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A comparative environmental life cycle assessment between a condensing boiler and a gas driven absorption heat pump

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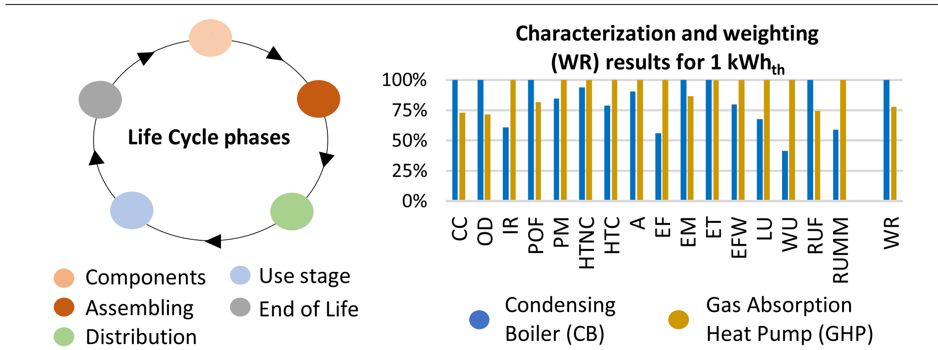
HIGHLIGHTS

- Gas heat pump is considered an alternative to boilers for residential heating.
- The two systems are compared with a LCA approach.
- 16 environmental impact categories were considered using the EF 3.0 method.
- The use phase contributes over 97% of the impact for both the energy systems.
- Changing from CB to GHP reduces potential impacts by 22%.

GRAPHICAL ABSTRACT



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ABSTRACT

Gas absorption heat pumps represent an alternative to condensing boilers for space heating and domestic hot water production in existing buildings. In particular, they enable fuel saving and the exploitation of renewable energy even in heating systems based on radiators, which require high supply temperature. However, in order to provide useful indications to policymakers, manufacturers, and system designers, a fair comparison of two technologies has to be based, besides the energy consumption and the direct CO_2 eq emissions, also the environmental impact over the entire life cycle. Thus, in this paper, the environmental profiles of a condensing boiler and a gas driven absorption heat pump are compared as competing technologies to provide space heating and domestic hot water in old (constructed before 1980) and not refurbished buildings. The assessment was carried out for three buildings located in three representative European climates, using 1 kWh of thermal energy produced by the two systems as the functional unit. The Ecoinvent 3.6 was used as background database and the EF 3.0 normalization as weighting set method. Uncertainty and sensitivity analysis were also included. The results show that the use phase contributes for more than 97% of the total impact for both the energy systems in the three climate zones. Despite the higher electricity consumption, the gas driven absorption heat pump offered a lower environmental profile compared with the condensing boiler, mainly because of the lower amount of natural gas needed in the use phase. In particular, an average reduction of 27% was found for CO_2 eq, 25% for fossil resource consumption, and 22% for weighting results.

1. Introduction

The building sector is recognized as a significant contributor to the overall environmental impact of humankind's activities. For instance, the sector accounts for about 30–40% of total energy consumption in the European Union (European Commission - Directorate-General for

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Nomenclature

U_{door}	thermal transmittance of doors, W/m^2 K
U_{floor}	thermal transmittance of floors, W/m^2 K
U_{roof}	thermal transmittance of roofs, W/m^2 K
U_{wall}	thermal transmittance of walls, W/m^2 K
$U_{windows}$	thermal transmittance of windows, W/m^2 K
$\Delta U_{t.\ brid.}$	transmittance increase due to thermal bridges, W/m^2 K

Subscripts

el	electric
in	input
th	thermal

Abbreviations

A	Acidification
CB	Condensing Boiler
CC	Climate Change
CO_2 eq	Carbon dioxide equivalent
DHW	Domestic Hot Water
EC	European Commission
EF	Eutrophication Freshwater
EFW	Ecotoxicity Freshwater
EM	Eutrophication Marine
EoL	End of Life
EPD	Environmental Product Declaration
ET	Eutrophication Terrestrial
GHP	Gas-driven absorption Heat Pump
HHV	Higher Heating Value
HTC	Human Toxicity Cancer
HTNC	Human Toxicity Non-Cancer
IR	Ionizing Radiation
JRC	Joint Research Center
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
LU	Land Use
NF	Normalization Factor
OD	Ozone Depletion
P	Probability
PM	Particulate Matter
POF	Photochemical Ozone Formation
RUF	Resource Use, Fossils
RUMM	Resource Use, Mineral and Metals
SCOP	Seasonal Coefficient Of Performance
S-LCA	Social-Life Cycle Assessment
WU	Water Use

Energy and Transport, 2007; IEA, 2016), with the associated severe environmental burdens (Takano et al., 2015). Besides, as underlined by Babiker et al. (2018), the global building stock shall significantly reduce the CO_2 eq emissions (80–90% by 2050) in response to the threat of climate change (1.5 °C pathways). Furthermore, the building sector was identified as one of the key areas for European policies initiative due to its great potential for reducing environmental impacts. According to previous studies (European Environment Agency, 2015; European Parliament, 2010, 2016), 80% of the energy used in households was dedicated to space heating and Domestic Hot Water (DHW). Thus, to reduce energy consumption and environmental emissions, the mitigation strategy shall be focused on these two services. Considering that most of the European buildings stock is represented by buildings constructed before 1990 (Baldassarri et al., 2017), a strong focus on existing buildings is required to achieve these targets. Here, massive saving potential with available and demonstrated technologies could be implemented, utilizing refurbishing measures on both envelope and energy production systems. In particular, thanks to its higher renovation rate, approx. 3.6% against 0.5%–1.2%, the improvement of the energy system may represent a faster option to reduce the energy consumptions compared with measures focusing on the building envelope (Ascione et al., 2011; Eichhammer et al., 2009; Lavagna and Sala, 2018; Scoccia et al., 2018). Additionally, in the case of occupied buildings, changes in the energy systems usually have less impact than actions aiming to improve the building envelope.

Usually, heating systems are compared based on their efficiency, primary energy consumption or running costs for the given application. However, high efficiency and low energy consumption are usually achieved with complex systems, which have a higher cost and a higher environmental impact when manufactured. Additionally, when comparing systems using different energy carriers (e.g., natural gas and/or electricity), an accurate picture of their impact requires that other aspects besides greenhouse gases emission are considered. Thus, the Life Cycle Assessment (LCA) (ISO, 2006a, 2006b) methodology, the leading methodology for environmental metrics, represents a useful tool to evaluate the eco-profile of buildings, energy systems, and building materials (Cellura et al., 2017) according to a comprehensive and scientifically reliable approach. The LCA method consists of a complete analysis that accounts for materials, energy inputs, and emissions associated with each stage of a product life cycle (Sala et al., 2017). For more than a decade, it has been an important, voluntary reference tool for European environmental policy to draft significant political and legislative initiatives.

Among the other energy-efficient and low-carbon solutions considered, heat pumps help achieve energy-efficiency improvements in buildings and constructions (European Union, 2009), using renewable energy sources (air, ground, and water). Previous works compare residential vapor compression heat pump technologies with conventional energy systems with a life cycle approach. Some of them: i) air-source heat pumps (Genkinger et al., 2012; Greening and Azapagic, 2012; Latorre-Biel et al., 2018; Shah et al., 2008), ii) ground-source heat pumps (Abusoglu and Sedeeq, 2013; Greening and Azapagic, 2012; Heikkilä, 2008; Litjens et al., 2018; Russo et al., 2014), iii) water-source heat pumps (Abusoglu and Sedeeq, 2013; Greening and Azapagic, 2012), iv) wastewater-source heat pumps (Chen et al., 2012), v) article reviews on heat pumps (Bayer et al., 2012; Marinelli et al., 2019). The studies highlighted the mitigation of the environmental emissions derived from the use of heat pump systems. Moreover, underlined the use phase as the most significant phase for these technologies, due to electricity consumption and refrigerant gas leakages. In particular, Greening and Azapagic (2012) compared a gas boiler with an air-source heat pump and a groundwater-source heat pump, Latorre-Biel et al. (2018) replace an electric resistive space heating system with an air-source heat pump, Abusoglu and Sedeeq (2013) compared a coal and a gas boiler with a ground-source heat pump, Russo et al. (2014) evaluated a liquified petroleum gas hot air generator and a ground-source heat pump, Chen et al. (2012) compared a coal and gas boiler with a wastewater-source heat pump.

