SUPPLEMENTARY MATERIALS

A. CHRS LIST OF MATERIALS

The materials involved in the installation of the plant and the need for use of specific machines, means of transportation and electricity, were assessed through a real scale plant design, construction and utilization performed by the research group. These data were used to perform the LCA study and are listed in Table A.1 and table A.2.

Table A. 1 List of necessary materials to build an average CHRS, considered to perform the LCA study

		Value	Unit
LIST OF MATERIALS CONSIDERED	HYDRAULIC SYSTEM		
	POLIETHYLENE PIPE 32mm PN16	500	m
	PE KNEE-CONNECTION	10	#
	PE T-CONNECTION	6	#
	LEACHATE RICIRCULATION PUMP	1	#
	FLEXIBLE PE PIPE 25 mm FOR LEACHATE RICIRCULATION	10	m
	CONCRETE WELL	1	#
	GEOTHERMAL COLLECTORS (STAINLESS STEEL)	1	#
	PRESSURE SAFETY	1	#
	AIR SEPARATOR	1	#
	IMPURITIES FILTER	1	#
	PIPES THERMOMETER	1	#
	MECHANICAL ELECTROVALVE	1	#
	TIMER	1	#
	EXCHANGE FLUID RICIRCULATION PUMP	1	#
	CLOSED EXPANSION VESSEL 35 l	1	#
	DRAINAGE FLEXIBLE CORRUGATED PIPE 90mm	15	m
	EXTERNAL STRUCTURE		
	BREATHABLE WATERPROOF MEMBRANE – TENSILE STRENGHT 350 – 50 mm	36	mq
	STAINLESS STEEL WELDED MESH 8mm (20x20)	53	mq
	STAINLESS STEEL WELDED MESH 6mm (10x10)	20	mq
	PLASTIC TIES	500	#
	AERATION SYSTEM		
	POLIETHYLENE CORRUGATED PIPE DOUBLE WALLED 120mm	20	m
	ELECTRICAL SYSTEM		
	MONITORING UN-T - ESP32 DevKitV1	1	#
	PROBES DS18B20	10	#
	INSULATION SYSTEM		
	HAY BALES 100*40*40 cm	15	mc
	FILLING MATERIAL		
	WOODY BIOMASS (WOODCHIP)	26,101	kg

Table A. 2 Machine consumption to build an average CHRS, considered to perform the LCA study

