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Heat Pumps, Wood Biomass and Fossil Fuel Solutions in the Renovation of Buildings: A Techno-Economic Analysis Applied to Piedmont Region (NW Italy)

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Abstract: The levelized cost of heat (LCOH) and the technical feasibility in the specific context of building construction or renovation are the major drivers of users' choices for space heating and cooling solutions. In this work, the LCOH was assessed for the most diffused heating technologies in Piedmont (NW Italy): that is, fossil fuels (methane, heating oil and liquefied petroleum gas—LPG), wood biomass (wood logs and pellet) and heat pumps (air-source and ground-source), both in heating-only and in a heating and cooling configuration. A sensitivity analysis of the main LCOH drivers was performed to assess whether and how each technology is vulnerable to energy price and upfront cost changes. The results show that heat pumps are competitive against gas boilers, but they are heavily dependent on refurbishment incentives and penalized by the high electricity prices in Italy; on the other hand, wood biomasses are competitive even in the absence of incentives. The analysis confirmed that LPG and heating oil are no more competitive with renewable heating. Acting on the taxation of natural gas and electricity is key to making heat pumps the most economically convenient solution to cover the heating and cooling needs of buildings.

Keywords: LCOH; life-cycle cost; heating; cooling; heat pump; fossil fuel; biomass; greenhouse gas

Citation: Ruffino, E.; Piga, B.; Casasso, A.; Sethi, R. Heat Pumps, Wood Biomass and Fossil Fuel Solutions in the Renovation of Buildings: A Techno-Economic Analysis Applied to Piedmont Region (NW Italy). *Energies* **2022**, *15*, 2375. https://doi.org/10.3390/en15072375

Academic Editors: Cynthia Hou and Joseph H. K. Lai

Received: 7 February 2022
Accepted: 21 March 2022
Published: 24 March 2022

1. Introduction

In July 2021, the European Union adopted a challenging plan for cutting emissions, called "Fit for 55", as part of the European Green Deal [1]. "Fit for 55" aims to reduce greenhouse gas (GHG) emissions by at least 55% by 2030, compared to 1990 levels, as a step towards becoming the first climate-neutral continent by 2050. The foreseen measures are the consolidation of already existing systems, such as the EU Emissions Trading System [2], brand new mechanisms, such as the Carbon Border Adjustment Mechanism [3], and energy efficiency policies, combined with a significant increase in production from renewable energy sources (RES). The new Renewable Energy Directive (RED 2) increased the target of RES share in 2030 from 32% (as set in 2018 by the RED) to 40% [4]. Moreover, the Energy Efficiency Directive set a 39% reduction in primary energy consumption compared to 1990 through increasing efficiency. Therefore, RES are a cornerstone of European climate policies, and the EU population is aware of their importance. However, citizens see energy prices and their stability as a source of concern and, despite the fact that RES often outperform fossil fuels in the production of electricity in terms of the levelized cost of energy (LCOE) [5], the high initial investment required hinders the diffusion of renewables. The LCOE and its heat counterpart, the LCOH (levelized cost of heat), are widely used indicators of energy costs based on operational expenditure and initial investment, distributing the cost over the lifetime energy production with a discounting method [6]. The initial investment required to produce electricity from RES has decreased at a much faster pace than that for fossil fuels-based power production. For example, the LCOE of utility-scale solar photovoltaics decreased by 89% from 2009 to 2019, compared to a 33% reduction observed for gas combined cycle turbines in the same period [7,8]. Such a significant cost reduction is related to the "learning curve" of renewables, i.e., an effect of increasing installations [7,9], and this effect is therefore likely to continue in the future.

While the economic viability of electrical RES is acknowledged, this does not always apply to thermal RES for space heating and domestic hot water (DHW) production [10]. The studies available in the literature are fewer compared to those on power production. Doračić et al. (2018, 2020) presented the concept of the levelized cost of excess heat to assess the economic viability of recovering waste heat to supply a district heating network and tested it in the Croatian city of Ozalj [11,12]. Li et al. (2019) used the LCOH to find the optimal combination of CHP, biomass, and bio-oil boilers [13]. Vivian et al. (2018) evaluated the LCOH of booster heat pumps to be installed as substations in low-temperature district heating networks (15 °C to 45 °C) [14]. The economic analysis highlighted that this solution is already competitive with natural gas boilers if the low-temperature heat source is sufficiently cheap. The results of cost comparisons between technologies are often country-dependent, e.g., in the United Kingdom (UK), the LCOH of a gas boiler is lower than both an air-source (ASHP) and ground-source heat pump (GSHP) [15–17], whereas the opposite occurs in France [18], although the countries have a similar climate [19]. As pointed out by the European Heat Pump Association [20], the ratio between the unit cost of electricity and gas is critical for heat pump diffusion: the lower this ratio is, the easier it is for heat pumps to penetrate the market. Indeed, based on Eurostat data as of 2020 [21], this ratio is equal to 2.63 in France and 4.63 in the UK.

Although they are not always the most economically convenient solution, heat pumps are expected to play a relevant role in the energy transition. For instance, the Italian Integrated National Energy and Climate Plan (INECP) aims to reach 5.7 Mtoe of heat pump heat production by 2030, i.e., 12.8% of the heating demand compared to the current 4.7% (2.65 Mtoe) [22]. This choice is due to several reasons, including: (i) the wide range of applications of heat pumps in existing buildings, (ii) the absence of any pollutant emissions on site, which makes them suitable for urban areas, and (iii) their possible role as a flexible regulator of the electrical grid [23–25]. The economic convenience of heat pumps, however, is key to achieving the expected growth of this technology. As well as the above-described cost ratio between electricity and gas, the other key factor is the presence of incentives. As pointed out in several studies, the most effective way to boost the energy efficiency of buildings is represented by incentives and standards and, in particular, by performance-based incentives [26–28], whereas informative campaigns are hardly effective. Fewer studies are available on the effect of such policies on the adoption of renewable heating technologies; however, a similar effect of incentives is expected since, in both cases, they increase the economic viability of the targeted interventions.

The studies presented above provide insights into the economic viability of heating and cooling technologies. However, a recent and comprehensive comparison is missing, especially for detached houses and blocks of flats, since the few articles addressing LCOH generally deal with district heating or, when dealing with individual plants, they consider a few heating and/or cooling technologies (e.g., the aforementioned studies on heat pumps vs. gas boilers). This study aims to fill this gap and focuses on the technical feasibility and the economic viability of fossil fuels (methane, heating oil and LPG), wood biomass (logs and pellet) and heat pumps (aerothermal and geothermal) for the heating, cooling and DHW supply in the context of the refurbishment of existing buildings. In the case of heat pump, a photovoltaic (PV) system was included in the analysis and sized to meet the electrical demand of the heat pump. Existing buildings were chosen because, due to the slow renewal rate of building stock [29], they are the key to the decarbonization of the housing sector. The renovation was assumed to be realized on a single detached house and an apartment block, which are the most widespread types of buildings in Northern Italy and, especially, in Piedmont [30–32]. Two settlements representing the typical climates of the Piedmont Region, Turin and Oulx (temperate and cold continental climate, respectively), are the selected spots where model buildings are located. Our analysis included the analysis of the impact of incentives on the LCOH values of each technology, as well as the effect of considering or not the space cooling demand in the calculation of the LCOH. In addition, a sensitivity analysis was performed to evaluate the impact of variable parameters, i.e., the unit costs of energy, the installation costs of the main components and the interest rate used for discounting. This sensitivity analysis permits extending the validity of results for territories other than Piedmont (NW Italy) but with a comparable climate.

The paper is structured as follows. Section 2 describes the methodology adopted, i.e., the selection of representative case studies, the assessment of the energy demand of the buildings in different climatic conditions, the sizing of the heating and cooling systems with different techniques, and the estimation of the installation and operational costs. Section 3 presents the results, focusing on life-cycle costs and their sensitivity to possible future changes in the most influential parameters. Section 4 reports a discussion with a comparison of the results with other studies and with some insights on the diffusion of renewable heating technologies. Conclusions and policy implications are reported in Section 5.

2. Methods

The economic analysis conducted in this article is based on the thermal needs simulated for two benchmark buildings, namely a single detached house and an apartment block of 10 flats. The energy simulation of benchmark buildings and the estimation of the related thermal needs (heating, cooling and DHW) are discussed in Section 2.1. Thermal needs were used as the input for the plant sizing and the assessment of fuel demand (Section 2.2), which are, respectively, the input for estimating the initial investment (Section 2.3) and operating costs (Section 2.4). The levelized cost of heat (LCOH) was chosen as the indicator to identify the most economically convenient technologies, and the estimation method is described in Section 2.5.

The boundaries of all the economic analyses are represented by the heating, DHW and cooling systems (if any), plus the possible replacement of heating/cooling terminals. The interventions on the building envelope were not considered because this analysis aims to assess, case-by-case, the economic viability of heating and cooling technologies with the aim of supporting policies for RES-based technologies.