Similarly, this work aims to evaluate through a life cycle approach (attributional) the environmental performances of an air-source gas-driven absorption heat pump (GHP), from now on also referred to as “heat pump”, for space heating and domestic hot water production in single-family houses, as an alternative to condensing boiler (CB), from now on also referred to as “boiler”. This technology is particularly interesting for old and not retrofitted buildings, with radiators as emission system. In this application, representing a large share of the European building stock, vapor compression heat pumps find limited application because of the high capacity and supply temperature required. Moreover, the gas heat pumps benefit from the natural gas network's high capacity and has a limited impact on the electric grid. The focus on this fuel drive technologies is interesting both in a short-term scenario and in the perspective of a future availability in the natural gas network of hydrogen from renewable energy sources or biogas.

Two works in the literature are available for what concerns gas-driven heat pumps to the best of the authors' knowledge. Wang et al. (2013) investigated the potential environmental impacts of a vapor compression heat pump driven by a gas engine for domestic hot water production with a life cycle approach. Unlike in the present work, the focus was only on domestic hot water production. Additionally, heat pumps driven by a gas engine are usually of medium to large capacity, suitable for commercial or large residential buildings. Nitkiewicz and Sekret (2014) compared a gas-driven heat pump, an electric heat pump, and a gas boiler as alternative technologies for district heating at 40–50 °C. The capacity of the appliances was 400 kW, significantly higher than the one considered in this work. As well, the heat pumps operated under very favorable conditions since the exploited geothermal water at about 20 °C as heat source.

In this paper, the comparison between gas heat pump and boiler was performed considering the two technologies as alternative options for replacing an existing conventional boiler once it reaches its end of life, with the purpose of assessing and comparing their environmental impact over the entire life cycle. In particular, the comparison was implemented for three cases, corresponding to buildings located in the three reference climatic conditions (cold, average, and warm) defined by the European ERP Directive (European Parliament, 2009). The analysis was conducted following the comparative LCA studies (ISO, 2006a, 2006b; JRC, 2010). 16 potential different impact categories were outlined for the two alternative systems, and the contribution of each life cycle stage was determined. Also, detailed data (life cycle inventory data) on GHP, energy systems not yet totally covered by the LCA scientific community are provided.

Uncertainty and sensitivity analysis were also performed to test the results obtained. The uncertainties analysis was executed through the software SimaPro 9.1.08 following the Monte Carlo method. The sensitivity analysis was conducted on two relevant aspects not directly covered by the Monte Carlo method, i.e., the Life Cycle Impact Assessment (LCIA) method and the emissions evaluation method during the natural gas combustion in the use phase. For both these aspects, two alternative methods were selected and compared to assess their impact on the results. Other aspects, beyond the environmental perspective, concerning the Life Cycle Sustainability Analysis method, such as the Life Cycle Cost and Social-Life Cycle Assessment, were considered outside the scope of this work. A standard and internationally recognized methodology for those indicators is still under development (Liu and Qian, 2019).

2. Methodology

In this chapter, the methodology used to compare the two energy systems under evaluation is presented, detailing the approaches followed in the definition of the system boundaries, the allocation and cut-off rules, functional unit, the life cycle impact assessment method, and the uncertainty and sensitivity analysis.

In the attributional LCA modeling, the technological and environmental models have the following characteristics: linear, stationary, and adopt the Ceteris Paribus assumption. What is not directly modified by the system under analysis is not modeled because in random isolation, i.e., not affected by the system (JRC, 2010).

2.1. System boundaries

The study was conducted with a cradle-to-grave approach, which includes all steps from the extraction of raw materials to the end of life (Klöpffer and Grahl, 2014). In particular, the following phases were considered:

a) component productions (raw material supply and production);
b) assembling (manufacturing with energy and water consumptions, welding, waste, transport of components plus packaging);
c) distribution;
d) use stage (electricity and natural gas consumption plus maintenance and the related transports);
e) end of life stage (transport, waste processing for reuse, recovery or/and recycling, and disposal.

Installation was excluded from the analysis for both technologies because of the lack of data concerning their process and the limited impact of this phase, as highlighted in (Favi et al., 2018; Oregi et al., 2015). The water consumption (in terms of mass) during the use phase (domestic hot water service) was also neglected. It was considered irrelevant for the comparison, being attributable to the user behavior. Fig. 1 shows a simplified flow chart of the two products. The blocks that were fully or partially evaluated using primary (company-specific) data were reported in grey. The phases evaluated totally with secondary data, i.e., sourced from a third-party (e.g., industry-average-data, life cycle inventory database, etc.) are reported in white.

2.2. Allocation and cut-off rules

The environmental burdens of a process for co-production or end-of-life treatment were assessed by the multifunctionality approach recommended by ISO (2006a, 2006b). Two types of allocation were used in this work. i) For the manufacturing phase, the energy (electricity and heat) and water consumption were allocated by mass. In particular, the reports by (Jungbluth, 2012; Primas, 2007), providing data per kg of product obtained from the annual consumption of reference companies, were used. ii) For the end-of-life-modeling, the cut-off approach proposed in the Ecoinvent database (Wernet et al., 2016) was used. The idea behind this approach is that the primary production of materials is always assigned to the primary user. If the material is recycled, the primary producer receives no environmental benefits for the supply of recyclable materials. Consequently, recyclable materials are available without burdens for the recycling processes, and the recycled materials bear just the impacts of recycling processes.

The cut-off rule was set at 1% in terms of environmental impact within the system boundaries described above, meaning that inputs and outputs below this threshold were not included in the LCA models. E.g., seals, glues, transport, and transport of packaging materials to the manufacturing sites.

2.3. Functional unit

The functional unit (FU) is the quantified performance of a produced system used as a reference unit (ISO, 2006b). In this article, the functional unit was set as 1 kWh of thermal energy provided for space heating and domestic hot water service, replacing a conventional gas boiler. The surface of the dwelling was established equal to 140 m^2 (with specific geometric characteristics and thermophysical performances) located in three cities (Helsinki, Strasbourg, and Athens) representative of the different climate zones, as defined by the European ERP Directive (European Parliament, 2009). Lifespan was set equal to 20 years (conservatively estimated).

2.4. Life cycle impacts assessment

The environmental profile of boiler and heat pump was expressed considering 16 impact categories, following the EF method 3.0 normalization and weighting set – impact assessment method of Environmental Footprint initiative (Fazio et al., 2018): [1] Climate Change (CC) with a time horizon of 100 years; [2] Ozone Depletion (OD) with a time horizon of 100 years; [3] Ionizing Radiation (IR); [4] Photochemical

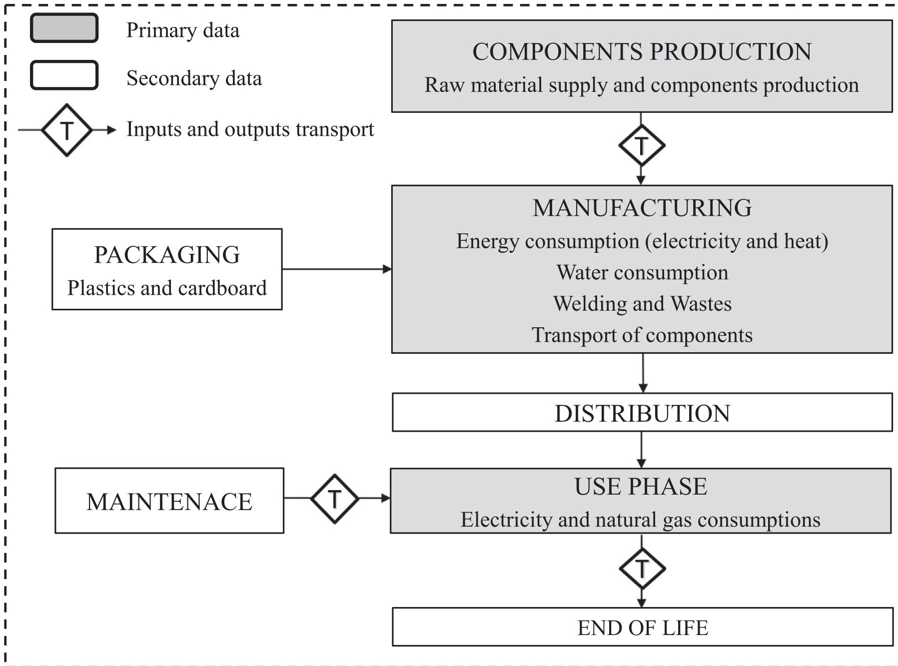

Fig. 1. System boundaries.

