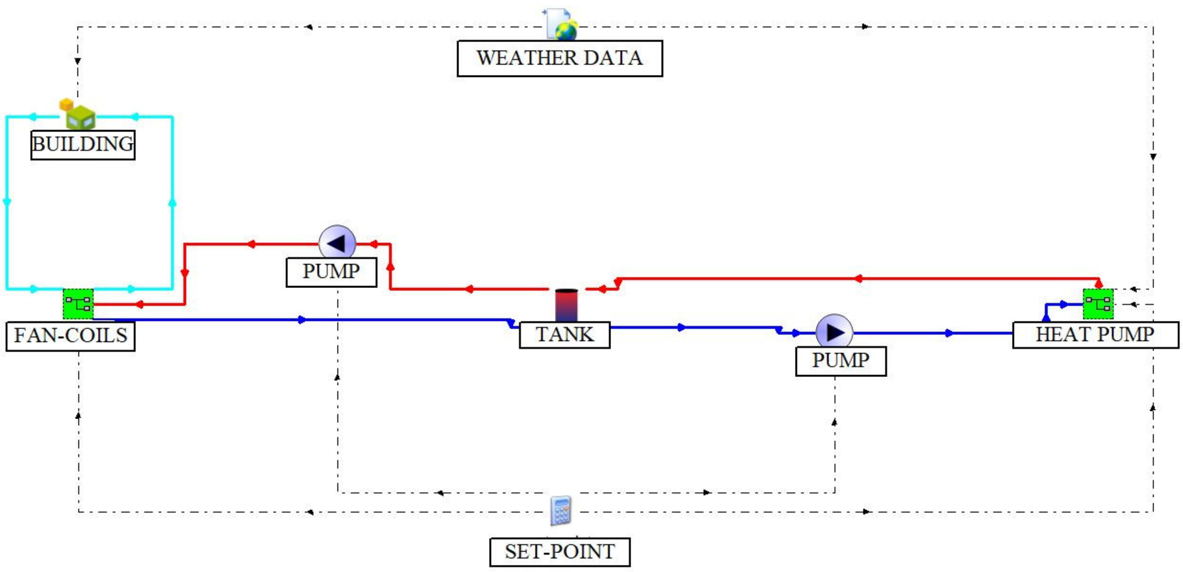

Figure 3. Layout of the heating system.

The air-to-water heat pump in all the dynamic simulations was sized to satisfy the thermal power requested by the building under the design winter conditions (reported in Table 4); nine different heat pumps, in order to satisfy the load of the nine buildings into account, were considered. In Figure 4, the thermal power output and the coefficient of performance (*COP*) of the heat pump are reported for building B1, placed in Milan, at different inverter frequencies. The other heat pumps presented the same *COP*, but a different thermal output, scaled by a factor; to better explain, the heat pump employed for building B1 in Milan guaranteed a maximum thermal power of 10 kW when it operated at an air outdoor temperature of −5 °C, while the heat pump for the building B1 placed in Naples guaranteed a maximum thermal power of 7.5 kW when the outdoor temperature was 2 °C.

