Supplementary Materials

Article: Assessment of energetic, economic and environmental performance of ground-coupled heat pumps

Authors: Matteo Rivoire (matteo.rivoire@gmail.com), Alessandro Casasso (alessandro.casasso@polito.it), Bruno Piga (bruno.piga89@gmail.com) and Rajandrea Sethi (corresponding author, rajandrea.sethi@polito.it, tel. +39 01109077365).

Affiliation: Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, corso Duca degli Abruzzi 24, 10129 Torino, Italy

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1 Supporting information on methods

Some additional assumptions regarding the models are reported in this section.

1.1 Stratigraphy of building envelope elements

In the main text, on **Table 3**, the values of thermal transmittance of a number of building envelope elements are reported. We hereby report the details on the stratigraphy. The convention adopted in the list of layers is always from indoor to outdoor.

1.1.1 Good insulation

1.1.1.1 External wall

Total thickness: 0.53 m
U-Value: 0.28 $Wm^{-2}K^{-1}$

Table S1. Stratigraphy of the external wall in "good insulation" buildings.

Layer	**Thickness (m)**	**Thermal conductivity ($Wm^{-1}K^{-1}$)**	**Thermal capacity ($kJkg^{-1}K^{-1}$)**	**Density (kgm^{-3})**	**Thermal resistance (m^2KW^{-1})**
Air	-	-	-	-	0.10
Plaster	0.02	0.70	1.00	1400	0.03
Brick	0.26	0.72	0.84	1800	0.36
Rockwool	0.12	0.04	1.03	40	2.79
Hollow brick	0.11	0.30	0.84	800	0.37
Plaster	0.02	0.70	1.00	1400	0.03
Air	-	-	-	-	0.04

1.1.1.2 Under-roof slab

Total thickness: 0.35 m
U-Value: 0.51 $Wm^{-2}K^{-1}$

Table S2. Stratigraphy of the under-roof slab in the "good insulation" buildings.

Layer	**Thickness (m)**	**Thermal conductivity ($Wm^{-1}K^{-1}$)**	**Thermal capacity ($kJkg^{-1}K^{-1}$)**	**Density (kgm^{-3})**	**Thermal resistance (m^2KW^{-1})**
Air	-	-	-	-	0.13
Lightweight concrete	0.05	0.31	1.00	1000	0.16
Polyurethane	0.04	0.03	1.45	36	1.25
Brick slab	0.25	0.67	1.00	1800	0.38
Plaster	0.02	0.70	1.00	1400	0.03
Air	-	-	-	-	0.13

1.1.1.3 Roof

Total thickness: 0.24 m

U-Value: 0.24 $Wm^{-2}K^{-1}$

Table S3. Stratigraphy of the roof in the "good insulation" buildings.

Layer	**Thickness (m)**	**Thermal conductivity ($Wm^{-1}K^{-1}$)**	**Thermal capacity ($kJkg^{-1}K^{-1}$)**	**Density (kgm^{-3})**	**Thermal resistance (m^2KW^{-1})**
Air	-	-	-	-	0.13
Wood	0.03	0.70	1.00	1400	0.04
Rockwool	0.16	0.04	1.03	40	3.86
Waterproofing	0.04	0.30	0.84	800	0.13
Roof tiles	0.01	0.70	1.00	1400	0.02
Air	-	-	-	-	0.04

1.1.1.4 Basement floor on cellar

Total thickness: 0.24 m

U-Value: 0.48 $Wm^{-2}K^{-1}$; Equivalent U-value: 0.24 $Wm^{-2}K^{-1}$ (the transmittance of a slab floor on cellars can be reduced of 50% according to UNI 11300-1 [1]).

Table S4. Stratigraphy of the basement slab on cellar in the "good insulation" buildings.

Layer	**Thickness (m)**	**Thermal conductivity ($Wm^{-1}K^{-1}$)**	**Thermal capacity ($kJkg^{-1}K^{-1}$)**	**Density (kgm^{-3})**	**Thermal resistance (m^2KW^{-1})**
Air	-	-	-	-	0.13
Tiles	0.02	1.30	0.84	2000	0.01
Concrete	0.02	1.15	1.00	1800	0.02
Polyurethane	0.20	0.03	1.45	36	6.09
Waterproofing	0.01	0.30	0.84	800	0.03
Lightweight concrete	0.04	0.31	1.00	1000	0.13
Brick slab	0.25	0.67	1.00	1800	0.38
Plaster	0.02	0.70	1.00	1400	0.03
Air	-	-	-	-	0.08

1.1.2 Poor insulation

1.1.2.1 External wall

Total thickness: 0.45 m

U-Value: 1.60 $Wm^{-2}K^{-1}$

Table S5. Stratigraphy of the external wall in the “poor insulation” buildings.

Layer	**Thickness (m)**	**Thermal conductivity ($Wm^{-1}K^{-1}$)**	**Thermal capacity ($kJkg^{-1}K^{-1}$)**	**Density (kgm^{-3})**	**Thermal resistance (m^2KW^{-1})**
Air	-	-	-	-	0.10
Plaster	0.02	0.70	1.00	1400	0.03
Brick	0.41	0.72	0.84	1800	0.36
Plaster	0.02	0.70	1.00	1400	2.79
Air	-	-	-	-	

1.1.2.2 Under-roof slab

Total thickness: 0.24 m

U-Value: 1.76 $Wm^{-2}K^{-1}$

Table S6. Stratigraphy of the under-roof slab in the “poor insulation” buildings.