Ozone Formation (POF); [5] Particulate Matter (PM); [6] Human Toxicity Non-Cancer (HTNC); [7] Human Toxicity Cancer (HTC); [8] Acidification (A); [9] Eutrophication Freshwater (EF); [10] Eutrophication Marine (EM); [11] Eutrophication Terrestrial (ET); [12] Ecotoxicity Freshwater (EFW); [13] Land Use (LU); [14] Water Use (WU); [15] Resource Use, Fossil (RUF); [16] Resource Use, Mineral and Metals (RUMM). The authors were not decided to reduce the number of impact categories not risk losing information defined by the European Commission. The method has also recently been adopted by EN 15804: +A2 (CEN, 2019) standard covering the Environmental Product Declarations (EPDs) for the construction sector (normalization and weighting excluded).

2.5. Uncertainty and sensitivity analysis

The uncertainties related to input data were combined and propagate to obtain overall uncertainties (Raynolds et al., 1999). Within an LCA study, two types of uncertainty are present (Raynolds et al., 1999): i) associated with activity data collected for the Life Cycle Inventory (LCI), e.g., amount of steel to produce the CB and the GHP, and related to the secondary dataset contained by the commercial background database used to represent a specific process, e.g., the average steel production process in Europe taken from Ecoinvent 3.6 (Steen, 1997). ii) Associated with the methodological procedures, i.e., system boundaries selected, models used to translate the LCI results in LCIA results, and method used to assess the uncertainties. In this study, the uncertainty related to the system boundaries is negligible, thanks to the from cradle to grave approach.

A simplified procedure was developed to quantify data uncertainty in input: this simplified approach, also used in the Ecoinvent database, involves a qualitative assessment of the data quality indicators, based on a pedigree matrix. This matrix was introduced and developed by Weidema and Wesnaes (1996). It is named pedigree matrix because the data quality indicators refer to the history or origin of the data, as a family tree reports the pedigree of an individual. Basic uncertainty factors, provided by Frischknecht, were used for the input and output types considered (Frischknecht et al., 2005). After the uncertainty characterization of the input data, their distributions were propagated using the Monte Carlo method (random sampling), obtaining the potential environmental impacts with their probability distribution (Heijungs et al., 2005). According to the Ecoinvent database, every input parameter was considered a stochastic variable with a lognormal probability distribution in the Monte Carlo method. The number of executions was fixed precautionary equal to 2000 with a 95% confidence interval, as recommended by Raynolds et al. (1999) to ensure convergence between the mean system impact and the uncertainty in system impact.

Finally, the One-At-a-Time (OAT) method for sensitivity analysis was applied to two relevant aspects not directly covered by the Monte Carlo method to understand how much influence they have on the final results. For what concerns the first aspects, since the use phase has the highest environmental impact (Marinelli et al., 2019; Wang et al., 2013), an alternative method, developed by EEA (2019) and IPCC (2006), was selected and compared with the data provided by Emmenegger et al. (2012) used in this article, to assess the impact of this modeling choice on CO_2, N_2O, and CH_4 emissions. A second sensitivity analysis was performed for the LCIA method, as indicated in ISO 14044 (ISO, 2006b). The results obtained with EF method 3.0 normalization and weighting set selected for this paper – impact assessment method of Environmental Footprint initiative (Fazio et al., 2018) were compared with the results obtained with ReCiPe 2016 (Hierarchist - H) (Huijbregts et al., 2017). The ReCiPe method was chosen, compared to the other methods in SimaPro, concerning the impact categories recommended by the European Commission - Joint Research Centre (2011); European Commission - Joint Research Centre (2012), beyond the wide application in scientific articles. The LCIA method's choice is crucial, especially when considering the normalization and weighting steps (considered optional in LCA), to support the results' interpretation. Normalization and weighting steps help to understand better the relative significance of impact categories (Benini and Sala, 2016) and to implement the comparison between the two energy systems.

3. Life cycle inventory analysis

In this section, the life cycle inventory analysis was explained, providing the compilation and the quantification of inputs and outputs for boiler and heat pump throughout their life cycles.

3.1. Reference buildings

The environmental impact related to the use phase of the appliance was calculated for reference buildings, shaped based on the outcome of Task 44 "Solar and Heat Pump Systems" of the IEA Solar Heating and Cooling program (Dott, 2012). The buildings are single-family houses made of two levels, with a floor area of 70 m^2 each. The features of the envelope were differentiated on the basis of the location, assuming different structures for the three climates on the basis of the results of the European projects TABULA and EPISCOPE (Institut Wohnen und Umwelt GmbH, 2016), which provided details about the typical buildings of different European regions, differentiated by the period of construction. Among the building typologies available in the database, the reference buildings to characterize the envelope was chosen as the one with the highest number of constructions among the one's antecedent the implementation of energy efficiency regulation. In Table 1, the resulting U-values for the different surfaces and each building are reported, with the U-value incrementation to include the thermal bridges' effect. A heating setpoint of 20 °C was chosen for daytime hours (6:00 and 22:00), while a lower value (16 °C) was used for the remaining hours.

The modeling approach for both building envelope and heating system is the same as the one adopted in Scoccia et al. (2018), where a detailed description can be found.

The resulting space heating needs and maximum heating load are:

- Warm climate: 208.1 $\frac{kWh}{m^2y}$; 19.1 kW.
- Average climate: 230.6 $\frac{kWh}{m^2y}$; 14.3 kW.
- Cold climate: 202.8 $\frac{kWh}{m^2y}$; 12.2 kW.

For what concerns the DHW needs, in the model, the tapping profiles defined in the Commission Delegated Regulation (EU) No 812/2013 (European Commission, 2013) were implemented. The cycles define a DHW demand over 24 h, specifying for each tapping the typology, the beginning time, and the energy content in hot water. In the present work, the tapping cycle "L", corresponding to the DHW demand of four inhabitants, was used, coherent with the selected building typology. The resulting energy needs for DHW is 11.7 kWh per day, corresponding to 200 l of water equivalent at 60 °C drawn over the 24-h cycle.

In Table 2, information about the use phase scenario are reported for both the boiler and the heat pump. In particular, the table provides:

- the energy consumptions in terms of electricity and natural gas calculated for the three cases;
- the efficiency as an average for the space heating and domestic hot water productions;
- the Higher Heating Value (HHV) of natural gas used for the analysis.

3.2. Condensing boiler model with internal DHW tank

A boiler with 35 kW of nominal gas input (HHV) was selected for the study. The maximum steady-state load of the buildings is 19 kW; thus, the boiler results oversized for the actual needs. However, this design approach is commonly used in real applications and is motivated by two main reasons:

- a nominal gas input of about 35 kW allows instantaneous DHW production, making the storage tank unnecessary. However, a small storage tank is often integrated into the boiler to smooth the DHW demand and reduce the burner's number of cycles, positively impacting on efficiency and maintenance. For the present study, a boiler with an integrated tank of 40 l was selected.
- The cost of a boiler and the material required for its construction are only slightly affected by the capacity. Thus, on the one hand, some oversizing is expected in a real application; on the other, this has little impact on the product's life cost analysis.

Table 1
Buildings selected as reference.

	U $\frac{W}{m^2K}$		
	Average	Cold	Warm
U_{wall}	1.10	0.41	2.20
U_{roof}	0.80	0.36	3.70
U_{floor}	1.00	0.90	0.95
$U_{windows}$	2.80	2.80	4.70
U_{door}	3.00	3.00	3.00
$\Delta U_{t.\ brid.}$	0.10	0.10	0.15

Table 2
Energy consumption of the buildings selected as reference.

Energy consumptions	CB	GHP
Electricity [kWh/m^2 year]	4.03 (average) 3.09 (cold) 3.16 (warm)	10.76 (average) 10.84 (cold) 9.11 (warm)
Natural gas [kWh/m^2 year]	296.77 (average) 264.92 (cold) 268.30 (warm)	200.60 (average) 188.81 (cold) 172.09 (warm)
HHV natural gas [kWh per Nm^3]	11.2	11.2

The Life Cycle Inventory (LCI) of the boiler was realized by collecting primary data from an international boiler manufacturer concerning the mass of components and type of materials (via questionnaires and personal interviews). Other data concerning the manufacturing processes, transport in input and outputs, packaging, and end-of-life scenarios were collected based on different publications (Butera et al., 2015; Emmenegger et al., 2012; Kemna et al., 2019; Wernet et al., 2016). The details of the different activity data used for the evaluation are listed in Table 3. Whereas the reference background database was Ecoinvent 3.6 (Wernet et al., 2016).

