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Heat pumps for space heating and domestic hot water production in residential buildings, an environmental comparison in a present and future scenario

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ABSTRACT

The hydrogen vector stands as a potentially important tool to achieve the decarbonization of the energy sector. It represents an option to store the periodic excesses of energy generation from renewable electrical sources to be used as it is as a substitute for fossil fuels in some applications or reconverted into electricity when needed. In this context, hydrogen can significantly decarbonize the building sector as an alternative fuel for gas-driven devices. Along with hydrogen, the European strategic vision indicates the electrification of heat among the main energy transition pathways. The potential environmental benefits achievable from renewable hydrogen in thermally-driven appliances and the electrification of residential heat through electric heat pumps were evaluated and compared in this work. The novelty of the research consists of a consequential comparative life cycle assessment (16 impact categories) evaluation for three buildings (old, old retrofitted, and new) supplied by three different appliances (condensing boiler, gas absorption heat pump, and electric heat pump), never investigated before. The energy transition was evaluated for 2020 and 2030 scenarios, considering the impact of gaseous fuels (natural gas and European green hydrogen) and electricity based on the pathway of the European electricity grid (27 European member states plus the United Kingdom). The results allowed to compare the environmental profile in deterministic and stochastic approaches and confirm if the increase of renewables reduces the impact in the operational phase of the appliances. The results demonstrate that despite the increased renewable share, the use phase remains the most significant for both temporal scenarios, contributing to 91% of the environmental profile. Despite the higher footprint in 2020 compared to the electric heat pump (198–200 vs. 170–196 gCO_2eq/kWh_{th}), the gas absorption heat pump offered a lower environmental profile than the others in all the scenarios analyzed.

1. Introduction

The building sector is recognized as a significant contributor to the environmental impacts of humankind's activities, being responsible for about 35 % of the final energy use [1]. The heating systems to provide space heating and domestic hot water account for a substantial share of the building environmental emissions in Europe, approximately equal to 80 % of the energy used in households [2]. Although in the next future, heat demand is expected to decrease at the expense of an increase in the cooling demand (at least in Southern and Central Europe), as shown by the scenarios Representative Concentration Pathway (RCP) used for climate modeling and research [3], reducing its environmental emissions remain of paramount importance. The hydrogen vector stands as a potentially important tool to achieve this objective. On the one hand, it constitutes one of the possible ways to store the periodic excesses of generation from renewable electrical sources. On the other hand, it offers itself as a substitute for fossil fuels, reducing all pollutants and climate-changing emissions during the combustion phase [4]. Even if, in the next years, hydrogen will probably be used prevalently for the decarbonization of the transport and industry sectors, some so-called hydrogen valley projects are springing up across Europe to create hydrogen supply chains that combine in a single region production, infrastructure, and use, including the one for space heating and domestic hot water production in buildings. Moreover, it is expected that even outside those hydrogen valleys, the gas supply will involve the usage of mixed H_2 and methane, called Hydrogen Enriched Natural Gas [5].

From the point of view of environmental competitiveness, hydrogen production from 100 % renewable electrical energy through electrolysis (green hydrogen) is today the sector of most significant interest. It refers

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Nomenclature

μ	mean
σ	standard deviation
$\tilde{x}$	median
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
COP	Coefficient Of Performance
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
ER	Energy Resources: non-renewable
ET	Eutrophication Terrestrial
GHP	Gas driven absorption Heat Pump
GUE	Gas Utilization Efficiency
HENG	Hydrogen Enriched Natural Gas
HHV	Higher Heating Value
HTC	Human Toxicity, Carcinogenic
HTNC	Human Toxicity, Non-Carcinogenic
IR	Ionizing Radiation
JRC	Joint Research Center
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Analysis
LHV	Lower Heating Value
LU	Land Use
MC	Monte Carlo
MRM	Material Resources: Metals/minerals
NF	Normalization Factor
OD	Ozone Depletion
P	Probability
PV	Photovoltaics
PM	Particulate Matter formation
POF	Photochemical Ozone Formation
SAEF	Seasonal Auxiliary Energy Efficiency
SCOP	Seasonal Coefficient of Performance
SGUE	Seasonal Gas Utilization Efficiency
SH	Space Heating
S-LCA	Social-Life Cycle Assessment
WU	Water Use

to available technologies and does not imply the use of fossil fuels, as for the gray and blue hydrogen produced from fossil fuels, respectively, with or without carbon capture. According to the European Union's hydrogen strategy, at least 6 GW of electrolyzed powered by renewables for green hydrogen production will be installed within 2024 [6]. However, it is essential to emphasize that the current labeling system (in gray, blue, green, etc.) is lacking because the assessment only considers the type of energy used for production and does not include an evaluation of the environmental burden in the life cycle. Dawood et al. [7] declared that the current color-coding does not determine precisely how clean (low-carbon-emission) hydrogen is, raising a question about whether all renewable energy resources have lower emissions than the blue method for hydrogen production. The Life Cycle Assessment (LCA) evaluation [8] is a mandatory step to respond appropriately to it this question. In fact, LCA is considered the most reliable analytical method to evaluate complex systems' environmental impact [9] and thus represents a valuable tool for assessing the eco-profile of products, such as energy systems, building materials, whole buildings, etc..

1.1. Literature review

Previous works evaluate residential technologies (boilers, gas heat pumps, electric heat pumps, etc.) to provide Space Heating (SH) and Domestic Hot Water (DHW) with a life cycle approach. Table 1 reports the scientific articles in which energy systems technologies were evaluated following the standards ISO 14040 [8] and 14044 [10] for process-based Life Cycle Assessment, where:

- the first column lists the authors grouped according to three technologies deemed interesting in this article (natural gas boilers, gas absorption heat pumps, and electric heat pumps);
- the second column describes the goal of the works;
- the third column represents the boundaries of the studies (i.e., cradle-to-grave or cradle-to-gate), the life cycle assessment modeling (i.e., attributional or consequential) [11], and if the authors implemented an uncertainty analysis via error propagation (i.e., Monte Carlo method);
- the fourth column describes the time horizon of the evaluations, i.e., whether the study provides results related to future scenarios;
- the last column on the right reports the residential building typology evaluated (old not retrofitted, renovated – old retrofitted, and new).

The studies listed in Table 1 mainly highlighted the mitigation of the environmental emissions (beyond Greenhouse Gases - GHGs) derived from the use of heat pumps when compared with condensing boilers. Moreover, they underlined the use phase as the most contributor to the environmental profile of the different technologies analyzed. Investigating the modeling and the environmental aspect examined, it can be concluded that i) only Neumann et al. (2022) implemented a study using the consequential modeling, ii) only Famiglietti et al. (2021) executed an uncertainty analysis via error propagation (comparing the probability results), and iii) 4 out of 14 research works provides future scenarios, but no one of them considers hydrogen as a possible energy vector. To the best of the authors' knowledge, only Schiro et al. [5] analyzed the impact of hydrogen-enriched natural gas on domestic gas boilers from a decarbonization perspective. The approach adopted is not "life cycle" and does not comply with ISO 14040-44, thus not listed in the previous table.

As an introduction to the next section, the authors emphasized four works, reported in Table 1, that partially investigate some aspects related to the scope of this work, i.e., the decarbonization of the electricity grid in future scenarios and consequential modeling. The

Table 1
Summary of the studies analyzed.