Layer	**Thickness (m)**	**Thermal conductivity ($Wm^{-1}K^{-1}$)**	**Thermal capacity ($kJkg^{-1}K^{-1}$)**	**Density (kgm^{-3})**	**Thermal resistance (m^2KW^{-1})**
Air	-	-	-	-	0.13
Lightweigth concrete	0.05	0.31	1.00	1000	0.16
Brick slab	0.17	0.67	1.00	1800	0.25
Plaster	0.02	0.70	1.00	1400	0.03
Air	-	-	-	-	0.13

1.1.2.3 Roof

Total thickness: 0.19 m

U-Value: 2.38 $Wm^{-2}K^{-1}$

Table S7. Stratigraphy of the roof in the "poor insulation" buildings.

Layer	**Thickness (m)**	**Thermal conductivity ($Wm^{-1}K^{-1}$)**	**Thermal capacity ($kJkg^{-1}K^{-1}$)**	**Density (kgm^{-3})**	**Thermal resistance (m^2KW^{-1})**
Air	-	-	-	-	0.13
Brick slab	0.18	0.67	1.00	1800	0.27
Tiles	0.01	0.70	1.00	1400	0.02
Air	-	-	-	-	0.04

1.1.2.4 Basement floor on cellar

Total thickness: 0.37 m

U-Value: 1.50 $Wm^{-2}K^{-1}$; Equivalent U-value: 0.75 $Wm^{-2}K^{-1}$ (the transmittance of a slab floor on cellars can be reduced of 50% according to UNI 11300-1 [1]).

Table S8. Stratigraphy of the basement slab on cellar in the "poor insulation" buildings.

Layer	**Thickness (m)**	**Thermal conductivity ($Wm^{-1}K^{-1}$)**	**Thermal capacity ($kJkg^{-1}K^{-1}$)**	**Density (kgm^{-3})**	**Thermal resistance (m^2KW^{-1})**
Air	-	-	-	-	0.13
Tiles	0.02	1.30	0.84	2000	0.01
Concrete	0.02	1.15	1.00	1800	0.02
Crawl space	0.02	0.03	1.01	1	0.80
Lightweight concrete	0.04	0.31	1.00	1000	0.13
Brick slab	0.25	0.67	1.00	1800	0.38
Plaster	0.02	0.70	1.00	1400	0.03
Air	-	-	-	-	0.08

1.2 Schedules

The building occupancy schedules are linked to temperature setpoint, ventilation and internal gains generation timetables. Four people are present in the House from 4 pm to 8 am during the working days and the whole day during the weekend, while 20 people occupy the Office during the working days from 8 am to 6 pm. Differently, the Hotel has a seasonal schedule with two high-season (from 1st July to 15th September and from 20th December to 20th March) and two low-season (from 16th September to 19th December and from 21st March to 30th June) periods [2]. The number of people present in the Hotel first floor and upper floors, in different times, is reported in Table S9.

Table S9. Occupancy levels (number of people) in the Hotel during different times at the first floor and upper floors. (WD: Working Days, WE: Weekend days).

Season	**Time period**	**First floor**		**Upper floors**	
		WD	**WE**	**WD**	**WE**
High Season	0 – 6 am	0	0	84	112
	6 – 10 am	42	56	42	56
	10 am – 6 pm	8.4	11.2	8.4	11.2
	6 – 12 pm	42	56	42	56
Low Season	0 – 6 am	0	0	14	28
	6 – 10 am	7	14	7	14
	10 am – 6 pm	1.4	2.8	1.4	2.8
	6 – 12 pm	7	14	7	14

The internal gains contributions were assumed from EN ISO 7730 [3] and Italian normative [4] as they are generated by people, equipment and artificial lighting. The normative also defines the internal air changes of different buildings [4].

1.3 Ventilation

The infiltration and ventilation boxes in TRNSYS offer the possibilities to control the airflows through the zones. Infiltration box is a simplification of the ventilation which considers all the air as exchanged with the external ambient (i.e. the inlet airflow presents the temperature and humidity of the ambient air).

The parameters used to define the air changes rate are:

- the number of Air Changes, i.e. the volume of air replaced in one hour over the total volume of the zone (1/h);
- the airflow temperature (°C);
- the airflow relative humidity (%).

Heating and cooling loads are covered by fancoils units, and the ventilation implies an additional load as outdoor air has a different temperature compared to indoor. To control the entering airflow temperature and humidity, an Air Handling Unit (AHU) can be installed, which can include a heat recovery to reduce the ventilation losses ($\dot{Q}_{vent,i}$ in Eq.1 and 4 of the article).

Small residential units usually do not have an AHU and do not need a humidity level control and, hence, both them were not included in the House case.

The Office and Hotel require a better control of the air quality; hence, an AHU must support the fancoils. The sensible heating and cooling charges are covered by fancoils, the AHU provides the control of humidity level (latent charge) and the conditioning of replaced air. No thermal recovery from outgoing air was supposed.

The infiltration tool controls the House air changes, with fresh air entering the building from open windows at outside temperature and humidity conditions. The AHU provides air change in Office and Hotel at the setpoint temperatures defined in Section 2.2.2 of the main text. Moreover, the AHU injects humidified or dehumidified air in the buildings with a relative humidity ranging 50% ± 20%, thus covering the latent charge at the setpoint conditions (Section 2.2.2.).