3.3. Gas-driven absorption heat pump model

The capacity of the gas heat pump was selected to deal with the highest of the peak loads of the three investigated cases, i.e., one of the old building in the warm climate. According to this, the GHP resulted in a nominal gas input of 16.9 kW, which corresponds to a heating capacity of 19.1 kW at 0 °C of air temperature and 65 °C of supply water temperature. The selected capacity does not allow for instantaneous DHW production; thus, external storage with a volume of 80 l was added. The choice of a single capacity for the heat pump is motivated by the small number of GHP models currently on the market and the consequently limited manufacturing data availability. Additionally, differentiating the capacity based on the location would have made it difficult to clearly and concisely present the study results. Thus, the average and cold climate results will be slightly affected by the use of an oversized appliance, which will lead to an overestimation of the environmental cost due to the production. On the one hand, the oversize appliance will give conservative outcomes and, on the other, may have a relatively small impact on the overall results since, as discussed, the use phase is expected to be the most impacting.

The Life Cycle Inventory (LCI) of the analyzed heat pump was realized by collecting confidentially primary data from a manufacturer concerning the mass of components and type of materials and scaling them according to the capacity selected for this study. As for the boiler, other data concerning some manufacturing processes, transport in input and outputs, packaging, and end-of-life scenario were collected on the base of different publications (Butera et al., 2015; Emmenegger

Table 3
Activity data and references for the condensing boiler (61 kg in total).

Characteristic	Value	Reference
General information		
Nominal heat input	35.0 kW	Manufacturer data
Yearly efficiency (HHV)	89.8% (average) 90.2% (cold) 89.2% (warm)	Trnsys model
Lifespan	20 years	Kemna et al., 2019
Total weight	61 kg	Manufacturer data
Components		
Copper (pipes, engines, wirings)	6.0 kg	Manufacturer data
Aluminum (motor die-casting, gas valve, inlet door)	7.8 kg	Manufacturer data
Steel (heat exchangers, expansion tank, storage tank, structural elements, and body)	32.5 kg	Manufacturer data
Stainless steel (heat exchangers and body)	9.5 kg	Manufacturer data
PVC (flue system, hydronic circuits, insulations)	0.02 kg	Manufacturer data
PP (flue system, hydronic circuits, insulations)	0.2 kg	Manufacturer data
ABS (flue system, hydronic circuits, insulations)	4.0 kg	Manufacturer data
Electronic components	1.0 kg	Manufacturer data
Manufacturing process		
Welding	4.6 kg	Jungbluth, 2012
Water consumption	337.3 kg	Jungbluth, 2012
Electricity	36.0 kWh	Jungbluth, 2012
Heat	87.3 kWh	Jungbluth, 2012
Transport input	61.0 tkm	Kemna et al., 2019
Hazardous waste	0.2 kg	Jungbluth, 2012
Wastewater	279.8 kg	Jungbluth, 2012
Packaging		
Plastic film	0.3 kg	Kemna et al., 2019
Polystyrene	0.1 kg	Kemna et al., 2019
Corrugated board	0.3 kg	Kemna et al., 2019
Distribution		
Transport from manufacturer to consumer	45.8 tkm	Kemna et al., 2019
Maintenance		
Components substitution	0.6 kg	Kemna et al., 2019
Transport to consumer	0.3 tkm	Kemna et al., 2019
End of life		
Copper	Recycling 97% Landfill 3%	Kemna et al., 2019
Aluminum	Recycling 97% Landfill 3%	Kemna et al., 2019
Steel	Recycling 97% Landfill 3%	Kemna et al., 2019
Plastic	Municipal incineration 70% Landfill 30%	Kemna et al., 2019
Electronic components	Municipal incineration 70% Landfill 30%	Kemna et al., 2019
Packaging	Recycling 52% Municipal incineration 17% Landfill 31%	Wernet et al., 2016
Transport from consumer to treatment plant	1.8 tkm	Butera et al., 2015

et al., 2012; Kemna et al., 2019; Primas, 2007; Wernet et al., 2016). The details of the different activity data used for the evaluation are listed in Table 4. Even in this case, the reference background database was Ecoinvent 3.6 (Wernet et al., 2016).

3.4. Use phase model and emissions

The information about the emission factors based on energy input (based on HHV) used are reported in Table 5 for both the boiler and the heat pump. Data on emissions, which occur during natural gas combustion, were taken from Emmenegger (2012b). Emmenegger provides data determined with direct measurement (not stochiometric analysis) implemented by the Swiss Society of Gas and Water Industry on a sample of Swiss furnaces, later transcribed in the Ecoinvent 3.6 database (Wernet et al., 2016). The dataset selected to model the emissions for the use phase scenario was: *Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atm. Low-NOx condensing non-modulating < 100 kW | Cut-off, U.*

The emissions to water represent the emissions through the condensate, which depend on condensate quantities, considered in the reference equal to 0.015 kg per MJ_{in} for boilers.

Specific data for the heat pump are not available. However, as suggested in (Primas, 2007), the same data used for the boiler can be applied, given the very similar operation on the combustion side.

4. Results and discussion

In this chapter, the magnitude of potential environmental impacts was determined and evaluated for both energy systems in the three climate zones. An uncertainty and sensitivity analysis were

Table 4
Activity data and references for the gas driven absorption heat pump (167.5 kg in total).

Characteristic	Value	Reference
General information		
Nominal heat input	16.9 kW	Manufacturer data
SCOP (based on the HHV)	1.33 (average) 1.27 (cold) 1.40 (warm)	Trnsys model
Lifespan	20 years	Kemna et al., 2019
Total weight	167.5 kg	Manufacturer data
GHP components		
Copper (pipes, engines, wirings)	1.1 kg	Manufacturer data
Aluminum (motor die-casting, gas valve, inlet door)	3.0 kg	Manufacturer data
Steel (heat exchangers, expansion tank, storage tank, and body)	2.0 kg	Manufacturer data
Stainless steel (heat exchangers and body)	84.1 kg	Manufacturer data
Ferrite (hematite Fe 2O3/magnetite Fe 3O4)	0.5 kg	Manufacturer data
Brass	50.0 g	Manufacturer data
Alumina	0.4 kg	Manufacturer data
ABS	0.1 kg	Manufacturer data
PTFE	43.3 g	Manufacturer data
NBR	10.0 g	Manufacturer data
Synthetic rubber	0.10 kg	Manufacturer data
Ammonia	4.0 kg	Manufacturer data
Water	7.0 kg	Manufacturer data
Electronic components	3.0 kg	Manufacturer data
Mineral wool with aluminum protection (insulation)	1.48 kg	Manufacturer data
HFO polyurethane foam (insulation)	1.98 kg	Manufacturer data
EPDM sheath (insulation)	0.56 kg	Manufacturer data
Finned battery (steel)	14.8	Manufacturer data
Finned battery (aluminum)	10.6	Manufacturer data
Fan air (HDPE and Copper)	1.9 kg	Manufacturer data
Pump 60-100 W	2,42 kg	Manufacturer data
Storage tank components (80 l)		
Polyvinylchloride (PVC)	1.5 kg	Manufacturer data
Rigid polyurethane (PU)	1.6 kg	Manufacturer data
Stainless steel	23.2 kg	Manufacturer data
GHP manufacturing process		
Lubricant oil	0.2 kg	Manufacturer data
Welding (AISI 316)	1.82 kg	Manufacturer data
Water consumption	172.02 kg	Primas, 2007
Electricity	75.01 kWh	Primas, 2007
Heat	535.8 kWh	Primas, 2007
Transport input	167.5 tkm	Kemna et al., 2019
Hazardous waste	0.1 kg	Jungbluth, 2012
Wastewater	143.0 kg	Primas, 2007
Storage tank (80 l) manufacturing process		
Electricity	17.2 kWh	Jungbluth, 2007
Heat	10.6 kWh	Jungbluth, 2007
Welding	0.05 kg	Jungbluth, 2007
Packaging		
Plastic film	0.9 kg	Kemna et al., 2019
Polystyrene	0.5 kg	Kemna et al., 2019
Corrugated board	0.9 kg	Kemna et al., 2019
Distribution		
Transport from manufacturer to consumer	125.6 tkm	Kemna et al., 2019
Maintenance		
Components substitution	1.68 kg	Kemna et al., 2019
Transport to consumer	0.8 tkm	Kemna et al., 2019
End of life		
Copper	Recycling 97% Landfill 3%	Kemna et al., 2019
Aluminum	Recycling 97% Landfill 3%	Kemna et al., 2019
Steel	Recycling 97% Landfill 3%	Kemna et al., 2019
Plastic	Municipal incineration 70% Landfill 30%	Kemna et al., 2019
Brass	Recycling 97% Landfill 3%	Kemna et al., 2019
Rubber	Municipal incineration 70% Landfill 30%	Kemna et al., 2019
Other components (ferrite, alumina, and mineral wool with aluminum protection)	Landfill 100%	Worst case scenario
Electronic components	Municipal incineration 70% Landfill 30%	Kemna et al., 2019
Water/ammonia mixture	Recovery 100%	Kemna et al., 2019
Packaging	Recycling 52% Municipal incineration 17% Landfill 31%	Wernet et al., 2016
Transport from consumer to treatment plant	4.9 tkm	Butera et al., 2015

Table 5
Use phase scenario for both CB and GHP.