Authors	Goal of the study	Life Cycle approach and modeling	Geographical location – case study	Time horizon scenario	Building typology
Natural gas boilers					
Giuntoli et al. [12]	Comparison of bioenergy systems with a natural gas condensing boiler.	Without error propagation – the other information are not declared.	Not declared.	Future scenarios provided.	Not declared.
Electric heat pumps					
Saner et al. [13]	Geothermal source heat pump system compared with fuel oil boiler and gas furnace heating.	Cradle-to-grave, attributional without error propagation.	Weihenstephan (Germany), Madrid, and Karlstad (Sweden).	No future scenarios provided.	Not declared.
Koroneos and Nanaki [14]	Evaluation of a ground source heat pump.	Cradle-to-gate, without error propagation.	Pylaia (Greece).	No future scenarios provided.	Not declared.
Latorre et al. [15]	Comparison of an electric resistive space heater and an air-source heat pump.	Cradle-to-grave, attributional without error propagation.	Madrid, Bilbao, and Florence.	No future scenarios provided.	Not declared.
Famiglietti et al. [16]	Comparison of individual water source heat pumps and district heating network.	Cradle-to-grave, attributional without error propagation.	Milan.	Future scenarios provided.	New.
Natural gas boiler and electric heat pumps					
Greening and Azapagic [17]	Natural gas boiler compared with air, ground, and water source heat pumps.	Cradle-to-grave, attributional, without error propagation	The United Kingdom.	Future scenarios provided.	Not declared.
Abusoglu et al. [18]	Comperison among a coal boiler, a condensing natural gas boiler, and a ground source heat pump.	Cradle-to-grave, attributional without error propagation.	Gaziantep (Turkey).	No future scenarios provided.	New.
Litjens et al. [19]	Comparison of a ground source heat pump and a condensing gas boiler.	Cradle-to-gate, without error propagation.	The Netherlands.	No future scenarios provided.	Average Netherlands dwellings.
Sevindik et al. [20]	Comparison among a condensing boiler, an air source heat pump, and a ground source heat pump.	Cradle-to-grave, attributional without error propagation.	The United Kingdom.	Future scenarios provided.	Average UK household.
Lin et al. [21]	Comparison of a hybrid heat pump and a condensing gas boiler.	Cradle-to-grave, attributional without error propagation.	United Kingdom.	No future scenarios provided.	Average UK household.
Neumann et. al. [22]	Comparison between an air-source heat pump and a condensing boiler.	Cradle-to-grave, attributional, and consequential without error propagation.	Straubing (Germany).	No future scenarios provided.	New.
Gas boilers, gas absorption heat pumps, and electric heat pumps					
Nitkiewicz and Sekret [23]	Comparison of an electric heat pump, a gas absorption heat pump, and a gas boiler for suppling a district heating network.	Cradle-to-gate, without error propagation.	Silesia (Poland).	No future scenarios provided.	Not declared.
Famiglietti et al. [24]	Gas absorption heat pump compared with a condensing boiler.	Cradle-to-grave, attributional with error propagation	Helsinki, Strasbourg, and Athens.	No future scenarios provided.	Old.
Famiglietti et al. [25]	Data-driven LCA tool at the urban scale: energy performance of the building sector	Cradle-to-grave, attributional without error propagation.	Milan.	No future scenarios provided.	Old, retrofitted and new.

decarbonization of the electricity grid devised in the Integrated National Energy Climate Plan was investigated by Greening et al. (2012), Famiglietti et al. (2021), and Sevindik et al. (2021). Greening et al. examined the environmental profile of three individual energy systems with 10 kW capacity, an air-source heat pump, a ground-source heat pump, a water-source heat pump, and a gas condensing boiler installed in UK residential houses. The analysis was conducted assuming different levels of penetration of renewables in the electricity mix. Famiglietti et al. compared a high-capacity air–water heat pump (450 kW) with a fourth-generation district heating for new building applications, considering the decarbonization scenario of the Italian electricity grid in 2030 devised in the Integrated National Energy Climate Plan (PNIEC). Sevindik et al. evaluated the environmental loads of an air-source heat pump, a ground-source heat pump, and a natural gas boiler (10 kW each) for UK household applications. The authors developed three scenarios for 2050. Naumann et al. (2022) conducted a comparison of the environmental profile of an air-source heat pump (5 kW) and a condensing boiler (1.7–14 kW) for a single-family house located in Straubing, southern Germany. As already pointed out, the analysis was conducted using consequential modeling unique among the articles shown in Table 1.

1.2. Focus and aims of the research

In this work, a comparative life cycle approach to the environmental performances is carried out on three alternative heating technologies: i) a Condensing Boiler (CB) from now-on also referred to as “boiler”, ii) an air-source Gas-driven absorption Heat Pump (GHP) from now-on also referred to as “gas heat pump”, and iii) an air source Electric-driven Heat Pump (EHP) from now-on also referred to as “electric heat pump”. The analysis is performed in 6 scenarios, obtained by combining 3 residential building typologies (old not retrofitted, renovated - old retrofitted, and new) and 2 temporal boundaries (2020 and 2030) with three different aims:

- comparing the environmental profile of the appliances in different conditions to assess whether any of them face limitations in its application.
- performing a comparison between the present (2020) and the short-term (2030) scenarios to assess the impact of feeding fuel-driven technologies (CB and GHP) with green hydrogen and EHP with electricity from a more renewable energy mix. In particular, the use of green hydrogen for fuel-driven appliances is seen as an option for storing excess of renewable. At the same time, EHP, currently considered the reference heating technology for 2030, is supposed to run with the average electricity from the future network based on the decarbonization pathway of European member states. The question that will be answered is whether the increase of renewables effectively reduces the impact in the operational phase of the appliances and whether the capital equipment’s eco-design could soon lead to a positive contribution to the environmental profile (i.e., the material used in the construction, the lifespan, the end-of-life treatment processes, etc.).
- providing quantitative estimates of uncertainties and investigating whether the choice among the alternatives can be made with sufficient statistical confidence (error propagation with the null hypothesis test).

The first novelty of this work is the case studies’ choice. In fact, while most studies simply focus on one building, in this work, the heating technologies are evaluated under different conditions by changing: the envelope quality (with an impact on the yearly delivered energy) and the heat distribution system (with an impact on the seasonal energy efficiency). Three relevant buildings were considered based on these considerations: old-not retrofitted, old-retrofitted, and new. Moreover, unlike previous studies, in this work i) used the consequential Life Cycle Inventory (LCI) modeling, ii) green hydrogen is considered in future scenarios, including an error propagation analysis of the results based on a comprehensive null hypothesis test; iii) a decarbonization scenario of the whole European electricity grid (EU 27 plus the United Kingdom) is derived and used for the analysis.

As stated, no comparative consequential LCA study on home appliances for SH and DHW in different temporal scenarios and comprehensive decarbonization of the energy vector commonly used (natural gas and electricity) has not yet been produced. Thus, the article’s novelty can be traced to the innovative outcomes obtained. 16 potential different impact categories were outlined, and the contribution of each life cycle stage was determined. Detailed life cycle inventory data of the European electricity decarbonization scenario and production of green hydrogen were also provided. The electricity decarbonization pathway among European member states (EU 27 plus the United Kingdom) between 2020 and 2030 was also investigated, while Greening et al., Famiglietti et al., and Sevindik et al. focused their analysis only at the national level – the UK and Italy. The evaluation was performed by assessing an average value at the European level considering each State’s production from the open-source database EU Reference scenario [26]. Uncertainty analysis via error propagation was as well performed to test the results obtained, which are commonly not treated in LCA studies, limiting the decision-support role of the method [27]. The uncertainties analysis was executed following the Monte Carlo (MC) simulation method. The consistency of the results achieved from the MC method was tested: i) by comparing the probability that the environmental impact of one energy system is higher than another (typically used in commercial software) and ii) by the null hypothesis test.

2. Materials and methods

This section explains the methodology used to compare the energy systems according to LCA principles [28]. System boundaries, multi-functionalities, cut-off rules, functional unit, life cycle impacts assessment, and uncertainty analysis via error propagation are described. The LCA results were calculated using *Brightway2* open-source software [29].

2.1. Product systems

The analysis was conducted by applying the “from cradle to grave” approach for each appliance selected, including the following phases:

- component productions (raw material supply and production);
- assembling (manufacturing, including energy and water consumptions, welding, waste, transport of components plus packaging);
- distribution;
- use stage (electricity, natural gas, and hydrogen consumption plus maintenance and the related transports);
- end of life stage (transport, waste processing for reuse, recovery, recycling, and disposal).

Famiglietti et al. [16] mentioned that the installation phase of the appliances was excluded for lack of data. This phase was also highlighted as not significant in terms of environmental impacts by previous authors, Favi et al. [30] and Oregi et al. [31]. The water consumption during the domestic hot water service was also neglected since it is attributable to consumer behavior and not a function of the heating device.