2.1. Benchmark Buildings and Thermal Needs Assessment

2.1.1. Choice of Representative Buildings and Locations

The techno-economic analysis was based on two representative buildings with constructive characteristics, chosen according to a review of studies on the building stock in Italy and, especially, Piedmont (NW Italy). Two EU-funded projects, TABULA and EPISCOPE [30,31], provide detailed datasets on residential buildings of different ages [32]. According to these references, 35% of buildings in Piedmont were built in the 1960s and the 1970s, and only 18% later on. For this reason, a single detached house and a small block of flats (10 apartments) with building envelope characteristics typical of the 1970s were selected as benchmarks for our study. According to TABULA and EPISCOPE [30,31], these benchmark buildings are the most representative types in Piedmont from the point of view of both structural and envelope thermal characteristics. The assigned thermal transmittance values (hereby, U-values, $Wm^{-2}K^{-1}$) of different elements of the building envelope are reported in Table 1 and compared with current legislative requirements [33], which are aimed at reducing the heating loads and, thus, at saving energy.

Table 1. Thermal transmittance (U-value, $Wm^{-2}K^{-1}$) of the benchmark buildings of this study, based on the TABULA/EPISCOPE databases [30,31], along with the current legislative requirements [33] considered for the simulation of fully refurbished buildings.

Component	Original U-Value	Climatic Zone	Required U-Value
Upper roof	1.65	E	0.20
		F	0.19
Lower floor	1.30	E	0.25
		F	0.23
Perimetral walls	1.26	E	0.23
		F	0.22
Windows	2.8	E	1.30
		F	1.00

Two types of refurbishments were hypothesized for these two buildings: a partial renovation, i.e., replacing only windows and the HVAC system, and a complete renovation of the building envelope, i.e., including an external insulation coating of external walls. Both these interventions are eligible for tax deductions, but they must comply with the legislative requirements on the transmittance of building envelope elements (U-values reported in Table 1). The partial renovation is performed, for example, on buildings where interventions on external walls are not possible due to architectural or technical constraints. On the other hand, a complete renovation makes old buildings almost as well-insulated as brand-new ones due to the very demanding Italian legislative requirements, and, as shown later, this results in a significant difference in thermal needs. Legislative requirements in Table 1, which are given by the regulation on the eligibility of building refurbishment interventions for tax deductions [33], show slightly different U-values depending on the climatic zones set by the Italian DPR 412/93 [34]. The whole territory of Piedmont falls into the two coldest zones if Italy, namely "E" and "F". For this reason, two representative climate data sets were chosen: the capital Turin (temperate continental climate) and the mountain village of Oulx (cold continental climate); based on the Italian norms, the heating degree-days (HDD) are, respectively, 2617 and 4100, calculated with a reference indoor temperature of 20 °C.

Figures 1 and 2 report the plan view of the benchmark buildings analyzed. They are modelled based on the geometrical construction characteristics of buildings suggested by the projects TABULA and EPISCOPE [30]. In more detail, the reference states that an average single detached house from the 1970s has a net floor area of 156 m^2 and a typical small apartment block of 10 housing units has an overall floor area of 934 m^2 (i.e., 187 m^2 per floor). The shape factors (surface over volume ratio) are S/V = 0.73 and S/V = 0.54, respectively. The higher the S/V value, the higher the impact of the transmittance of the building external envelope. For this reason, the thermal needs per m^2 of the apartment block (which has a more compact shape) are expected to be lower than those of the single detached house, being insulation equal. Each apartment is considered a singular thermal zone; therefore, the layout of the internal walls (Figure 2) does not affect the computation of thermal needs.

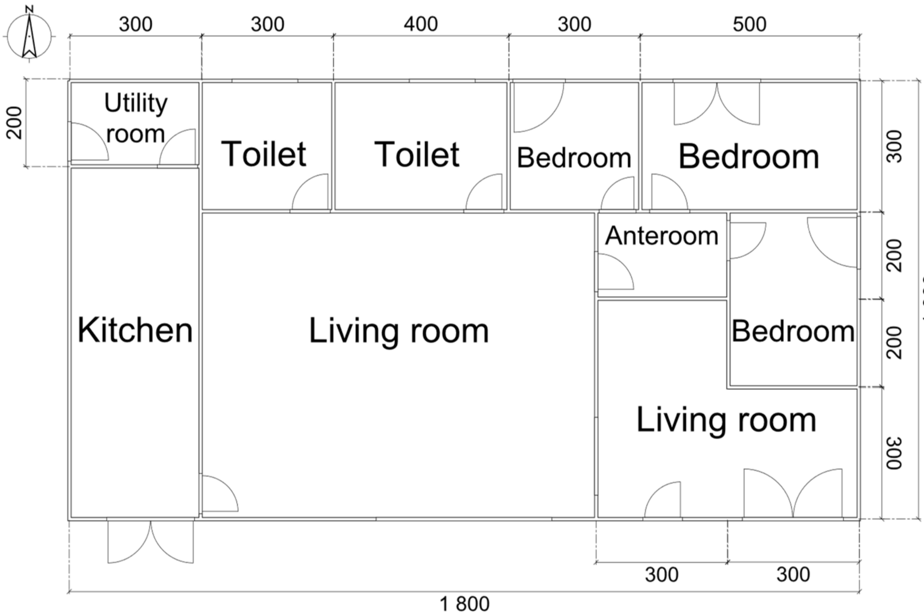

Figure 1. Plan views of the benchmark single detached house (dimensions in cm).

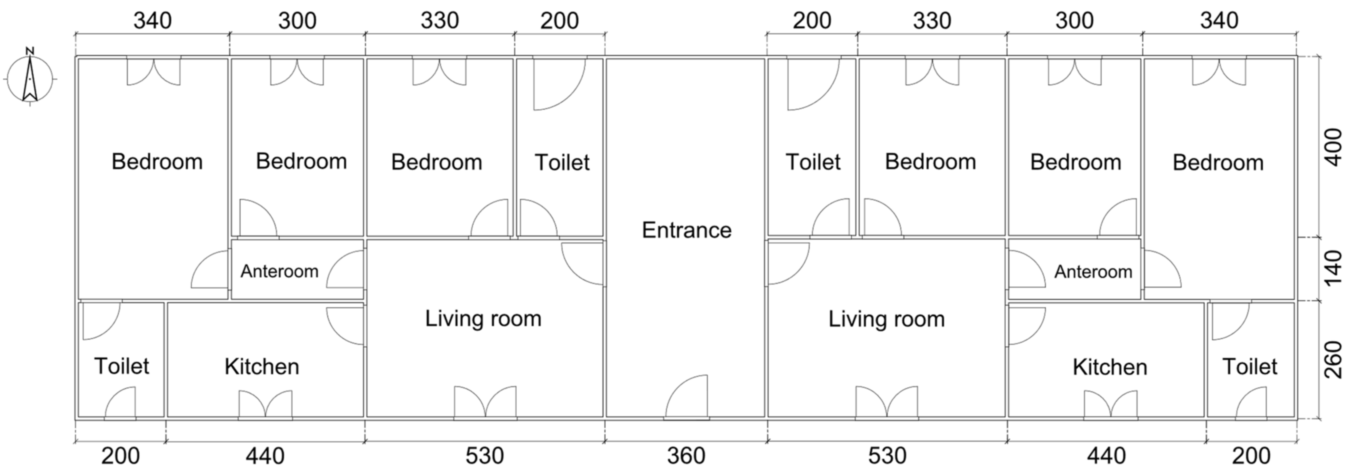

Figure 2. Plan views of one storey of the benchmark apartment block (dimensions in cm).

2.1.2. Assessment of Thermal Needs

The thermal needs (heating, cooling, DHW) of the two benchmark buildings were assessed considering three different levels of insulation (original building, partial renovation, total renovation of the building envelope) and two climatic conditions (Torino and Oulx). Therefore, 12 energy simulations were performed using the computer suite developed by ANIT [35], and they are hereby indicated as scenarios S01–S12. The ANIT package consists of several programs, among which the main one is called LETO. LETO is based on the Italian standard series UNI/TS 11300 [36], i.e., the national implementation of the international standard ISO 13790:2008 [37] and successive/related norms. The UNI/TS 11300 is prescribed by Italian law for the energy certification of every new built, refurbished, sold, or rented housing unit or building. The calculation of thermal losses from the building envelope uses monthly mean outdoor temperatures, whereas the peak thermal loads are calculated steady state using the design temperatures (minimum for heating, maximum for cooling) prescribed by the related norm UNI 10349:2016 [38]. Part 4 of the UNI/TS 11300 [36] prescribes the use of the temperature bin method to calculate the COP and EER of heat pumps and air conditioners.

Table 2 reports the yearly heating and cooling needs calculated with the software LETO for the 12 scenarios. The results of the energy simulations show that a reduction of 9–12% in heating loads is achieved with a partial renovation; instead, a more substantial reduction (73–85%) is obtained with a refurbishment of the whole envelope. Climate conditions also have an influential role, as the heating needs in Oulx are up to 58% higher than those in Turin. As expected, this percentage is in line with the difference in heating degree-days according to DPR 412/93 [34] (+56.7% in Oulx, i.e., 4100 vs. 2617), with direct consequences in the monthly energy demand (see Section 2.1 of the Supplementary Materials). On the other hand, the improvement in the building thermal insulation results in an increase in cooling needs up to +146% in the case of a total renovation of the envelope. Cooling needs are typically low in Piedmont and, not surprisingly, only 13.3% of residential buildings in this region currently have a cooling system installed [39]. Hence, our analysis first focused only on heating and DHW. Cooling loads were subsequently included, and the analysis was limited to the completely renovated buildings (S09–12) since, as shown in Table 2, they are the only ones where cooling demand is relevant.

Table 2. Heating and cooling demand (MWh/year) and, between brackets and in italics, the demand per unit heated/cooled area (kWh/m^2/year) of the modelled buildings.