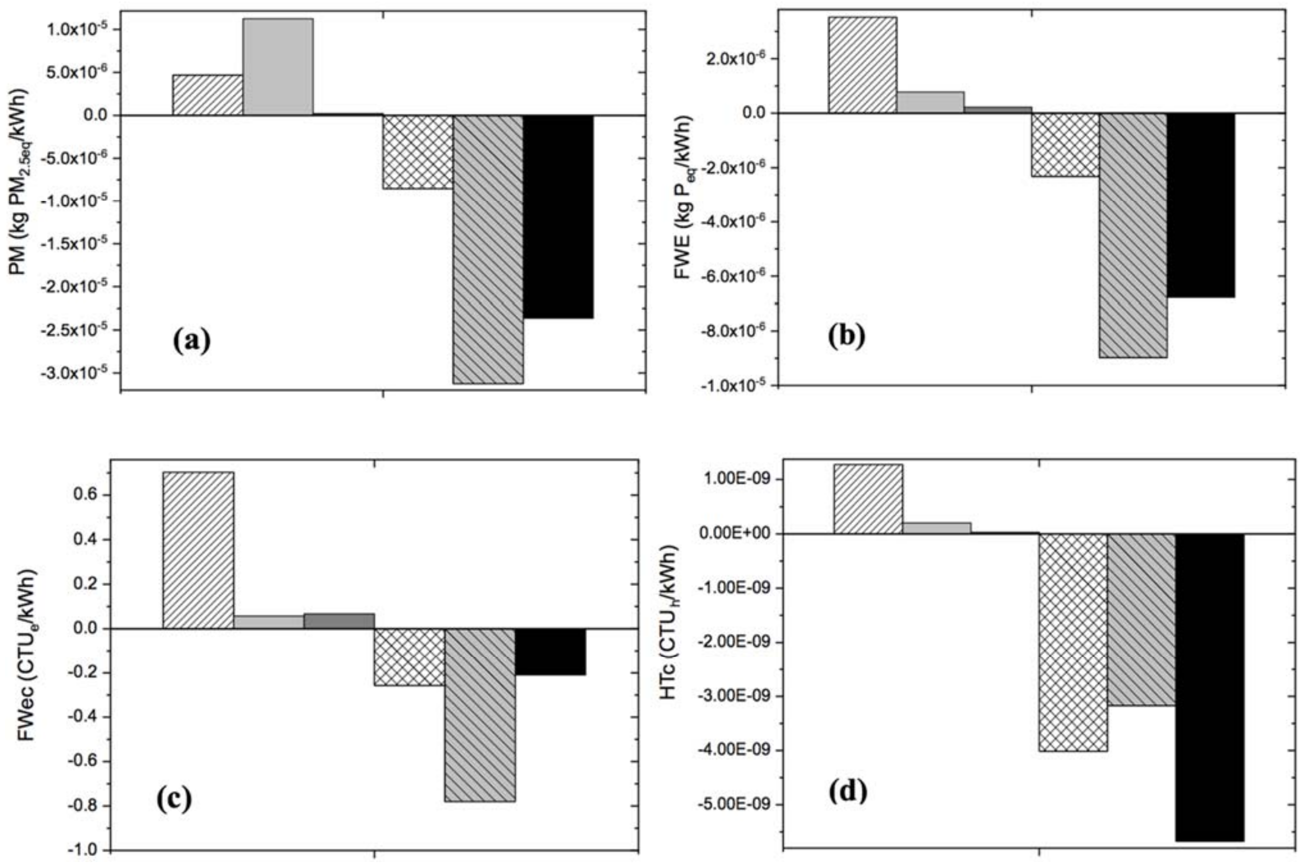
		Value	Unit
MACHINERY AND PUMPS CONSUMPTION	WOODCHIP MACHINE		
	BIOMASS TO BE CHIPPED PER YEAR	26	t/y
	AVERAGE WOODCHIP MACHINE CONSUMPTION	2	l/t
	DIESEL OIL CONSUMED YEARLY	39	l/y
	PUMPS		
	LEACHATE RICIRCULATION	82	h/y
	EXCHANGE FLUID RECIRCULATION	2,190	h/y
	WHEEL LOADER		
	PLANT FILLING (CONSTRUCTION AND YEARLY MAINTENANCE)	8	h/y
	AVERAGE WHEEL LOADER CONSUMPTION	18	l/h
	DIESEL OIL CONSUMED YEARLY	142	l /y
	WOODCHIP TRANSPORT		
	TRUCK CAPACITY	7	t/y
	NUMBER OF TRIP (CONSTRUCTION AND YEARLY MAINTENANCE)	4	trip/y
	MATERIAL TRANSPORT		
	NUMBER OF TRIP (CONSTRUCTION AND YEARLY MAINTENANCE)	1	trip/y

B. LCA RESULTS

In the present LCA, not only the GWP impact, but also the following ones were assessed: Particulate Matter (PM) ($kg_{PM2.5eq}$); Fresh Water Eutrophication (FWE) (kg_{Peq}); Fresh Water Ecotoxicity (FWec) (CTU_e – Comparative Toxic Unit for ecosystems); Human Toxicity, cancer effects (HT_c) (CTU_h – Comparative Toxic Unit for Human Health); Human Toxicity, non cancer effect (HT_{nc}) (CTU_h).

For the midpoint the ILCD 2010+ method. For the Human Health (HH) endpoint (DALY – Disability Adjusted Life Year), the IMPACT 2000+ assessment method was used.

From the study emerged that all the impacts related to the implementation of a CHRSs due to direct and indirect emissions, are lower respect to the benefits due to the replacement of natural gas used as traditional thermal energy production and the replacement of mineral fertilizers. Indeed, the calculated emissions in all the considered impact categories are lower respect to the emissions avoided thanks to the implementation of the CHRS. This is easy to understand from the graphical representation of the midpoint and endpoint indicators given below (Fig. B.1)