For natural ventilation only (i.e., the House case) the UNI 11300-1 [1] norm prescribes a ventilation:

$$q_{ve,k,mn} = q_{ve,0} \cdot f_{ve,t,k} \tag{1}$$

where $q_{ve,0}$ (m^3/s) is described in Eq. (2), and $f_{ve,t,k}$ is a correction factor equal to 0.6 for House, 0.59 for the Office and 0.5 for the Hotel.

For the house case, $q_{ve,0}$ is assumed equal to an air change rate of 0.5h^{-1} (i.e., a ventilation flow rate of half of the room volume per hour), and hence we get $q_{ve,k,mn}$ equal to an air change rate of $0.5\text{h}^{-1}\cdot 0.6 = 0.3\text{h}^{-1}$.

For the Office and Hotel buildings, it is defined by the following equation:

$$q_{ve,0} = \left(\sum_k n_{per,k} \cdot q_{ve,0,p,k} + \sum_k A_{f,k} \cdot q_{ve,0,s,k} \right) \cdot \frac{0{,}8}{\varepsilon_{ve,c}} \cdot (C_1 \times C_2) \tag{2}$$

where

- $q_{ve,0}$ (m^3/s) is the minimum required air entering a zone for hygiene reasons;
- $q_{ve,0,p,k}$ (m^3/s) is the specific airflow per person for the k-th zone, as defined by UNI 10339 [5], it is considered equal to $11\cdot 10^{-3}$ m^3/s for Office, $8\cdot 10^{-3}$ m^3/s for Hotel first floor and $11\cdot 10^{-3}$ m^3/s for the upper floors;
- $n_{per,k} = n_{s,k} \cdot A_{f,k}$ is the number of people occupying the k-zone as defined in Section S1.2, where $n_{s,k}$ (m^{-2}) is the crowding index, equal to 0.06 m^{-2} for the Office, 0.2 m^{-2} for the first floor of the Hotel and 0.05 m^{-2} for the room floor of the Hotel and $A_{f,k}$ (m^2) is the area of the k-th zone;
- $q_{ve,0,s,k}$ (m/s) is the specific airflow of external air brought to the k-th zone by the ventilation

system, per unit area;

- $\varepsilon_{ve,c}$ is the ventilation efficiency, equal to 0.8 [5];
- $C1$ is a correction coefficient, equal to 1 [5];
- $C2$ is the altitude correction coefficient, assumed equal to 1 [5];

In addition, the natural ventilation due to thermal differences and wind is accounted for the AHU systems in Office and Hotel and calculated as:

$$q'_{ve,x} = \frac{V \times n_{50} \times e}{3600} \tag{3}$$

where V (m^3) is zone volume, $n_{50} = 4h^{-1}$ are the air changes due to pressure differences [1], and $e = 0.07$ is the wind exposition coefficient. Since the inlet and the outlet flow rates of the ventilation system are equal, $q_{ve,x} = q'_{ve,x}$ (Eq. 41 in Ref. [1]).

The ventilation flow rate in the k-th zone is:

$$q_{ve,k,mn} = (q_{ve,0} + q'_{ve,x}) \cdot (1 - \beta_k) + \left(q_{ve,f} \cdot b_{ve} \cdot FC_{ve} + q_{ve,x}\right) \times \beta_k \tag{4}$$

where:

- the first part could be elided as β_k (utilization of the plant) was set equal to 1 in the calculation of the input flow rate, since the mechanical ventilation is always on;
- $q_{ve,f}$ (m^{3}s^{-1}) is the nominal flow rate of the ventilation system;
- b_{ve} is a temperature-correction which is equal to 1 if no preheating is performed [1];
- FC_{ve} is the efficiency of the plant regulation, prescribed equal to 0.8 [1];
- $q_{ve,x}$ is the natural ventilation flow rate which is equal, as stated before, to $q'_{ve,x}$ (Eq.2)

Summarizing, the ventilation requirements are composed of two terms: a minimum hygiene flow and an infiltration one. The first term is a function of the zone occupation, the second term is a constant.
The resulting air change rates are equal to 0.3 h^{-1} for the House, and are reported in Table S10 for the Office building and Table S11 for the Hotel building.

Table S10. Ventilation flow rates $q_{ve,k,mn}$ expressed as number of air changes (h^{-1}) in the Office building.

Time period	WD	WE
0 – 6 am	0.28	0.28
6 – 10 am	0.70	0.28
10 am – 6 pm	0.28	0.28
6 – 12 pm	0.28	0.28

Table S11. Ventilation flow rates $q_{ve,k,mn}$ expressed as number of air changes (h^{-1}) in the Hotel building.

Season	**Time period**	**First floor**		**Upper floors**	
		WD	**WE**	**WD**	**WE**
High Season	0 – 6 am	0.28	0.28	0.51	0.59
	6 – 10 am	0.51	0.58	0.40	0.44
	10 am – 6 pm	0.33	0.34	0.30	0.31
	6 – 12 pm	0.51	0.58	0.40	0.44
Low Season	0 – 6 am	0.28	0.28	0.32	0.36
	6 – 10 am	0.32	0.36	0.30	0.32
	10 am – 6 pm	0.29	0.30	0.28	0.29
	6 – 12 pm	0.32	0.36	0.30	0.32

1.4 Heat pump sizing: reference temperatures

The estimation of building heating peak load was based on the 0.4% quantile lower air temperature according to ASHRAE method [6]. The reference air temperature were determined from Meteonorm data and displayed in Table S12.

Table S12. Reference temperatures for design heating load in different climate zones.