Model Building	Location	Original Building			Partial Renovation			Complete Renovation		
		#	Heating	Cooling	#	Heating	Cooling	#	Heating	Cooling
Single detached house	Turin	S01	29.05 *(186.22)*	0.87 *(5.58)*	S05	26.42 *(169.36)*	0.83 *(5.32)*	S09	7.85 *(50.32)*	2.34 *(15.00)*
	Oulx	S02	42.61 *(273.14)*	0.00 *(0.00)*	S06	38.62 *(247.56)*	0.00 *(0.00)*	S10	10.96 *(70.26)*	0.51 *(3.27)*
Apartment block	Turin	S03	115.37 *(123.52)*	12.32 *(13.19)*	S07	101.25 *(108.40)*	12.53 *(13.42)*	S11	17.03 *(18.23)*	24.81 *(26.56)*
	Oulx	S04	172.89 *(185.11)*	0.68 *(0.73)*	S08	152.35 *(163.12)*	0.89 *(0.95)*	S12	26.91 *(28.81)*	13.14 *(14.07)*

2.2. Heating and Cooling Plant Sizing

Thermal needs calculated in the different buildings and climate conditions are the input for the sizing of heating, cooling and DHW production plants. Seven technologies were considered for the heating and DHW production system: a condensing boiler powered by fossil fuels (natural gas, LPG, or diesel oil) or wood biomass (wood log or pellet), and two types of heat pumps (air source and ground source). Heat pumps can cover every thermal need with a unique system; on the other hand, split air-source chillers were assumed to provide cooling in cases where fossil fuel and wood biomass boilers were installed for heating and DHW production.

The size of every heating and cooling generator was determined based on the maximum thermal loads resulting from simulations. In particular, the peak load is calculated in steady state, imposing a design temperature calculated by the software LETO using the standard UNI 10,349:2016 [38]. The resulting design temperatures for heating are −8 °C for Turin (scenarios S01, S03, S05, S07, S09, S11) and −12.84 °C for Oulx (scenarios S02, S04, S06, S08, S10, S12).

Although the peak heating power requested was lower, such as in the well-insulated case studies, the minimum capacity considered for fossil fuel and biomass boilers was about 30 kW (with slight differences depending on the brand and model) as it is the entry-level power for most manufacturers and it permits production of DHW on demand (i.e., without storage tank). On the other hand, the heat pump units were sized according to the effective values of peak heating and cooling demand.

For ground-source heat pumps, it is necessary to size the Borehole Heat Exchangers (BHEs) as well. For this purpose, the software Earth Energy Designer (EED) [40] was used, which is based on the Eskilson subsurface heat transport model [41]. Three different values of ground thermal conductivity (low: 1.6 $Wm^{-1}K^{-1}$, medium: 2.4 $Wm^{-1}K^{-1}$, high: 3.2 $Wm^{-1}K^{-1}$) were hypothesized to cover the range of most likely values [42]. A minimum operating temperature was set to −3 °C, assuming that the BHE runs with propylene glycol 25% vol. (freezing point: −10 °C) as a heat carrier fluid [43]. Supplementary Materials (Section 2.3) report further details on the sizing procedure and results. In Supplementary Materials Section S.2.3, the area occupied by the BHE field is reported as well, and this is a key figure to assess the feasibility of the shallow geothermal solution, especially in urban areas.

The benchmark buildings considered in our analysis use radiators as heating terminals. When a heat pump was hypothesized, we assessed whether existing radiators could cover the peak heating demand with an operating temperature reduced from the typical value used for boilers (average inlet–outlet 70 °C) to a lower value (inlet at 45 °C) suitable for single-stage heat pumps. The thermal power provided by a radiator is described by the relation

$$P(\Delta T) = a \cdot \Delta T^{1.3} \tag{1}$$

where a ($W{\cdot}K^{-1.3}$) is a constant that depends on the radiator size and ΔT (K) is the temperature difference between the average water temperature in the radiator and the ambient temperature (set to 20 °C). The nominal power of radiators P_{nom} is provided for $\Delta T = 50$ °C, i.e., for an average radiator temperature of 70 °C. The maximum delivery temperature for radiators working with heat pumps was set in this study to 45 °C (with the return at 40 °C) to guarantee a sufficient coefficient of performance (COP). At this operating temperature, the thermal power delivered by the radiator is

$$P(\Delta T) = P_{nom} \cdot \left(\frac{\Delta T}{50}\right)^{1.3} \tag{2}$$

Therefore, with the maximum delivery and return temperatures considered (45 °C and 40°, respectively, i.e., $\Delta T = 22.5$ °C), the nominal thermal power of radiators that is needed to cover the peak demand P_{max} is

$$P_{nom} = \left(\frac{50}{22.5}\right)^{1.3} \cdot P_{max} = 2.824 \cdot P_{max} \tag{3}$$

For each scenario, we checked if the nominal power installed was sufficient to cover the peak thermal demand and, if not, the radiators were replaced with larger ones, and their cost was considered in the economic analysis (see Section 2.3). More details on the sizing of radiators are reported in the Supplementary Materials (Section S2.2).

Of course, radiators cannot provide cooling. Therefore, when the cooling demand was included in the analysis, the existing radiators were replaced with fan coils (and their cost accounted in the LCOH calculations) in the cases of air-source and ground-source heat pumps. In the case of fossil fuel and biomass boilers, additional mono-split air conditioners were installed in each room to provide this service. The size of air conditioners is based on the peak cooling needs derived from the energy simulations.

Coupling a heat pump with radiators needs thermal storage since the working temperature difference of a heat pump is usually equal to 5 °C, whereas radiators operate with larger temperature differences (10–20 °C). The thermal storage tank was sized equal to 20 L per kW of heat pump nominal power (see Supplementary Materials, Section S2.2). In addition, hot water storage (200 L/apartment, considering four residents) is required because DHW heat pumps are not sized to produce hot water instantaneously in the same way as a boiler.

Finally, photovoltaic (PV) panels were sized considering only the actual electricity yearly demand of the thermal plant and not the consumption related to other components, such as electrical appliances. Therefore, PV panels were not simulated in the case of boilers because they require a small amount of electricity just for the ignition and the control systems. Concerning heat pumps and additional split systems, PV panels were instead sized according to both the energy demand and the legislative requirements. In particular, the Legislative Decree 28/2011 imposes a minimum PV power of 1 kW installed per each 50 m^2 of plan view footprint of the building [44]. Therefore, the installed capacity to cope with this requirement is 3.6 kW for the detached house and 4.3 kW for the block of flats. The PV plants were sized according to these thresholds, i.e., to provide at 3.6 kW or 4.3 kW, respectively, for the detached house and the block of apartments. Further details on PV system sizing are reported in Section S2.4 of the Supplementary Materials.

2.3. Estimation of the Initial Investment

The initial investment for the energy refurbishment of buildings was estimated considering only the equipment for heating, cooling and DHW production, without accounting for the other cost items that are equal for all technological configurations assumed. For this reason, the study did not include the expenditure for the (partial or complete) refurbishment of the building envelope. Instead, the cost items considered are the procurement and the installation of the heating, cooling and DHW supply systems, PV panels and, when required, the replacement of radiators.

Each thermal plant required a different approach in determining its price despite using similar references, such as market surveys and catalogues from manufacturers. Only two models of boilers were chosen: a small-capacity one (below 35 kW) for the single detached house (scenarios S05, S06, S09, S10) and all the deeply refurbished block of apartments (scenarios S11, S12), and a more powerful boiler (65–70 kW) for the block of apartments that underwent a partial refurbishment (scenarios S07, S08). The reason lies in the small dependence of boiler price on thermal power, as the data in Table 3 show.

Table 3. Boilers unitary prices considering heater, accessories, and installation cost (excluding VAT) [45–50].

Typology	Cost (<35 kW)	Cost (65–70 kW)
Gas boiler	EUR 6860	EUR 9255
LPG boiler	EUR 6860	EUR 9255
Oil boiler	EUR 7175	EUR 9255
Wood logs boiler	EUR 7015	EUR 9270
Pellet boiler	EUR 7015	EUR 9270

On the other hand, the price of heat pumps strongly depends on their capacity, and a typical approach adopted in the literature is therefore to calibrate a power–cost correlation based on known values [51,52]. As shown in Figure 3, two correlations can be found between the thermal power P (kW) and the cost C (EUR) for air-source and ground-source heat pumps, respectively

$$C_{\text{ASHP}} = 1168 \cdot P^{0.8364} \text{ with } P < 1 \text{ MW} \quad (4)$$

$$C_{\text{GSHP}} = 2485 \cdot P^{0.6094} \text{ with } P < 1.7 \text{ MW} \quad (5)$$

Finally, a linear capacity–cost correlation was found for mono-split air conditioners, based on the regional price list [53]

$$C_{\text{Mono split}} = 82.70 + 361.49 \cdot P \text{ with } P < 7 \text{ kW} \quad (6)$$