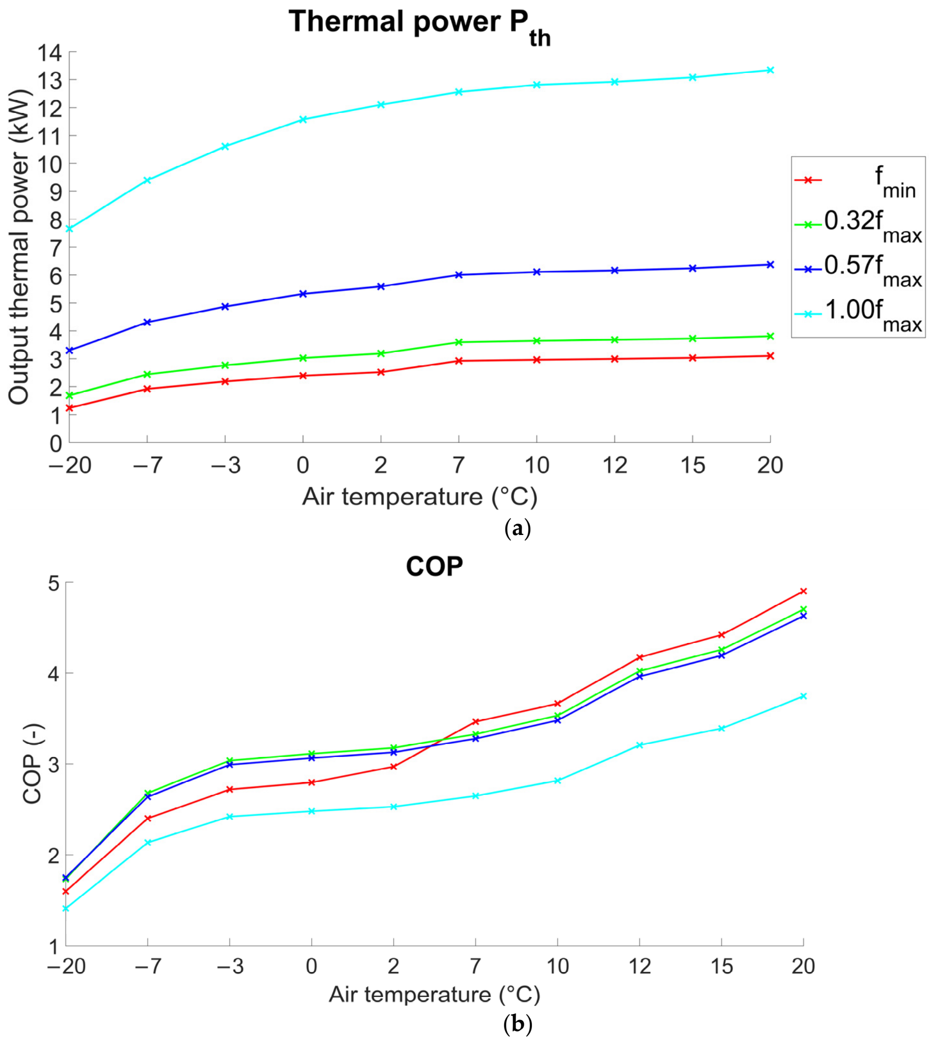

Figure 4. Thermal power output (**a**) and *COP* (**b**) characteristics of the heat pump installed as a generation system in building B1 located in Milan.

2.3. Dynamic Simulation Set-Up and Parameters

Dynamic simulations were carried out using Trnsys software, version 17, [22,23], in order to determine the thermal and electric energy demand of the heat pump during the heating season. The building was modeled by means of type 56 multizone building [22], while the heat pump was modeled by means of types that permit interpolation between given values; in fact, the *COP* and the output thermal power of the heat pump were known for different inverter frequencies, as reported in Section 2.2. The simulation timestep was set to 30 s, and a total of 27 dynamic simulations were performed, considering the three different buildings placed in the three different municipalities and considering a different set-point temperature t_{set} of the building thermal zones as reported in Table 5; the values were 20 °C, 19 °C and 18 °C, except for zone BA (bathroom), in which the set-point was set to 22 °C in scenario S1. The decision to conduct analyses considering different indoor air set-point temperatures from the typical comfort temperature of 20 °C came from the recent disposition of Italian government that imposes the reduction in temperature in residential buildings, in response to the energy crisis [7]. Results from the dynamic simulations are useful to establish the reduction in thermal energy demand for the three buildings in the municipalities into account and are presented in Section 4.1.

Table 5. Set-point temperatures of thermal zones of the building.

Scenario	t_{set} (°C)—Zone BA	t_{set} (°C)—Other Zones
S1	22	20
S2	19	19
S3	18	18

3. Economic Analysis

In this section, the set-up of the economic analysis performed is presented, aiming to determine the competitiveness of the heat pump with respect to a gas boiler for building heating.