Fig. 1 shows a simplified flow chart of the three product systems (boiler, gas heat pump, and electric heat pump). The blocks that were fully or partially evaluated using primary (company-specific) data were reported in grey. The phases assessed with secondary data, i.e., sourced from a third party (e.g., industry-average data, life cycle inventory database, etc.), were reported in white.

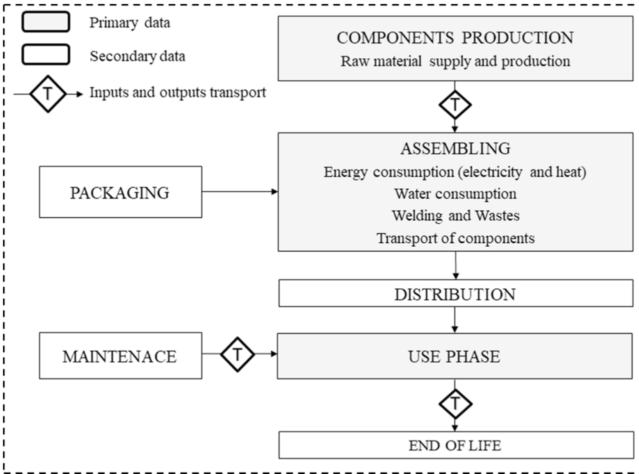

Fig. 1. Flow chart related to system products.

2.2. Technical system boundaries

The environmental burdens of co-production or end-of-life treatment processes were assessed utilizing the system expansion (substitution) through the library ecoinvent 3.8 – consequential model [32]. The consequential model was chosen because the analysis investigates the environmental consequence in the near future (2030) of the shift in energy carriers for space heating and domestic hot water services in European buildings. Using the substitution approach, the authors provided credits based on avoided burdens from the supply chain replaced (e.g., the aluminum recycling process avoids primary production of aluminum), i.e., the recycled material substitutes the primary one [33], as shown in Fig. 2. The substitution ratio and the recycling efficiency were taken by default from the ecoinvent database.

Oxygen is co-produced in the hydrogen electrolysis process, but it was not considered as such in this article (conservative approach) since Koj et al. [34] mentioned that most applications vent oxygen into the air. Also, other authors implemented the same assumptions, i.e., Bahndari et al. 2014 [35], Bauer et al. 2022 [36], Palmer et a. 2021 [37], Reiter et al. 2015 [38], etc..

The cut-off rule was set at 1% [39] 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.

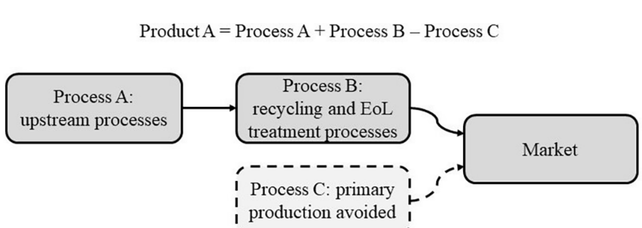

Fig. 2. System expansion (substitution). Boxes show full processes, solid lines show material flows, and dashed line show material flow avoided - End Of Life (EoL).

2.3. Functional unit

The functional unit for the analysis was set as 1 kWh of thermal energy provided for space heating and domestic hot water service. The surface of the dwelling was established equal to 140 m^2 (with specific geometric characteristics and thermophysical performances) located in Strasbourg, representative of the average climate zones as defined by the European ERP Directive [40]. Lifespans were set equal to 19 years (boiler) and 21 years (gas and electric heat pump), as indicated by Famiglietti et al. [25]. The functional unit was defined following the indications reported by Klöpffer and Grahl 2014 [41], Hauschild et al. 2018 [42], and previous scientific articles listed in Table 1.

2.4. Life cycle impacts assessment

The environmental profile of the two energy services is expressed considering 16 impact categories, following the Environmental Footprint (EF) method 3.0 normalization and weighting set – impact assessment method of EF initiative [43]: (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 Ozone Formation (POF); (5) Particulate Matter (PM) formation; (6) Human Toxicity, Non-Carcinogenic (HTNC); (7) Human Toxicity, Carcinogenic (HTC); (8) Acidification (A); (9) Eutrophication Freshwater (EF); (10) Eutrophication Marine (EM); (11) Eutrophication Terrestrial (ET); (12) Ecotoxicity Freshwater (EF); (13) Land Use (LU); (14) Water Use (WU); (15) Energy Resources (ER) non-renewable; (16) Material Resources: Metals/minerals (MRM).

2.5. Uncertainty analysis via error propagation

The results obtained were also evaluated by error propagation using the Monte Carlo (MC) simulation method. The MC was performed, as described by Clavreul et al. [44] and Pizzol [45], considering the epistemic uncertainty (related to an incomplete state of knowledge) and the stochastic uncertainty (related to the inherent variability of the natural world) on the activity data collected and the background exchanges provided directly from ecoinvent 3.8. For the activity data collected, the geometric standard deviations (σ_g) used in the MC model were assessed utilizing the pedigree matrix provided by Frischknecht et al. [46]. The number of executions was fixed equal to 1 000 with dependent sampling for each system (18 000 in total). It can be considered a valid approach to stochastic comparative LCA studies because it simultaneously maintains the same error propagation [47]. Details about the model are provided in the supplementary data (see Microsoft Excel files “Models 2020” and “Models 2030”).

The consistency of the results obtained from the MC method was tested following two approaches:

- by comparing the probability that the environmental impact of one energy system is higher than another (typically used in commercial software);
- by the null hypothesis testing, checking firstly the normality of the results utilizing the Shapiro-Wilk test [48], and then applying, as suggested by Pizzol [45]:
  - o the paired test ($\alpha = 0.05$) and Bonferroni correction (α / m, where m is the number of hypotheses) to avoid false positives for normally distributed results;
  - o the nonparametric pairwise Wilcoxon Rank Sum test ($\alpha = 0.05$ and Bonferroni correction) for not normally distributed results [49].

This second approach starts with the hypothesis that different energy systems are associated with significantly different impact categories results; the MC results were used to test this hypothesis statistically (the null hypothesis is equal impacts between energy systems), as described by Henriksson et al. [50].

3. Life cycle inventory analysis

In this section, the life cycle inventory analysis is explained, providing all the exchanges with the Technosphere and the Nature of the energy systems throughout their life cycle.

3.1. Reference buildings

The reference building is a single-family house defined based on the outcomes of Task 44 "Solar and Heat Pump Systems" of the IEA Solar Heating and Cooling program [51]. The building consists of two levels, with a floor of equal surface for an overall area of 140 m^2. The characteristics of the envelope reported in Table 2 are based on the results of the European projects TABULA and EPISCOPE [52]. The sum of infiltration and natural ventilation rates is assumed to be 0.4 h^{-1} for the old and renovated buildings, while for the new building, an infiltration rate of 0.1 h^{-1} is assumed, complemented by a mechanical ventilation system providing heat recovery with an efficiency of 60 %, which provides additional 0.3 h^{-1}. The heating setpoint was 20 °C between 6:00 and 22:00 and 16 °C for the rest of the day. For what concerns the DHW needs, the tapping cycle "L" as defined in the Commission Delegated Regulation (EU) No 812/2013 [53] was considered. The reference buildings were modeled in Trnsys to calculate the heating and DHW loads, as detailed in Scoccia et al. [54].

Table 2
Buildings selected as reference.