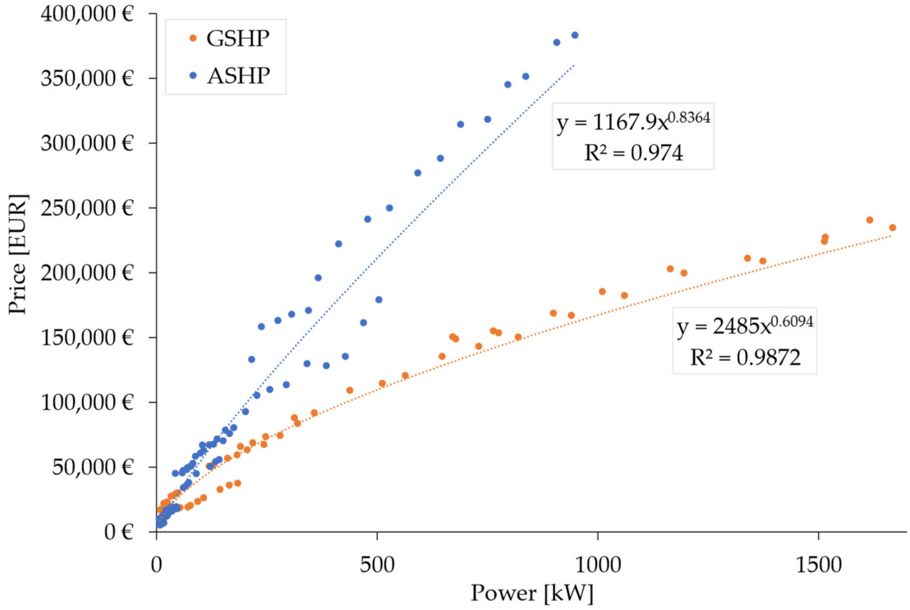

Figure 3. Correlations between capacity and cost for air- and ground-source heat pumps (elaboration from Refs. [54,55]).

The drilling and installation cost of BHEs was set to 50 EUR/m, VAT excluded, based on personal communications from Italian practitioners. This value lies in the range of other literature sources, such as references [56,57].

As for the purchase and installation costs of the PV plant, the price of PV panels is 750 EUR/kW, and the price of a single-phase inverter (5 kW) is EUR 980. The installation cost was estimated at 148.58 EUR/m^2, based on regional price lists. Considering that PV panels occupy 5.45 m^2/kW, the purchase and installation of PV panels imply a total cost of 1755 EUR/kW (excluding value-added tax—VAT).

In the cases where radiators needed to be replaced, steel radiators were considered, with a cost of 130 EUR/kW of nominal power (P_{nom}) calculated with Equation (3).

As mentioned above, the replacement of radiators with fan coils was hypothesized only if cooling was considered. A linear correlation of their cost with the heating capacity (valid from 0 kW to 17 kW) was found

$$C_{\text{Fan coil}} = 132.19 + 32.73 \cdot P \text{ for } P < 17 \text{ kW} \quad (7)$$

In this case, the reference temperature for thermal power is 45 °C in heating mode and 7 °C in cooling mode. These temperatures were assumed as the working points in the energy simulations.

2.4. Estimation of Operation and Maintenance Costs

The operational costs were assessed by estimating the quantity of fuel (for boilers) and electricity from the grid (for heat pumps) needed to cover the heating and cooling demand (if any), adopting the unit costs available in the literature.

The maintenance costs were set considering the different actions that needed to be periodically taken, depending on the technology, and assigning the costs of such actions based on a market inquiry.

2.4.1. Purchase of Fuel and Electricity

The fuel costs for the different boilers considered in this study were calculated considering the unit costs reported in Table 4, which were derived from European and local surveys [21,58,59].

Table 4. Unit prices of energy sources.

Energy Source	Value	Unit	Validity Range Min	Max	Unit	Reference
Natural gas for household consumers	148	EUR/MWh	-	6	MWh	[21]
	93	EUR/MWh	6	56	MWh	
	74	EUR/MWh	56	-	MWh	
Diesel oil	1.34	EUR/l	-	-	-	[58]
	135	EUR/MWh	-	-	-	
LPG (tank on loan)	1.53	EUR/l	-	-	-	[58]
	230	EUR/MWh	-	-	-	
Wood logs	150	EUR/ton	-	-	-	[58]
	41	EUR/MWh	-	-	-	
Pellet (15 kg bags)	290	EUR/ton	-	-	-	[58]
	58	EUR/MWh	-	-	-	
Electricity for household consumers	252	EUR/MWh	1	2.5	MWh	[21]
	234	EUR/MWh	2.5	5	MWh	
	232	EUR/MWh	5	15	MWh	
	225	EUR/MWh	15	-	MWh	
National price of electricity with on-site power exchange	67	EUR/MWh	-	-	-	[59]

The fuel demand (FD_h) for boilers was calculated using the heating demand (Q_h) resulting from the energy simulations (Sections 2.1 and 2.2) and hypothesizing fixed efficiency values for heat generation, distribution, regulation, and emission.

$$FD_h = \frac{Q_h}{\eta \cdot LHV} \tag{8}$$

where Q_h (kWh/year) is the heating demand, η (dimensionless) is the efficiency of the boiler and LHV is the lower heating value of the fuel (kWh/m^3 for gas, kWh/L for LPG and heating oil, and kWh/kg for wood logs and pellet).

The electricity demand (ED_h) for the heat pump in heating mode was derived with the following formula

$$ED_h = \frac{Q_h}{COP} \tag{9}$$

where the coefficient of performance (COP) was calculated referring to catalogues including several combinations of source and supply temperatures [60]. These input data allowed developing COP maps such as those shown for ground-source (Figure 4A) and air-source (Figure 4B) heat pumps. As for the air-source type, Figure 4B shows COP values at full and 50% of nominal power. This representation highlights the positive effect of the inverter on the heat pump performance. In the coldest climate zone (Oulx), only the use of an inverter driven ASHP allows the minimum Seasonal Performance Factor value (SPF = 2.243) set by the Italian legislation to be coped with in order to consider the heat pump a renewable heat source. The nominal power of the ASHP is always greater than for the GSHP due to the need to ensure a sufficient thermal power and COP, both of them diminishing as the outdoor temperature diminishes. The difference, for each scenario, between the nominal power of the ASHP and GSHP is moderate in the detached house cases, whereas this relative difference can be as high as 45% for the larger capacities needed by the block of flats (i.e., above 40 kW). The reason is that the minimum size of ASHPs available on the market often exceeds the maximum thermal power needed by the detached house configurations.

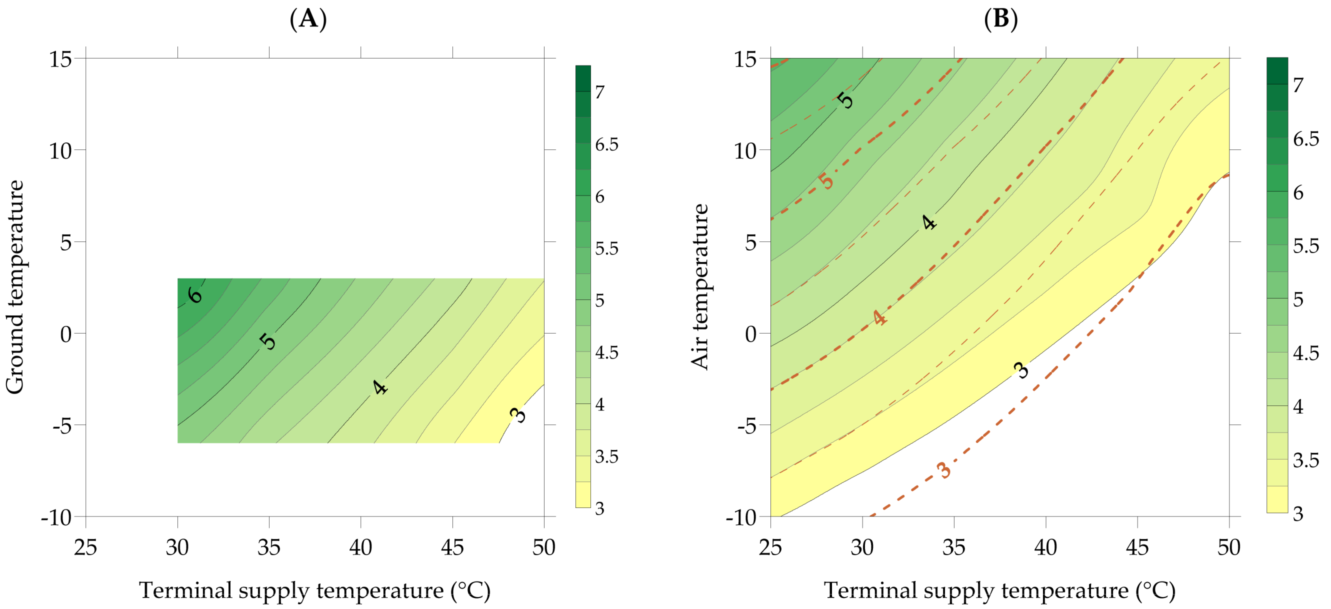

Figure 4. Examples of COP maps of heat pumps (own elaboration with data from [60]): (**A**) GSHP, nominal power 40.3 kW; (**B**) ASHP, nominal power 78.6 kW at full power (black full lines + gradient map) and at 50% power (orange dot lines).

Maps like those reported in Figure 4 were developed for the energy efficiency ratio (EER) and the electrical demand (ED_c) to cover the cooling demand Q_c was calculated with the following formula

$$ED_c = \frac{Q_c}{EER} \tag{10}$$

Both the values of COP in Equation (9) and of EER in Equation (10) are calculated using the air temperature bins in the case of the use of an ASHP and split air conditioners, or the monthly average fluid temperatures calculated with the software EED (see Section 2.3 and, in the Supplementary Materials, Section S2.3), in the case where a GSHP is adopted.