We supposed to compare the annual cost of electricity demand of the heat pump (obtained with the 27 dynamic simulations performed) to the annual cost of the gas that a gas boiler requires. In particular, in all the 27 cases, a gas boiler that presented an efficiency (η) of 0.88 and a lower heating value of the gas (LHV) of 9.5 kWh/Sm^3 was considered.

3.1. Data for the Analysis

Data related to prices of electricity and gas were obtained by Italian Regulatory Authority for Energy, Networks and Environment (ARERA) [24,25]. In Italy, household customers can choose, for electricity and gas supply, between market offers and standard-offer market. In the first case, the gas/electricity price is regulated by the agreement signed between the customer and the energy provider, and the price per unit (EUR/kWh for electricity or EUR/Sm^3 for natural gas) can be fixed for a certain period or can be variable. In the case of the standard-offer market, the price of electricity and gas is variable and is established by ARERA every 3 months. According to the ARERA report [26], 41.5% of household customers in 2021 had a standard-offer market for electricity and 34.6% for natural gas. Due to the large variability of electricity and gas prices in the market offers, this analysis considered the price defined by Italian Regulatory Authority from the year 2019 to the year 2022; therefore, the analysis results refer to the "standard-offer market" prices; however, as reported above, this reflects the gas and electricity prices paid by an important part of the total Italian household customers.

In this analysis, the "fixed costs" (i.e., costs that cannot be related to the unit of energy, such as the annual cost of the gas flow/electricity meter) were not considered. More in detail, the unit electricity and natural gas prices analyzed consist of four components, as stated by ARERA: energy price, transportation and meter-management price, system charges and taxes (excise duties and VAT).

Focusing on the electricity price, Figure 5 shows that the cost of electricity hugely increased starting from the final quarter of the year 2021 to the final quarter of the year 2022 (from 0.190 EUR/kWh to 0.674 EUR/kWh). If we considered the entire analyzed period (2019–2022), it could be also observed that the price component shares strongly changed; during the year 2019, the energy price and system charges showed approximately the same share in the composition of final unitary electricity price (30–45% for both), while during the last year, the energy price component was the largest part, reaching up to 84% of the unitary electricity price. Furthermore, it could be observed that starting from final quarter of 2021, the share of system charges was 0%, because the Italian government eliminated them for customers, in order to limit the electricity price increase.

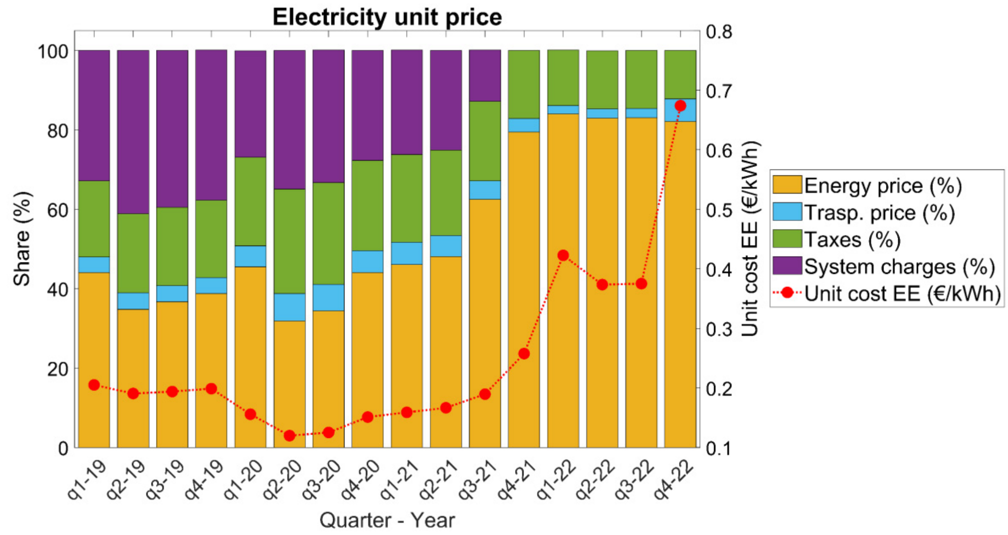

Figure 5. Unit electricity price (EUR/kWh) and price component share (%), period of 2019–2022.