	$U\left(\frac{W}{m^2K}\right)$		
	Old	Renovated	New
U_{wall}	1.10	0.23	0.15
U_{roof}	0.80	0.41	0.13
U_{floor}	1.00	0.31	0.15
$U_{windows}$	2.80	1.30	1.10
U_{door}	3.00	1.30	1.30
$\Delta U_{t.\ brid.}$	0.10	0.10	0.05

3.2. Energy systems

The emission system of the old and renovated buildings is based on radiators, while an underfloor heating system was assumed for the new building. For what concerns the supply temperature, the old building requires 65 °C. In comparison, 55 °C was used for the renovated building, assuming that the load reduction due to the renovation of the building envelope allows a decrease in the temperature at the radiators. In contrast, the nominal supply temperature for the new building with underfloor heating was set at 35 °C. The selected temperatures are widely recognized as the reference temperatures for low, high, and very high-temperature applications. They are formalized in the European standards for the performance tests of heat pumps, the EN 14825 [55] and the EN 12309 [56]. Additionally, a climatic curve is used to decrease the supply temperature when the outdoor temperature increases, benefiting both comfort and system efficiency.

The capacity of the boiler and heat pumps was based on the maximum heating demand, assuming monovalent appliances. The only exception is for the system with the EHP in the old building, where electrical resistance is used in series to boost the supply temperature in those cases when a value above the maximum supply temperature of the heat pump (55 °C) is required.

The resulting capacity, expressed in terms of maximum gas input for the boiler and the GHP and nominal heating capacity at 7 °C of ambient temperature and 40/50 °C of return/supply water temperature, are:

- condensing boilers: 14.3 kW, 10 kW, and 10 kW for the old, renovated, and new buildings, respectively, with an integrated DHW tank of 40 L. It was decided to keep 10 kW as a minimum boiler capacity since further reduction is unrealistic. Besides, it does not significantly impact the manufacturing process and materials;
- gas absorption heat pumps: 14.1 kW, 5.9 kW, and 3.7 kW, with an external DHW tank with 80 L;

Table 3
Energy consumption of the buildings selected as a reference.

Indicator	CB	GHP	EHP
Electricity [kWh / (m^2 year)]	0.6 (old) 0.4 (renovated) 0.4 (new)	7.4 (old) 3.2 (renovated) 2.1 (new)	117.9 (old) 45.1 (renovated) 22.0 (new)
Natural gas or Hydrogen [kWh / (m^2 year)]	290.9 (old) 107.2 (renovated) 61.3 (new)	196.4 (old) 71.2 (renovated) 40.6 (new)	–
Seasonal Gas Utilization Efficiency (SGUE)	0.90 (old) 0.90 (renovated) 0.91 (new)	1.33 (old) 1.35 (renovated) 1.37 (new)	–
Seasonal Coefficient of Performance (SCOP) or Seasonal Auxiliary Energy Efficiency (SAEF)	403.4 (old) 251.6 (renovated) 155.5 (new)	35.2 (old) 30.2 (renovated) 26.2 (new)	2.21 (old) 2.13 (renovated) 2.52 (new)
HHV natural gas [kWh / Nm^3]	11.2	11.2	–
Density natural gas [kg / Nm^3]	0.80	0.80	–
HHV hydrogen [kWh / Nm^3]	3.54	3.54	–
Density hydrogen [kg / Nm^3]	0.09	0.09	–

Table 4
Gross electricity generation by source in the EU.

Source	2020 [GWh_{el}]	2020 [%]	2030 [GWh_{el}]	2030 [%]
Nuclear energy	772 986	23.0 %	777 743	22.0 %
Coal	767 262	22.9 %	562 741	16.0 %
Oil	21 835	0.7 %	19 341	0.5 %
Gas	580 999	17.3 %	654 930	18.6 %
Biomass-waste	213 112	6.3 %	283 469	8.0 %
Hydro	375 589	11.2 %	378 979	10.7 %
Wind	462 720	13.8 %	608 460	17.2 %
Solar	154 722	4.6 %	232 129	6.6 %
Geothermal	8 461	0.3 %	9 736	0.3 %
Total	3 357 685	100.0 %	3 527 528	100.0 %

Table 5
Gross electricity generation by member state (UE plus UK).

Member state	2020 [GWh_{el}]	2020 [%]	2030 [GWh_{el}]	2030 [%]
Austria	71 621	2.1 %	79 933	2.3 %
Belgium	73 694	2.2 %	72 313	2.0 %
Bulgaria	48 789	1.5 %	50 487	1.4 %
Croatia	14 108	0.4 %	14 117	0.4 %
Cyprus	4 921	0.1 %	5 493	0.2 %
Czech Republic	79 790	2.4 %	85 766	2.4 %
Denmark	30 716	0.9 %	35 263	1.0 %
Estonia	11 276	0.3 %	9 441	0.3 %
Finland	88 841	2.6 %	93 419	2.6 %
France	596 131	17.8 %	608 391	17.2 %
Germany	599 220	17.8 %	610 832	17.3 %
Greece	58 052	1.7 %	54 970	1.6 %
Hungary	33 045	1.0 %	41 925	1.2 %
Ireland	31 049	0.9 %	32 231	0.9 %
Italy	316 523	9.4 %	323 149	9.2 %
Latvia	6 626	0.2 %	7 539	0.2 %
Lithuania	5 902	0.2 %	14 421	0.4 %
Luxembourg	3 176	0.1 %	4 547	0.1 %
Malta	2 460	0.1 %	2 788	0.1 %
Netherlands	122 529	3.6 %	136 741	3.9 %
Poland	176 244	5.2 %	203 166	5.8 %
Portugal	48 507	1.4 %	48 243	1.4 %
Romania	71 417	2.1 %	75 464	2.1 %
Slovakia	33 934	1.0 %	38 296	1.1 %
Slovenia	16 444	0.5 %	18 787	0.5 %
Spain	282 996	8.4 %	287 052	8.1 %
Sweden	160 211	4.8 %	174 735	5.0 %
United Kingdom	369 460	11.0 %	398 021	11.3 %

- electric heat pumps: 15.4 kW plus an electric residence of 4.2 kW, 9.4 kW, and 6.3 kW, with external DHW storage with a volume of 80 L.

The outcomes of the yearly calculation of the energy consumption of the three buildings combined with the three heating systems are summarized in Table 3.

3.3. Electricity production modeling

To properly weigh the environmental impact of the electrical energy used, the decarbonization pathway among European member states (EU 27 plus the United Kingdom) between 2020 and 2030 was investigated. The average of each State's production was used to determine an average value at the European level. The open-source database EU Reference scenario [26] based on the EU PRIMES 6 was utilized as a source for the life cycle inventory data. The EU Reference scenario represents the baseline scenario for each country, i.e., it describes the evolution of the European energy systems with current policies and measures (conservative approach). Table 4 and Table 5 show the gross electricity generation by source and member state for 2020 and 2030.

Details about the model for electricity generation, transmission, and distribution to the final consumer using the datasets provided by

Table 6
Inputs for the production of 1 kg of H_2 by the alkaline electrolyzer.

Item	Amount	Unit
Alkaline electrolyzer operation		
Electricity	5.00E + 01	kWh
Deionized water	1.00E + 01	kg
Nitrogen	2.90E-04	kg
Potassium hydroxide	1.90E-04	kg
Steam	3.91E-02	MJ
Oxygen in air	7.94E + 00	kg
Transports		
Raw material to electrolyzer manufacturing (1 000 km)	3.13E-02	tkm
Electrolyzer to the hydrogen production site (1 000 km)	3.13E-02	tkm
Construction of the alkaline electrolyzer		
Copper	1.93E-04	kg
Unalloyed steel	1.93E-02	kg
Nickel	1.83E-03	kg
Aluminum	4.34E-05	kg
Calendered rigid plastic	7.52E-05	kg
Polytetrafluoroethylene	7.52E-06	kg
Acrylonitrile butadiene styrene	1.54E-05	kg
Polyphenylene sulfide	3.28E-05	kg
Polysulfones	2.51E-05	kg
N-Methyl-2-pyrrolidone	1.25E-04	kg
Aniline	4.72E-06	kg
Acetic anhydride	5.20E-06	kg
Terephthalic acid	8.48E-06	kg
Nitric acid	3.18E-06	kg
Hydrochloric acid	1.25E-05	kg
Graphite	4.14E-05	kg
Lubricating oil	4.63E-08	kg
Zirconium oxide	1.06E-04	kg
Carbon monoxide	1.45E-05	kg
Decarbonized water	1.06E-03	kg
Deionized water	8.29E-03	kg
Industrial machine production	1.54E-08	kg
Plaster mixing	7.52E-05	kg
Electricity	9.64E-04	kWh
Heat	8.48E-03	MJ
Steam	6.47E-05	MJ

Table 7
Share of green electricity production by member state (the UK included).