2.4.2. PV Systems and On-Site Exchange

In the case of heat pump and when installing additional splits for cooling, a PV system covers the electrical demand to reduce operational costs as much as possible. Each nominal kW installed was assumed to produce 1.1 MWh/year, i.e., a cautious hypothesis for a PV system installed in Piedmont.

The annual electricity expenditure was estimated considering the adoption of the "on-site exchange" mechanism managed by the national energy services authority [61]. With this mechanism, the self-consumed energy is free-of-charge, whereas that drawn from the grid is paid at the conventional fare (see Table 4). Finally, the amount delivered to the grid is paid by GSE at lower rates (from 90 EUR/MWh to 150 EUR/MWh) than those reported in Table 4 since taxes and invoices are not paid back. The rate for each case study was calculated according to the national guidelines [61].

The on-site exchange mechanism rewards self-consumption instead of delivering to the grid and, hence, thermal and electricity storage was assumed, aiming to reduce the electricity exchange with the grid as much as possible. Storage batteries were therefore hypothesized for accumulating the electricity produced by the PV panels during the day and not self-consumed instantaneously by the thermal plant. The sizing of the capacity (E_{bat}, kWh) depends on the ratio between the energy that would be delivered to the grid without batteries installed (E_{del}, kWh) and the energy consumed by the thermal plant when the PV panels are off (E_{off}, kWh). The battery capacity was calculated with the following relation

$$E_{bat} = \min\left(\frac{\sum_{i=1}^{365} E_{del,i}}{365}, 0.8 \cdot \frac{\sum_{i=1}^{365} E_{off,i}}{365}\right) \quad (11)$$

2.4.3. Maintenance Costs

Maintenance costs were evaluated considering both the operations that are compulsory by law (flue gas analyses every two years for boilers with solid and liquid fuel, and every four years for gaseous fuels) and those advised by boiler and heat pump manufacturers (e.g., refrigerant leakage control and possible replacement). The yearly maintenance costs (Table 5) were estimated integrating data from reference [62] and a market inquiry, finding a narrow difference between different heating and cooling technologies.

Table 5. Maintenance costs for boilers and heat pumps.

Intervention	Capacity Range (kW)	Cost (EUR, VAT Excl.)
Preventive maintenance for natural gas boilers	<35 kW 35–60 kW 60–100 kW	80 120 150
Preventive maintenance for oil boilers	<35 kW 35–60 kW 60–100 kW	110 130 180
Preventive maintenance for wood boilers	<35 kW 35–100 kW	150 250
Preventive maintenance for pellet boilers	<35 kW 35–100 kW	110 220
Combustion analysis	<35 kW 35–100 kW	40 50
Descaling of exchangers and boilers	<35 kW	50
Heat pumps and chillers	<35 kW 35–100 kW	150 250

As for the replacement of parts of the heating/cooling plant, the lifetime length of boilers, PV panels and heat pumps is supposed to be equal to 20 years at least, i.e., no replacement occurs for 20 years. While this is a straightforward assumption for boilers and PV panels, the operating lifetime of heat pumps is more debated [63–65]. In particular, the compressor of the heat pump is more prone to wearing and, hence, a replacement was considered in the 11th year of operation, i.e., after ten years of operation. The cost of such a replacement was estimated based on a market inquiry, and the following relation was found

$$C_{compressor} = 707.74 + 105.73 \cdot P \quad (12)$$

where P (kW) is the thermal power of the heat pump.

The replacement of the compressor was also considered for the split air conditioners installed to cover the cooling demand in a boiler-based configuration. This assumption is conservative since these plants operate for a limited number of hours per year (i.e., much less than heat pumps do), and hence the compressor is likely to last for the whole 20 year period.

As for the PV system, the panels are deemed to last well beyond 20 years, but the inverter is generally replaced every 10 years [66,67]. An inverter replacement was therefore considered in the 11th year of operation, and its cost was derived from a few data on a regional price list [53] as directly proportional to the plant power P (kW)

$$C_{inverter} = 196.05 \cdot P \quad (13)$$

2.5. Levelized Cost of Heat (LCOH)

The economic viability of different technologies for heating, cooling and DHW production was evaluated using the Levelized Cost of Heat (LCOH) during a lifetime of 20 years [62]. This period is short enough to assume that boilers, heat pumps and PV panels will not need to be entirely replaced [68].

The Levelized Cost of Heat *LCOH* (EUR/kWh) is defined by the following equation

$$LCOH = \frac{\sum_{t=1}^{n} \frac{I_t - R_t + F_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}} \quad (14)$$

where I_t (EUR) is the investment cost incurred in the year t, R_t (EUR) is the amount eventually refunded by incentives in year t (EUR), F_t (EUR) is the annual expenditure for energy sources, E_t (kWh) is the energy delivered by heating terminals directly to users, $n = 20$ is the lifetime of the system and I is the discount rate.

The discount rate I was assumed to be equal to 4%, a value that falls within the range of those adopted by several studies on energy and buildings [10,69–72]. However, the personal choices and needs of the customer and the economic conjuncture strongly affect the discount rate, which was therefore considered one of the critical parameters for the sensitivity analysis.

As for refunds (R_t), the Italian Ecobonus was considered, which consists of the reimbursement of 65% of the capital expense for the energy refurbishment of buildings, delivered in ten yearly equal payments.

3. Results

The presentation and discussion of the results of this study are divided into three sub-sections with three different insights levels. The first analysis, presented in Section 3.1, was performed on buildings without a cooling system (i.e., heating-only systems). Subsequently, cooling loads were included in the calculations, and the results are shown in Section 3.2. Finally, the limitations of our study are addressed in Section 3.3: the variability of some major cost items is evaluated with Monte Carlo simulation, and temporary factors influencing the LCOH values that are not considered by our study are described, drawing some qualitative conclusions on their influence.

3.1. Heating-Only Systems

The values of LCOH are reported in Table 6 for the two buildings (detached house and block of flats), the two levels of insulation (partial and total renovation of the envelope) and the two climate zones (Turin and Oulx). The values are calculated in the presence of incentives whose contribution to the reduction in the LCOH is shown.

The data reported highlight that there is generally a clear gap of LCOH values between renewable and fossil fuel heating technologies when the Ecobonus incentive is applied. The most expensive renewable heating technology (GSHP with the lowly conductive ground in the scenarios S06 and S08; pellet in the scenarios S05, S09, S10, S11, S12; ASHP in the scenario S07) is always cheaper than a natural gas boiler (with a gap up to 33.6%), except for the scenario S08 (partially renovated apartment block in Oulx) where the GSHP with lowly conductive ground is slightly more expensive than the gas boiler due to the very high costs for BHE drilling. The other two fossil fuels (LPG and heating oil) have an even wider gap: that is, renewable heating technologies allow an LCOH reduction of about 60–70% compared to LPG and 40–50% compared to heating oil.

Table 6. LCOH values (EUR/MWh) for the different heating-only systems. The LCOH with the application of incentives is reported in the first row of each case, whereas the relative reduction with respect to the scenario without incentives is in the second row. Legend: NG = natural gas condensing boiler, LPG = LPG condensing boiler, OIL = diesel oil condensing boiler, WL = wood logs boiler, PEL = pellet boiler, AS = air-source heat pump, GS = geothermal heat pump (subscripts stand for low, medium and high conductivity, respectively).

Building	Renovation	Location (Scenario)	NG	LPG	OIL	WL	PEL	AS	GS_{lc}	GS_{mc}	GS_{hc}
Single detached house	Partial	Turin (S05)	128.5	290.7	179.6	70.3	89.6	78.8	83.8	80.7	78.7
			−8%	−4%	−6%	−14%	−14%	−47%	−48%	−48%	−48%
		Oulx (S06)	127.2	296.6	180.2	62.1	84.1	72.6	84.5	75.4	73.2
			−6%	−2%	−4%	−11%	−11%	−46%	−47%	−50%	−49%
	Complete	Turin (S09)	142.2	292.6	198.6	97.7	118.7	96.2	114.6	111.3	109.4
			−18%	−9%	−16%	−24%	−26%	−48%	−50%	−50%	−50%
		Oulx (S10)	130.7	278.3	183.5	83.8	103.3	58.5	82.2	76.2	74.0
			−15%	−8%	−13%	−22%	−23%	−44%	−49%	−49%	−48%
Apartment block	Partial	Turin (S07)	92.5	273.9	163.9	55.7	72.1	81.9	71.7	64.4	61.3
			−4%	−1%	−2%	−5%	−4%	−38%	−49%	−49%	−49%
		Oulx (S08)	91.2	273.3	162.7	53.6	70.3	78.7	101.5	80.6	73.2
			−3%	−1%	−1%	−3%	−3%	−31%	−45%	−43%	−41%
	Complete	Turin (S11)	110.9	252.5	157.8	60.3	77.2	65.4	66.6	63.5	61.6
			−8%	−4%	−7%	−14%	−15%	−48%	−49%	−49%	−49%
		Oulx (S12)	109.8	252.9	155.9	57.1	73.7	62.0	71.1	66.6	64.4
			−6%	−3%	−5%	−11%	−12%	−47%	−49%	−48%	−48%

A conductive ground requires fewer BHEs to be installed, thus reducing the initial investment. Hence, the LCOH of GSHPs decreases as the thermal conductivity of the subsurface increases. Different impacts, however, are observed: while a slight LCOH increase occurs for detached houses, from 5.3% to 19.4%, the increment is substantial (up to 39.9%) for an apartment block. This fact can be explained considering two factors: (i) the mutual interference between probes in large BHE fields makes the borehole length increase hyper-linearly with the thermal power, and (ii) the drilling and installation of BHEs have practically no economy of scale, contrary to the other parts of a GSHP system; therefore, the cost of BHEs accounts for an increasing share of the overall installation costs (up to 60%) as the plant size increases. This result agrees with the literature results, such as reference [43].

