Data in Brief 31 (2020) 105919

Contents lists available at ScienceDirect

Data in Brief

journal homepage: www.elsevier.com/locate/dib

Data Article

Data on the environmental performance analysis of a dual-source heat pump system

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A R T I C L E I N F O

Article history:
Received 25 May 2020
Revised 18 June 2020
Accepted 19 June 2020
Available online 21 June 2020

Keywords:
Dual-source
Heat pump
Life cycle assessment
Environmental impact
Energy consumption
Renewable energy

A B S T R A C T

This data article reports supplementary input and output data related to the research article "Environmental performance analysis of a dual-source heat pump system" on the life cycle assessment evaluation of an heat pump prototype, able to use alternatively the air and the ground as external heat sources. Primarily, the present article shows the life cycle inventory input data of the system under study and of the conventional air and ground heat pump systems, which were used for comparison. Secondly, complete numerical results are exposed, which are showed only graphically and in an aggregated form in the main article. Data include normalised and unaggregated environmental impacts of each investigated life cycle phase. The article also reports the complete results of the sensitivity analysis conducted using different assumptions on the energy mix and on the energy use.

DOI of original article: 10.1016/j.enbuild.2020.110180

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https://doi.org/10.1016/j.dib.2020.105919

Specifications Table

Subject	Renewable Energy, Sustainability and the Environment
Specific subject area	Life cycle assessment (LCA) Heat pump (HP) technologies Dual-source heat pump (DSHP)
Type of data	Table
How data were acquired	Primary data mainly related to raw materials, manufacturing processes and transport distances were acquired by means of direct questions to the manufacturers. Operating data were obtained by personal communications with the designers of the DSHP prototype. Secondary data, mainly related to the maintenance and the end-of-life (EoI) processes, were acquired by the study of the specific literature and the consultation of reference databases.
Data format	Raw and unaggregated Processed and aggregated Adapted (from original sources)
Parameters for data collection	Site-specific Temporal, geographical and technological coverage Representativeness Reproducibility Consistency
Description of data collection	Primary data (i.e. raw materials, manufacturing processes, transport distances, operating data, etc.) were collected via face-to-face, telephone and email communications with the manufacturers and the designers of the DSHP prototype. Secondary data (i.e. maintenance operations, refrigerant leakage, etc.) were gathered from reliable technical and academic literature, international and EU standards and life cycle assessment databases (i.e. Ecoinvent v. 3.4 and 3.5).
Data source location	City/Town/Region: Bologna (Emilia Romagna) Country: Italy (IT) Latitude and longitude: 44°29′N, 11°21′E
Data accessibility	With the article
Related research article	Marinelli, S., Lolli, F., Butturi, M.A., Rimini, B., Gamberini, R. Environmental performance analysis of a dual-source heat pump system. DOI: 10.1016/j.enbuild.2020.110180

Value of the Data

- The presented data constitute the first complete dataset useful for modelling the dual-source heat pump emerging technology focusing on the environmental point of view.
- The data could be used by researchers as starting point when studying or developing similar solutions, heat pump manufacturers to improve the design and performance of their products, and by designers in their selection of thermal technologies.
- The data can support similar analysis, considering both heating and cooling, performed in different climate and geological conditions and energy-mix; further insights could take into account variations in the manufacturing and technologies, as well as different regulations.
- An innovative life cycle modelling approach has been adopted to describe the system, with the aim to support LCA practitioners involved in studies related to heat pump emerging technologies.

Data Description

This data article reports supplementary input and output data related to the research study conducted by Marinelli et al. [1] on the life cycle assessment (LCA) evaluation of a dual-source heat pump (DSHP) prototype, able to use alternatively the air and the ground as external heat

Table 1
Inventory for the DSHP manufacturing.

Size		
	kW	10
Basic materials		
	Steel (unalloyed and low alloyed) [kg]	128.85
	Aluminium [kg]	47.16
	Copper [kg]	39.17
	Refrigerant [kg]	6.40
	Lubricant oil [kg]	1.60
	Others (rubber. tin. etc.) [kg]	4.20
Resources		
	Water [m^3]	0.70
Energy		
	Natural gas [m^3]	1400
	Electricity. medium voltage [kWh]	140
Lifespan		
	Years	15

Table 2
Average mass and transports of main DSHP assemblies.

		Case	Heat exchangers (n.2)	Compressor	Expansion valves (n.2)	Wiring	Piping
Materials [kg]							
	Aluminium	NA	15.720	NA	NA	NA	NA
	Copper	NA	11.220	NA	NA	0.869	4.640
	Steel. unalloyed	77.23	7.261	8.600	NA	NA	NA
	Steel. low alloyed	0.107	6.800	NA	0.732	NA	NA
	Plastics (mixed)	NA	NA	NA	NA	0.004	NA
	Rubber. elastomer	NA	NA	NA	0.844	1.014	0.6
	Tin	NA	NA	0.728	NA	NA	NA
Transports [km]	Lorry. 3.5–16t	200	300	300	100	100	200

sources. Tables 1–3 include the complete inventory for the DSHP prototype manufacturing. Table 4 reports the main parameters related to the building selected to assess the energy requirement during use. In Table 5 are listed the Global Warming Potential (GWP) values of the refrigerant used to model the maintenance phase. In the main paper only selected impact categories are shown selected on the basis of their normalised impacts showed in Table 6 with the total results. Tables 7 and 8 report the environmental impacts results for life cycle stages and for the main components of the system, respectively. In Table 9 are listed the energy performance indicators of the air-source heat pump (ASHP) and the ground-source heat pump (GSHP) compared with the system under study. The results of the comparison are reported in Table 10, while the environmental impacts of the five main life cycle phases of both the ASHP and the GSHP are reported in Tables 11 and 12. Table 15 reports the results of the sensitivity analysis conducted with different electricity mixes, whose carbon intensity values are highlighted in Table 13, and with the use of photovoltaic energy calculated on the basis of the monthly average daily solar irradiation listed in Table 14. Table 16 and 17 show the results of different scenarios calculated with a variation in energy use in the range of ±10%, ±30%, ±60%.

Experimental design. materials. and methods

The analysis is related to the Functional Unit (FU) of "*1 MJ of energy*" delivered by a DSHP (air and ground) for heating and cooling a single-family residential building located in Bologna (Northern Italy), considering a lifetime of 15 years. Data related to the production and construction phases of the heat pump and the borehole heat exchangers were obtained by means of di-

Table 3
Inventory for the manufacture of the borehole heat exchanger field.