Emissions	CB and GHP
Emission to air [mg/MJ_{in}]	
Acetaldehyde	0.001
Acetic acid	0.15
Benzene	0.39
Benzo(*a*)pyrene	0.00001
Butane	0.68
Carbon dioxide, fossil	54.06
Carbon monoxide, fossil	30.0
Dinitrogen monoxide	0.48
Formaldehyde	0.10
Mercury	0.00003
Methane, fossil	1.93
Nitrogen oxides	19.31
PAH, polycyclic aromatic hydrocarbons	0.01
Particulates, < 2.5 um	0.10
Pentane	1.16
Propane	0.19
Propionic acid	0.02
Sulfur dioxide	0.48
Toluene	0.19
Emission to water [mg/MJ_{in}]	
Nitrate	0.13
Nitrite	0.003
Sulfate	0.05
Sulfite	0.05

also implemented to identify the incidence of the uncertainty related to input data on the results and assess the robustness of assumptions and modeling choices.

4.1. Potential environmental impacts

Characterization, normalization, and weighting results for 1 kWh_{th} provided by CB and GHP are showed in Tables 6 and 7. Table 6 shows each category's impact in terms of absolute value and then after normalization and weighting process. According to ISO 14040 and 14044 (ISO, 2006a, 2006b), normalization and weighting are optional elements for an LCA study; however, they are useful tools to improve the results' understanding. Table 7 presents the characterization results for Climate Change subdivided in fossil, biogenic, and land use and land-use change contribution. Besides, Human Toxicity Non-cancer, Human toxicity cancer, and Ecotoxicity freshwater, the impact categories are subdivided into organic, inorganic, and metal.

Once the weighting is performed, the effect of Climate change, Resource Use Fossils, and Acidification cumulatively contributed approximately to 93% of the total environmental impact (sum of weighting results) for both boiler and heat pump in the three climate zones. The weighting results also showed that the use phase contributes for about 98.9% and 97.3% of the overall impact for CB and GHP, respectively. Confirming that the most relevant impact is related to this stage, followed by the components production phase (approx. 0.7% and 2.3%). The share of the other life cycle phases (manufacturing, packaging, distribution, maintenance, and end of life) is always within 0.3%.

Looking at the differences among climate zones, with the heat pump, the weighting results (single score) decrease by about 10% going from the cold to the warm climate, mainly due to the improved Seasonal Coefficient Of Performance (SCOP). At the same time, with the boiler, the potential impact is very similar in each climate zones.

More details about the share of the different life cycle phases for each impact category can be found in Fig. 2. The reported data refer to the average climate, considered the reference scenario, as it provides average results compared to the cold and the warm climate (worst case and best case for the heat pump repsectively). For both the energy systems, the main contribution to all the environmental impact categories, as seen for the weighting results, is related to the use phase (electricity and natural gas consumptions). It ranged from 99.9% (Climate Change, Ozone Depletion, and Resource Use Fossils) to 34.5% (Resource Use Mineral and Metals) for CB and from 99.5% (Resource Use Fossils) to 63.3% (Human Toxicity Cancer) for GHP. The only exception is associated to the components production phase for GHP, where Resource Use Mineral and Metals played the most important role (62.6%), mainly due to the electronic components (27.7%), steel, aluminum, and copper (14.6%), insulation materials (12.5%), fan (4.6%), and finned battery (3.0%). For the CB, the components' production phase impacts (38.2%) are also linked to electronic and metal parts. This phase as well significantly affects the following impact categories, Human Toxicity Cancer (8.0% and 35.7%), Human Toxicity Non-Cancer (9.4% and 11.4%), Eutrophication Freshwater (19.9% and 10.0%), and Ecotoxicity Freshwater (9.0% and 10.1%), for CB and GHP respectively. The main contribution is copper production, except for Human Toxicity Cancer, where steel shows a higher potential impact.

The manufacturing phase for both the technologies is significant for Eutrophication Freshwater (7.4% and 2.6%), Human Toxicity Non-Cancer (3.4% and 2.1%), and Ecotoxicity Freshwater (3.5% and 1.8%). The impacts are mainly related to the welding process. The activity data used is company-specific only for the GHP. For the CB, the amount of welding material was determined by linear interpolation, based on the appliance mass, using the data provided by Jungbluth, 2012. This detailed level was considered sufficient, given the low relevance of the manufacturing phase (0.3% of the weighting results). The other life cycle phases (i.e., packaging, distribution, maintenance, and end of life) are not significant, contributing to all impact categories under 0.6%.

Considering the use phase, the contribution from the electricity consumption ranges from 77% (Water Use) to 1% (Ozone Depletion) for CB and from 94% (Water Use) to 5% (Ozone Depletion) for GHP. The high contribution to the Water Use category is related to the use of nuclear and hydropower plants. On the other hand, the natural gas contribution (extraction, distribution) ranges from 99% (Ozone Depletion) to 21% (Climate Change) for CB and 95% (Ozone Depletion) to 6% (Water Use) for GHP.

Concerning the boiler, these findings were in line with those shown by commercial background database Ecoinvent 3.6 and EF database (Heck, 2018; Thinkstep, 2018) and Giuntoli et al. (2015), while to the best of the authors' knowledge, no LCA studies about small capacity gas absorption heat pump are available in the literature for comparison.

4.2. Comparison of the two energy systems

The environmental profiles of the two energy systems are compared in Fig. 3, where the average climate's characterization results are graphically reported. From the chart, it can be seen that the GHP assure a lower potential environmental impact concerning the CB on five categories, i.e., Climate Change (−27%), Ozone Depletion (−29%), Photochemical Ozone Formation (−18%), Eutrophication Marine (−14%), and Resource Use Fossils (−25%); due to lower natural gas consumption and the associated lower emissions from extraction, distribution, to combustion (0.019 Nm^3 / kWh_{th} for GHP Vs. 0.028 Nm^3 / kWh_{th} for CB). The CB guarantees a lower potential environmental impact on, IR (−39%), PM (−15%), Human Toxicity Non-Cancer (−6%), Human Toxicity Cancer (−21%), Acidification (−9%), Eutrophication Freshwater (−44%), Ecotoxicity Freshwater (−20%), Land Use (−32%), Water Use (−59%), Resource Use Mineral and Metals (−41%). The differences in these impact categories are explained by the higher electricity consumption of the GHP compared with the CB (0.011 kWh_{el} / kWh_{th} Vs. 0.004 kWh_{el} / kWh_{th})

Table 6
Impact assessment results for FU.