The share of LCOH reduction reported in Table 6 highlights the fact that incentives have a strong impact on the economic viability of heat pumps, reducing their LCOH values between 31% and 49%. This result is explained by the fact that, contrary to feed-in tariffs or fixed incentivization, the Ecobonus refunds 65% of the initial investment, thus improving the economic viability of technologies with high installation costs but low operational costs. This effect is expected to be even stronger with the recently introduced Superbonus (110% tax refund of installation costs, see reference [33]), which was not considered in this analysis due to its temporary nature.

3.2. Heating and Cooling Systems

The analysis reported in the previous paragraph deals with heating-only configurations that, as already stated, are quite common in Northern Italy due to its climate [39]; however, the request for cooling systems is increasing due to the higher cooling loads of new, better-insulated buildings (as also shown in Table 2). For this reason, the analysis was extended to cover the cooling demand, and the LCOH was re-calculated combining heating, DHW and cooling. Only the case studies with complete renovation were considered since they involve the most relevant space cooling demand.

The inclusion of a cooling service depends on the different heating technologies adopted and the resulting supplying mode:

- The reversible heat pump models chosen in the heating-only analysis have a sufficient size to cover the cooling demand (except for scenario S11—the completely renovated apartment block in Turin—which requires an additional power of just 3 kW). However, including the cooling service makes it necessary to replace all radiators with fan coils (see Section 2.3).

- For biomass and fossil fuel boilers, the cooling needs were deemed to be covered by a few mono-split air conditioners and, hence, a modest additional investment is needed.

When space cooling is included in the economic analysis, this results in an increase or a decrease in LCOH values, as shown in Table 7. Indeed, the initial investment is shared on a larger quantity of heat (delivered to or removed from the building), and, in some cases, cooling has a lower unit cost compared to heating. In these cases, including the cooling service leads to a reduction in LCOH values. GSHPs noticeably benefit from the inclusion of the cooling demand because this reduces the heat imbalance underground, thus leading to a lower overall BHE depth to drill. This effect is particularly evident for the block of flats due to the above-mentioned BHE mutual interference. There are, however, several cases where the inclusion of cooling increases the overall LCOH. The reason lies in a combination of three possible factors, namely (i) low demand for cooling, as in the cold climate zone (Oulx), (ii) a lower LCOH for heating than for cooling, as is the case of biomass boilers and (iii) the need to replace radiators with fan coils to cover a modest cooling demand (e.g., for scenario S10).

Table 7. LCOH values (EUR/MWh) with incentives referred to heating and cooling solutions and the relative variation compared to the heating-only case ($\Delta_{h\&c}$). Legend: NG = natural gas condensing boiler, LPG = LPG condensing boiler, OIL = diesel oil condensing boiler, WL = wood logs boiler, PEL = pellet boiler, AS = air-source heat pump, GS = geothermal heat pump (subscripts stand for low, medium, and high conductivity, respectively).

Building	Location	Quantity	NG	LPG	OIL	WL	PEL	AS	GS_{lc}	GS_{mc}	GS_{hc}
Single detached house	Turin (S09)	LCOH	171.3	293.4	217	134.4	155	93.1	110.8	108.4	107.1
		$\Delta_{h\&c}$	20%	0%	9%	38%	31%	−3%	−3%	−3%	−2%
	Oulx (S10)	LCOH	176.2	318.4	227.1	130.7	152.5	88.5	108.6	102.9	100.8
		$\Delta_{h\&c}$	35%	14%	24%	56%	48%	51%	32%	35%	36%
Apartment block	Turin (S11)	LCOH	106.8	184.8	132	78.1	89.8	56	52.6	48.7	47.1
		$\Delta_{h\&c}$	−4%	−27%	−16%	30%	16%	−14%	−21%	−23%	−24%
	Oulx (S12)	LCOH	114.8	223.8	149.4	74.2	88.7	60.6	54.5	52.4	50.7
		$\Delta_{h\&c}$	5%	−12%	−4%	30%	20%	−2%	−23%	−21%	−21%

3.3. Study Limitations

3.3.1. Uncertainty on Cost Items: Sensitivity Analysis

The LCOH is an easily understandable indicator and makes the comparison among different technologies very immediate despite some inevitable simplifications [10]. A major limitation is represented by the variability in some installation cost components, such as the unit cost of BHE drilling, which depends on the geological characteristics of the ground and the local, nearly monopolistic market [73,74]. For this reason, the estimation of LCOH requires the sensitivity analysis to be more rigorous [5,62].

We identified the prices of energy sources, heat pumps, BHEs and batteries, and the discount rate as the most sensitive parameters and, therefore, as sources of uncertainty. The sensitivity analysis focused on verifying how LCOH varies according to those parameters. The study was performed through a Monte Carlo simulation hypothesizing that variables randomly range between a minimum and a maximum value (Table 8).

Table 8. Minimum and maximum values assumed in the sensitivity analysis.

Variable	Unit	Min	Max	Notes
Electricity price for household consumers	EUR/MWh	49	334	1000–2500 kWh
	EUR/MWh	98	301	2500–5000 kWh
	EUR/MWh	95	280	5000–15,000 kWh
	EUR/MWh	95	313	>15,000 kWh
National price on power exchange	EUR/MWh	0	163	-
Natural gas price for household consumers	EUR/MWh	31	160	<20 GJ
	EUR/MWh	28	107	20–200 GJ
	EUR/MWh	27	104	>200 GJ
Diesel oil	EUR/l	1.06	1.51	-
LPG	EUR/l	1.45	1.62	-
Wood	EUR/kg	0.13	0.18	-
Pellet	EUR/kg	0.24	0.34	-
BHEs drilling and setting cost	EUR/m	40	75	-
ASHP cost	Variation	−9%	+9%	-
GSHP cost	Variation	−9%	+9%	-
Batteries cost	Variation	−12%	+12%	-
Discount rate	%	2%	6%	-

As the Italian prices for the energy sources were assumed in our study, the sensitivity analysis considered a possible variation in their values with different assumptions. As for electricity and natural gas, the adopted range for the sensitivity analysis is between the lowest and the highest unit cost in Europe for every consumption band by Eurostat [21]; the lowest and the highest electricity prices are usually in Bulgaria and Germany, respectively. Instead, the unit prices of natural gas for different demand ranges are quite different depending on the country [21]. The variations in heating oil, LPG and wood biomass prices were hypothesized based on the surveys published by the Chamber of Commerce of Turin in the years 2017–2020 [58]. The reference for the maximum BHE cost is the regional price list [53]; the minimum cost is the result of a survey performed by the authors among workers in the sector. The minimum heat pump cost was computed considering that the price may decrease by 9% until 2030 (a 9% annual drop) [75,76]. Symmetrically, the maximum value accounted for a 9% increase in the capital cost. In the same way, battery prices ranged from −12% to +12% [77]. Heat pumps and batteries were considered sources of uncertainty because they are less consolidated technology compared to boilers and require critical materials, such as rare-earth metals. Finally, the discount rate varied between 2% and 6% based on the work of Cui et al. [10].

Figure 5 reports the sensitivity analysis results for the single detached house in Turin (all the other cases are in Section S3 of the Supplementary Materials). The plots show that diesel oil and LPG boilers are usually the two most expensive solutions under every hypothesis of random price combination. The LCOH values for other energy sources, especially wood log boilers, exhibit a low variability from its median. Only the curve of gas boilers has a steeper slope due to the gas prices' fluctuation. Gas boilers are usually more expensive than ASHP and wood boilers, particularly when incentives apply. GSHPs also turn out to be cheaper than gas boilers only in the presence of incentivization; on the other hand, gas boilers are usually cheaper than GSHPs. Although it considered wide ranges for input parameter values, the sensitivity analysis showed a ranking of LCOH values such as those presented in Sections 3.1 and 3.2 with the default parameter values.

