

Heat pumps, wood biomass and fossil-fuel solutions in the renovation of buildings: a techno-economic analysis applied to Piedmont Region (NW Italy)

Supplementary materials

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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 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 heating and cooling needs of buildings.

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

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S.1. Introduction

Table S1. Electricity prices for household and non-household consumers. Minimum, maximum, and median are related to the choice of Eurostat (2020) to subdivide each class of prices according to consumption ranges.

Customers	Taxes and levies	Minimum price (€/kWh)	Maximum price (€/kWh)	Median price (€/kWh)
Household consumers (ITA)	Excluding all	0.10	0.29	0.13
	Excluding VAT/recoverable taxes and levies	0.16	0.42	0.20
	Including all	0.18	0.46	0.22
Non-household consumers (ITA)	Excluding all	0.06	0.16	0.08
	Excluding VAT/recoverable taxes and levies	0.07	0.26	0.13
	Including all	0.07	0.32	0.15
Household consumers (EU-27)	Excluding all	0.10	0.27	0.13
	Excluding VAT/recoverable taxes and levies	0.15	0.34	0.18
	Including all	0.18	0.39	0.21
Non-household consumers (EU-27)	Excluding all	0.05	0.15	0.07
	Excluding VAT/recoverable taxes and levies	0.06	0.21	0.11
	Including all	0.11	0.98	0.17

S.2. Methods

S.2.1 Heating, cooling, and domestic hot water needs

Heating, cooling, and domestic hot water (DHW) loads are reported in the following tables. Heating needs diminish as the insulation improves, and vice versa for cooling loads: however, the reduction of heating loads decreasing is always higher than the increase for cooling.

The DHW demand has been assumed as constant and depending on the number of occupants (4 per each housing unit).

Table S2. Heating loads (KWh/year) for the single-detached house.

Month	Turin			Oulx		
	Original building	Partial renovation	Complete renovation	Original building	Partial renovation	Complete renovation
January	6809	6207	2016	8786	7976	2449
February	5276	4806	1459	7057	6403	1864
March	3599	3265	812	5557	5032	1294
April	1188	1069	211	2956	2665	590
May	0	0	0	0	0	0
June	0	0	0	0	0	0
July	0	0	0	0	0	0
August	0	0	0	0	0	0
September	0	0	0	0	0	0
October	1494	1348	309	3687	3326	794
November	4418	4017	1200	6331	5738	1677
December	6261	5704	1844	8240	7477	2294
TOTAL	29046	26416	7851	42614	38617	10962

Table S3. Cooling loads (KWh/year) for the single-detached house.

Month	Turin			Oulx		
	Original building	Partial renovation	Complete renovation	Original building	Partial renovation	Complete renovation
January	0	0	0	0	0	0
February	0	0	0	0	0	0
March	0	0	0	0	0	0
April	0	0	0	0	0	0
May	0	0	108	0	0	0
June	136	128	632	0	0	123
July	586	569	883	0	0	294
August	143	136	612	0	0	98
September	0	0	103	0	0	0
October	0	0	0	0	0	0
November	0	0	0	0	0	0
December	0	0	0	0	0	0
TOTAL	866	833	2338	0	0	514

Table S4. DHW loads (KWh/year) for the single-detached house.

Month	Turin			Oulx		
	Original building	Partial renovation	Complete renovation	Original building	Partial renovation	Complete renovation
January	194	194	194	228	228	228
February	175	175	175	206	206	206
March	194	194	194	228	228	228
April	187	187	187	221	221	221
May	194	194	194	228	228	228
June	187	187	187	221	221	221
July	194	194	194	228	228	228
August	194	194	194	228	228	228
September	187	187	187	221	221	221
October	194	194	194	228	228	228
November	187	187	187	221	221	221
December	194	194	194	228	228	228
TOTAL	2280	2280	2280	2683	2683	2683

Table S5. Heating loads (KWh/year) for the apartment block.