Potential impacts	Climate	Units	Characterization		Units	Normalization		Units	Weighting	
			CB	GHP		CB	GHP		CB	GHP
	Warm		2.86E-01	1.98E-01		3.53E-05	2.44E-05		7.44E+00	5.14E+00
Climate change (CC)	Average	kg CO_2 eq	2.85E-01	2.08E-01	–	3.52E-05	2.57E-05	μPt	7.41E+00	5.41E+00
	Cold		2.84E-01	2.19E-01		3.51E-05	2.70E-05		7.39E+00	5.70E+00
	Warm		3.76E-08	2.54E-08		7.02E-07	4.74E-07		4.43E-02	2.99E-02
Ozone depletion (OD)	Average	kg CFC11 eq	3.75E-08	2.67E-08	–	6.98E-07	4.98E-07	μPt	4.41E-02	3.14E-02
	Cold		3.73E-08	2.81E-08		6.96E-07	5.23E-07		4.39E-02	3.30E-02
	Warm		2.49E-03	4.06E-03		5.90E-07	9.62E-07		2.96E-02	4.82E-02
Ionizing radiation (IR)	Average	kBq U-235 eq	2.62E-03	4.31E-03	–	6.20E-07	1.02E-06	μPt	3.11E-02	5.11E-02
	Cold		2.70E-03	4.74E-03		6.40E-07	1.12E-06		3.21E-02	5.63E-02
	Warm		2.72E-04	2.10E-04		6.70E-06	5.18E-06		3.20E-01	2.48E-01
Photochemical ozone formation (POF)	Average	kg NMVOC eq	2.72E-04	2.21E-04	–	6.69E-06	5.45E-06	μPt	3.20E-01	2.61E-01
	Cold		2.72E-04	2.35E-04		6.70E-06	5.78E-06		3.20E-01	2.76E-01
	Warm		9.05E-10	1.03E-09		1.52E-06	1.73E-06		1.36E-01	1.55E-01
Particulate matter (PM)	Average	disease inc.	9.10E-10	1.07E-09	–	1.53E-06	1.81E-06	μPt	1.37E-01	1.62E-01
	Cold		9.25E-10	1.16E-09		1.55E-06	1.95E-06		1.39E-01	1.75E-01
	Warm		4.85E-10	4.98E-10		2.11E-06	2.17E-06		3.89E-02	3.99E-02
Human toxicity, non-cancer (HTNC)	Average	CTUh	4.84E-10	5.15E-10	–	2.11E-06	2.24E-06	μPt	3.88E-02	4.13E-02
	Cold		4.95E-10	5.58E-10		2.16E-06	2.43E-06		3.97E-02	4.47E-02
	Warm		2.69E-11	3.39E-11		1.59E-06	2.01E-06		3.39E-02	4.27E-02
Human toxicity, cancer (HTC)	Average	CTUh	2.66E-11	3.37E-11	–	1.58E-06	2.00E-06	μPt	3.36E-02	4.25E-02
	Cold		2.70E-11	3.65E-11		1.60E-06	2.16E-06		3.40E-02	4.60E-02
	Warm		2.67E-04	2.83E-04		4.80E-06	5.09E-06		2.98E-01	3.16E-01
Acidification (A)	Average	mol H+ eq	2.70E-04	2.98E-04	–	4.87E-06	5.37E-06	μPt	3.02E-01	3.33E-01
	Cold		2.74E-04	3.23E-04		4.94E-06	5.81E-06		3.06E-01	3.60E-01
	Warm		1.65E-06	2.91E-06		1.03E-06	1.81E-06		2.87E-02	5.07E-02
Eutrophication freshwater (EF)	Average	kg P eq	1.69E-06	3.03E-06	–	1.05E-06	1.89E-06	μPt	2.95E-02	5.28E-02
	Cold		1.81E-06	3.37E-06		1.13E-06	2.09E-06		3.16E-02	5.87E-02
	Warm		6.72E-05	5.53E-05		3.44E-06	2.83E-06		1.02E-01	8.38E-02
Eutrophication marine (EM)	Average	kg N eq	6.73E-05	5.82E-05	–	3.44E-06	2.98E-06	μPt	1.02E-01	8.82E-02
	Cold		6.75E-05	6.20E-05		3.46E-06	3.17E-06		1.02E-01	9.39E-02
	Warm		7.84E-04	7.48E-04		4.44E-06	4.23E-06		1.65E-01	1.57E-01
Eutrophication terrestrial (ET)	Average	mol N eq	7.92E-04	7.89E-04	–	4.48E-06	4.46E-06	μPt	1.66E-01	1.66E-01
	Cold		7.98E-04	8.48E-04		4.52E-06	4.80E-06		1.68E-01	1.78E-01
	Warm		3.70E-01	4.49E-01		8.66E-06	1.05E-05		1.66E-01	2.02E-01
Ecotoxicity freshwater (EFW)	Average	CTUe	3.73E-01	4.67E-01	–	8.73E-06	1.09E-05	μPt	1.68E-01	2.10E-01
	Cold		3.84E-01	5.10E-01		9.00E-06	1.19E-05		1.73E-01	2.29E-01
	Warm		8.72E-02	1.26E-01		1.06E-07	1.54E-07		8.45E-03	1.22E-02
Land use (LU)	Average	Pt	8.99E-02	1.33E-01	–	1.10E-07	1.62E-07	μPt	8.71E-03	1.29E-02
	Cold		9.23E-02	1.45E-01		1.13E-07	1.77E-07		8.94E-03	1.41E-02
	Warm		2.31E-03	5.80E-03		2.02E-07	5.05E-07		1.72E-02	4.30E-02
Water use (WU)	Average	m^3 depriv.	2.52E-03	6.11E-03	–	2.20E-07	5.33E-07	μPt	1.87E-02	4.54E-02
	Cold		2.69E-03	6.80E-03		2.34E-07	5.93E-07		2.00E-02	5.05E-02
	Warm		4.32E+00	3.05E+00		6.64E-05	4.70E-05		5.52E+00	3.91E+00
Resource use, fossils (RUF)	Average	MJ	4.31E+00	3.22E+00	–	6.62E-05	4.95E-05	μPt	5.51E+00	4.12E+00
	Cold		4.30E+00	3.39E+00		6.61E-05	5.21E-05		5.50E+00	4.34E+00
	Warm		9.38E-08	1.58E-07		1.47E-06	2.48E-06		1.11E-01	1.88E-01
Resource use, mineral and metals (RUMM)	Average	kg Sb eq	8.80E-08	1.49E-07	–	1.38E-06	2.34E-06	μPt	1.04E-01	1.77E-01
	Cold		9.53E-08	1.65E-07		1.50E-06	2.59E-06		1.13E-01	1.95E-01

and by the higher mass (61 kg Vs. 167.5 kg). More in detail, the electricity consumption is dominant over the mass of the appliances for all the impacts except for Human Toxicity Cancer and Resource Use Mineral and Metals.

The normalization results (Fig. 4), based on the EF 3.0 normalization and weighting set method, show that the contribution of Ozone Depletion, Ionizing Radiation, Particulate Matter, Human Toxicity Non-Cancer, Human Toxicity Cancer, Eutrophication Freshwater, Eutrophication Marine, Land Use, Water Use, and Resource Use Mineral and Metals is negligible. The method used the world population to calculate the normalization factor (NF) per person, equal to 6,895,889,018. Considering the significant impact categories, the GHP has a lower contribution to Climate change (−27%), Photochemical Ozone Formation (−18%), Eutrophication Terrestrial (−0.4%), and Resource Use Fossils (−25%). On the other hand, it has a higher contribution to Acidification (10%) and Ecotoxicity Freshwater (25%). Fig. 4 also shows the three highest significant impact categories for normalization, Resource Use Fossils, Climate Change, and Ecotoxicity Freshwater.

With weighting, the magnitude of the normalization results is converted by using numerical factors based on value-choices. The EF 3.0 method uses a panel-based method for weighting, giving the higher factor to Climate Change and the lower to Human Toxicity Non-Cancer (Sala et al., 2018).

It must be noticed that, even if the boiler has a lower impact on a higher number of impact categories, the overall better performance of the heat pump is explained with its advantage in the two most impacting categories (Climate Change and Resource Use Fossils). It can be seen in Fig. 5a, which presents the weighting results of the two energy systems in Points (Pt) over the 20 years of expected lifespan (average climate). Additionally, Fig. 5b reports Functional Unit's weighting results derived from the cumulative sum of each impact category (in μPt) for the three representative European climates. The weighting results over 20 years, even if the outcomes are shown as a function of time, were calculated as released at the beginning of the assessment period (year zero). The effect of timing was shown but not considered in the assessment, this is a common practice in LCA (Kendall, 2012), and it is also indicated by ISO (2018).

Table 7
Characterization results for FU considering only CC, HTNC, and HTC.

Potential impacts	Climate	Unit	CB	GHP
Climate change– fossil	Warm	kg CO_2 eq	2.86E-01	1.98E-01
	Average		2.85E-01	2.08E-01
	Cold		2.84E-01	2.19E-01
Climate change – biogenic	Warm	kg CO_2 eq	6.61E-05	1.30E-04
	Average		7.08E-05	1.38E-04
	Cold		7.40E-05	1.53E-04
Climate change - land use and LU change	Warm	kg CO_2 eq	1.89E-05	4.31E-05
	Average		2.05E-05	4.56E-05
	Cold		2.16E-05	5.07E-05
Human toxicity, non-cancer - organics	Warm	CTUh	5.72E-11	3.93E-11
	Average		5.67E-11	4.12E-11
	Cold		5.69E-11	4.34E-11
Human toxicity, non-cancer - inorganics	Warm	CTUh	1.98E-10	1.45E-10
	Average		1.96E-10	1.52E-10
	Cold		1.96E-10	1.60E-10
Human toxicity, non-cancer - metals	Warm	CTUh	2.78E-10	3.45E-10
	Average		2.78E-10	3.55E-10
	Cold		2.89E-10	3.89E-10
Human toxicity, cancer - organics	Warm	CTUh	1.79E-11	1.40E-11
	Average		1.77E-11	1.46E-11
	Cold		1.78E-11	1.54E-11
Human toxicity, cancer - inorganics	Warm	CTUh	0.00E+00	0.00E+00
	Average		0.00E+00	0.00E+00
	Cold		0.00E+00	0.00E+00
Human toxicity, cancer - metals	Warm	CTUh	8.96E-12	1.99E-11
	Average		8.88E-12	1.92E-11
	Cold		9.20E-12	2.11E-11
Ecotoxicity freshwater - organics	Warm	CTUe	3.51E-03	3.64E-03
	Average		3.47E-03	3.78E-03
	Cold		3.50E-03	4.04E-03
Ecotoxicity freshwater - inorganics	Warm	CTUe	6.77E-02	5.57E-02
	Average		6.76E-02	5.84E-02
	Cold		6.78E-02	6.22E-02
Ecotoxicity freshwater - metals	Warm	CTUe	2.99E-01	3.90E-01
	Average		3.02E-01	4.05E-01
	Cold		3.13E-01	4.43E-01