Regarding natural gas unitary price over the last three years (Figure 6), an important increase starting from the last quarter of the year 2021 until the entire 2022 (from 0.745 EUR/Sm^3 to 1.191 EUR/Sm^3) could be noticed, similarly to the electricity price. In the natural gas case, the energy price component and the taxes were the most important components in terms of shares, up to the third quarter of 2021; later on, the energy price component became predominant. To limit the gas price increase, two measures were adopted by Italian government, starting from the last quarter of 2021: the reduction in VAT on gas from 22% to 5% and the elimination of the system charges (in some cases, giving them negative values, as can be observed in Figure 6). Concerning the analysis of unitary gas prices, three relevant aspects were considered and should be briefly explained:

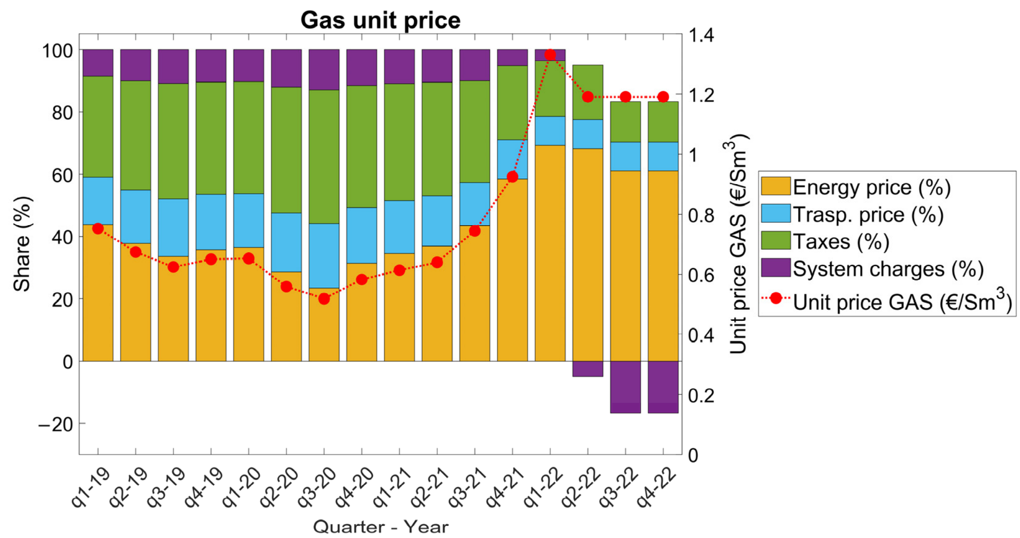

Figure 6. Unit gas prices (EUR/Sm^3) and price component shares (%), period of 2019–2022. The figure refers to unit gas prices for Milan.

- Starting from October 2022, ARERA decided to update the gas price for the standard-offer market monthly, to better define its real price, in relation to the possible fluctuations that characterize the market after the beginning of the 2021 global energy crisis. At the time of writing this manuscript, only gas prices up to 30 October 2022 defined by ARERA were available; therefore, in the economic analysis of the last two months of 2022, the gas prices used referred to October 2022.