Month	Turin			Oulx		
	Original building	Partial renovation	Complete renovation	Original building	Partial renovation	Complete renovation
January	27993	24738	5313	36772	32606	7012
February	21218	18672	3293	28921	25562	4854
March	13530	11714	1008	21722	19023	2511
April	4170	3524	17	11036	9548	722
May	0	0	0	0	0	0
June	0	0	0	0	0	0
July	0	0	0	0	0	0
August	0	0	0	0	0	0
September	0	0	0	0	0	0
October	5324	4646	249	14077	12224	1140
November	17507	15340	2422	25925	22881	4184
December	25629	22617	4732	34434	30509	6486
TOTAL	115372	101250	17034	172887	152353	26909

Table S6. Cooling loads (KWh/year) for the apartment block.

Month	Turin			Oulx		
	Original building	Partial renovation	Complete renovation	Original building	Partial renovation	Complete renovation
January	0	0	0	0	0	0
February	0	0	0	0	0	0
March	0	0	0	0	0	0
April	0	0	319	0	0	0
May	93	137	3152	0	0	1178
June	3124	3272	5901	127	177	3578
July	5859	5729	6930	431	529	4464
August	3151	3241	5521	124	179	3111
September	95	150	2820	0	0	814
October	0	0	168	0	0	0
November	0	0	0	0	0	0
December	0	0	0	0	0	0
TOTAL	12322	12529	24812	682	885	13144

Table S7. DHW loads (KWh/year) for apartment block.

Month	Turin			Oulx		
	Original building	Partial renovation	Complete renovation	Original building	Partial renovation	Complete renovation
January	1207	1207	1207	1421	1421	1421
February	1091	1091	1091	1283	1283	1283
March	1207	1207	1207	1421	1421	1421
April	1168	1168	1168	1375	1375	1375
May	1207	1207	1207	1421	1421	1421
June	1168	1168	1168	1375	1375	1375
July	1207	1207	1207	1421	1421	1421
August	1207	1207	1207	1421	1421	1421
September	1168	1168	1168	1375	1375	1375
October	1207	1207	1207	1421	1421	1421
November	1168	1168	1168	1375	1375	1375
December	1207	1207	1207	1421	1421	1421
TOTAL	14215	14215	14215	16729	16729	16729

S.2.2 Sizing of radiators

Concerning the simulation of buildings from the 60s and 70s, it is necessary to consider that the radiators installed used to be designed to work at high temperatures, whereas heat pumps (and, to a lesser extent, condensing boilers) need to work at much lower temperatures. A high-temperature radiator provides an inlet temperature of about 80 °C and an outlet temperature of 60 °C (-> average temperature 70°C), while condensing boilers and heat pumps reach high efficiencies with a flow of water at 50-55 °C and 35-45 °C, respectively. In addition, radiators typically operate with a temperature difference between inlet and outlet of 20 °C, while most heat pumps are designed for a supply and return temperature difference of 5 °C. This obstacle can be overcome with a heat storage tank or, if the distribution network permits it, by increasing the flow rate.

Tables 8 and 9 report the sizing results for the detached house and the block of flats, respectively. The tables report the inlet temperature, the number of elements needed, the nominal power of the radiators, the peak heating power per unit surface, the flow rate required for the distribution system and the difference compared to the base case. Considering that the advised flow velocity for heating networks is 1-2 m/s, a maximum increase of flow rate of 76% is acceptable if the initial distribution system was sized appropriately.

Table S8. Sizing of radiators for the single-detached house configurations.

Renovation project	Location	Type	T _{in} (°C)	Number of elements	Power per housing unit (kW)	Power per unit of surface (W/m ²)	Flow rate (kg/h)	Δ _{flowrate} (%)
Original building	Turin	Radiator	80	109	15.3	95.6	440.74	0%
	Oulx	Radiator	80	133	18.7	116.9	581.43	0%
Partial renovation	Turin	Radiator	45	114	13.7	85.8	775.62	76%
	Oulx	Radiator	45	136	16.3	102.3	1018.35	75%
Complete renovation (heating-only)	Turin	Radiator	45	35	4.6	30.6	239.15	-46%
	Oulx	Radiator	45	43	5.6	37.5	290.47	-50%
Complete renovation (heating and cooling)	Turin	Fan coil	45	-	6.4	42.7	164.28	-63%
	Oulx	Fan coil	45	-	7.8	52.2	200.17	-66%

Table S9. Sizing of radiators for the apartment block configurations.