Member state	PV [%]	Wind [%]	Hydro [%]
Austria	0.5 %	0.6 %	0.3 %
Belgium	0.3 %	0.1 %	0.0 %
Bulgaria	1.3 %	0.6 %	0.0 %
Croatia	0.3 %	0.3 %	0.1 %
Cyprus	0.2 %	0.0 %	0.0 %
Czech Republic	0.8 %	0.2 %	0.0 %
Denmark	0.5 %	1.5 %	0.0 %
Estonia	0.1 %	0.6 %	0.0 %
Finland	0.3 %	1.4 %	0.1 %
France	6.6 %	6.5 %	0.4 %
Germany	4.3 %	2.3 %	0.1 %
Greece	0.6 %	3.6 %	0.0 %
Hungary	1.5 %	0.8 %	0.0 %
Ireland	0.6 %	2.7 %	0.0 %
Italy	3.3 %	2.9 %	0.3 %
Latvia	0.3 %	1.8 %	0.0 %
Lithuania	0.4 %	1.5 %	0.0 %
Luxembourg	0.0 %	0.0 %	0.0 %
Malta	0.0 %	0.0 %	0.0 %
Netherlands	0.5 %	2.0 %	0.0 %
Poland	3.0 %	3.1 %	0.0 %
Portugal	0.5 %	0.5 %	0.1 %
Romania	3.0 %	2.2 %	0.1 %
Slovakia	0.4 %	0.2 %	0.0 %
Slovenia	0.1 %	0.0 %	0.0 %
Spain	4.3 %	11.4 %	0.2 %
Sweden	0.5 %	4.5 %	0.5 %
United Kingdom	2.5 %	9.4 %	0.0 %
Total	36.6 %	61.0 %	2.4 %

ecoinvent 3.8 are presented in the supplementary data (see Microsoft Excel files "Models 2020" and "Models 2030").

3.4. Green hydrogen production modeling

The LCI of a 6 MW pressurized alkaline electrolyzer, as provided by Koj et al. [34], was utilized to model the hydrogen production. As previously mentioned, oxygen is assumed to be vented into the air, not representing a co-product generated by the alkaline electrolyzer. As the lifetime was considered 80 000 operating hours. Table 6 reports the life cycle inventory data used in the model.

The electricity used during the operational phase, equal to 50 [kWh / kg H_2], was modeled considering the renewable energy supply potential data indicated by Kakoulaki et al. [4] and reported in Table 7. The work provided by Kakoulaki et al. was selected for this study because it gave a European picture of the excess of potential renewable energy generation after covering the annual electricity demand of each State (EU27 and UK).

Concerning transportation, the hydrogen can be distributed from the production site to the user utilizing four alternative options:

- compressed and transported via pipelines;
- liquefied and transported by ships;
- transported in the form of ammonia;
- compressed and transported by trucks.

For this study, the latter alternative was used, assuming gaseous hydrogen, compressed at 70 MPa and with a density of 38 kg / m^3, transported for an average of 100 km in a diesel-powered truck with 16–32 t of gross capacity and an average load factor of 5.79 t. It is considered the preferred, even if not the most efficient, option for distances in the order of hundreds of kilometers and limited amounts [57].

3.5. Use phase model and emissions

The information on the emissions generated during the operational phase of the two thermally-driven appliances (CB and GHP) was deducted:

- for the 2020 scenario (natural gas combustion), by the ecoinvent library as shown by Famiglietti et al. [24], considering the data provided by the Swiss Society of Gas and Water Industry through direct measurement on a sample of Swiss furnaces;
- for the 2030 scenario (hydrogen combustion), by information provided by Schiro et al. [5], utilizing as a base the following reaction:

$$H_2 + 0.5^* \lambda^* (O_2 + 3.76^* N_2) \rightarrow H_2O + 1.88^* \lambda^* N_2 + (\lambda - 1)^* 0.5^* O_2 \quad (1)$$

Where λ is defined as the ratio between the actual air–fuel ratio and the stoichiometric air–fuel ratio (air–fuel equivalence ratio), fixed equal to 1.25 [5].

In order to consider the NO_x emissions generated during the combustion, the reaction (1) was slightly modified. 72 mg / kWh of hydrogen in input (based on the Higher Heating Value - HHV) were considered during the combustion phase - a value in line with the scenario utilized for the natural gas combustion provided by ecoinvent (higher than the European limit equal to 56 mg / kWh - precautionary approach). Table 8 provides all the exchanges between Technosphere and Nature during hydrogen combustion.

In the 2030 scenario, the authors considered the use of 100 % hydrogen to emphasize within the article the two extreme bounds, natural gas in 2020 and hydrogen in 2030. Therefore, the environmental profile of the use of blended hydrogen is within the two extremes depending on the characteristics of the hydrogen-enriched natural gas. Moreover, this analysis also provides an evaluation of the environmental impact of hydrogen as a way to store renewable energy to be used for domestic heating.

Table 8
Use phase scenario for CB and GHP (2030).

Exchange with nature and Technosphere	kg / kg of H_2 burned
Substances from air and Technosphere	
Hydrogen	1.00E+00
Oxygen	1.00E+01
Nitrogen	3.29E+01
Emissions in air	
Water (vapor)	6.79E-01
Nitrogen	3.29E+01
Oxygen	2.00E+00
NO_X	2.83E-03
Emissions to water	
Water (condensate)	8.32E+00

4. Results and discussion

In this section, the outcomes obtained for the three energy systems in the six scenarios (three building typologies and two years of analysis) are presented. The potential environmental impacts were assessed using the deterministic (without uncertainty analysis) and the stochastic approaches (with uncertainty analysis based on error propagation).

4.1. Characterization results - deterministic

The characterization results for 1 kWh_{th} delivered by CB, GHP, and EHP are reported in Table 9 for each scenario. From these results, obtained by deterministic LCA calculation, the EHP has the lowest potential impact on Climate Change (CC) in the 2020 scenarios, while for 2030, the lowest mark is given by GHP. In particular, in 2020, a Seasonal Coefficient of Performance (SCOP) above 2.1 for the three types of buildings (see Table 3) guarantees to the EHP the best climate profile - taking into account the emissions factors for electricity and gas for Europe, which are 397 gCO_2eq / kWh_{el} (production, transmission, and distribution included) and 268 gCO_2eq / kWh (combustion emissions included) for the natural gas. On the other hand, in 2030, the GHP will become the best option concerning Climate Change for the 3 different building types because it combines: i) the use of green hydrogen (77 gCO_2eq / kWh based on HHV) with a better climate profile compared with European electricity (319 gCO_2qe / kWh_{el}) and ii) higher efficiency compared to CB (about 1.35 vs. 0.90 respectively).

The results obtained considering the Climate Change impact category (in 2020) were consistent with what was found in previous studies. For CB, the order of magnitude was in line with two articles provided by Famiglietti et al. [24] and [25], Naumann et al. [22], Sevindik et al. [20], Giuntoli et al. [12], Greening and Azapagic [17], and Saner et al. [13]. GHP results aligned with Famiglietti et al. [24]. EHP outcomes align with Famiglietti et al. [25], Naumann et al., Sevindik et al., Latorre-Biel et al. [15], and Greening and Azapagic. Summarizing the scientific articles report the following values range:

- from 341 to 241 [gCO_2eq / kWh_{th}] for natural gas boilers;
- from 267 to 198 [gCO_2eq / kWh_{th}] for gas-absorption heat pumps;
- and from 276 to 88 [gCO_2eq / kWh_{th}] for air source heat pumps.

In the latter case, the high variability can be justified by the large differences among geographical boundaries considered in the studies, which impact the climate profile of the electricity, strongly dependent on the energy mix. It is important to underline that only Naumann et al. (2022) assessed the environmental profile utilizing the consequential approach, while the others used the attributional. Concerning 2030 outcomes, to the best of the authors' knowledge, no LCA studies about

Table 9
Characterization results for FU.