Size		
	Geothermal probes [nr]	2
	Geothermal probes length [mt]	90
	Vertical boreholes diameter [mm]	152
	U-tube external diameter [mm]	32
	U-tube internal diameter [mm]	26
Basic materials		
	Polyethylene [kg]	152.00
	Reinforcing steel [kg]	27.87
	Propylene glycol [kg]	86.13
	Bentonite [kg]	6.76
	Cement [kg]	27.86
Resources		
	Water [m^3]	8.61
Energy		
	Diesel in building machine [MJ]	14,947
Lifespan		
	Years	50

Table 4
Main building characteristics and operating design parameters.
Adaptation from Grossi et al. [2].

Parameter Building		
	Location	Bologna (IT)
	Net floor area [m^2]	111.6
	External wall surface area [m^2]	137.8
	Windows area [m^2]	8.6
	Net volume [m^3]	301.5
	U-value [$Wm^{-2}K^{-1}$]	External wall: 0.38 Roof: 0.22 Floor: 0.31 Windows: 1.77
Design		
	External air design temperature [°C]	Winter: −7 Summer: 35
	Internal set-point temperature [°C]	Winter: 21 Summer: 26
	Design load [kW]	Heating: 8.6 Cooling: 2.8

Table 5
Fluorinated greenhouse gases Global Warming Potential (GWP).
Adaptation from Annex I of Regulation (EU) No 517/2014 [10].

Substance Industrial designation	Chemical name (Common name)	Chemical formula	GWP
HFC-32	Difluoromethane	CH_2 F_2	675
HFC-134a	1.1.1.2-tetrafluoroethane	CH_2 FCF_3	1430
R-410A	Trademark names (e.g. EcoFluor R410. Forane 410A. etc.)	CH_2 F_2 (50%) CH_2 FCF_3 (50%)	2088

rect communications with the prototype manufacturers and by consulting technical datasheets. Data on the maintenance were collected from reliable literature and EU standards. The system end-of-life phase was modelled in accordance with the current regulations and statistical data in this sector. For whom it concern the use phase, this paper is based on the dynamic modelling

Table 6
DSHP total and normalised impacts with ReCiPe Midpoint (H) LCIA method.

Impact category	Unit	Total	Normalised impacts
Global warming	kg CO2 eq	5.80E-02	7.26E-06
Stratospheric ozone depletion	kg CFC11 eq	3.82E-08	6.38E-07
Ionizing radiation	kBq Co-60 eq	6.76E-03	1.41E-05
Ozone formation. Human health	kg NOx eq	1.60E-04	7.75E-06
Fine particulate matter formation	kg PM2.5 eq	8.78E-05	3.43E-06
Ozone formation. Terrestrial eco	kg NOx eq	1.63E-04	9.16E-06
Terrestrial acidification	kg SO2 eq	2.49E-04	6.08E-06
Freshwater eutrophication	kg P eq	2.48E-05	3.83E-05
Marine eutrophication	kg N eq	1.89E-06	4.09E-07
Terrestrial ecotoxicity	kg 1.4-DCB	3.56E-01	3.44E-04
Freshwater ecotoxicity	kg 1.4-DCB	4.65E-03	3.79E-03
Marine ecotoxicity	kg 1.4-DCB	6.24E-03	6.05E-03
Human carcinogenic toxicity	kg 1.4-DCB	2.46E-03	8.89E-04
Human non-carcinogenic toxicity	kg 1.4-DCB	9.56E-02	6.42E-04
Land use	m2a crop eq	1.84E-03	2.97E-07
Mineral resource scarcity	kg Cu eq	2.85E-04	2.38E-09
Fossil resource scarcity	kg oil eq	1.43E-02	1.46E-05
Water consumption	m3	9.79E-03	3.67E-05

Table 7
Environmental impacts of the five main life cycle phases of the DSHP.

Method	Impact category	Unit	Total	Production	Installation	Use	Maintenance	Eol
Recipe Midpoint (H)	Global warming	kg CO_2 eq	5.80E-02	1.23E-02	2.63E-03	3.78E-02	4.78E-03	5.41E-04
				21.13%	4.54%	65.16%	8.23%	0.93%
	Stratospheric ozone depletion	kg CFC11 eq	3.82E-08	1.18E-08	1.53E-09	2.71E-08	4.42E-10	−2.66E-09
				30.98%	4.01%	70.82%	1.16%	−6.96%
	Ionizing radiation	kBq Co-60 eq	6.76E-03	1.15E-03	3.71E-05	5.38E-03	2.96E-05	1.72E-04
				17.00%	0.55%	79.47%	0.44%	2.55%
	Ozone formation. Human health	kg NOx eq	1.60E-04	5.28E-05	3.12E-05	6.97E-05	2.15E-06	3.69E-06
				33.10%	19.54%	43.70%	1.35%	2.31%
	Fine particulate matter formation	kg PM2.5 eq	8.78E-05	2.69E-05	7.34E-06	5.24E-05	1.03E-06	1.45E-07
				30.60%	8.36%	59.70%	1.17%	0.17%
	Ozone formation. Terrestrial eco	kg NOx eq	1.63E-04	5.42E-05	3.17E-05	7.09E-05	2.24E-06	3.76E-06
				33.32%	19.46%	43.53%	1.38%	2.31%
	Terrestrial acidification	kg SO2 eq	2.49E-04	6.82E-05	1.46E-05	1.63E-04	2.38E-06	7.98E-07
				27.35%	5.86%	65.51%	0.96%	0.32%
	Freshwater eutrophication	kg P eq	2.48E-05	1.16E-05	1.20E-07	1.30E-05	1.89E-07	−5.08E-08
				46.67%	0.48%	52.29%	0.76%	−0.20%
	Marine eutrophication	kg N eq	1.89E-06	7.09E-07	9.28E-09	1.14E-06	1.39E-08	1.29E-08

(*continued on next page*)

Table 7 (*continued*)