Renovation project	Location	Type	T _{in} (°C)	Number of elements	Power per housing unit (kW)	Power per unit of surface (W/m ²)	Flow rate (kg/h)	Δ _{flowrate} (%)
Original building	Turin	Radiator	80	59	8.31	88.8	240.24	0%
	Oulx	Radiator	80	71	9.99	106.7	311	0%
Partial renovation	Turin	Radiator	45	62	7.49	80.0	421.96	76%
	Oulx	Radiator	45	76	9.10	97.2	546.81	76%
Complete renovation (heating-only)	Turin	Radiator	40	17	1.68	18.0	75.32	-69%
	Oulx	Radiator	40	21	2.02	21.6	103.03	-67%
Complete renovation (heating and cooling)	Turin	Fan coil	45	-	2.01	21.5	51.59	-79%
	Oulx	Fan coil	45	-	2.78	29.7	67.52	-72%

S.2.3 Sizing of borehole heat exchangers (BHEs)

Borehole heat exchangers (BHEs) were sized using the software Earth Energy Design (EED) (BLOCON, 2016), which is based on the subsurface heat transport model of Eskilson (Eskilson, 1987). Once the ground and fluid characteristics were set as indicated in the article, EED requires building thermal needs (kWh) and heat pumps peak power (kW) as inputs.

Therefore, the results of the EED simulations are the dimensional properties of the BHEs, which are reported in the following tables. In this case, vertical boreholes were considered; therefore, the dispositions and the measures of distance and occupied area are related to horizontal dimension, whereas length to vertical one.

Table S10. BHEs characteristics for the heating-only case.

Thermal conductivity (W/mK)	Building	Renovation	Location	BHE no.	Arrangement	Distance (m)	Well length (m)	Total length (m)	Occupied area (m ²)
1.6 (low)	Single-detached house	Partial	Turin	2	1 x 2 line	16	114	228	16
			Oulx	4	2 x 2 rectangle	19	102	408	19
		Complete	Turin	1	Single	0	93	93	1
			Oulx	2	1 x 2 line	10	75	150	10
	Apartment block	Partial	Turin	12	4 x 4 rectangle	6	108	1296	324
			Oulx	36	6 x 6 rectangle	5	107	3852	625
		Complete	Turin	2	1 x 2 line	16	110	220	16
			Oulx	4	2 x 2 rectangle	19	107	428	361
2.4 (average)	Single-detached house	Partial	Turin	2	1 x 2 line	10	93	186	10
			Oulx	3	2 x 2 L-shape	19	106	318	19
		Complete	Turin	1	Single	0	77	77	1
			Oulx	1	Single	0	111	111	1
	Apartment block	Partial	Turin	8	3 x 3 open rectangle	9	111	888	324
			Oulx	18	5 x 6 open rectangle	5	119	2142	500
		Complete	Turin	2	1 x 2 line	12	87	174	12
			Oulx	3	2 x 2 L-configuration	19	111	333	361
3.2 (high)	Single-detached house	Partial	Turin	2	1 x 2 line	9	79	158	9
			Oulx	3	1 x 2 line	17	92	276	17
		Complete	Turin	1	Single	0	68	68	1
			Oulx	1	Single	0	97	97	1
	Apartment block	Partial	Turin	6	2 x 3 rectangle	9	119	714	162
			Oulx	13	5 x 5 U-configuration	6	118	1534	576
		Complete	Turin	2	1 x 2 line	10	72	144	10
			Oulx	3	2 x 2 L-configuration	17	96	288	17

Table S11. BHEs characteristics for the heating and cooling case (completely renovated buildings).