Climate zones	**Reference temperature**
A	3.00 °C
B	-4.49 °C
C	5.17 °C
D	-10.79 °C
E	-11.02 °C
F	-17.69 °C

1.5 BHEs properties

The borehole heat exchangers and ground properties, reported in Table S13, were assumed from De Rosa et al. case study [7] and from Eppelbaum et al. book [8].

Table S13. Borehole heat exchangers and ground properties [7, 8].

Property	Value	Unit
Storage heat capacity	2200	$kJ\ m^{-3}K^{-1}$
Storage thermal conductivity	2.09	$Wm^{-1}K^{-1}$
Fill thermal conductivity	2.09	$Wm^{-1}K^{-1}$
Pipe thermal conductivity	0.45	$Wm^{-1}K^{-1}$
Borehole diameter	150	mm
External U-pipe diameter	32	mm
Internal U-pipe diameter	25.4	mm
Shank spacing (centre-to-centre)	70	mm
Borehole spacing	3	m

1.6 BHE lengths

The ASHRAE boreholes sizing method [9] is based on the annual, monthly and peak heat exchanged with the ground. The total borehole length calculated for each building case is reported in Table S14.

Table S14. Borehole total length for the different building and climates calculated with the ASHRAE method [9].

Building type	Climate zone	Borehole length (m) High insulation	Borehole length (m) Low insulation
House	A	300	480
	B	200	500
	C	200	240
	D	160	600
	E	160	600
	F	300	900
Office	A	1300	1400
	B	1100	1000
	C	1000	600
	D	400	1400
	E	400	1500
	F	600	2200
Hotel	A	9000	11300
	B	7500	8500
	C	6600	7800
	D	3000	9000
	E	3700	9500
	F	3800	14500

2 Supporting information on results

In this section some additional results are reported. In detail, the additional energy results are the specific energy consumption, the full load equivalent hours and the Domestic Hot Water (DHW) demand of the different buildings cases. In the economic results sub-section, the cost curve of the system components is reported and additional analyses on system profitability at different electricity/fuel price ratio are displayed. Finally, the effectiveness of windows replacement was analysed.

2.1 Energy results

In the paper, the energy demand of buildings is presented as function of heating or cooling degree days. Here the specific annual needs of the buildings (kWh/m^2) are reported for the different climates, in both heating and cooling conditions (Figure S1).