Potential impacts	Climate	Units	Characterization (2020)			Characterization (2030)		
			CB	GHP	EHP	CB	GHP	EHP
Climate change (CC)	Old	kg CO_2 eq	2.76E−01	1.98E−01	1.87E−01	8.70E−02	6.86E−02	1.47E−01
	Renovated		2.77E−01	1.99E−01	1.97E−01	8.80E−02	7.07E−02	1.54E−01
	New		2.76E−01	2.00E−01	1.71E−01	8.88E−02	7.34E−02	1.32E−01
Ozone depletion (OD)	Old	kg CFC11 eq	3.83E−08	2.70E−08	1.85E−08	8.41E−09	6.83E−09	9.46E−09
	Renovated		3.84E−08	2.74E−08	2.29E−08	8.48E−09	7.56E−09	1.05E−08
	New		3.82E−08	2.80E−08	2.46E−08	8.52E−09	8.42E−09	9.79E−09
Ionizing radiation (IR)	Old	kBq U-235 eq	6.98E−04	5.33E−03	8.12E−02	2.94E−03	6.66E−03	7.82E−02
	Renovated		9.90E−04	6.22E−03	8.45E−02	3.22E−03	7.50E−03	8.15E−02
	New		1.46E−03	7.29E−03	7.15E−02	3.66E−03	8.52E−03	6.90E−02
Photochemical ozone formation (POF)	Old	kg NMVOC eq	2.62E−04	2.05E−04	4.27E−04	4.42E−04	3.21E−04	3.39E−04
	Renovated		2.66E−04	2.11E−04	4.50E−04	4.46E−04	3.25E−04	3.59E−04
	New		2.71E−04	2.20E−04	3.92E−04	4.49E−04	3.31E−04	3.14E−04
Particulate matter (PM) formation	Old	disease inc.	7.63E−10	7.57E−10	3.25E−09	5.91E−09	4.22E−09	3.01E−09
	Renovated		8.10E−10	8.46E−10	3.46E−09	5.96E−09	4.25E−09	3.20E−09
	New		8.75E−10	9.55E−10	3.06E−09	5.97E−09	4.31E−09	2.84E−09
Human toxicity, non-carcinogenic (HTNC)	Old	CTUh	5.23E−10	5.04E−10	3.76E−09	6.46E−09	4.51E−09	3.24E−09
	Renovated		6.46E−10	5.80E−10	3.91E−09	6.61E−09	4.52E−09	3.47E−09
	New		8.73E−10	6.87E−10	3.57E−09	6.78E−09	4.56E−09	3.19E−09
Human toxicity, carcinogenic (HTC)	Old	CTUh	2.59E−11	3.83E−11	9.82E−11	2.66E−10	2.00E−10	9.26E−11
	Renovated		3.01E−11	5.13E−11	1.09E−10	2.71E−10	2.11E−10	1.04E−10
	New		3.75E−11	6.62E−11	1.07E−10	2.76E−10	2.24E−10	1.02E−10
Acidification (A)	Old	mol H + eq	2.35E−04	2.17E−04	9.61E−04	3.50E−04	2.80E−04	6.93E−04
	Renovated		2.48E−04	2.33E−04	1.01E−03	3.64E−04	2.92E−04	7.32E−04
	New		2.67E−04	2.54E−04	8.75E−04	3.80E−04	3.09E−04	6.43E−04
Eutrophication freshwater (EF)	Old	kg P eq	2.76E−06	1.12E−05	1.44E−04	4.05E−05	3.43E−05	1.08E−04
	Renovated		3.97E−06	1.34E−05	1.52E−04	4.13E−05	3.58E−05	1.13E−04
	New		5.40E−06	1.62E−05	1.30E−04	4.22E−05	3.77E−05	9.71E−05
Eutrophication marine (EM)	Old	kg N eq	6.32E−05	5.36E−05	1.68E−04	1.33E−04	9.81E−05	1.30E−04
	Renovated		6.48E−05	5.60E−05	1.76E−04	1.34E−04	9.95E−05	1.37E−04
	New		6.64E−05	5.90E−05	1.51E−04	1.35E−04	1.01E−04	1.19E−04
Eutrophication terrestrial (ET)	Old	mol N eq	6.91E−04	5.71E−04	1.59E−03	1.44E−03	1.06E−03	1.27E−03
	Renovated		7.09E−04	5.94E−04	1.67E−03	1.46E−03	1.07E−03	1.34E−03
	New		7.28E−04	6.25E−04	1.45E−03	1.47E−03	1.09E−03	1.17E−03
Ecotoxicity freshwater (EFW)	Old	CTUe	3.91E−01	4.73E−01	3.68E+00	5.99E+00	4.22E+00	3.33E+00
	Renovated		5.21E−01	5.59E−01	3.96E+00	6.11E+00	4.25E+00	3.55E+00
	New		6.97E−01	6.73E−01	3.55E+00	6.23E+00	4.31E+00	3.20E+00
Land use (LU)	Old	Pt	9.11E−02	1.80E−01	1.81E+00	3.79E+00	2.70E+00	2.17E+00
	Renovated		1.05E−01	2.12E−01	1.90E+00	3.81E+00	2.70E+00	2.27E+00
	New		1.29E−01	2.54E−01	1.64E+00	3.80E+00	2.71E+00	1.95E+00
Water use (WU)	Old	m^3 depriv.	1.60E−03	5.18E−03	6.42E−02	8.70E−02	6.26E−02	6.08E−02
	Renovated		1.88E−03	6.20E−03	6.72E−02	8.73E−02	6.28E−02	6.36E−02
	New		2.33E−03	7.41E−03	5.74E−02	8.69E−02	6.31E−02	5.43E−02
Energy Resources (ER) non−renewable	Old	MJ	3.84E+00	2.82E+00	3.67E+00	9.68E−01	8.60E−01	3.25E+00
	Renovated		3.86E+00	2.84E+00	3.84E+00	9.86E−01	9.01E−01	3.39E+00
	New		3.85E+00	2.87E+00	3.27E+00	1.00E+00	9.52E−01	2.90E+00
Material Resources: Metals/minerals (MRM)	Old	kg Sb eq	9.10E−07	6.54E−07	6.83E−06	2.20E−05	1.50E−05	6.80E−06
	Renovated		1.44E−06	8.77E−07	7.06E−06	2.27E−05	1.50E−05	7.45E−06
	New		2.42E−06	1.22E−06	7.03E−06	2.35E−05	1.52E−05	7.36E−06

small capacity appliances are available in the literature for comparison.

The discussion can be extended to all the impact categories considering the data reported in Fig. 3, where a comparison of the three energy systems in 2020 and 2030 for the renovated building and considered the average scenario can be found. In the 2020 scenario (Fig. 3a), the thermally-driven devices have the highest potential impact on Climate Change (CC), Ozone Depletion (OD), and Energy Resources – non renewable (ER), as already mentioned, due to natural gas extraction, distribution, and combustion. For the other impact categories, the main contributor is the EHP; already noted by Famiglietti et al. [25,16], electrical energy has the worst environmental profile compared to natural gas in the following categories:

- Ionizing Radiation (IR) due to the electricity from nuclear plants;
- Photochemical Ozone Formation (POF), toxic categories (HTNC, HTC, and EFW), Acidification (A), and eutrophication categories (EF, EM, and ET) caused by electricity production from coal plants;
- Particulate Matter (PM) formation produced by coal, oil, and biomass plants;
- Land Use (LU) caused by biomass plants;
- Water Use (WU) because of electricity produced by hydropower and nuclear plants;
- Material Resources Mineral/metals (MRM) due to the amount of copper used in renewable energy systems for electricity production, mainly linked with photovoltaic plants.