Method	Impact category	Unit	Total	Production	Installation	Use	Maintenance	EoI
				37.57%	0.49%	60.52%	0.74%	0.68%
	Terrestrial ecotoxicity	kg 1.4-DCB	3.56E-01	2.69E-01	2.71E-03	7.90E-02	3.94E-03	1.69E-03
				75.47%	0.76%	22.19%	1.11%	0.48%
	Freshwater ecotoxicity	kg 1.4-DCB	4.65E-03	1.92E-03	1.13E-05	2.61E-03	8.28E-05	2.58E-05
				41.27%	0.24%	56.15%	1.78%	0.56%
	Marine ecotoxicity	kg 1.4-DCB	6.24E-03	2.79E-03	1.78E-05	3.30E-03	1.06E-04	3.12E-05
				44.69%	0.29%	52.83%	1.69%	0.50%
	Human carcinogenic toxicity	kg 1.4-DCB	2.46E-03	1.23E-03	4.90E-05	1.20E-03	4.42E-05	−6.45E-05
				49.96%	1.99%	48.87%	1.79%	−2.62%
	Human non-carcinogenic toxicity	kg 1.4-DCB	9.56E-02	6.96E-02	3.41E-04	2.47E-02	8.80E-04	1.14E-04
				72.77%	0.36%	25.84%	0.92%	0.12%
	Land use	m2a crop eq	1.84E-03	2.45E-04	7.56E-06	1.53E-03	2.23E-05	2.93E-05
				13.36%	0.41%	83.42%	1.22%	1.59%
	Mineral resource scarcity	kg Cu eq	2.85E-04	2.08E-04	4.10E-06	7.59E-05	5.00E-06	−8.08E-06
				73.04%	1.44%	26.61%	1.75%	−2.83%
	Fossil resource scarcity	kg oil eq	1.43E-02	3.24E-03	8.75E-04	9.85E-03	2.87E-04	6.82E-05
				22.61%	6.11%	68.81%	2.00%	0.48%
	Water consumption	m3	9.79E-03	9.07E-03	5.35E-06	6.68E-04	3.71E-06	4.22E-05
				92.66%	0.05%	6.82%	0.04%	0.43%
Recipe Endpoint (H)	Human health	DALY	1.61E-07	6.84E-08	7.34E-09	7.90E-08	5.44E-09	4.88E-10
				42.57%	4.57%	49.17%	3.39%	0.30%
	Ecosystems	species.yr	4.03E-10	1.93E-10	1.48E-11	1.78E-10	1.47E-11	2.92E-12
				47.83%	3.67%	44.14%	3.64%	0.72%
	Resources	USD2013	4.50E-03	1.23E-03	3.86E-04	2.72E-03	1.17E-04	5.30E-05
				27.34%	8.57%	60.31%	2.61%	1.18%
CED	Non renewable. fossil	MJ	6.56E-01	1.48E-01	4.01E-02	4.52E-01	1.31E-02	3.08E-03
				22.59%	6.10%	68.84%	2.00%	0.47%
	Non-renewable. nuclear	MJ	1.25E-01	1.95E-02	3.61E-04	1.01E-01	5.04E-04	3.23E-03
				15.57%	0.29%	81.15%	0.40%	2.59%
	Non-renewable. biomass	MJ	1.50E-04	1.93E-05	1.95E-07	1.22E-04	7.10E-07	7.86E-06
				12.90%	0.13%	81.25%	0.47%	5.25%
	Renewable. biomass	MJ	3.13E-02	2.31E-03	5.27E-05	2.83E-02	1.10E-04	5.04E-04
				7.38%	0.17%	90.49%	0.35%	1.61%
	Renewable. wind. solar. geo	MJ	6.14E-01	4.39E-04	2.99E-05	6.13E-01	2.94E-05	9.14E-05
				0.07%	0.00%	99.90%	0.00%	0.01%
	Renewable. water	MJ	8.83E-02	4.44E-03	1.46E-04	8.36E-02	1.86E-04	−1.77E-05
				5.02%	0.17%	94.62%	0.21%	−0.02%
IPCC 100a	IPCC GWP 100a	kg CO2 eq	5.57E-02	1.18E-02	2.62E-03	3.66E-02	4.15E-03	5.56E-04
				21.11%	4.70%	65.74%	7.44%	1.00%

Table 8
Relative contributions of the main components to the Production (Manufacturing and assembly) phase.