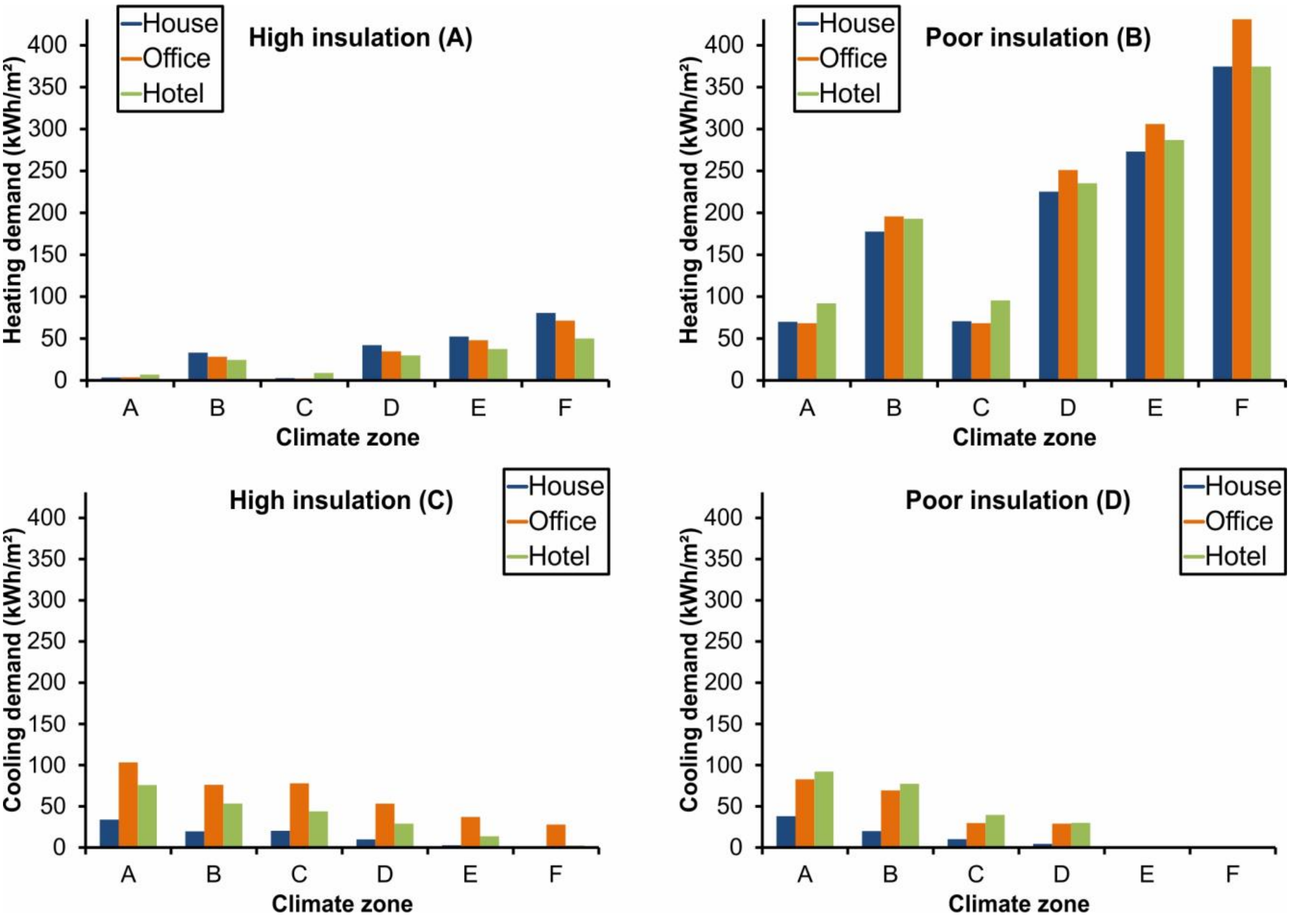

Figure S1. Specific heating demand for highly-insulated (A) and poorly-insulated (B) buildings, specific cooling demand for highly-insulated (C) and poorly-insulated (D) buildings

The Full Load Equivalent Hours (FLEH) of the heat pump operation were assessed in the different buildings and reported in Figure S2. The FLEH are related to the system peak load and building energy demand.

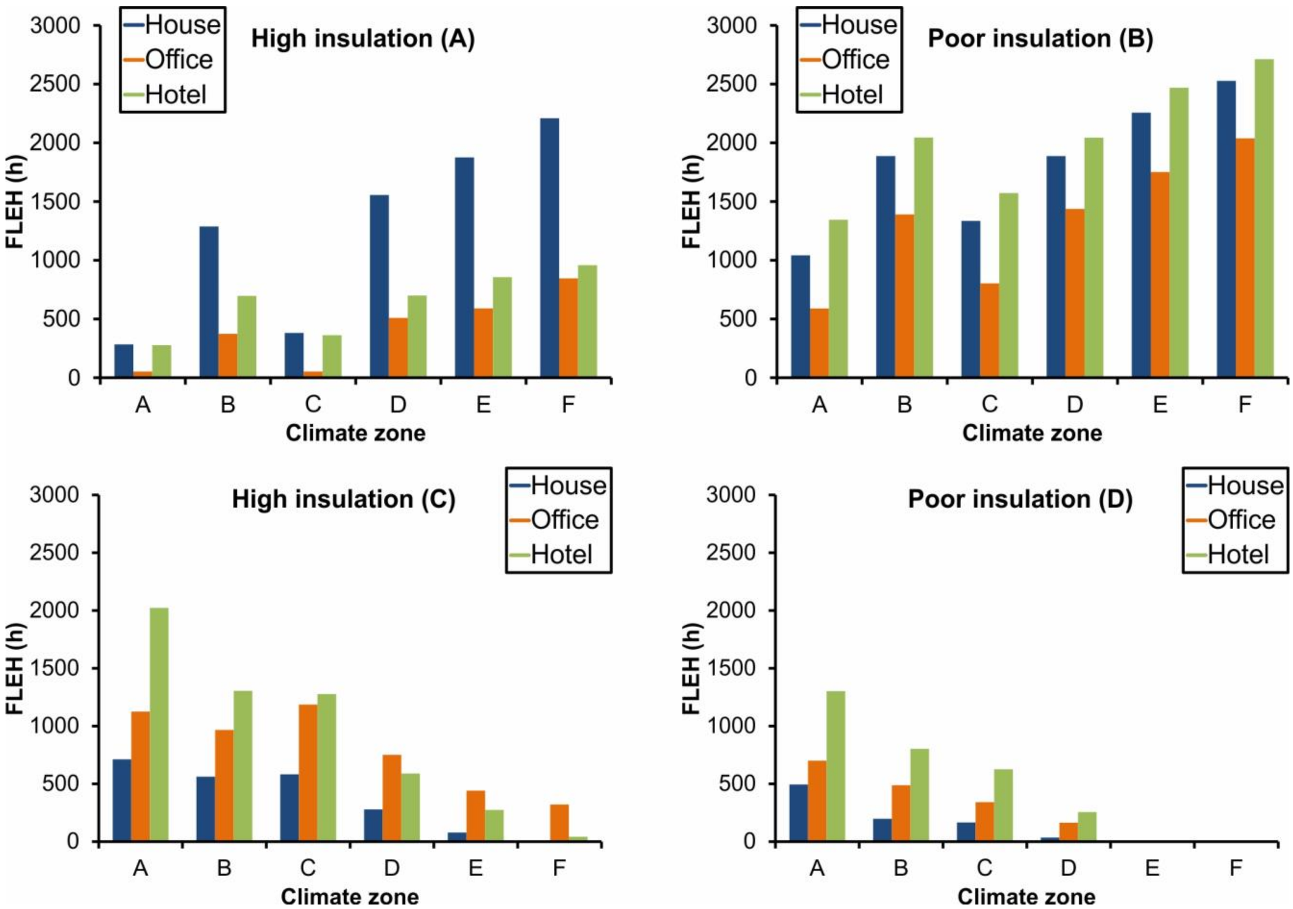

Figure S2. Full Load Equivalent Hours (FLEH) of heat pump operation for highly-insulated (A) and poorly-insulated (B) buildings in heating conditions, FLEH for highly-insulated (C) and poorly-insulated (D) buildings in cooling conditions.

The share of DHW need over the total building energy need was analysed in the different cases and shown in **Errore. L'origine riferimento non è stata trovata.**. The peak load required by DHW is very low if compared to the building thermal peak load (between 0 and 13%).