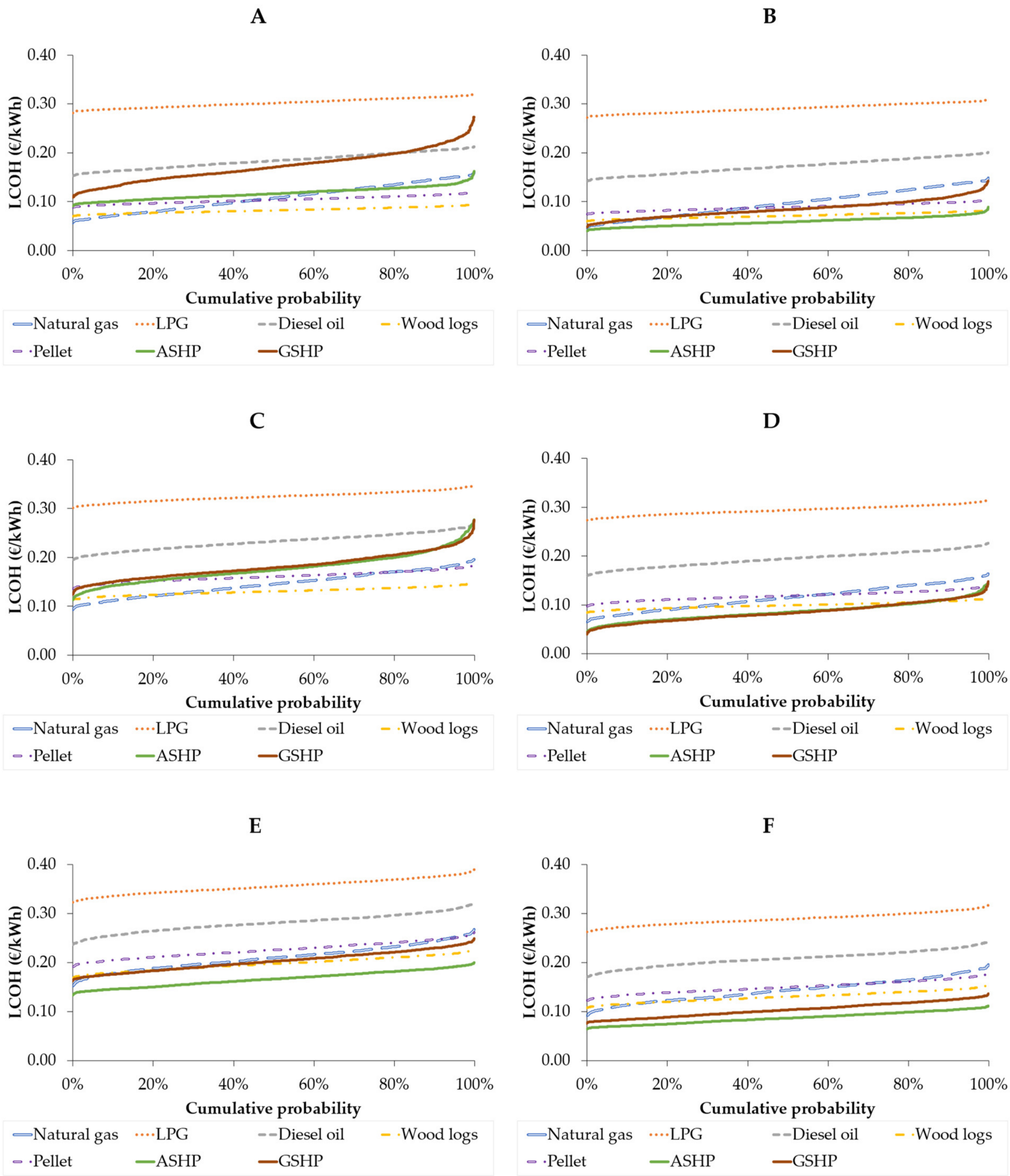

Figure 5. Probabilistic distributions of LCOH values in a detached house in Turin in the following cases: (**A**) heating-only after partial renovation without incentives; (**B**) heating-only after partial renovation with incentives; (**C**) heating-only after complete renovation without incentives; (**D**) heating-only after complete renovation with incentives; (**E**) heating and cooling after complete renovation without incentives; (**F**) heating and cooling after complete renovation with incentives.

3.3.2. Temporary Factors Influencing LCOH

Our study did not consider two temporary factors, namely (i) the introduction of Superbonus in 2020 [33] and (ii) the energy price increase occurring since late 2021 and recently exacerbated by the war in Ukraine.

As stated above, the Superbonus is the refunding of 110% of the initial investment for the energy refurbishment of a building, which is provided in the form of a tax deduction (5 yearly payments after the conclusion of the building restoration). This tax deduction can be transferred to a bank, thus receiving an immediate refund of about 95% of the installation costs incurred. As this incentive virtually nullifies the upfront costs of a building refurbishment intervention, the LCOH is significantly reduced for heat pumps, which require the greatest initial investment. The Superbonus, therefore, represents a strong incentive to adopt heat pump technologies and, to a lesser extent, biomass boilers. However, this is expected to last for a short time: at present, its phase-out is foreseen for December 2022 for detached houses and for December 2023 for other buildings.

Since the second half of 2021, the price of fossil fuels has been increasing at a fast rate due to the post-COVID pandemic economic rebound, with a consequent rapid increase in the demand, and to several supply reduction issues [78]. At the beginning of 2022, with the increasing tensions culminating with the Russian invasion of Ukraine, gas prices increased to unprecedented price levels: for example, the natural gas EU Dutch TTF price—which never exceeded 40 EUR/MWh between 2010 and 2020—exceeded 200 EUR/MWh in March 2022 [79]. The impact of this energy price shock is currently unpredictable, especially if put into a 20-year perspective. The only partial conclusion that can be drawn is that this price shock moves the focus of an economic viability analysis from the upfront costs to the operation and maintenance costs.

4. Discussion

The results reported above highlight that the Ecobonus makes fossil fuel boilers no longer an economically convenient option for the renovation of buildings. While the margin is still narrow compared to gas boilers, in the case of LPG/heating oil boilers it is so wide that it should stimulate the replacement of all these heating systems with renewable energy technologies in the areas not reached by gas pipelines. This result is consistent with a recent study by Casasso et al. (2019, [23]) in the region of Aosta Valley (NW Italy, bounding with Piedmont). A good agreement is also observed with a previous study of Martinopoulos et al. (2018, [80]) based on slightly older figures (the year 2014) in 16 countries, including Italy. The LCOH values of gas boilers in a detached house were higher compared to the analysis of Wang et al. (2018, [15]) in the UK (i.e., 127.2–142.2 EUR/MWh compared to about 95 EUR/MWh, respectively), whereas the LCOH values of air-source and ground-source heat pumps were lower (respectively: 58.5–96.2 EUR/MWh vs. about 120 EUR/MWh; 75.4–111.3 EUR/MWh vs. about 135 EUR/MWh). As shown later, this discrepancy is explained by the differences in electricity and gas costs in Italy and the UK. Compared to the recent study of Novelli et al. (2021, [81]), the values of LCOH of our study are higher. Nevertheless, the ranking of the economic viability of technologies is the same (GSHPs are slightly more convenient than gas boilers and much better performing than oil boilers), and the effect of the Ecobonus incentive on the LCOH of GSHPs is similar. In addition, the impact of a rooftop PV system on the LCOH of a heat pump appears to be limited in both studies.

The figures on the economic viability of heating technologies can be analyzed considering the diffusion of renewable heating technologies. The coverage of residential heating demand in Italy from 1990 to 2015 has seen a gradual phase-out of oil heating, a noticeable increase in biomass heating in the mid-2000s and the onset of district heating in the 2010–2015 period [82]. More recently, heat pumps have been significantly increasing in Italy. A recent report by the Polytechnic University of Milan estimated an overall investment in 2019 of EUR 1514 M on heat pumps and of only EUR 381 M for condensing boilers [83]. Although heat pumps have overtaken boilers in terms of investments, the absolute numbers of installations are still lower due to the lower costs of boilers compared to heat pumps. However, this result highlights the effectiveness of the Ecobonus in reducing the barrier of the higher upfront cost of heat pumps, which, for example, is still very considerable in the UK [84]. In Italy, the issue of the investment cost has been further addressed by introducing credit transfer of the incentives: the credit owner can transfer it to other legal entities and retrieve almost all the money spent immediately, rather than in 10 yearly quotas [85]. These institutions, such as banks and firms, use the entire credit as their own and generate a margin equal to the percentage not reimbursed to the applicant.

As stated in the introduction, the electricity-to-gas unit cost ratio is a key parameter to drive the electrification of heating through the introduction of heat pumps [20]. Figure 6A shows the trend of this quantity, since 2007, for the European Union (average of 27 EU countries), Italy, the two largest EU economies (Germany and France), the best-performing country from this point of view (Sweden) and the worst-performing country (Belgium). The dashed lines report the cost ratio excluding all taxes and levies from electricity and gas costs. The values of the electricity-to-gas cost ratio of Italy is in line with the EU-27 average and is almost not influenced by taxation. The taxation on electricity is generally higher than for gas, increasing the cost ratio and hindering the diffusion of heat pumps. As shown in Figure 6A, an exception was represented by Sweden up to 2019, where natural gas was more taxed than electricity but, currently, it is slightly lower. Conversely, the German taxation on electricity has soared in the last decade, thus slowing down the increase in the heat pump market. This evidence is confirmed by Figure 6B, which shows a clear inverse relationship between the electricity-to-cost ratio and the turnover of the national heat pump markets (EUR/year per inhabitant, 2019 figure). Both values are, for Italy, very close to the European average.