In 2030 (Fig. 3b), the outcomes change radically compared with 2020. EHP appliance has the higher impact on Climate Change (CC) than CB and GHP, resulting in 57 % and 46 % lower than EHP. Moreover, EHP

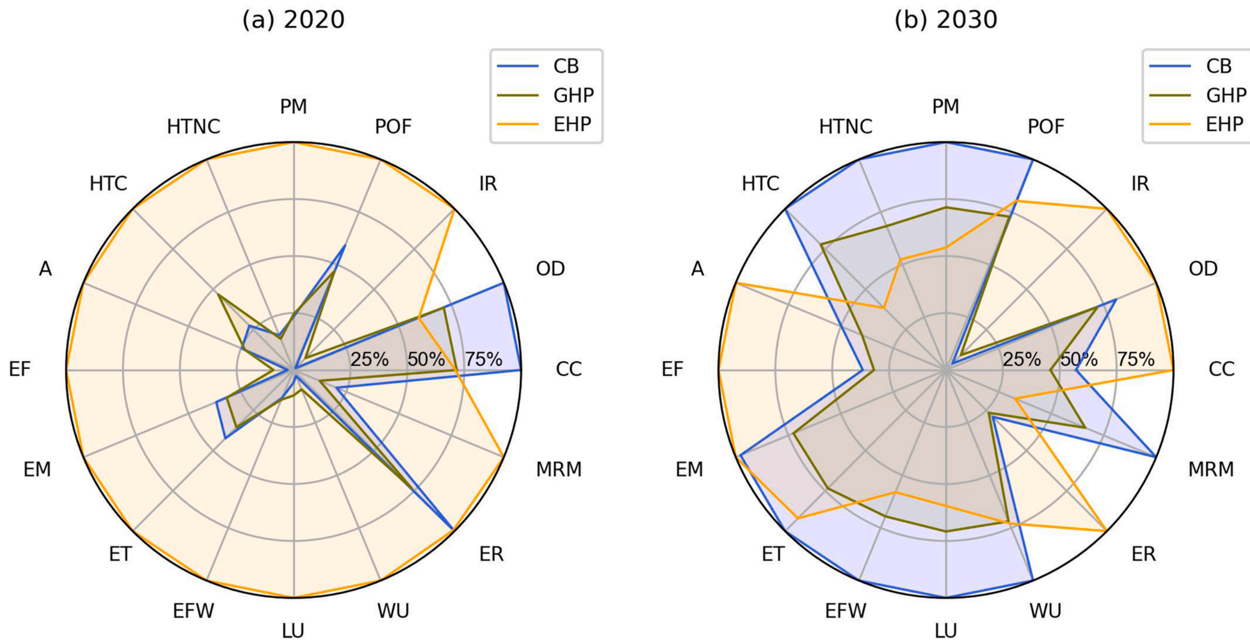

Fig. 3. Characterization results for FU [%] - renovated building.

is by far the major contributor to Ionizing Radiation (IR), Acidification (A), Eutrophication Freshwater (EF), and Eutrophication Marine (EM) for the reasons mentioned above in the bullet points (2020 results). Compared with CB and GHP, the EHP also contributes more to: i) Ozone Depletion (OD) caused by leakage of *Methane, bromochlorodifluoro-, Halon 1211* used as fire gas in the compression stations for the long-distance distribution of the natural gas for electricity production [58], and ii) Energy Resources – nren (ER) due to electricity production linked with coal, natural gas and nuclear plants that supply the European grid. On the other hand, thermally-driven appliances become the major contributors to Particulate Matter (PM) formation, toxic categories (HTNC, HTC, EFW), Land Use (LU), Water Use (WU), and Material Resources Mineral/metals (MRM). It is caused by the higher electricity consumption to provide 1 kWh_{th} from green hydrogen, equal to 1.4 and 1.0 kWh_{el} for CB and GHP, respectively, compared to 0.5 kWh_{el} of the EHP. In detail:

- the Particulate Matter (PM) formation and toxic categories were caused by particulates and heavy metals emissions (in air, soil, and water) during the manufacturing of renewable energy plants for electricity supply in hydrogen production;
- Land Use (LU) impact category due to Photovoltaics (PV) panels in open-ground installation;
- Water Use (WU) - still in the electricity supply for hydrogen production;
- and Material Resources Mineral/metals (MRM) due to the amount of copper used in renewable energy systems for electricity production.

For the Photochemical Ozone Formation (POF) and Eutrophication Terrestrial (ET), Fig. 3b shows the EHP has intermediate results between the two thermally-driven appliances. These impact categories are caused by coal consumption for electricity production and metal manufacturing processes.

Fig. 4, like Fig. 3, provides the characterization results for the three energy systems analyzed, but in this case, the comparison was implemented between the temporal scenarios. The bar charts emphasize the percentage magnitude of environmental burdens shifting from 2020 to 2030 for each appliance evaluated in this study.

Fig. 5 presents the outcomes for the two scenarios (2020 and 2030) related to the renovated building, showing the contribution of each life cycle stage for each impact category. For 2020 and 2030, the main contribution to all the environmental impact categories is the use phase (electricity, natural gas, and hydrogen consumption evaluated with the life cycle approach).

In 2020, the use phase ranged as follows:

- for CB, from 99.8 % (Ozone Depletion) to 8.4 % (Material Resources Metals/minerals);
- for GHP, from 98.7 % (Energy Resources, non-renewable) to 37.7 % (Human toxicity, carcinogenic);
- for EHP, from 99.3 % (Ionizing Radiation) to 55.9 % (Ozone Depletion).

As shown in Fig. 2a, for CB, the higher impact on Ozone Depletion (OD) is linked with emissions of *Methane, bromochlorodifluoro-, Halon 1211* during natural gas distribution. Energy Resources - non-renewable (ER) influenced mainly the use phase of the GHP due to natural gas consumption. The nuclear plants used to supply electricity on the European grid (equal to 23 % of the share - Table 4) caused a higher impact related to Ionizing Radiation (IR) for EHP compared with the other phases and impact categories. Fig. 5a and Fig. 5c show that for CB and GHP, the use phase is not the main contributor to the impact category Material Resources Metals/minerals (MRM) and Human Toxicity, Carcinogenic (HTC), respectively. In fact, for those categories, the life phase components (raw material supply and production) is the main contributor due to the copper (for CB) and the steel (for GHP) used for the manufacturing. Negative values associated with the End of Life (EoL) phase are due to recycling processes or waste-to-energy facilities.

For what concerns the 2030 scenario (see Fig. 5b, d, and f), the use phase is confirmed as the most significant, contributing to:

- for CB, from 99.8 % (Water Use) to 93.8 % (Acidification);
- for GHP, from 98.8 % (Water Use) to 81.9 % (Ozone Depletion);