Method	Impact category	Unit	GPs	Case	Heat exchanger	Compressor	Expansion valves	Wiring	Piping	PWB	Refrigerant
Recipe Midpoint (H)	Global warming	kg CO2 eq	0.001544	5.70E-03	1.19E-03	8.43E-04	1.04E-03	8.42E-04	8.78E-04	8.99E-05	1.28E-04
	Stratospheric ozone depletion	kg CFC11 eq	1.54E-10	4.41E-09	7.08E-10	5.60E-10	5.98E-10	1.64E-10	2.37E-10	5.48E-11	4.95E-09
	Ionizing radiation	kBq Co-60 eq	2.99E-05	7.31E-04	1.42E-04	8.10E-05	8.54E-05	2.85E-05	3.81E-05	9.17E-06	3.45E-06
	Ozone formation. Human health	kg NOx eq	2.73E-06	3.98E-05	2.92E-06	1.98E-06	2.40E-06	1.10E-06	1.32E-06	2.91E-07	1.71E-07
	Fine particulate matter formation	kg PM2.5 eq	1.49E-06	1.10E-05	4.23E-06	3.50E-06	3.84E-06	9.73E-07	1.46E-06	2.30E-07	1.22E-07
	Ozone formation. Terrestrial eco	kg NOx eq	2.92E-06	4.07E-05	3.03E-06	2.04E-06	2.47E-06	1.15E-06	1.38E-06	3.09E-07	1.86E-07
	Terrestrial acidification	kg SO2 eq	3.46E-06	2.83E-05	1.09E-05	9.63E-06	1.02E-05	1.71E-06	3.13E-06	4.55E-07	2.84E-07
	Freshwater eutrophication	kg P eq	2.14E-07	2.91E-06	2.45E-06	2.36E-06	2.45E-06	3.16E-07	6.78E-07	1.89E-07	2.08E-08
	Marine eutrophication	kg N eq	1.22E-08	1.82E-07	1.58E-07	1.44E-07	1.48E-07	1.63E-08	3.84E-08	7.20E-09	1.53E-09
	Terrestrial ecotoxicity	kg 1.4-DCB	0.001575	8.00E-02	5.58E-02	5.68E-02	5.73E-02	3.30E-03	1.24E-02	1.20E-03	1.79E-04
	Freshwater ecotoxicity	kg 1.4-DCB	2.15E-06	4.87E-04	4.12E-04	4.13E-04	4.20E-04	3.49E-05	1.00E-04	2.93E-05	2.15E-06
	Marine ecotoxicity	kg 1.4-DCB	3.00E-06	7.16E-04	5.97E-04	5.98E-04	6.09E-04	4.97E-05	1.44E-04	4.24E-05	3.00E-06
	Human carcinogenic toxicity	kg 1.4-DCB	2.74E-06	3.72E-04	1.87E-04	1.36E-04	1.93E-04	1.21E-04	1.37E-04	1.09E-05	2.74E-06
	Human non-carcinogenic toxicity	kg 1.4-DCB	6.14E-05	1.78E-02	1.50E-02	1.52E-02	1.54E-02	1.10E-03	3.52E-03	1.00E-03	6.14E-05
	Land use	m2a crop eq	7.68E-07	1.18E-04	4.06E-05	2.55E-05	2.80E-05	6.83E-06	1.04E-05	3.13E-06	7.68E-07
	Mineral resource scarcity	kg Cu eq	1.89E-07	5.68E-05	3.75E-05	3.47E-05	4.15E-05	1.20E-05	1.72E-05	3.11E-06	1.89E-07
	Fossil resource scarcity	kg oil eq	1.69E-05	1.74E-03	2.44E-04	1.48E-04	1.83E-04	1.20E-04	1.31E-04	2.33E-05	1.69E-05
	Water consumption	m3	1.05E-06	8.99E-03	2.40E-05	2.05E-05	8.22E-06	4.83E-06	5.56E-06	8.56E-07	1.05E-06
Recipe Endpoint (H)	Human health	DALY	2.74E-09	3.75E-08	7.85E-09	6.94E-09	7.54E-09	2.06E-09	3.00E-09	4.95E-10	2.24E-10
	Ecosystems	species.yr	5.87E-12	1.53E-10	9.30E-12	7.73E-12	8.37E-12	3.26E-12	4.14E-12	5.89E-13	4.81E-13
	Resources	USD2013	2.39E-04	7.27E-04	7.08E-05	5.20E-05	6.06E-05	3.23E-05	3.70E-05	6.10E-06	5.09E-06
CED	Non renewable. fossil	MJ	2.86E-02	7.98E-02	1.12E-02	6.76E-03	8.40E-03	5.51E-03	6.00E-03	1.07E-03	7.74E-04
	Non-renewable. nuclear	MJ	2.61E-03	9.08E-03	2.82E-03	1.65E-03	1.74E-03	5.46E-04	7.45E-04	1.75E-04	8.67E-05
	Non-renewable. biomass	MJ	1.54E-07	3.83E-06	6.85E-06	3.58E-06	3.62E-06	2.51E-07	8.18E-07	1.82E-07	1.94E-08
	Renewable. biomass	MJ	1.91E-04	5.55E-04	5.98E-04	3.55E-04	3.76E-04	7.23E-05	1.23E-04	2.82E-05	1.03E-05
	Renewable. wind. solar. geo	MJ	5.35E-05	9.99E-05	6.87E-05	4.87E-05	5.74E-05	4.40E-05	4.63E-05	1.44E-05	5.59E-06
	Renewable. water	MJ	4.97E-04	1.76E-03	7.21E-04	3.84E-04	4.45E-04	2.45E-04	2.81E-04	7.15E-05	2.70E-05
IPCC 100a	IPCC GWP 100a	kg CO_2 eq	1.51E-03	5.59E-03	1.11E-03	7.77E-04	9.68E-04	7.79E-04	8.14E-04	8.82E-05	1.17E-04

Table 9
ASHP and GSHP energy performance indicators used for the comparison with the DSHP.

	SCOP		SEER		APF	
	1st year	15th year	1st year	15th year	1st year	15th year
DSHP	3.40	3.35	4.31	4.31	3.49	3.41
ASHP	2.79	2.79	2.92	2.92	2.80	2.80 (−17.90%)
GSHP	3.52	3.42	4.25	4.25	3.57	3.47 (+ 1.76%)

Table 10
Environmental impact comparison between the DSHP and conventional systems (ASHP and GSHP).

Method	Impact category	Unit	Baseline	ASHP	GSHP
Recipe Midpoint (H)	Global warming	kg CO_2 eq	5.80E-02	6.02E-02 3.81%	5.87E-02 1.24%
	Stratospheric ozone depletion	kg CFC11 eq	3.82E-08	4.54E-08 18.90%	4.14E-08 8.44%
	Ionizing radiation	kBq Co-60 eq	6.76E-03	7.81E-03 15.55%	6.71E-03 −0.75%
	Ozone formation. Human health	kg NOx eq	1.60E-04	1.36E-04 −14.80%	1.66E-04 4.02%
	Fine particulate matter formation	kg PM2.5 eq	8.78E-05	8.92E-05 1.62%	8.90E-05 1.40%
	Ozone formation. Terrestrial eco	kg NOx eq	1.63E-04	1.39E-04 −14.70%	1.70E-04 4.18%
	Terrestrial acidification	kg SO2 eq	2.49E-04	2.64E-04 6.06%	2.51E-04 0.78%
	Freshwater eutrophication	kg P eq	2.48E-05	2.72E-05 9.73%	2.48E-05 −0.20%
	Marine eutrophication	kg N eq	1.89E-06	2.10E-06 11.33%	1.88E-06 −0.76%
	Terrestrial ecotoxicity	kg 1.4-DCB	3.56E-01	3.68E-01 3.30%	3.57E-01 0.22%
	Freshwater ecotoxicity	kg 1.4-DCB	4.65E-03	5.18E-03 11.44%	4.62E-03 −0.74%
	Marine ecotoxicity	kg 1.4-DCB	6.24E-03	6.90E-03 10.61%	6.20E-03 −0.68%
	Human carcinogenic toxicity	kg 1.4-DCB	2.46E-03	2.59E-03 5.41%	2.47E-03 0.54%
	Human non-carcinogenic toxicity	kg 1.4-DCB	9.56E-02	1.00E-01 4.56%	9.55E-02 −0.08%
	Land use	m2a crop eq	1.84E-03	2.14E-03 16.42%	1.82E-03 −1.16%
	Mineral resource scarcity	kg Cu eq	2.85E-04	2.90E-04 1.87%	2.87E-04 0.64%
	Fossil resource scarcity	kg oil eq	1.43E-02	1.48E-02 3.68%	1.45E-02 1.41%
	Water consumption	m3	9.79E-03	9.91E-03 1.21%	9.79E-03 −0.01%
Recipe Endpoint (H)	Human health	DALY	1.61E-07	1.65E-07 2.63%	1.62E-07 0.69%
	Ecosystems	species.yr	4.03E-10	4.15E-10 2.86%	4.06E-10 0.76%
	Resources	USD2013	4.50E-03	4.42E-03 −1.86%	4.60E-03 2.18%
CED	Non renewable. fossil	MJ	6.56E-01	6.80E-01 3.62%	6.65E-01 1.33%
	Non-renewable. nuclear	MJ	1.25E-01	1.43E-01 14.45%	1.24E-01 −0.65%
	Non-renewable. biomass	MJ	1.50E-04	1.76E-04 17.16%	1.48E-04 −1.36%
	Renewable. biomass	MJ	3.13E-02	3.72E-02 18.85%	3.09E-02 −1.24%
	Renewable. wind. solar. geo	MJ	6.14E-01	7.94E-02 −87.07%	7.72E-01 25.71%
	Renewable. water	MJ	8.83E-02	1.06E-01 19.50%	8.72E-02 −1.26%
IPCC 100a	IPCC GWP 100a	kg CO_2 eq	5.57E-02	5.78E-02 3.78%	5.64E-02 1.23%