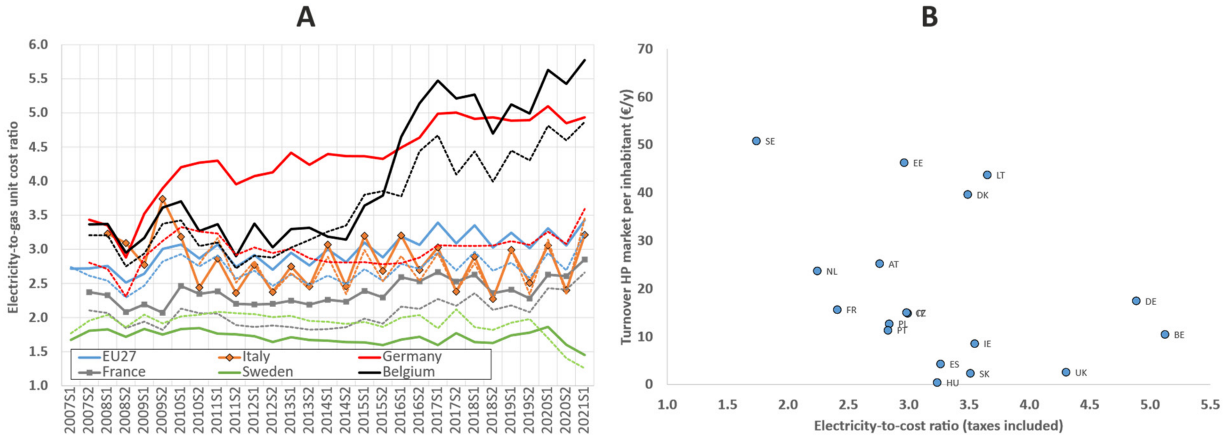

Figure 6. (**A**) The trend of the electricity-to-gas cost ratio in the European Union (EU27), Italy, Germany, France, Sweden and Belgium between 2007 and 2021. The full-line curves refer to the cost ratio, including all taxes and levies, whereas dashed lines refer to the cost ratio without taxes. Data sources: Eurostat database [21], electricity prices for households (500 to 5000 kWh/year), gas prices for households (20 to 200 GJ/year). (**B**) Scatterplot of the electricity-to-gas cost ratio (2019, 2nd semester) vs. the turnover of the heat pump market (the year 2019) normalized on the population (source: EHPA [86]) for 18 European countries.

Statistics on energy consumption in households (Eurostat 2020, [87]) show that biomass heating covers 22.4% of the heating demand in the European Union (EU-27). As shown in Figure 7, the diffusion of biomass heating is correlated with the gas cost expressed as the purchasing power standard (EUR PPP/MWh, source: Eurostat, 2020 [21]). Again, Italy (23.9%) is quite aligned with the EU-27 average figure. Available data do not distinguish between wood logs and pellets; however, specific data on pellet sales are provided by Bioenergy Europe for a few countries [88]. The largest markets for pellet in 2019 were the UK (9 Mton/year), Italy (3.3 Mton/year), Denmark (2.5 Mton/year), Germany (2.3 Mton/year), Sweden (1.8 Mton/year) and France (1.7 Mton/(year). Based on such data, the highest share of heating demand coverage with pellets are observed for Denmark (31.9%) and Sweden (22.8%).

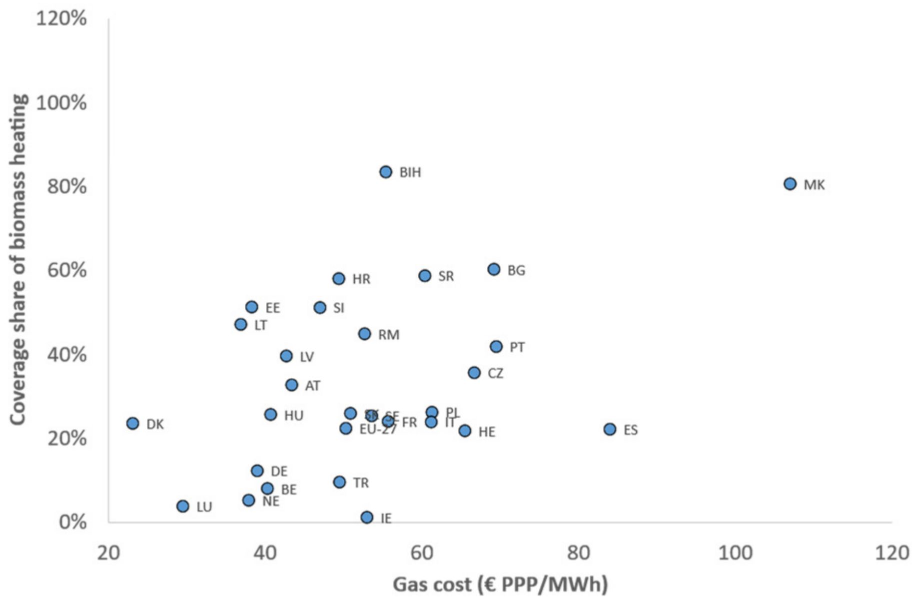

Figure 7. Scatterplot of the coverage share of biomass heating vs. the gas cost (purchasing power parity). Source: Eurostat [21,87].

Based on the diffusion of space heating technologies in the EU, two main conclusions can be drawn, regardless of the incentives in force in each country:

- A low electricity-to-gas cost ratio has a positive effect on the diffusion of heat pumps.
- A high gas cost (compared to purchasing power) has a positive effect on the diffusion of biomass heating.

These facts can be used to shape energy policies to promote the use of heat pumps and, to a lesser extent, biomass heating. As for biomass heating, however, the well-known environmental issues related to wood burning—air pollution, storage space requirements and biomass availability—suggest that the room for further expansion of biomass heating is quite limited, especially in urban areas [89–92].

5. Conclusions and Policy Implications

This study aimed to provide insights into the economic viability of the most common heating and cooling technologies, i.e., fossil fuel boilers (natural gas, diesel oil and LPG), biomass boilers (wood logs and pellet), and heat pumps (both air- and ground-sourced). The analysis was based on an energy simulation of model buildings located in Turin and Oulx, which represent the two main climatic zones of the region, namely the temperate continental and the cold-temperate continental climate.

The installation costs of heating and cooling systems were estimated based on the literature values, regional price lists and catalogues. The LCOH was chosen as the indicator to compare the different technologies. The analysis considered the presence/absence of the Ecobonus incentive and the cooling service. A sensitivity analysis was performed on the most relevant and variable input parameters of the economic analysis.

Overall, the results of this study highlight that, in Italy:

- The Ecobonus incentive regime (and, a fortiori, with the Superbonus) makes renewable energy sources already the most economically viable solutions for space heating and DHW production.
- Wood log boilers are generally the most affordable technology for space heating. Heat pumps (both air-source and ground-source) and pellet boilers follow in this ranking, with variable positions depending on the scenario.
- The impact of the climate zone on LCOH values is generally modest. The only exception is represented by the GSHP systems installed in an apartment block. In this

case, a colder climate (and, consequently, higher heating needs) leads to a relevant increase in the upfront costs of the BHE field.

- Completely refurbished buildings are characterized by a higher LCOH value compared to partially refurbished buildings. This is because life-cycle costs are distributed based on lower heating demand.
- In the climate zones of Piedmont, only completely renovated buildings have a relevant cooling demand.
- The inclusion of space cooling demand makes heat pumps the most economically convenient solution to cover the thermal needs in the residential sector, with a slight advantage of the air-source type for detached houses and of the ground-source type for the blocks of apartments.
- According to the sensitivity analysis carried out, the variability in input parameters of the economic analysis does not substantially alter the ranking of the economic viability of heating technologies.

The results agree with the few studies available in the literature on the LCOH of heating technologies in individual and building centralized plants.

Some policy implications can be drawn from the results of this study and the comparison with energy costs data and heating technologies' breakdown:

- The Ecobonus incentive is a sufficient stimulus to promote renewable heating, at least from the point of view of the LCOH.
- The ratio between electricity and gas unit costs (EUR/MWh) is the critical parameter that drives the diffusion of heat pumps.
- The unit cost of gas (normalized to the purchasing power of the country) is a good predictor of the diffusion of biomass heating.
- Based on the above-reported facts, displacing the taxation from electricity-to-gas and reducing the cost of electricity (e.g., promoting self-production from PV such as in energy communities) can provide a further boost to the growth of heat pump installations.

This study did not deepen the effect of two temporary driving forces that are altering the economic viability of heating technologies: the introduction of the Superbonus and the energy price shock occurring since late 2021. The former virtually nullified the upfront costs of heating and cooling systems, thus benefiting heat pumps; the latter is still difficult to evaluate in the 20-years perspective adopted in the LCOH estimation but seems to be pushing toward a focus on operational costs rather than on the initial investment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15072375/s1. Section S.1: Introduction; Section S.2: Methods; Section S.2.1: Heating, cooling, and domestic hot water needs; Section S.2.2: Sizing of radiators; Section S.2.3: Sizing of borehole heat exchangers (BHEs); Section S.2.4: Sizing of photovoltaic systems; Section S.2.5: Energy and fuel consumption; Section S.3: Sensitivity analysis.

Author Contributions: Conceptualization, E.R., B.P., A.C. and R.S.; methodology, E.R., B.P., A.C. and R.S.; writing—original draft preparation, E.R. and A.C.; writing—review and editing, E.R., B.P., A.C. and R.S.; supervision, A.C. and R.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was performed within a contract (number: CIG Z882DAC7B3) of the Polytechnic of Turin with the regional administration of Piedmont—Sustainable energy development sector (Regione Piemonte—Settore sviluppo energetico sostenibile).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article or supplementary material. Further information is available on request.

Acknowledgments: The authors gratefully acknowledge the regional administration of Piedmont—Regione Piemonte—Sustainable energy development sector (Silvia Riva, responsible for area; Filippo Baretti, Silvia Bonapersona and Giovanni Nuvoli) for their valuable feedback during the research work. The authors also acknowledge the valuable contribution of Sofia Credaro, who assisted in the proofreading and language editing of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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