Thermal conductivity (W/mK)	Building	Location	BHE no.	Arrangement	Distance (m)	Well length (m)	Total length (m)	Occupied area (m ²)
1.6 (low)	Single-detached house	Turin	1	Single	0	87	87	1
		Oulx	2	1 x 2 line	9	73	146	9
	Apartment block	Turin	3	2 x 2 L-configuration	13	120	360	169
		Oulx	3	2 x 2 L-configuration	14	119	357	196
2.4 (average)	Single-detached house	Turin	1	Single	0	73	73	1
		Oulx	1	Single	0	108	108	1
	Apartment block	Turin	3	1 x 3 line	8	85	255	16
		Oulx	3	1 x 3 line	9	100	300	18
3.2 (high)	Single-detached house	Turin	1	Single	0	65	65	1
		Oulx	1	Single	0	94	94	1
	Apartment block	Turin	2	1 x 2 line	6	107	214	6
		Oulx	3	1 x 3 line	9	85	255	18

S.2.4 Sizing of photovoltaic systems

The installed capacity was sized based on the electricity needs (overall kWh requested in one year) of each thermal plant. Table 12 reports the sizing results for the heating-only configuration, whereas Table 13 reports the results for the heating-and-cooling configuration.

Concerning heating-only solutions, the installed capacity exceeded the requirements set by the Legislative Decree 28/2011 (Repubblica Italiana, 2011) for every heat pump configuration with the only exception of the insulated single-detached house, since the heating loads are very low; the same occurred for the heating-and-cooling case.

Table S12. Installed capacity (kW) of photovoltaic panels in the heating-only scenario (each panel provides for 300 W).

Building	Renovation level	Location	NG	LPG	OIL	WL	PEL	AS	GS
Single-detached house	Partial	Turin	0	0	0	0	0	28	21
		Oulx	0	0	0	0	0	39	33
	Complete	Turin	0	0	0	0	0	13	13
		Oulx	0	0	0	0	0	13	13
Apartment block	Partial	Turin	0	0	0	0	0	66	66
		Oulx	0	0	0	0	0	66	66
	Complete	Turin	0	0	0	0	0	29	22
		Oulx	0	0	0	0	0	43	31

Table S13 Installed capacity (kW) of photovoltaic panels in the heating & cooling scenario (each panel provides for 300 W).

Building	Renovation project	Location	NG	LPG	OIL	WL	PEL	AS	GS
Single-detached house	Complete	Turin	13	13	13	13	13	13	13
		Oulx	13	13	13	13	13	16	13
Apartment block		Turin	30	30	30	30	30	60	43
		Oulx	18	18	18	18	18	66	45

S.2.5 Energy and fuel consumption

The annual amount of energy shown in the tables below corresponds to the fuel used by combustion technologies and the electricity used by heat pumps that would be drawn from the grid in the absence of batteries (i.e., the amount of electricity from PV that is not directly self-consumed). The amount of fuel represents a direct source of expense since it is purchased from the market, while the electricity is the basis for battery sizing.

Table S14. Annual amount of energy (in MWh) produced extra situ and delivered to the plant for heating and DHW only. Concerning heat pumps, the values refer to electrical power and do not consider batteries, whereas thermal energy regarding the other technologies.

Benchmark building	Location	Thermal plant	Original building	Partial renovation	Complete renovation
Single-detached house	Turin	Natural gas	44.9	33.8	10.9
		LPG	44.9	33.8	10.9
		Oil	45.2	33.8	10.9
		Wood	50.0	35.6	11.4
		Pellet	50.0	33.6	10.8
		ASHP	0.0	6.2	1.5
		GSHP	0.0	4.3	0.8
	Oulx	Natural gas	65.9	51.0	14.5
		LPG	65.9	51.0	14.5
		Oil	66.2	51.0	14.5
		Wood	73.4	49.3	15.1
		Pellet	73.4	49.3	14.3
		ASHP	0.0	9.3	2.6
		GSHP	0.0	6.5	1.5
Apartment block	Turin	Natural gas	176.0	134.2	32.1
		LPG	176.0	134.2	32.1
		Oil	176.0	134.2	32.1
		Wood	197.1	136.6	33.3
		Pellet	197.1	128.8	31.4
		ASHP	0.0	27.8	4.7
		GSHP	0.0	15.4	3.0
	Oulx	Natural gas	262.1	197.3	45.5
		LPG	262.1	197.3	45.5
		Oil	262.1	197.3	45.5
		Wood	293.2	201.1	47.1
		Pellet	293.2	189.6	44.5
		ASHP	0.0	42.8	7.4
		GSHP	0.0	28.7	4.9