Table 11
Environmental impacts of the five main life cycle phases of the ASHP used for the comparison with the DSHP.

Method	Impact category	Unit	Production	Installation	Use	Maintenance	Eol
Recipe Midpoint (H)	Global warming	kg CO_2 eq	1.07E-02	1.78E-06	4.52E-02	4.86E-03	−5.68E-04
	Stratospheric ozone depletion	kg CFC11 eq	1.17E-08	1.10E-12	3.30E-08	3.67E-09	−2.91E-09
	Ionizing radiation	kBq Co-60 eq	1.12E-03	3.83E-08	6.55E-03	3.18E-05	1.12E-04
	Ozone formation. Human health	kg NOx eq	5.01E-05	2.43E-09	8.49E-05	2.26E-06	−9.47E-07
	Fine particulate matter formation	kg PM2.5 eq	2.54E-05	1.56E-09	6.38E-05	1.11E-06	−1.07E-06
	Ozone formation. Terrestrial eco	kg NOx eq	5.13E-05	2.57E-09	8.63E-05	2.36E-06	−9.54E-07
	Terrestrial acidification	kg SO2 eq	6.47E-05	3.46E-09	1.99E-04	2.57E-06	−2.00E-06
	Freshwater eutrophication	kg P eq	1.14E-05	1.93E-10	1.58E-05	2.03E-07	−1.95E-07
	Marine eutrophication	kg N eq	6.96E-07	1.48E-11	1.39E-06	1.49E-08	2.28E-09
	Terrestrial ecotoxicity	kg 1.4-DCB	2.67E-01	1.51E-05	9.62E-02	4.06E-03	1.47E-04
	Freshwater ecotoxicity	kg 1.4-DCB	1.90E-03	3.95E-08	3.18E-03	8.42E-05	1.71E-05
	Marine ecotoxicity	kg 1.4-DCB	2.76E-03	6.24E-08	4.01E-03	1.08E-04	1.86E-05
	Human carcinogenic toxicity	kg 1.4-DCB	1.16E-03	5.48E-08	1.47E-03	4.59E-05	−8.13E-05
	Human non-carcinogenic toxicity	kg 1.4-DCB	6.91E-02	1.46E-06	3.01E-02	9.20E-04	−1.49E-04
	Land use	m2a crop eq	2.34E-04	5.04E-08	1.87E-03	2.28E-05	1.97E-05
	Mineral resource scarcity	kg Cu eq	2.03E-04	5.02E-09	9.25E-05	5.12E-06	−1.04E-05
	Fossil resource scarcity	kg oil eq	2.61E-03	5.96E-07	1.20E-02	2.98E-04	−8.41E-05
	Water consumption	m3	9.06E-03	5.31E-09	8.13E-04	4.39E-06	3.06E-05
Recipe Endpoint (H)	Human health	DALY	6.57E-08	3.16E-12	9.54E-08	5.59E-09	−1.43E-09
	Ecosystems	species.yr	1.87E-10	6.90E-15	2.14E-10	1.50E-11	−1.65E-12
	Resources	USD2013	9.92E-04	2.53E-07	3.31E-03	1.21E-04	−2.94E-06
CED	Non renewable. fossil	MJ	1.20E-01	2.73E-05	5.50E-01	1.37E-02	−3.90E-03
	Non-renewable. nuclear	MJ	1.69E-02	5.36E-07	1.24E-01	5.60E-04	2.15E-03
	Non-renewable. biomass	MJ	1.92E-05	1.86E-09	1.48E-04	7.23E-07	7.59E-06
	Renewable. biomass	MJ	2.12E-03	1.41E-07	3.45E-02	1.17E-04	4.39E-04
	Renewable. wind. solar. geo	MJ	3.85E-04	4.16E-08	7.89E-02	3.30E-05	6.52E-05
	Renewable. water	MJ	3.94E-03	1.94E-07	1.02E-01	2.03E-04	−4.33E-04
IPCC 100a	IPCC GWP 100a	kg CO_2 eq	1.03E-02	1.77E-06	4.39E-02	4.22E-03	−5.50E-04

Table 12
Environmental impacts of the five main life cycle phases of the GSHP used for the comparison with the DSHP.