- The unitary gas price in the standard-offer market varies in relation to the gas amount consumed during the year by household costumers; some progressive consumption bands were defined by Authority (the 1st band refers to yearly gas consumption up to 120 Sm^3, the 2nd band between 121 and 480 Sm^3 and the 3rd band between 481 and 1560 Sm^3 [25]) and were thus considered in the economic analysis.
- Unlike the electricity price, which is the same for the entire Italian territory, the gas unit price varies across the Italian territory because of different local taxation on natural gas. Generally, the gas price tends to be cheaper in the north of Italy and more expensive in the center and south of Italy. In this study, the different gas unit prices due to the different local taxation were considered, and Figure 7 reports the different unitary gas prices for Milan, Rome and Naples [27].

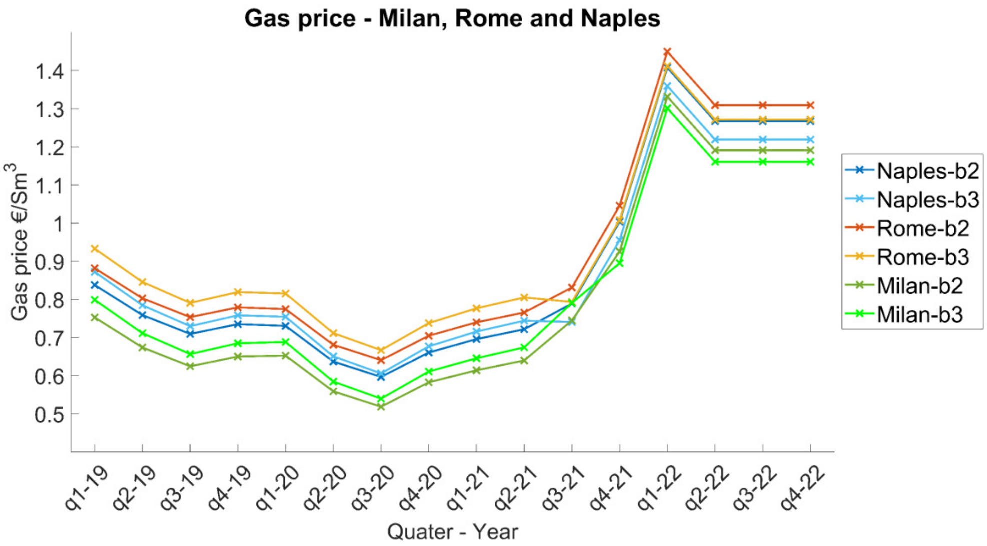

Figure 7. Unit gas prices (EUR/Sm^3) for Milan, Rome and Naples (2nd and 3rd consumption bands).

4. Results

In Section 4.1, the results obtained with the dynamic simulations are presented, focusing in particular on the thermal and electric energy differences arising from a different building's set-point temperature; in Section 4.2, attention is paid to the economic analysis, i.e., the determination of energy costs for the heating season in the cases of a heat pump and of a gas boiler.

4.1. Energy Analysis Results

In Table 6, the results of the dynamic simulations performed are reported. *ET* refers to the annual thermal energy demand of the building; *EE* refers to the annual electric energy demand of the heat pump; *EP* is the annual thermal energy demand of the corresponding building referred to the floor area; *SCOP* is the seasonal coefficient of performance of the heat pump considered, defined as the ratio between the heat pump thermal energy output and the total electric energy input during the heating season. In Table 6, the annual gas consumption, V_{gas} (Sm^3), is also reported, considering the case in which the building heating demand (*ET*) is supplied by a gas boiler, instead of a heat pump. The gas consumption is determined as

$$V_{gas} = \frac{ET}{\eta LHV}, \quad (1)$$

where *LHV* is the lower heating value of natural gas.

Table 6. Results from dynamic simulations performed. Values reported refer to the entire heating season.