Table S15. Annual amount of energy (in MWh) produced extra situ and delivered to the plant for heating, cooling and DHW and the increase (Δ) compared to the case without cooling.

Benchmark building	Location	Thermal plant	Thermal energy	Electrical energy	Δ_{therm}	Δ_{elect}
Single-detached house	Turin	Natural gas	10903	0	0	0
		LPG	10903	0	0	0
		Oil	10903	0	0	0
		Wood	11379	0	0	0
		Pellet	10750	0	0	0
		ASHP	0	2057	0	520
		GSHP	0	1136	0	303
	Oulx	Natural gas	14499	0	0	0
		LPG	14499	0	0	0
		Oil	14499	0	0	0
		Wood	15149	0	0	0
		Pellet	14312	0	0	0
		ASHP	0	3029	0	474
		GSHP	0	1862	0	316
Apartment block	Turin	Natural gas	32141	3570	0	3570
		LPG	32141	3578	0	3578
		Oil	32141	3588	0	3588
		Wood	33267	3592	0	3592
		Pellet	31443	3592	0	3592
		ASHP	0	6071	0	1421
		GSHP	0	3102	0	152
	Oulx	Natural gas	45470	2238	0	2238
		LPG	45470	2238	0	2238
		Oil	45470	2240	0	2240
		Wood	47077	2236	0	2236
		Pellet	44507	2236	0	2236
		ASHP	0	10254	0	2884
		GSHP	0	5510	0	561

S.3. Sensitivity analysis

The following figures show the sensitivity analysis results for the case studies not reported directly in the article.