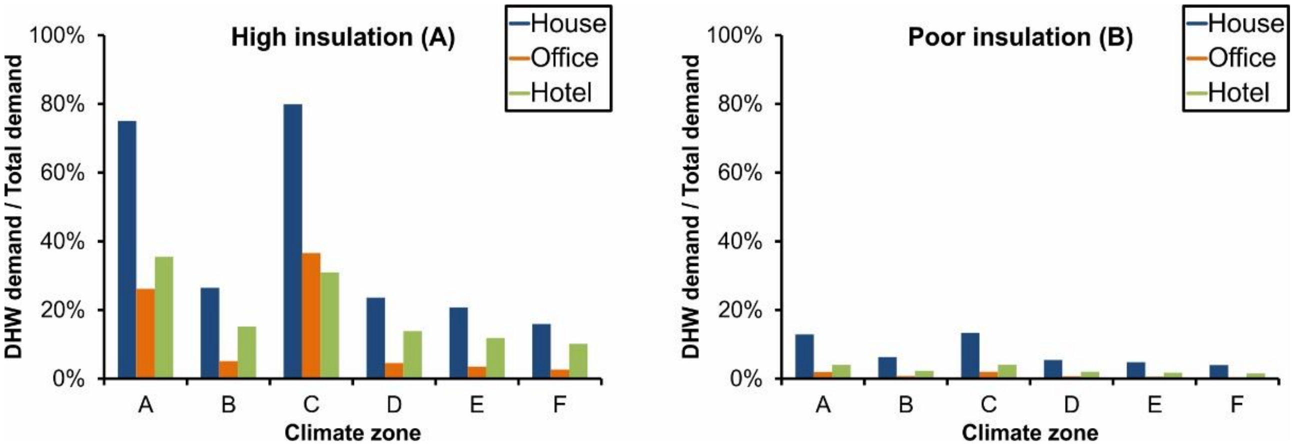

Figure S3. Share of Domestic Hot Water (DHW) demand over the total energy demand for the different building cases in heating (A) and cooling (B) conditions.

2.2 Economic results

2.2.1 Cost curves for components

The cost of each system component was assessed from commercial catalogues [10-14], thus providing the cost-capacity curve reported in Table S15 and eventually used for the installation cost estimation of the building cases.

Table S15. Cost curve in Euro for different components related to specific capacities. A linear cost was supposed for the Borehole Heat Exchanger (BHE). (DHW: Domestic Hot Water, ACS: Air Conditioning System).

Component	Capacity	Behaviour	Curve	(R^2)
HP	kW	linear	$y = 297.8x + 5313.4$	0.98
Buffer tank	l	linear	$y = 0.7x + 770.5$	0.98
DHW tank	l	linear	$y = 1.2x + 962.2$	0.93
Fancoils	kW	linear	$y = 70.7x + 356.8$	0.98
Ground pump	W	power	$y = 18.9x^{0.46}$	0.88
BHE	m	linear	$y = 60x$	-
Expansion tank	l	linear	$y = 1.2x + 33.1$	0.97
Glycol	l	power	$y = 3.9x^{0.91}$	0.97
Boiler	kW	linear	$y = 64.1x + 622.5$	0.95
ACS	kW	linear	$y = 289.6x + 1201.7$	0.98

2.2.2 Incidence of BHEs on the total cost

Figure S4 shows how the share of BHE drilling on the total installation costs varies with the installed BHE length. The BHE share increases with the installed length, since BHE drilling generally has no economies of scale, contrary to heat pump and other HVAC components (see Table S15).

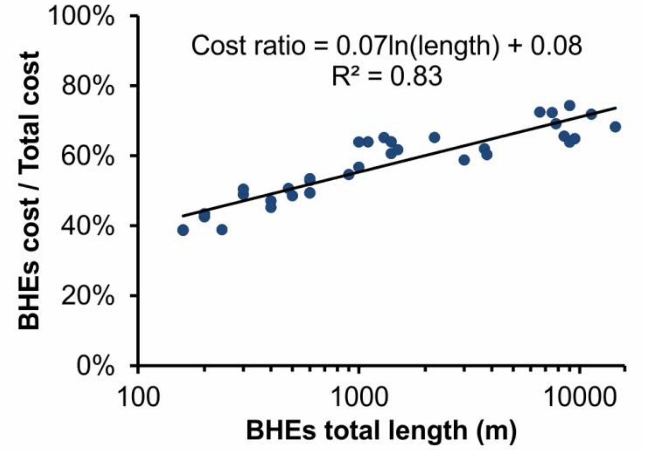

Figure S4. Incidence of BHE costs on the total cost of a GCHP.

2.2.3 Discounted Payback Period (DPP)

In the paper, the Discounted Payback Period (DPP) of subsidised poorly-insulated building in E climate zone was reported in comparison with the electricity/fuel price ratio (Section 3.2.2, Fig.10). In Figure S5-A, the additional case of highly-insulated brand new buildings with no subsidies was displayed. Moreover, in Figure S5-B and Figure S5-C the Net Present Value (NPV, in €/m^2) at the end of the geothermal systems life was compared with the electricity/fuel price ratio for the different buildings.