Method	Impact category	Unit	Production	Installation	Use	Maintenance	Eol
Recipe Midpoint (H)	Global warming	kg CO_2 eq	1.25E-02	3.22E-03	3.72E-02	4.86E-03	8.99E-04
	Stratospheric ozone depletion	kg CFC11 eq	1.19E-08	1.88E-09	2.66E-08	3.67E-09	−2.60E-09
	Ionizing radiation	kBq Co-60 eq	1.15E-03	4.58E-05	5.28E-03	3.18E-05	1.94E-04
	Ozone formation. Human health	kg NOx eq	5.33E-05	3.75E-05	6.85E-05	2.26E-06	4.87E-06
	Fine particulate matter formation	kg PM2.5 eq	2.71E-05	8.86E-06	5.15E-05	1.11E-06	4.64E-07
	Ozone formation. Terrestrial eco	kg NOx eq	5.47E-05	3.81E-05	6.96E-05	2.36E-06	4.95E-06
	Terrestrial acidification	kg SO2 eq	6.87E-05	1.76E-05	1.60E-04	2.57E-06	1.57E-06
	Freshwater eutrophication	kg P eq	1.16E-05	1.51E-07	1.28E-05	2.03E-07	−1.11E-09
	Marine eutrophication	kg N eq	7.11E-07	1.16E-08	1.12E-06	1.49E-08	1.65E-08
	Terrestrial ecotoxicity	kg 1.4-DCB	2.69E-01	3.75E-03	7.77E-02	4.06E-03	2.20E-03
	Freshwater ecotoxicity	kg 1.4-DCB	1.92E-03	1.49E-05	2.57E-03	8.42E-05	2.88E-05
	Marine ecotoxicity	kg 1.4-DCB	2.79E-03	2.35E-05	3.24E-03	1.08E-04	3.55E-05
	Human carcinogenic toxicity	kg 1.4-DCB	1.24E-03	6.07E-05	1.18E-03	4.59E-05	−5.92E-05
	Human non-carcinogenic toxicity	kg 1.4-DCB	6.97E-02	4.58E-04	2.43E-02	9.20E-04	2.03E-04
	Land use	m2a crop eq	2.47E-04	1.07E-05	1.51E-03	2.28E-05	3.26E-05
	Mineral resource scarcity	kg Cu eq	2.09E-04	5.09E-06	7.46E-05	5.12E-06	−7.32E-06
	Fossil resource scarcity	kg oil eq	3.34E-03	1.07E-03	9.68E-03	2.98E-04	1.09E-04
	Water consumption	m3	9.08E-03	6.60E-06	6.56E-04	4.39E-06	4.63E-05
Recipe Endpoint (H)	Human health	DALY	6.89E-08	8.91E-09	7.77E-08	5.59E-09	1.06E-09
	Ecosystems	species.yr	1.94E-10	1.80E-11	1.75E-10	1.50E-11	4.33E-12
	Resources	USD2013	1.27E-03	4.71E-04	2.67E-03	1.21E-04	6.71E-05
CED	Non renewable. fossil	MJ	1.53E-01	4.90E-02	4.44E-01	1.37E-02	4.96E-03
	Non-renewable. nuclear	MJ	1.99E-02	4.51E-04	9.97E-02	5.60E-04	3.62E-03
	Non-renewable. biomass	MJ	1.94E-05	2.96E-07	1.20E-04	7.23E-07	7.96E-06
	Renewable. biomass	MJ	2.34E-03	6.79E-05	2.79E-02	1.17E-04	5.27E-04
	Renewable. wind. solar. geo	MJ	4.48E-04	3.73E-05	7.71E-01	3.30E-05	1.00E-04
	Renewable. water	MJ	4.52E-03	1.82E-04	8.21E-02	2.03E-04	1.29E-04
IPCC 100a	IPCC GWP 100a	kg CO_2 eq	1.20E-02	3.20E-03	3.60E-02	4.22E-03	9.13E-04

Table 13
Carbon intensity of 1 kWh of the different electricity mixes considered in the DSHP LCA sensitivity analysis.

Method	Impact category	Unit	IT	PV (IT)	BE	ES	NO	RU
IPCC 100a	IPCC GWP 100a	kg CO_2 eq	4.10E-01	7.11E-02	2.71E-01	3.52E-01	3.27E-02	8.09E-01

Table 14
Monthly and daily solar irradiation of the location and corresponding potential electricity production.

Month	Average daily electricity production [kWh]	Average monthly electricity production [kWh]	Average daily sum of global irradiation per sqm [kWh/m^2]	Average sum of global irradiation
per sqm [kWh/m^2]				
January	1.55	48.0	1.89	58.6
February	2.93	82.1	3.63	102
March	3.82	119	4.94	153
April	4.11	123	5.45	164
May	4.61	143	6.25	194
June	4.64	139	6.46	194
July	4.96	154	6.97	216
August	4.62	143	6.48	201
September	4.03	121	5.50	165
October	2.89	89.7	3.78	117
November	1.86	55.8	2.35	70.5
December	1.59	49.2	1.94	60.1
Year	3.47	106	4.64	141
Total for year		1270		1690

and energy performance analysis conducted by Grossi et al. [2] using the TRNSYS17 software [3], whose results have been used to account for the performance and the energy consumption of both the DSHP under study and the conventional HPs used for the comparison. SimaPro software version 9.0 was used to perform the LCA study and with its associated database (professional). Mainly datasets from the Ecoinvent (v. 3.4 and 3.5) [4] database were used to model background processes and to obtain secondary or not available data. The environmental impacts were calculated with the following methods: Recipe Midpoint and Endpoint, both from the Hierarchist (H) perspective [5,6]; Cumulative Energy Demand (CED) [7]and IPCC [8]. Ecoinvent database country related energy mix have been used to conduct the sensitivity analysis on the variation of the energy mix. The photovoltaic energy available in the site has been estimated using the PVGIS web tool of the European Union [9].

Table 15
Sensitivity analysis for different energy mixes in comparison with the baseline scenario.