Municipality	Building	Set Point	*ET* (kWh)	*EE* (kWh)	*EP* (kWh/m²y)	*SCOP* (-)	V_{gas} (Sm³)
Milan	B1	S1	11,045	3334	138	3.31	1321
		S2	9741	2941	122	3.31	1165
		S3	8844	2676	111	3.30	1058
	B2	S1	5977	1807	75	3.31	715
		S2	5138	1569	64	3.27	615
		S3	4599	1418	57	3.24	550
	B3	S1	2797	855	35	3.27	335
		S2	2251	699	28	3.22	269
		S3	1945	621	24	3.13	233
Rome	B1	S1	6430	1796	80	3.58	752
		S2	5232	1470	65	3.56	617
		S3	4482	1269	56	3.53	530
	B2	S1	3014	850	38	3.55	356
		S2	2275	650	28	3.50	270
		S3	1855	540	23	3.44	220
	B3	S1	1104	317	14	3.49	131
		S2	725	212	9	3.42	85
		S3	541	161	7	3.35	63
Naples	B1	S1	6417	1786	80	3.59	739
		S2	5208	1454	65	3.58	609
		S3	4450	1251	56	3.56	523
	B2	S1	3052	857	38	3.56	358
		S2	2286	648	29	3.53	270
		S3	1849	531	23	3.48	219
	B3	S1	1123	319	14	3.52	132
		S2	739	213	9	3.46	86
		S3	547	161	7	3.40	63

4.2. Economic Analysis Results

In Table 7, the economic analysis results are reported, considering electricity and gas prices provided by ARERA and discussed in the previous section and employing the electricity demand in the case of a heat pump generation system for heating or the gas demand in the case of a gas boiler as the heating generation system. For each case, in Table 7, the annual costs for the two alternative generation systems (C_{GAS} (EUR/y) for the gas boiler and C_{EE} (EUR/y) for the heat pump) is reported, obtained using the following equations:

$$C_{GAS} = \sum_i V_{gas,i} \cdot uc_{GAS,i} \tag{2}$$

$$C_{EE} = \sum_i EE_i \cdot uc_{EE,i}. \tag{3}$$

Table 7. Economic analysis results, years 2019–2022: yearly costs for the two different heat generation systems.

			2019		2020		2021		2022	
Municipality	Building	Set Point	C_{GAS} (EUR/y)	C_{EE} (EUR/y)	C_{GAS} (EUR/y)	C_{EE} (EUR/y)	C_{GAS} (EUR/y)	C_{EE} (EUR/y)	C_{GAS*} (EUR/y)	C_{EE} (EUR/y)
Milan	B1	S1	979	674	854	510	986	661	1646	1735
		S2	864	595	754	450	868	582	1454	1528
		S3	784	541	684	410	787	529	1322	1390
	B2	S1	526	366	460	277	532	357	895	938
		S2	452	318	395	241	457	309	771	814
		S3	404	287	353	218	408	279	692	735
	B3	S1	242	173	212	131	248	168	423	443
		S2	193	141	170	107	199	138	342	363
		S3	166	126	146	96	172	123	296	323

Table 7. *Cont.*

			2019		2020		2021		2022	
Municipality	**Building**	**Set Point**	C_{GAS} (EUR/y)	C_{EE} (EUR/y)	C_{GAS} (EUR/y)	C_{EE} (EUR/y)	C_{GAS} (EUR/y)	C_{EE} (EUR/y)	C_{GAS*} (EUR/y)	C_{EE} (EUR/y)
Rome	B1	S1	654	357	579	270	655	351	1026	923
		S2	534	294	473	223	538	289	843	762
		S3	458	255	406	193	463	251	726	661
	B2	S1	304	170	270	129	311	168	491	441
		S2	228	131	203	99	236	129	374	340
		S3	185	109	164	83	192	107	306	282
	B3	S1	110	64	97	48	113	62	182	164
		S2	72	42	64	32	74	41	119	109
		S3	53	32	47	24	55	31	88	83
Naples	B1	S1	603	350	529	266	605	343	974	904
		S2	495	288	435	219	499	283	804	746
		S3	425	250	373	190	429	245	693	645
	B2	S1	288	171	254	130	294	167	477	440
		S2	216	130	191	99	223	127	363	335
		S3	175	107	154	81	179	104	295	275
	B3	S1	105	64	93	48	108	62	178	163
		S2	69	42	60	32	70	41	116	108
		S3	50	32	44	24	51	31	85	81

* Considering the gas price as reported in Section 3.1.