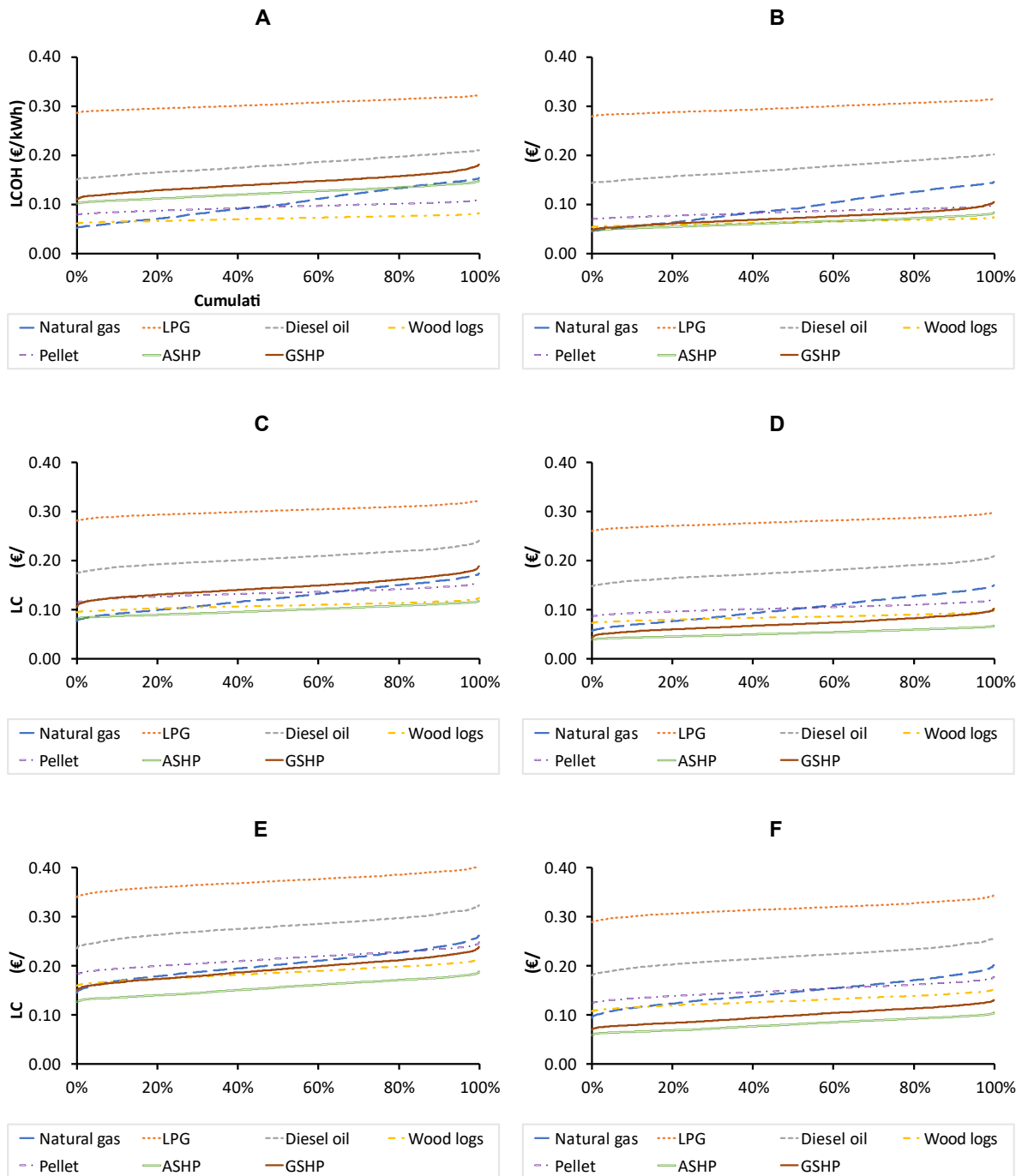


Figure S1. Probabilistic distributions of LCOH values in a detached house in Oulx in the following cases: A) heating-only after partial renovation without incentives; B) heating-only after partial renovation with incentives; C) heating-only after complete renovation without incentives; D) heating-only after complete renovation with incentives; E) heating and cooling after complete renovation without incentives; F) heating and cooling after complete renovation with incentives.