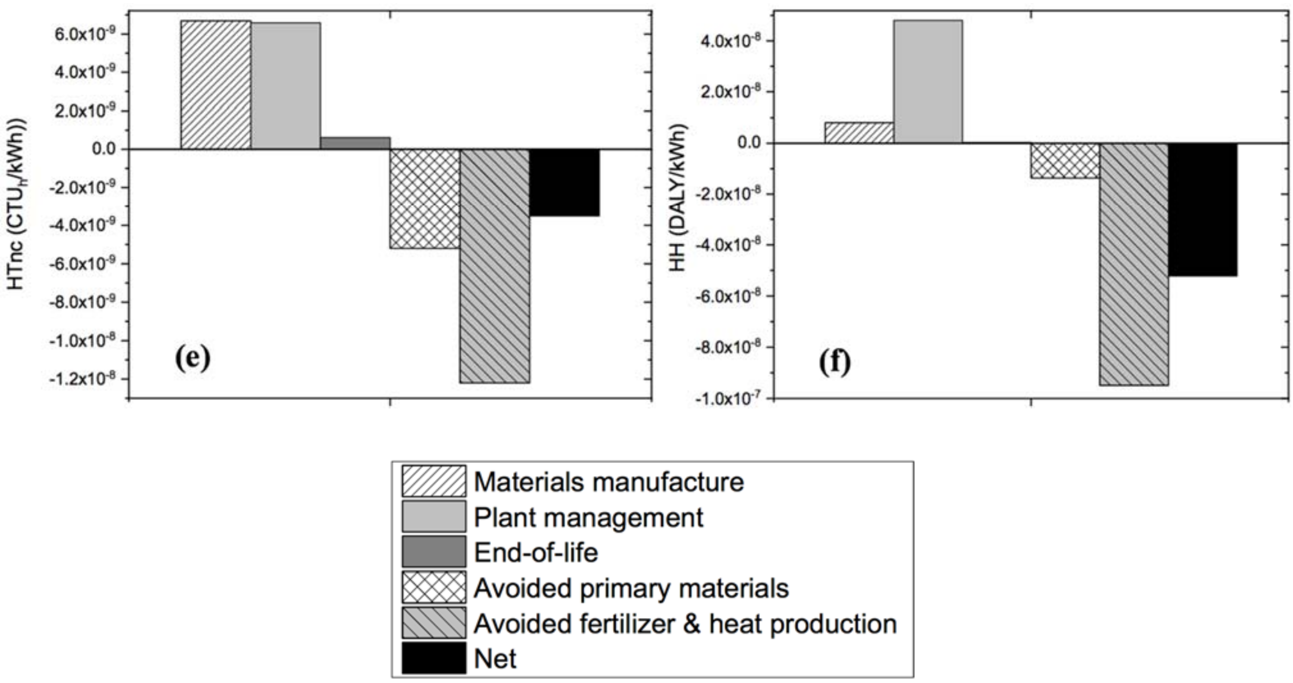


Figure B.1. Characterization of midpoint indicators PM (a), FWE (b), FWec (c), HTc (d), HTnc (e) and endpoint indicator HH (f)

Avoided impacts contributed for all the impact categories to a net negative value. This means that for each impact indicator considered to evaluate both environmental and human health consequences, positive emissions related to CHRS life cycle are less than negative emissions respect to a traditional domestic heating system and mineral fertilizers use. This because the combination of the benefits achieved by material recovery (avoided primary materials), avoided mineral fertilizers and avoided heat production are higher than the damages caused by materials manufacture, management in end-of life stage and plant management for the entire lifetime of 15 years, leading to negative net values.

All the LCA values represented in Fig. B.1, are reported in Table B.1.

Table B. 1 Numerical values of midpoint indicators PM ($kgP_{M2.5-eq}$), FWE (kg_{P-eq}), FWec (CTUe), HTc (CTUh), HTnc (CTUh) and endpoint indicator HH (DALY) expressed per kWh

IMPACT CATEGORY	PM	FWE	FWec	HTc	HTnc	HH
unit	$kg_{PM2.5-eq}$/kWh	kg_{P-eq}/kWh	CTUe/kWh	CTUh/kWh	CTUh/kWh	DALY/kWh
LCA STAGE						
MATERIALS MANUFACTURE	4.69E-06	3.52E-06	7.03E-01	1.27E-09	6.69E-09	8.07E-09
PLANT MANAGEMENT	1.12E-05	7.77E-07	5.73E-02	2.01E-10	6.59E-09	4.80E-08
END OF LIFE	2.11E-07	2.19E-07	6.68E-02	3.03E-11	6.16E-10	3.00E-10
AVOIDED PRIMARY MATERIALS	-8.52E-06	-2.32E-06	-2.57E-01	-4.01E-09	-5.21E-09	-1.37E-08
AVOIDED FERTILIZER AND HEAT PRODUCTION	-3.13E-05	-8.98E-06	-7.80E-01	-3.17E-09	-1.22E-08	-9.49E-08
NET VALUE	-2.36E-05	-6.78E-06	-2.10E-01	-5.68E-09	-3.51E-09	-5.22E-08

C. DETAILED GWP IMPACT VALUES

In the following tables (Table C.1 and C.2), the detailed GWP impact values emerged from LCA are reported.