In Equation (2), $V_{gas,i}$ (Sm^3) is the gas consumed by the gas boiler in the *i*-th quarter of the heating season, and $uc_{GAS,i}$ (EUR/Sm^3) is the unit gas cost of the *i*-th quarter; analogously, in Equation (3), EE_i (kWh) is the electricity consumption of the heat pump in the *i*-th quarter, and $uc_{EE,i}$ (EUR/kWh) is the unit electricity cost of the *i*-th quarter considered.

5. Discussion

5.1. Energy Analysis Discussion

Let us first focus on the energy analysis. Table 6 shows that the reduction of 1 K in the indoor temperature (cases in S2 with respect to cases in S1) led to a reduction in thermal energy demand of the building in all cases, but in particular, the percentage reduction was higher for buildings B2 and B3 (the percentage reduction for B1 in Milan was 11.8%, while for B2, it was 14.1%, and for B3, it was 19.5%). Therefore, it can be stated that the major reduction emerged for buildings that presented lower *EP*. It could also be observed that for the same building, the reduction was higher in mild climates (Rome and Naples) than in Milan; for instance, for building B1 in Milan, the thermal energy demand reduction was 11.8%, for Rome, it was 18.6%, and for Naples, it was 18.8%. Table 6 shows that the same conclusion could also be drawn considering buildings B2 and B3 in the three climates.

Now, focusing on a reduction in the indoor set-point temperature of 2 K, another important reduction in thermal energy demand could be observed, especially for buildings B2 and B3, in mild climates (the percentage reduction for B1 in Milan was 19.9%, while the maximum percentage reduction was observed for building B3 in Rome and Naples, reaching 51%).

Moreover, considering the thermal energy difference, in absolute value, between scenarios S1 and S2, building B1 displayed a major reduction with respect to buildings B2 and B3; the thermal energy demand of building B1 in Milan and under condition S1 was 1304 kWh/year lower than the same building under condition S2; for Rome, the reduction for B1 was 1198 kWh/year, and for Naples, 1209 kWh/year. Therefore, we could assert that the energy demand reduction in absolute values was higher for building B1 in all the municipalities considered, compared with buildings B2 and B3.

Concerning Table 6, let us now focus on the *SCOP* of the heat pump for all 27 simulations. As predictable, *SCOP* was higher for heat pumps installed in mild climates (Rome and Naples) than in colder climates (Milan). *SCOP* values for Milan ranged from 3.13 to 3.31, while for Naples, the range was 3.40–3.59. Moreover, for the same municipality, the *SCOP* generally decreased for buildings with lower *EP* and minor thermal energy demand

(B2 and B3); this may have been attributed to the efficiency decrease of the heat pump, which performs on–off cycles due to a building's low energy demand.

5.2. Economic Analysis Discussion

In Table 7, the yearly costs for the two different heat generation systems are reported for the years 2019–2022. From an economic point of view, the heat pump was almost, in all cases, the best generation system with respect to the gas boiler. The higher annual cost difference between the two systems was obtained from building B1 in Milan; for the year 2020, the difference was EUR 344. Smaller differences were obtained from building B3 in all the climates.

In Figure 8, the annual fuel cost differences between the gas boiler and the heat pump are reported for the years 2019–2022 in scenario S1. A general reduction in yearly fuel cost difference could be observed in the year 2022, corresponding to a minor economic benefit if adopting a heat pump with respect to a gas boiler. Moreover, the heat pump was more convenient than the gas boiler, except for buildings placed in Milan, i.e., the coldest climate investigated in the present analysis, for the year 2022.