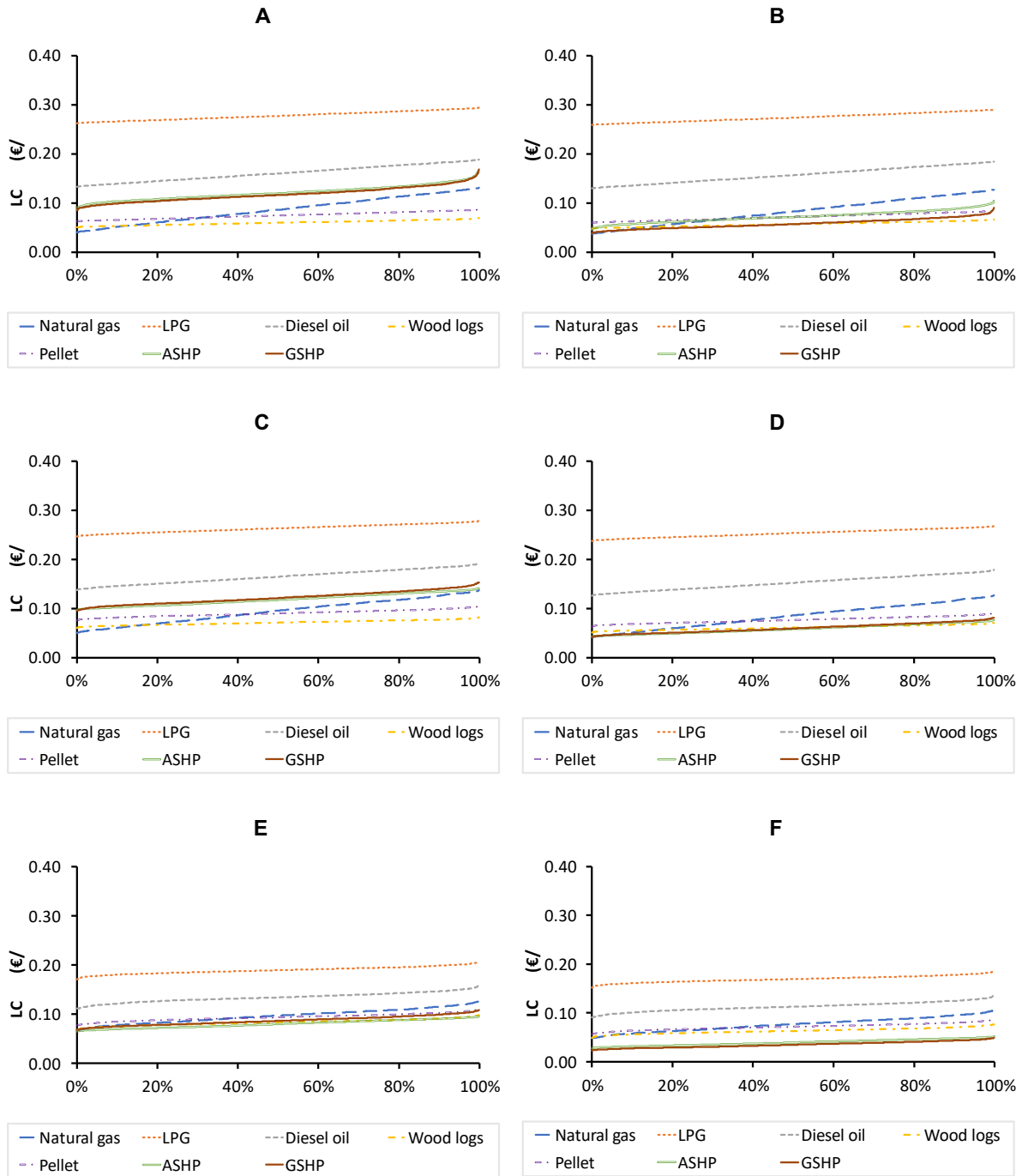


Figure S2. Probabilistic distributions of LCOH values in an apartment block in Turin in the following cases: A) heating-only after partial renovation without incentives; B) heating-only after partial renovation with incentives; C) heating-only after complete renovation without incentives; D) heating-only after complete renovation with incentives; E) heating and cooling after complete renovation without incentives; F) heating and cooling after complete renovation with incentives.