The emissions are expressed in kg_{CO2-eq} per kWh of thermal energy produced and detailed for every phase of the life cycle considered. Percentages are reported in order to provide an idea of which part of the plant or phase impact more on the environment.

Table C. 1 Total positive GWP emissions in kg_{CO2-eq}/kWh related to materials manufacture, plant management and end of life.

GWP TOTAL POSITIVE EMISSIONS		
MATERIALS MANUFACTURE	GWP kg_{CO2-eq}/kWh	%
HYDRAULIC SYSTEM		
POLIETHYLENE PIPE 32mm PN16	1.58E-03	29
FLEXIBLE PE PIPE 25 mm FOR LEACHATE RICIRCULATION	1.97E-05	0.4
DRAINAGE FLEXIBLE CORRUGATED PIPE 90mm	4.68E-05	1
EXTERNAL STRUCTURE		
BREATHABLE WATERPROOF MEMBRANE – TENSILE STRENGHT 350 – 50 mm	4.62E-04	9
STAINLESS STEEL WELDED MESH 8mm (20x20)	1.36E-03	25
STAINLESS STEEL WELDED MESH 6mm (10x10)	5.65E-04	10
AERATION SYSTEM		
POLIETHYLENE CORRUGATED PIPE DOUBLE WALLED 120mm	6.95E-05	1
LEACHATE RICIRCULATION PUMP	6.60E-04	12
EXCHANGE FLUID RICIRCULATION PUMP	6.20E-04	12
TOT MATERIALS MANUFACTURE	5.39E-03	100
PLANT MANAGEMENT	GWP kg_{CO2-eq}/kWh	%
WOODCHIP MACHINE USE	1.64E-02	29
LEACHATE RICIRCULATION	2.13E-09	0.000004
EXCHANGE FLUID RECIRCULATION	4.47E-04	1
WHEEL LOADER USE	2.08E-02	37
MATERIAL TRANSPORT	1.84E-02	33
TOT PLANT MANAGEMENT	5.61E-02	100
of which gas oil	5.56E-02	99
of which electricity	4.47E-04	1
END OF LIFE	GWP kg_{CO2-eq}/kWh	%
EXCHANGE FLUID RECIRCULATION PUMP		
Aluminium, wrought alloy {GLO}| market for | APOS, U	9.53E-07	0.4
Cast iron {GLO}| market for | APOS, U	4.70E-06	2
Copper {GLO}| market for | APOS, U	2.02E-05	9
Polyvinylchloride, emulsion polymerised {GLO}| market for | APOS, U	1.11E-07	0.05
Polyvinylchloride, suspension polymerised {GLO}| market for | APOS, U	7.61E-07	0.3
Steel, chromium steel 18/8, hot rolled {GLO}| market for | APOS, U	3.60E-06	2
Synthetic rubber {GLO}| market for | APOS, U	1.52E-06	1
LEACHATE RECIRCULATION PUMP		
Aluminium, wrought alloy {GLO}| market for | APOS, U	1.02E-06	0.4
Cast iron {GLO}| market for | APOS, U	5.00E-06	2
Copper {GLO}| market for | APOS, U	2.15E-05	9
Polyvinylchloride, emulsion polymerised {GLO}| market for | APOS, U	1.19E-07	0.1
Polyvinylchloride, suspension polymerised {GLO}| market for | APOS, U	8.11E-07	0.3
Steel, chromium steel 18/8, hot rolled {GLO}| market for | APOS, U	3.84E-06	2
Synthetic rubber {GLO}| market for | APOS, U	1.62E-06	1
PIPES		
POLIETHYLENE PIPE 32mm PN16	8.72E-05	37
FLEXIBLE PE PIPE 25 mm FOR LEACHATE RICIRCULATION	1.08E-06	0.5
DRAINAGE FLEXIBLE CORRUGATED PIPE 90mm	2.52E-06	1
POLIETHYLENE CORRUGATED PIPE DOUBLE WALLED 120mm	3.73E-06	2
BREATHABLE WATERPROOF MEMBRANE – TENSILE STRENGHT 350 – 50 mm	2.90E-05	12
STAINLESS STEEL WELDED MESH 8mm (20x20)	3.30E-05	14
STAINLESS STEEL WELDED MESH 6mm (10x10)	1.42E-05	6
TOT END OF LIFE	2.37E-04	100
TOTAL POSITIVE EMISSIONS	**6.17E-02**	

Table C. 2 Total negative GWP emissions in kg_{CO2-eq}/kWh related to avoided fertilizer, avoided heat production and avoided primary materials.