Method	5mpact category	Unit	Baseline	PV (IT)	BE	ES	NO	RU
Recipe Midpoint (H)	Global warming	kg CO_2 eq	5.80E-02	3.00E-02	4.65E-02	5.31E-02	2.68E-02	9.12E-02
				−48.28%	−19.83%	−8.45%	−53.79%	57.24%
	Stratospheric ozone depletion	kg CFC11 eq	3.82E-08	1.42E-08	2.98E-08	2.65E-08	1.78E-08	8.26E-08
				−62.83%	−21.99%	−30.63%	−53.40%	116.23%
	Ionizing radiation	kBq Co-60 eq	6.76E-03	2.00E-03	3.36E-02	1.75E-02	2.48E-03	1.49E-02
				−70.41%	397.04%	158.88%	−63.31%	120.41%
	Ozone formation. Human health	kg NOx eq	1.60E-04	1.05E-04	1.27E-04	1.89E-04	9.47E-05	1.95E-04
				−34.38%	−20.63%	18.13%	−40.81%	21.88%
	Fine particulate matter formation	kg PM2.5 eq	8.78E-05	4.98E-05	5.70E-05	1.11E-04	3.95E-05	1.85E-04
				−43.28%	−35.08%	26.42%	−55.01%	110.71%
	Ozone formation. Terrestrial eco	kg NOx eq	1.63E-04	1.08E-04	1.30E-04	1.92E-04	9.70E-05	2.00E-04
				−33.74%	−20.25%	17.79%	−40.49%	22.70%
	Terrestrial acidification	kg SO2 eq	2.49E-04	1.16E-04	1.44E-04	2.75E-04	9.60E-05	2.95E-04
				−53.41%	−42.17%	10.44%	−61.45%	18.47%
	Freshwater eutrophication	kg P eq	2.48E-05	1.73E-05	2.03E-05	2.57E-05	1.39E-05	4.52E-05
				−30.24%	−18.15%	3.63%	−43.95%	82.26%
	Marine eutrophication	kg N eq	1.89E-06	1.27E-06	1.86E-06	1.90E-06	8.87E-07	2.99E-06
				−32.80%	−1.59%	0.53%	−53.07%	58.20%
	Terrestrial ecotoxicity	kg 1.4-DCB	3.56E-01	4.44E-01	3.35E-01	3.49E-01	3.17E-01	3.39E-01
				24.72%	−5.90%	−1.97%	−10.96%	−4.78%
	Freshwater ecotoxicity	kg 1.4-DCB	4.65E-03	3.69E-03	4.36E-03	4.68E-03	4.12E-03	5.02E-03
				−20.65%	−6.24%	0.65%	−11.40%	7.96%
	Marine ecotoxicity	kg 1.4-DCB	6.24E-03	5.13E-03	5.85E-03	6.26E-03	5.50E-03	6.75E-03
				−17.79%	−6.25%	0.32%	−11.86%	8.17%
	Human carcinogenic toxicity	kg 1.4-DCB	2.46E-03	1.84E-03	2.13E-03	2.72E-03	1.71E-03	3.57E-03
				−25.20%	−13.41%	10.57%	−30.49%	45.12%
	Human non-carcinogenic toxicity	kg 1.4-DCB	9.56E-02	9.44E-02	8.93E-02	9.45E-02	8.19E-02	1.07E-01
				−1.26%	−6.59%	−1.15%	−14.33%	11.92%
	Land use	m2a crop eq	1.84E-03	4.81E-04	2.18E-03	1.17E-03	5.11E-04	5.26E-04
				−73.86%	18.48%	−36.41%	−72.23%	−71.41%
	Mineral resource scarcity	kg Cu eq	2.85E-04	2.86E-04	3.56E-04	2.87E-04	2.47E-04	2.65E-04
				0.35%	24.91%	0.70%	−13.33%	−7.02%
	Fossil resource scarcity	kg oil eq	1.43E-02	6.00E-03	1.11E-02	1.22E-02	5.17E-03	2.55E-02
				−58.04%	−22.38%	−14.69%	−63.85%	78.32%

(*continued on next page*)

Table 15 (*continued*)

Method	5mpact category	Unit	Baseline	PV (IT)	BE	ES	NO	RU
	Water consumption	m3	9.79E-03	9.33E-03	9.41E-03	9.40E-03	1.16E-02	1.02E-02
				−4.70%	−3.88%	−3.98%	18.49%	4.19%
Recipe Endpoint (H)	Human health	DALY	1.61E-07	2.58E-08	1.27E-07	8.91E-08	1.54E-08	1.77E-07
				−83.98%	−21.12%	−44.66%	−90.43%	9.94%
	Ecosystems	species.yr	4.03E-10	4.62E-11	3.44E-10	1.68E-10	2.85E-11	2.90E-10
				−88.54%	−14.64%	−58.31%	−92.93%	−28.04%
	Resources	USD2013	4.50E-03	3.79E-04	3.70E-03	1.71E-03	2.23E-04	5.91E-03
				−91.58%	−17.78%	−62.00%	−95.04%	31.33%
CED	Non renewable. fossil	MJ	6.56E-01	2.75E-01	5.10E-01	5.58E-01	2.37E-01	1.16E+00
				−58.08%	−22.26%	−14.94%	−63.87%	76.83%
	Non-renewable. nuclear	MJ	1.25E-01	3.53E-02	6.36E-01	3.25E-01	4.34E-02	2.72E-01
				−71.76%	408.80%	160.00%	−65.28%	117.60%
	Non-renewable. biomass	MJ	1.50E-04	4.21E-05	5.24E-05	4.06E-05	3.21E-05	3.32E-05
				−71.93%	−65.07%	−72.93%	−78.60%	−77.87%
	Renewable. biomass	MJ	3.13E-02	5.73E-03	4.54E-02	1.89E-02	7.19E-03	5.15E-03
				−81.69%	45.05%	−39.62%	−77.03%	−83.55%
	Renewable. wind. solar. geo	MJ	6.14E-01	8.64E-01	5.73E-01	6.43E-01	5.57E-01	5.50E-01
				40.72%	−6.68%	4.72%	−9.28%	−10.42%
	Renewable. water	MJ	8.83E-02	1.49E-02	1.61E-02	6.44E-02	3.25E-01	7.19E-02
				−83.13%	−81.77%	−27.07%	268.06%	−18.57%
IPCC 100a	IPCC GWP 100a	kg CO_2 eq	5.57E-02	2.81E-02	4.44E-02	5.10E-02	2.50E-02	8.83E-02
				−49.55%	−20.29%	−8.44%	−55.12%	58.53%

Table 16
Sensitivity analysis for a reduction in energy demand.
LCA results and contribution of the use phase on the total impacts for all the considered categories.