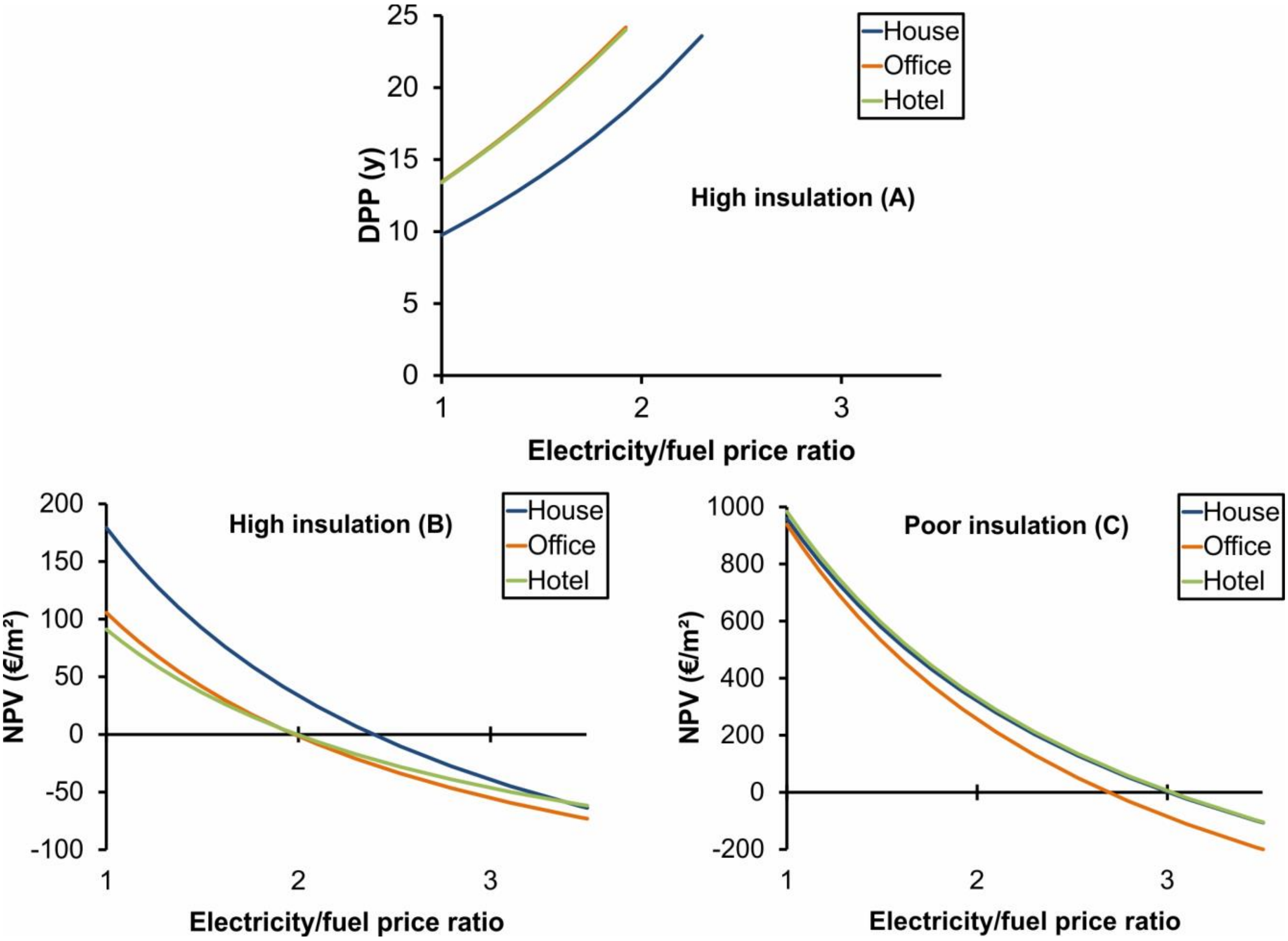

Figure S5. Discounted Payback Period (DPP) compared with the electricity/fuel price ratio for the brand new highly-insulated buildings in E climate zone (A), Net Present Value (NPV) compared with the electricity/fuel price ratio for the brand new highly-insulated buildings (B) and refurbished poorly-insulated building (C) in E climate zone.

2.3 Environmental benefits

2.3.1 Electric grid emission factors

Figure S6 shows the CO_2 reduction achieved in the 36 simulated cases, using three different grid emission factor: a low one (France), an average one (Italy), and a high one (Poland). Grid factors are taken from JRC (2017, [15]). As a term of comparison, the methane has an emission factor of 202 gCO_2/kWh (standard) and 240 gCO_2/kWh (LCA). Negative reduction values mean that the CO_2 emissions with a GCHP are higher than with a conventional system (gas boiler and, if needed, air-source chiller).

Table S16. Electricity CO_2 emission factors according to JRC (2017, [15]), calculated with two methods (standard and LCA), and the respective minimum and maximum CO_2 emission reductions achieved in the 36 simulated cases.