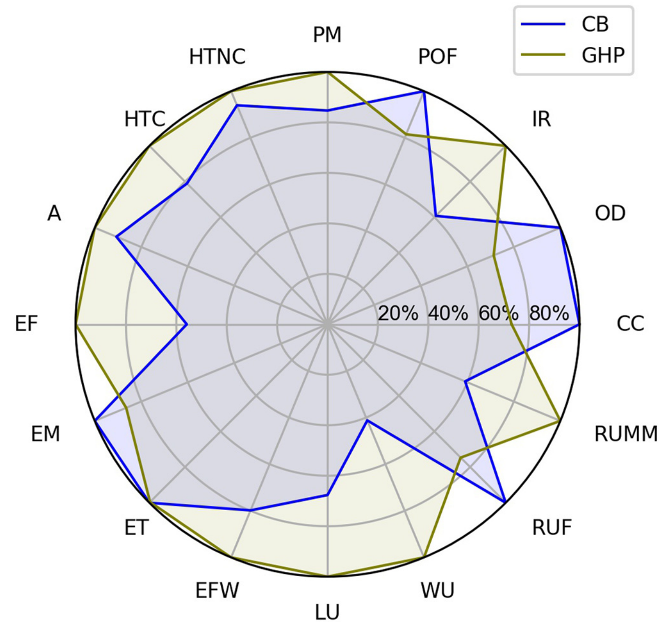

Fig. 3. Characterization results for FU [%] - average climate.

The weighting results over the 20 years of expected lifespan present a linear dependence on life expectancy. The intersection of the CB line with the GHP line is approx. at 2nd year. The higher impact of the construction stage (components production) of the GHP is compensated in 2 years by the better performance in the use phase (due to lower consumption of natural gas). The contribution of the end of life is negligible, as shown in Fig. 5b.

4.3. Uncertainty analysis

In this paragraph, the results obtained by the Monte Carlo method used to combined and propagate the uncertainties on the input data to find overall uncertainties are reported. In particular, the probability (P) that weighting CB results could be higher or equal than the GHP results was assessed for the three climates. The results were obtained by Monte Carlo analysis (2000 runs in total and 95% confidence interval). The values range from 81% of the cold climate, 91% for the average climate, to 93% of the warm climate. In the cold climate, the difference between the two appliances in terms of performance is smaller, while

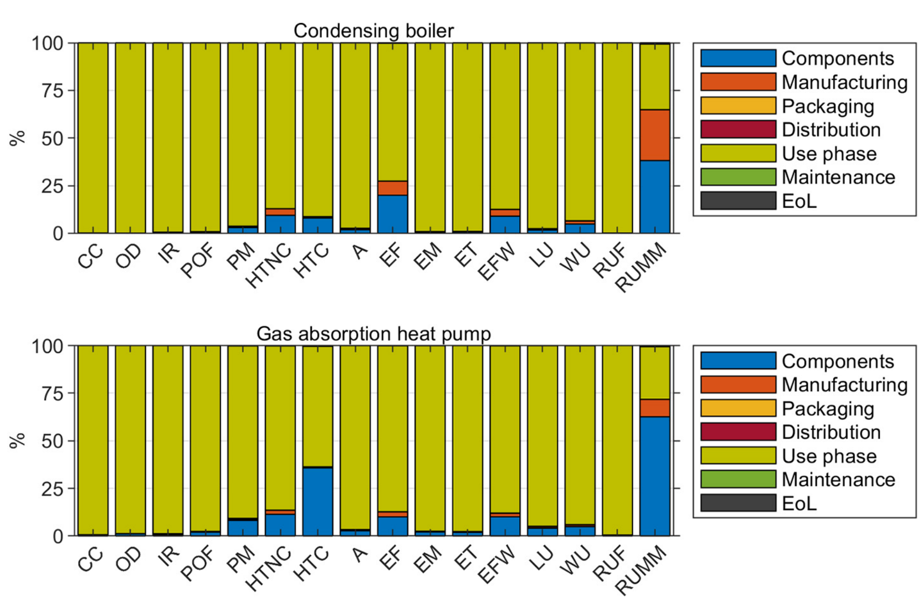

Fig. 2. Characterization results for FU -average climate.

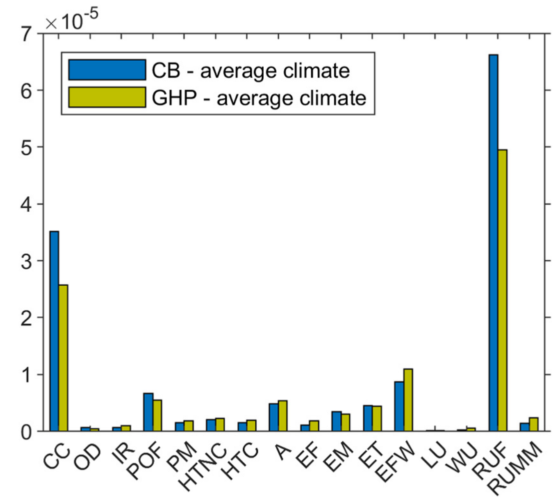

Fig. 4. Normalization results for FU - avrerage climate.

in the warm climate, the GHP efficiency benefits from the higher ambient temperature.

The uncertainty of the Monte Carlo analysis was extended at the category level. Its results are shown in Fig. 6, which reports for the average the probability (P) that the boiler has a higher or equal impact than the heat pump on the given category. Looking at the two most impacting categories, which account for about 90% of the overall impact, the *P* values obtained are 91.0% (Climate Change), 100% (Resource Use Fossils), i.e., favorable to the GHP. Instead, for the third most important impact category (Acidification), which contributes for about 3%, in none of the simulated cases, the P was favorable to the heat pump, mainly because of the higher electricity consumption.

4.4. Sensitivity analysis

A sensitivity analysis was conducted on two relevant aspects not directly covered by the Monte Carlo method. The first analysis is carried out on the method for assessing the combustion emission during the use phase, since the emission factors directly depend on the selected method. In particular, the results obtained with the data from Emmenegger (2012b) were compared with alternative data provided by EEA (2019) and IPCC (2006). For the CB, the former method provides values between 284 and 286 gCO_2 eq/kWh, while the latter from 303 to 305 gCO_2 eq/kWh, with differences in the range 5% (see Table 8). Thus, the choice of the emission values proposed by Emmenegger returns a conservative approach (worst case scenario), reducing the differences between CB and GHP. E.g., for the cold climate, we obtained a difference equal to 2.5 μPt using Emmenegger Vs. 2.8 μPt using the alternative method. Additionally, these values are also very close to the 277 gCO_2 eq/kWh reported in Giuntoli et al. (2015).

The second analysis address the impact of the method used for the LCIA, as recommended by ISO 14044 (ISO, 2006b). The calculation for the average climate was replicated testing the ReCiPe Midpoint (H – Hierarchist) (Huijbregts et al., 2017) as an alternative to the EF 3.0 used in this work. The results reported in Fig. 7 show that similar to EF 3.0 (see Fig. 4), also for the ReCiPe Midpoint method, the most significant impact categories are global warming and fossil resource scarcity, resulting in analogous outcomes when comparing CB and GHP. On the contrary, substantial differences between the two methods were found for the toxicity indicators (terrestrial, freshwater, marine, human carcinogenic, and human non-carcinogenic). Those discrepancies are related to the model used for the characterization of the results concerning toxicity impact categories, which is Van Zelm et al. (2009) for ReCiPe and USEtox (Fantke et al., 2017) for EF 3.0.

The ReCiPe 2016 Midpoint (H) does not allow the weighting of the impacts to obtain single score results, while this is possible with the ReCiPe 2016 Endpoint (H) method. By applying the Endpoint (H) method, it is confirmed that the GHP has a lower potential impact than the CB in all three cases and, in particular:

- 5.83 mPt Vs. 4.32 mPt in the warm climate (−26%);
- 5.82 mPt Vs. 4.54 mPt in the average climate (−22%);
- 5.82 mPt Vs. 4.80 mPt in the cold climate (−18%).