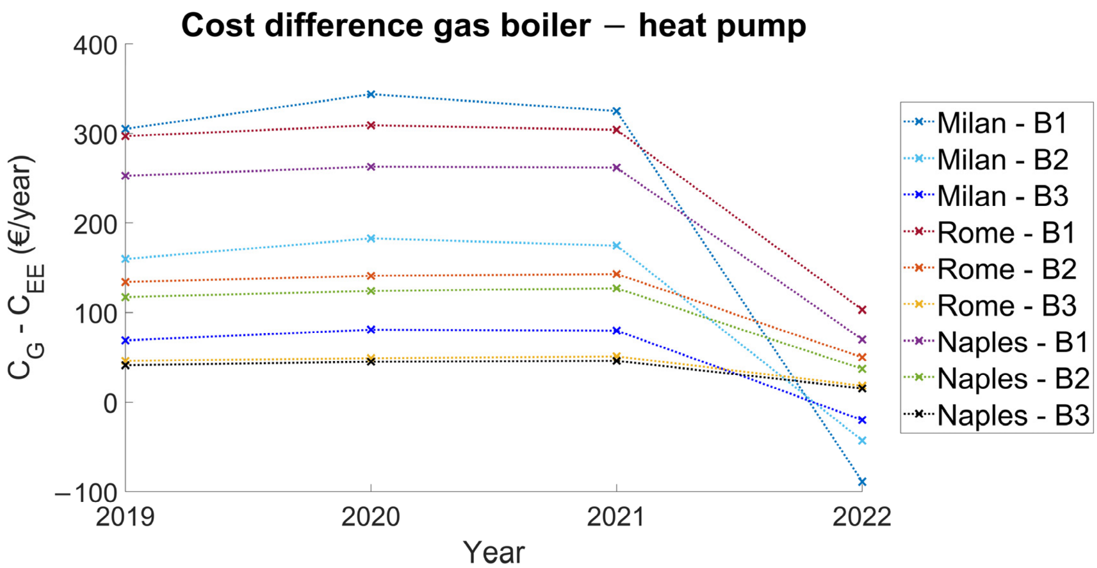

Figure 8. Yearly cost difference between gas boiler and heat pump; the figure refers only for cases in S1.

Lastly, Table 7 shows that the reduction of 1 K in the indoor set-point temperature reflected economic savings with both heating generation systems.

6. Conclusions

In the present paper, an analysis of the variation in building thermal energy demand for different indoor air set-point temperatures was conducted, and attention was paid to a comparison of the fuel costs of a heating generation system based either on an air-to-water heat pump or on a gas boiler. Dynamic simulations were performed, considering three different residential building characteristics of the Italian building stock and placing them in different Italian municipalities (Milan, Rome and Naples). For the economic analysis, the detailed gas and electricity prices related to the years 2019–2022 provided by Italian Regulatory Authority for Energy, Networks and Environment (ARERA) were employed.

The analysis led to the following conclusions:

- The energy prices and their variability strongly affect the use costs of a heating generation system, and the dependence is affected by the climate conditions. Moreover, energy prices are affected by government choices, such as taxation, that affect the economic opportunity of a generation system versus a different one.

- For heating, the management of a heat pump always resulted to be more economic than that of a gas boiler in Rome and Naples (mild climate); in the case of Milan, i.e., a colder climate, there was no economic advantage of a heat pump with respect to a gas boiler for the year 2022, due to an important increase in the electricity price since the last quarter of 2021.
- The reduction of 1 K in the indoor set-point temperature led to important reductions in the building energy demand, especially for most isolated buildings in mild climates, in percentage; if the absolute value of energy saved was considered, the major advantage was obtained for buildings in a cold climate (Milan).

Further developments of this work may consider the analysis of other building typologies and other, different heating systems. Moreover, the analysis could be extended to the influence of cooling systems. From an economic point of view, we could consider the energy prices of other European countries that have been affected by the global energy crisis of 2021. More in detail, in fact, the role of taxation on the different fuel energy prices and the interconnection of prices of energy fuels are aspects that, among others, may affect the convenience of a heating generation system with respect to another one.

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