GWP TOTAL NEGATIVE EMISSIONS		
AVOIDED FERTILIZER	GWP kg CO2 eq/kWh	%
N mineral fertilizer	-4.14E-03	9
P mineral fertilizer	-3.76E-04	1
K mineral fertilizer	-1.44E-03	3
CO2eq. stored in soil	-4.25E-02	88

TOT AVOIDED FERTILIZER	-4.85E-02	100
AVOIDED HEAT PRODUCTION	GWP kg CO2 eq/kWh	%
hot water production through natural gas domestic heating	-2.75E-01	100
TOT AVOIDED HEAT PRODUCTION	-2.75E-01	100
AVOIDED PRIMARY MATERIALS	GWP kg CO2 eq/kWh	%
EXCHANGE FLUID RECIRCULATION PUMP		
Aluminium, wrought alloy {GLO}| market for | APOS, U	-1.33E-05	0.2
Cast iron {GLO}| market for | APOS, U	-2.09E-04	4
Copper {GLO}| market for | APOS, U	-2.89E-05	0.5
Polyvinylchloride, emulsion polymerised {GLO}| market for | APOS, U	-6.19E-07	0.01
Polyvinylchloride, suspension polymerised {GLO}| market for | APOS, U	-3.46E-06	0.1
Steel, chromium steel 18/8, hot rolled {GLO}| market for | APOS, U	-2.83E-04	5
LEACHATE RECIRCULATION PUMP		
Aluminium, wrought alloy {GLO}| market for | APOS, U	-1.42E-05	0.2
Cast iron {GLO}| market for | APOS, U	-2.23E-04	4
Copper {GLO}| market for | APOS, U	-3.08E-05	1
Polyvinylchloride, emulsion polymerised {GLO}| market for | APOS, U	-6.59E-07	0.01
Polyvinylchloride, suspension polymerised {GLO}| market for | APOS, U	-3.69E-06	0.1
Steel, chromium steel 18/8, hot rolled {GLO}| market for | APOS, U	-3.01E-04	5
PIPES		
POLIETHYLENE PIPE 32mm PN16	-9.65E-04	16
FLEXIBLE PE PIPE 25 mm FOR LEACHATE RICIRCULATION	-1.20E-05	0.2
DRAINAGE FLEXIBLE CORRUGATED PIPE 90mm	-2.79E-05	0.5
POLIETHYLENE CORRUGATED PIPE DOUBLE WALLED 120mm	-4.13E-05	1
BREATHABLE WATERPROOF MEMBRANE – TENSILE STRENGHT 350 – 50 mm	0.00E+00	0
STAINLESS STEEL WELDED MESH 8mm (20x20)	-2.59E-03	44
STAINLESS STEEL WELDED MESH 6mm (10x10)	-1.11E-03	19
TOT AVOIDED PRIMARY MATERIALS	-5.86E-03	100
TOTAL NEGATIVE EMISSIONS	**6.00E-06**	

D. LITERATURE DATA COLLECTED

The main values found in literature are resumed in Table D.1. The table reports quantitative and qualitative descriptors of the evaluated technologies and the characteristics of the LCA studies, including the following: kind of plant (between Solar Hot Water Systems and Geothermal Heating Systems), Scale (Domestic or Utility scale), Operative Lifetime considered, LCA Calculation method, $kg_{CO2\text{-}eq}$/kWh and the references. When the values were not expressed in $kg_{CO2\text{-}eq}$/kWh, they were calculated or converted considering the aforementioned conversion factor. Calculated and/or converted values are marked.

Table D. 1 Quantitative and qualitative description of the considered LCA performed on the chosen Systems (Solar Hot Water Systems and Geothermal Systems) that passed the two-step screening providing a final estimate value of $kgCO_2$/kWh.