Method	Impact category	Unit	Energy demand variation −60%		−30%		−10%	
			Total	Use	Total	Use	Total	Use
ReCiPe Midpoint (H)	Global warming	kg CO_2 eq	3.53E-02	42.82%	4.67E-02	56.72%	5.42E-02	62.75%
	Stratospheric ozone depletion	kg CFC11 eq	2.20E-08	49.32%	3.01E-08	63.00%	3.55E-08	68.65%
	Ionizing radiation	kBq Co-60 eq	3.53E-03	60.85%	5.15E-03	73.11%	6.22E-03	77.76%
	Ozone formation. Human health	kg NOx eq	1.18E-04	23.60%	1.39E-04	35.09%	1.53E-04	41.01%
	Fine particulate matter formation	kg PM2.5 eq	5.64E-05	37.19%	7.21E-05	50.88%	8.26E-05	57.12%
	Ozone formation. Terrestrial eco	kg NOx eq	1.20E-04	23.53%	1.42E-04	35.00%	1.56E-04	40.91%
	Terrestrial acidification	kg SO2 eq	1.51E-04	43.23%	2.00E-04	57.13%	2.33E-04	63.14%
	Freshwater eutrophication	kg P eq	1.70E-05	30.56%	2.09E-05	43.51%	2.35E-05	49.76%
	Marine eutrophication	kg N eq	1.20E-06	37.90%	1.55E-06	51.65%	1.78E-06	57.86%
	Terrestrial ecotoxicity	kg 1.4-DCB	3.09E-01	10.24%	3.32E-01	16.65%	3.48E-01	20.43%
	Freshwater ecotoxicity	kg 1.4-DCB	3.08E-03	33.87%	3.87E-03	47.26%	4.39E-03	53.54%
	Marine ecotoxicity	kg 1.4-DCB	4.26E-03	30.93%	5.25E-03	43.94%	5.91E-03	50.19%
	Human carcinogenic toxicity	kg 1.4-DCB	1.74E-03	27.72%	2.10E-03	40.16%	2.34E-03	46.32%
	Human non-carcinogenic toxicity	kg 1.4-DCB	8.08E-02	12.24%	8.82E-02	19.61%	9.31E-02	23.88%
	Land use	m2a crop eq	9.21E-04	66.54%	1.38E-03	77.68%	1.69E-03	81.73%
	Mineral resource scarcity	kg Cu eq	2.39E-04	12.68%	2.62E-04	20.27%	2.77E-04	24.63%
	Fossil resource scarcity	kg oil eq	8.39E-03	46.99%	1.13E-02	60.80%	1.33E-02	66.60%
	Water consumption	m3	9.39E-03	2.84%	9.59E-03	4.87%	9.72E-03	6.18%
Recipe Endpoint (H)	Human health	DALY	1.14E-07	27.81%	1.37E-07	40.27%	1.53E-07	46.44%
	Ecosystems	species.yr	2.96E-10	24.02%	3.50E-10	35.62%	3.85E-10	41.56%
	Resources	USD2013	2.87E-03	37.83%	3.69E-03	51.57%	4.23E-03	57.79%
CED			3.85E-01	46.96%	5.20E-01	60.78%	6.11E-01	66.58%
			6.42E-02	63.23%	9.46E-02	75.06%	1.15E-01	79.46%
			7.70E-05	63.27%	1.13E-04	75.09%	1.38E-04	79.49%
			1.43E-02	79.34%	2.28E-02	87.05%	2.85E-02	89.63%
			2.46E-01	99.73%	4.30E-01	99.85%	5.53E-01	99.88%
			3.81E-02	87.66%	6.32E-02	92.56%	7.99E-02	94.11%
IPCC 100a	IPCC GWP 100a	kg CO2 eq	3.37E-02	43.42%	4.47E-02	57.32%	5.20E-02	63.32%

Table 17
Sensitivity analysis for an increase in energy demand.
LCA results and contribution of the use phase on the total impacts for all the considered categories.

Method	Impact category	Unit	Energy demand variation 10%		30%		+60%	
			Total	Use	Total	Use	Total	Use
ReCiPe Midpoint (H)	Global warming	kg CO_2 eq	6.18E-02	67.31%	6.93E-02	70.88%	8.07E-02	74.97%
	Stratospheric ozone depletion	kg CFC11 eq	4.09E-08	72.80%	4.63E-08	75.98%	5.44E-08	79.56%
	Ionizing radiation	kBq Co-60 eq	7.30E-03	81.04%	8.37E-03	83.47%	9.99E-03	86.14%
	Ozone formation. Human health	kg NOx eq	1.67E-04	45.94%	1.81E-04	50.10%	2.02E-04	55.28%
	Fine particulate matter formation	kg PM2.5 eq	9.30E-05	61.95%	1.04E-04	65.80%	1.19E-04	70.31%
	Ozone formation. Terrestrial eco	kg NOx eq	1.70E-04	45.83%	1.84E-04	50.00%	2.06E-04	55.17%
	Terrestrial acidification	kg SO2 eq	2.65E-04	67.68%	2.98E-04	71.22%	3.47E-04	75.28%
	Freshwater eutrophication	kg P eq	2.61E-05	54.76%	2.87E-05	58.86%	3.26E-05	63.78%
	Marine eutrophication	kg N eq	2.00E-06	62.66%	2.23E-06	66.48%	2.58E-06	70.94%
	Terrestrial ecotoxicity	kg 1.4-DCB	3.64E-01	23.89%	3.80E-01	27.06%	4.03E-01	31.34%
	Freshwater ecotoxicity	kg 1.4-DCB	4.91E-03	58.48%	5.43E-03	62.47%	6.22E-03	67.20%
	Marine ecotoxicity	kg 1.4-DCB	6.57E-03	55.19%	7.23E-03	59.27%	8.22E-03	64.17%
	Human carcinogenic toxicity	kg 1.4-DCB	2.58E-03	51.33%	2.82E-03	55.48%	3.18E-03	60.54%
	Human non-carcinogenic toxicity	kg 1.4-DCB	9.81E-02	27.71%	1.03E-01	31.18%	1.10E-01	35.80%
	Land use	m2a crop eq	1.99E-03	84.54%	2.30E-03	86.60%	2.76E-03	88.83%
	Mineral resource scarcity	kg Cu eq	2.93E-04	28.55%	3.08E-04	32.07%	3.31E-04	36.75%
	Fossil resource scarcity	kg oil eq	1.53E-02	70.91%	1.73E-02	74.23%	2.02E-02	78.00%
	Water consumption	m3	9.86E-03	7.45%	9.99E-03	8.69%	1.02E-02	10.48%
Recipe Endpoint (H)	Human health	DALY	1.69E-07	51.45%	1.85E-07	55.60%	2.08E-07	60.65%
	Ecosystems	species.yr	4.21E-10	46.50%	4.56E-10	50.67%	5.10E-10	55.84%
	Resources	USD2013	4.77E-03	62.60%	5.31E-03	66.42%	6.13E-03	70.88%
CED			7.01E-01	70.89%	7.92E-01	74.21%	9.27E-01	77.98%
			1.35E-01	82.55%	1.55E-01	84.82%	1.86E-01	87.31%
			1.62E-04	82.57%	1.87E-04	84.85%	2.23E-04	87.33%
			3.41E-02	91.35%	3.98E-02	92.58%	4.83E-02	93.89%
			6.75E-01	99.90%	7.98E-01	99.92%	9.82E-01	99.93%
			9.67E-02	95.13%	1.13E-01	95.85%	1.38E-01	96.60%
IPCC 100a	IPCC GWP 100a	kg CO2 eq	5.94E-02	67.85%	6.67E-02	71.38%	7.77E-02	75.42%

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships which have, or could be perceived to have, influenced the work reported in this article.

Acknowledgments

This study was supported by the regional project named “HEGOS”- nuove pompe di calore per l’Harvesting EnerGeticO in Smart buildings – Progetto Regione Emilia Romagna POR-FESR 2014–2020.

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