5. Conclusions

In this work, a condensing boiler and a gas-driven absorption heat pump, providing space heating and domestic hot water in old and not retrofitted residential buildings, were compared through the attributional life cycle approach. The comparison was implemented for three climatic conditions (cold, average, and warm) defined by the European ERP Directive (European Parliament, 2009). All the relevant phases of the lifecycle of the two appliances were included. To perform the assessment, detailed life cycle inventory data on gas-driven absorption heat pump, a technology not yet covered by the LCA scientific community, have been provided.

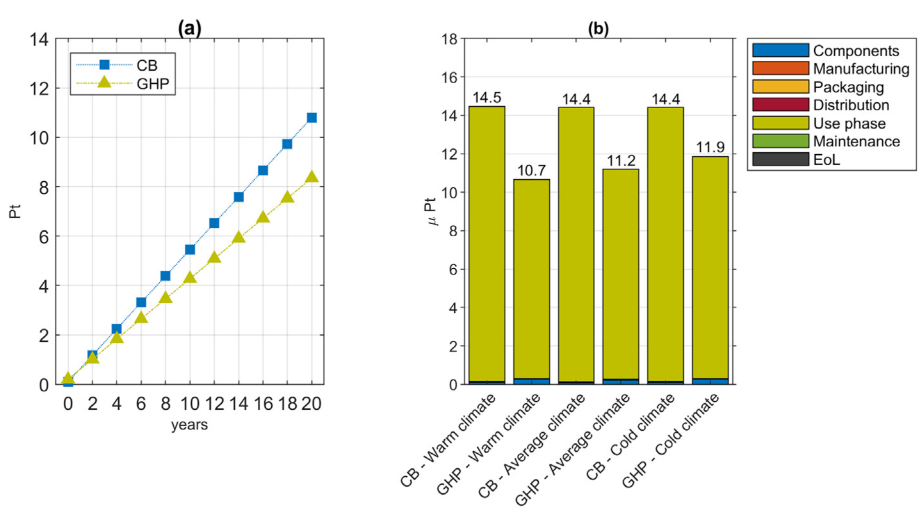

Fig. 5. Weighting results over 20 years – average climate (a) and weighting results for FU (b).

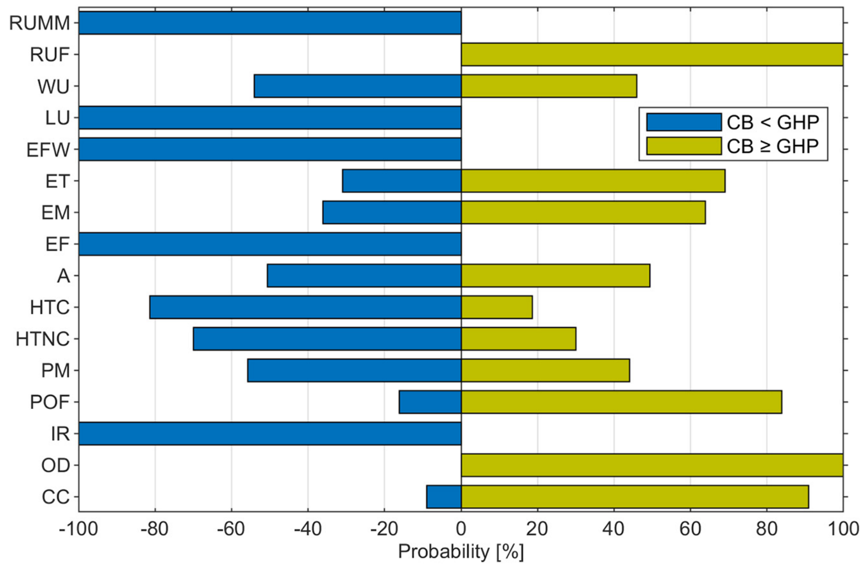

Fig. 6. Uncertainties results for FU - average climate.

Based on the collected data, the performed analysis showed that the use phase has the most significant impact, contributing to more than 97% of the energy systems' weighting impact in all the three climate zones. For this reason, the heat pump, which has a lower natural gas consumption during the use phase, has a lower environmental profile compared to the boiler, even if its electrical consumption is higher. In particular, the heat pump reduces the climate change impact by 31% in the warm zone, 27% in the average zone, and 23% in the cold zone. Whereas the impact of the boiler is lower for all the indicators related to the material and those associated with the use of electricity. However, being the use phase dominant, the weighting impact is lower for the heat pump than for the boiler (−26% in the warm zone, −22% in the average zone, and − 18% in the cold zone). The climates' differences are explained by the fact that the seasonal efficiency of the heat pump decreases when moving to colder climates, while the boiler performances remain approximately unchanged.

The consistency of these results was successfully tested through a series of analyses:

- an uncertainty analysis on the input data, based on the Monte Carlo method, assessed the probability that the environmental impact of the boiler is higher or equal to the impact of the heat pump, obtaining values ranging from 81% in the cold climate to 93% in the warm climate;
- a sensitivity analysis on the method to determine the emission due to natural gas combustion showed little differences between the method

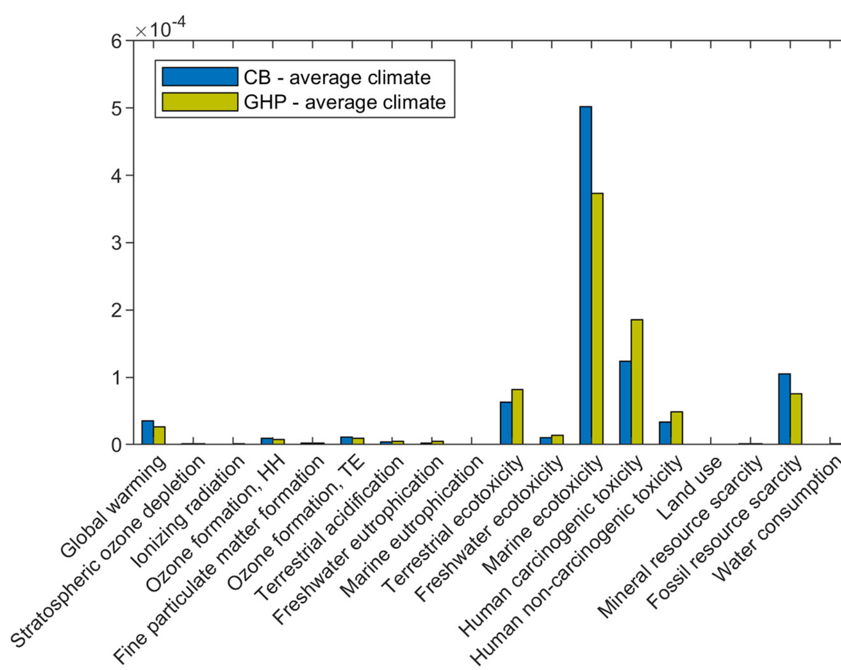

Fig. 7. Normalization results for FU - average climate (ReCiPe Midpoint H).

Table 8
Weighting results obtained with two different methods (Emmenegger Vs. alternative method).

Energy systems	Climate	Emmenegger [μPt]	Alternative method [μPt]	Variation [%]
	Warm	14.5	15.2	−5%
CB	Average	14.4	15.2	−5%
	Cold	14.4	15.2	−5%
	Warm	10.7	11.1	−4%
GHP	Average	11.2	11.7	−4%
	Cold	11.9	12.4	−4%

from Emmenegger (2012b) and the alternative method from EEA (2019) and IPCC (2006), with discrepancies in the overall results of about 4–5%;
- a sensitivity analysis on the selected method for the LCIA confirmed that by changing the LCIA method (from EF 3.0 to ReCiPe 2016), the environmental impact of the heat pump always results lower than the one of the boiler.

This work also provided detailed life cycle inventory data for gas-driven absorption heat pump, not previously available in the literature, that can be used as a reference for comparing various heating systems in specific applications. Moreover, the breakdown of the impacts under different categories allows the use of the data to investigate further aspects, as the effects of variation of the renewable share in the electrical and gas networks on the energy systems' environmental profile.

The starting point for further improvements of this article is to improve the quality of the primary data used, currently limited by the small number of products/prototypes available. Moreover, other aspects beyond the environmental perspective could be added to the investigation. The Life Cycle Cost and the Social-Life Cycle Assessment could also be considered, in addition to the Environmental-Life Cycle Assessment, obtaining a Life Cycle Sustainability Analysis.

CRediT authorship contribution statement

Jacopo Famiglietti: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Tommaso Toppi:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Project administration. **Lorenzo Pistocchini:** Investigation, Resources. **Rossano Scoccia:** Investigation, Resources. **Mario Motta:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.144392.

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