SCALE	KIND OF PLANT	OPERATIVE LIFETIME (y)	PROGRAM and ASSESSMENT METHOD USED	$kg_{CO2\text{-}eq}$/kWh		AUTHORS
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.05	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.07	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.05	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.07	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.07	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.07	*	(Martinopoulos et al., 2013)

residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.05	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.07	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.07	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.07	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.07	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.06	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System	15	SimaPro, Ecoindicator 99	0.07	*	(Martinopoulos et al., 2013)
residential	Solar Hot Water System (glazed)	10	Gabi software, Ecoindicator 99	0.04	*	(Comodi et al., 2016)
residential	Solar Hot Water System (unglazed)	10	Gabi software, Ecoindicator 99	0.004	*	(Comodi et al., 2016)
residential	Solar Hot Water System	20	GaBi software, Ecoinvent database, LCA Method	0.09		(Albertí et al., 2019)
utility	Geothermal Heating/Cooling System	30	OpenLCA, Ecoinvent 3.5, WEEE_LCI databases, LCIA Methodology of Cumulative Energy Demand and Recipe midpoint 2016 H	0.02		(A. S. Pratiwi & Trutnevyte, 2021)
utility	Geothermal Heating/Cooling System	30	OpenLCA, Ecoinvent 3.5, WEEE_LCI databases, LCIA Methodology of Cumulative Energy Demand and Recipe midpoint 2016 H	0.02		(A. S. Pratiwi & Trutnevyte, 2021)
utility	Geothermal Heating/Cooling System	30	OpenLCA, Ecoinvent 3.5, WEEE_LCI databases, LCIA Methodology of Cumulative Energy Demand and Recipe midpoint 2016 H	0.01		(A. S. Pratiwi & Trutnevyte, 2021)
utility	Geothermal Heating/Cooling System	30	OpenLCA, Ecoinvent 3.5, WEEE_LCI databases, LCIA Methodology of Cumulative Energy Demand and Recipe midpoint 2016 H	0.01		(A. S. Pratiwi & Trutnevyte, 2021)
utility	Geothermal Heating/Cooling System	30	OpenLCA, Ecoinvent 3.5, WEEE_LCI databases, LCIA Methodology of Cumulative Energy Demand and Recipe midpoint 2016 H	0.02		(A. S. Pratiwi & Trutnevyte, 2021)
utility	Geothermal Heating/Cooling System	30	OpenLCA, Ecoinvent 3.5, WEEE_LCI databases, LCIA Methodology of Cumulative Energy Demand and Recipe midpoint 2016 H	0.02		(A. S. Pratiwi & Trutnevyte, 2021)
utility	Geothermal Heating System	30	SimaPro, CML baseline impact, Cumulative Energy Demand (CED)	0.01		(Karlsdottir et al., 2014)
utility	Geothermal Heating System	/	/	0.08		(A. Pratiwi & Trutnevyte, 2020)
utility	Geothermal Heating System	25	OpenLCA , LCA method	0.01		(A. Pratiwi et al., 2018)
utility	Geothermal Heating System	25	OpenLCA, LCA method	0.00		(A. Pratiwi et al., 2018)
utility	Geothermal Heating System	25	OpenLCA, LCA method	0.00		(A. Pratiwi et al., 2018)
utility	Geothermal Heating System	25	SimaPro, Ecoinvent, LCA method	0.04		(Lacirignola & Blanc, 2013)
utility	Geothermal Heating System	30	Not specified, Ecoinvent, LCA method	0.01		(Frick et al., 2010)
residential	Electricity from power plant	15	SimaPro, Ecoindicator 99	1.41	*	(Martinopoulos et al., 2013)
utility	Electricity mix	/	/	1.18		(A. Pratiwi & Trutnevyte, 2020)
residential	Natural Gas Boiler	20	GaBi software, Ecoinvent database, LCA Method	0.27		(Albertí et al., 2019)

Conversion factor used: 3.6 MJ/kWh.
Values that were processed are marked with *

E. STATISTICAL ANALYSIS

Numerical values of percentiles, mean, median, minimum and maximum values and interquartile range related to literature data statistical analysis on SHWS and GHS, are provided in Table E.1.

Table E. 1 Statistics reported for the considered technologies (Solar Hot Water Systems and Geothermal Heating Systems). Processing of literature data collected. IQ range= Interquartile Range (75th - 25th percentile).

	SOLAR HOT WATER SYSTEM	GEOTHERMAL HEATING SYSTEM
	kg_{CO2-eq}/kWh	
Mean value	0.061	0.019
Min	0.004	0.004

25th percentile	0.059	0.006
Median	0.063	0.015
75th percentile	0.065	0.018
Max	0.092	0.082
IQ range	0.006	0.012