Country	**Standard emission factor in 2013 (gCO_2/kWh)**	**LCA emission factor in 2013 (gCO_2/kWh)**	**CO_2 reduction with GCHP (standard)**		**CO_2 reduction with GCHP (LCA)**	
			Min	**Max**	**Min**	**Max**
Austria	170	211	35%	79%	34%	78%
Belgium	198	239	33%	75%	33%	75%
Bulgaria	791	824	-14%	28%	0%	31%
Croatia	204	228	32%	74%	33%	76%
Cyprus	707	817	-2%	30%	1%	31%
Czech Republic	783	850	-13%	28%	-3%	30%
Denmark	331	380	28%	59%	28%	60%
Estonia	1977	2017	-185%	22%	-145%	22%
Finland	155	206	36%	80%	34%	78%
France	82	93	46%	90%	47%	90%
Germany	587	658	15%	35%	19%	37%
Greece	757	810	-9%	29%	2%	31%
Hungary	254	297	30%	68%	30%	69%
Ireland	464	523	25%	45%	26%	48%
Italy	343	424	28%	58%	27%	56%
Latvia	121	183	40%	85%	36%	81%
Lithuania	96	128	43%	88%	41%	86%
Luxembourg	91	108	44%	88%	44%	88%
Malta	871	1002	-26%	26%	-22%	27%
Netherlands	429	486	26%	49%	26%	51%
Poland	1013	1090	-46%	23%	-32%	25%
Portugal	314	368	28%	61%	28%	62%
Romania	502	532	25%	42%	26%	47%
Slovak Republic	199	241	33%	75%	33%	74%
Slovenia	399	424	26%	52%	27%	56%
Spain	297	343	29%	63%	29%	64%
Sweden	15	38	78%	98%	64%	96%
United Kingdom	515	589	23%	41%	25%	42%
Average EU-28	393	444	26%	52%	27%	54%

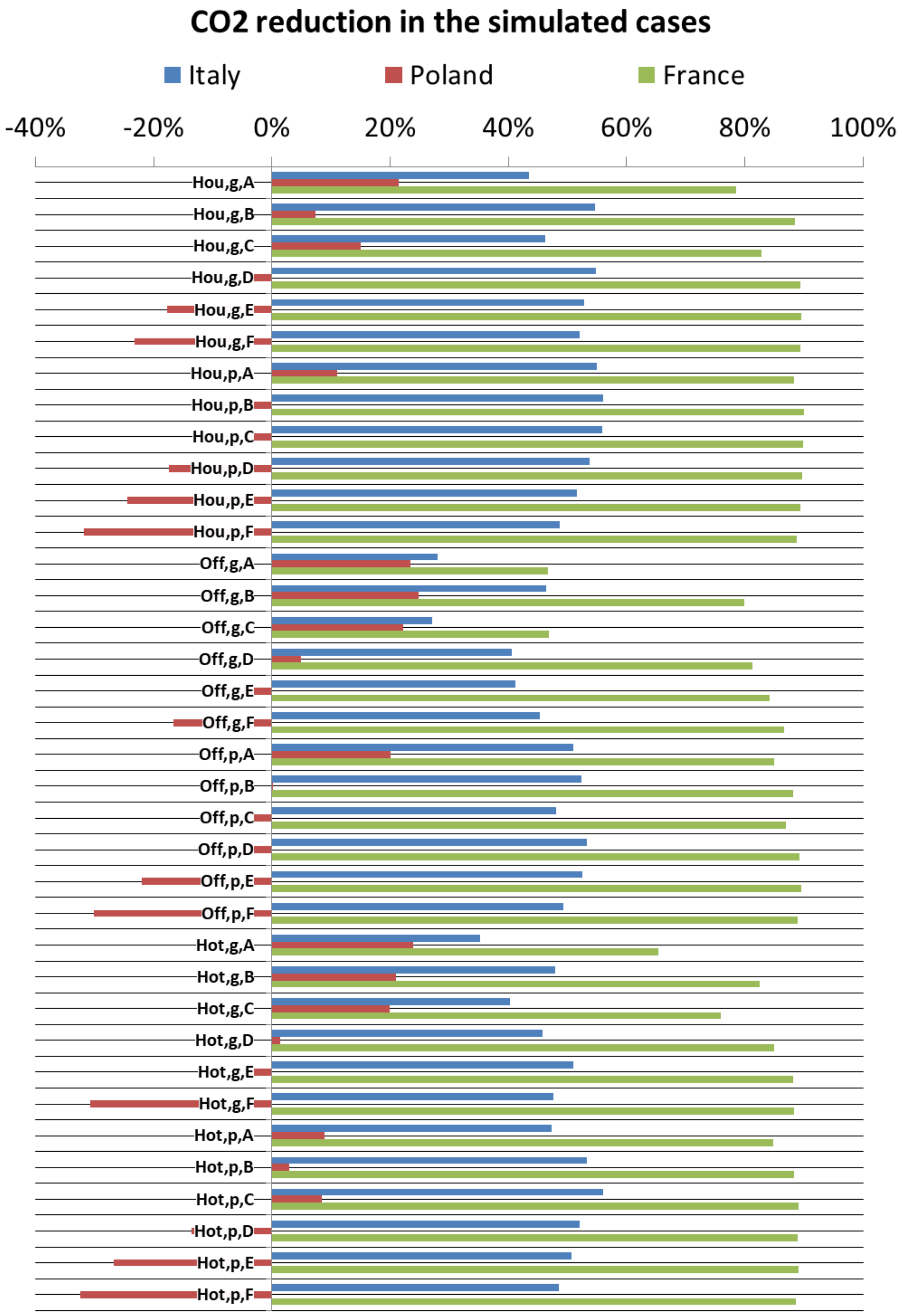

Figure S6. CO_2 reduction achieved for the 36 simulated cases, using electricity from the grid with a low (France, 93 g CO_2/kWh, in green), an average (Italy, 424 g CO_2/kWh, in blue) and a high (Poland, 1090 g CO_2/kWh, in red) CO_2 emission factor. (Hou=House, Off=Office, Hot=Hotel; g=good insulation, p=poor insulation; A,B,C,D,E,F are the climate zone according to Table 2 of the main text.

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