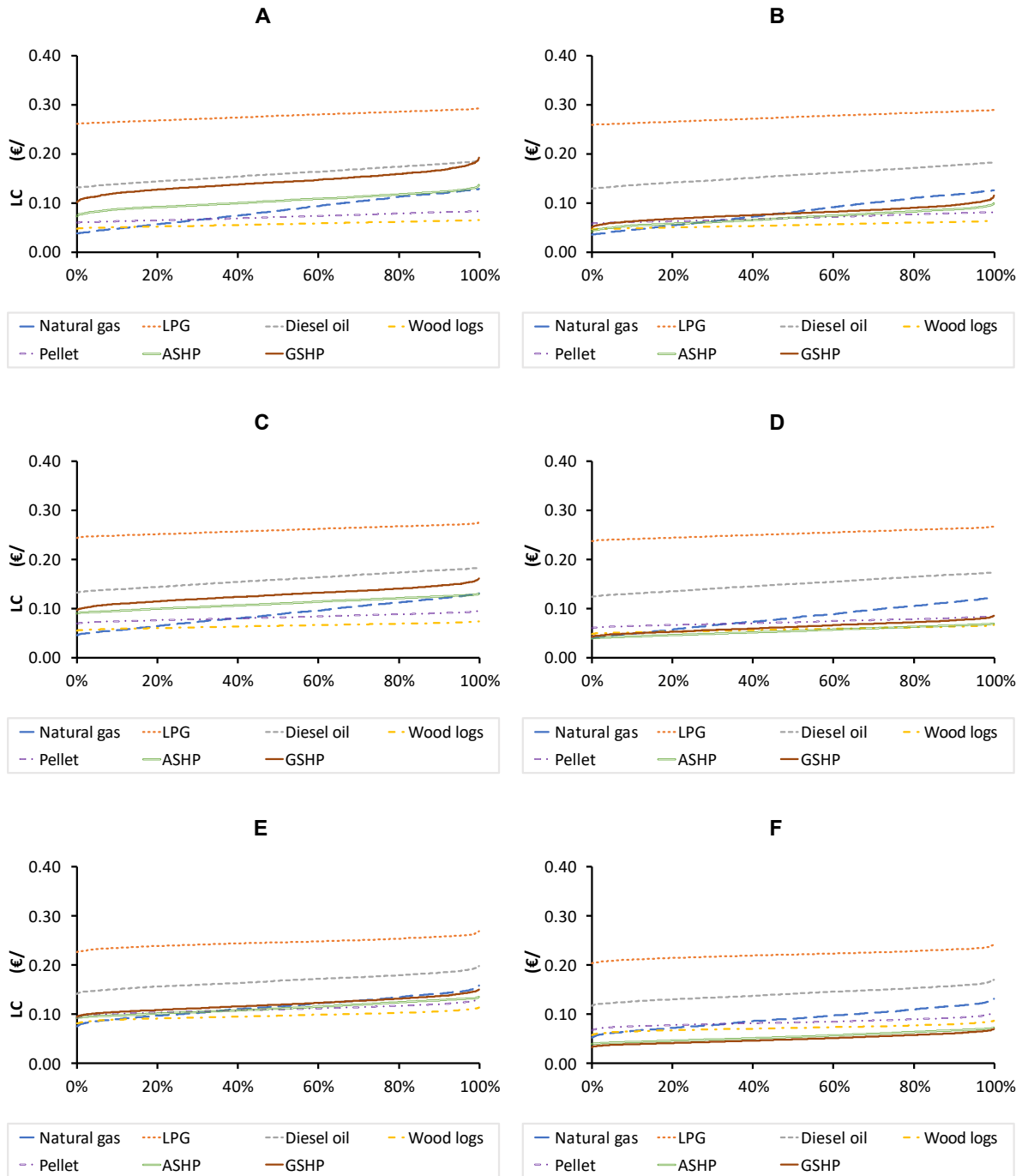


Figure S3. Probabilistic distributions of LCOH values in an apartment block in Oulx in the following cases: A) heating-only after partial renovation without incentives; B) heating-only after partial renovation with incentives; C) heating-only after complete renovation without incentives; D) heating-only after complete renovation with incentives; E) heating and cooling after complete renovation without incentives; F) heating and cooling after complete renovation with incentives.

Abbreviations and symbols

ANIT	Associazione Nazionale per l'Isolamento Termico e acustico (National Association of Thermal and Acoustic Insulation)
ASHP	Air Source Heat Pump
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BHE	Borehole Heat Exchanger
C	Cost (€)
COP	Coefficient of Performance
DHW	Domestic Hot Water
DPR	Decreto del Presidente della Repubblica (Decree of the President of the Republic)
E	Energy (kWh)
EED	Earth Energy Designer
F	Annual expenditure for energy sources (€)
GHG	Greenhouse Gas
GSE	Gestore dei Servizi Energetici (Italian energy services managing authority)
GSHP	Ground Source Heat Pump
I	Investment cost (€)
INECP	Integrated National Energy and Climate Plan
HDD	Heating Degree Days
HVAC	Heating, Ventilating, and Air Conditioning
LCOE	Levelized Cost of Energy
LCOH	Levelized Cost of Heat
LPG	Liquefied Petroleum Gas
O&M	Operation & Maintenance
P	Power (kW)
PV	Photovoltaic
R	Refund (€)
RES	Renewable Energy Source
VAT	Value-added tax
ΔT	Temperature difference

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