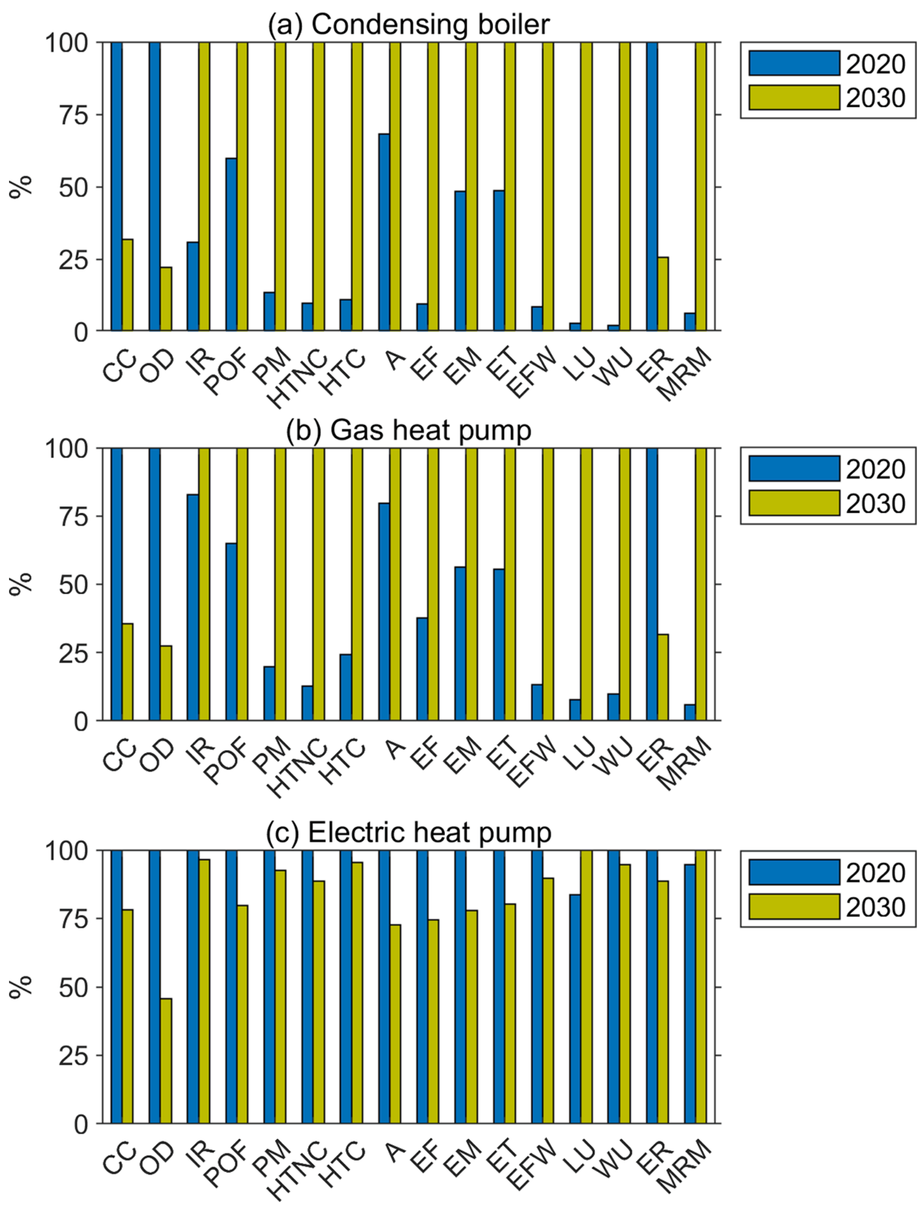

Fig. 4. Characterization results 2020 vs. 2030 for FU [%] - renovated building.

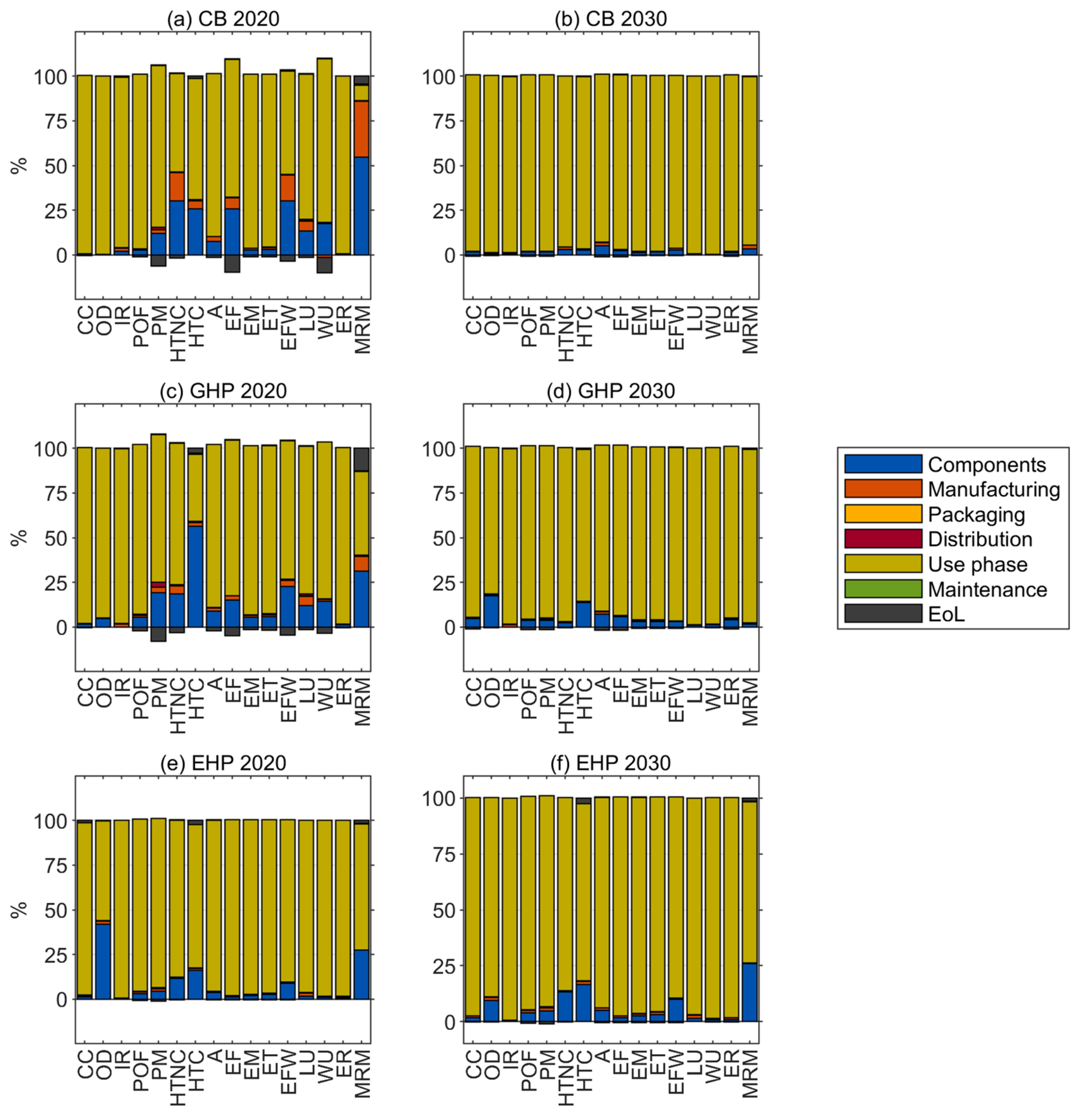

Fig. 5. Characterization results for life cycle phase [%] – renovated building.

- for EHP, from 99.3 % (Ionizing Radiation) to 72.1 % (Material Resources Metals/minerals).

As previously mentioned, for EHP, the higher impact on Ionizing Radiation linked with the use phase is caused by the nuclear plants supplying electricity to the European grid. The more significant contribution of the CB and GHP is related to the renewable electricity supply for hydrogen production.

4.2. Weighting results -deterministic

As stated within the international standard documents, ISO 14040 [8] and 14044 [10], weighting, together with normalization, is an optional step in LCA, and they are used to understand better the results obtained. The weighting results are obtained, by normalizing the impact categories values, thus dividing by selected reference, and then converting by using numerical factors based on value-choices. The Environmental Footprint (EF) 3.0 method utilizes i) the global annual released mass of each impact category per person (considering a world population equal to 6 895 889 018) to calculate the normalization factors and ii) a panel-based method for weighting. The EF 3.0 method gives a higher factor to climate change and a lower factor to human toxicity non-cancer [59].

Following this approach, the weighting results reported in Fig. 6 of the renovated building in the 2020 scenario were obtained. Subplots (a) to (c) show the contribution of each life cycle phase for the impact categories, while subplot (d) presents the same results in aggregated form - single score as a sum of the impact of each category. As indicated in the characterization results (section 4.1), the use phase was still the most significant phase for the three appliances (CB, GHP, and EHP), ranging from (88 %, 92 %, and 89 %), followed by the component productions phase (8 %, 6 %, 10 %), and the manufacturing phase (4 %, 1 %, 1 %), respectively. The other stages are negligible (lower than 1 %). The figure also emphasizes Climate Change (CC), Energy Resources non-renewable (ER), and Material Resources Metals/minerals (MRM) as the most significant impact categories. As mentioned in [25] and [16], to date, the electrification of the heating production in Europe (from thermally-driven to electrically-driven appliances) causes a burden-shifting from Climate Change (CC) to other impact categories, which results in a decrease in the impact related to CC vs. an increase in other

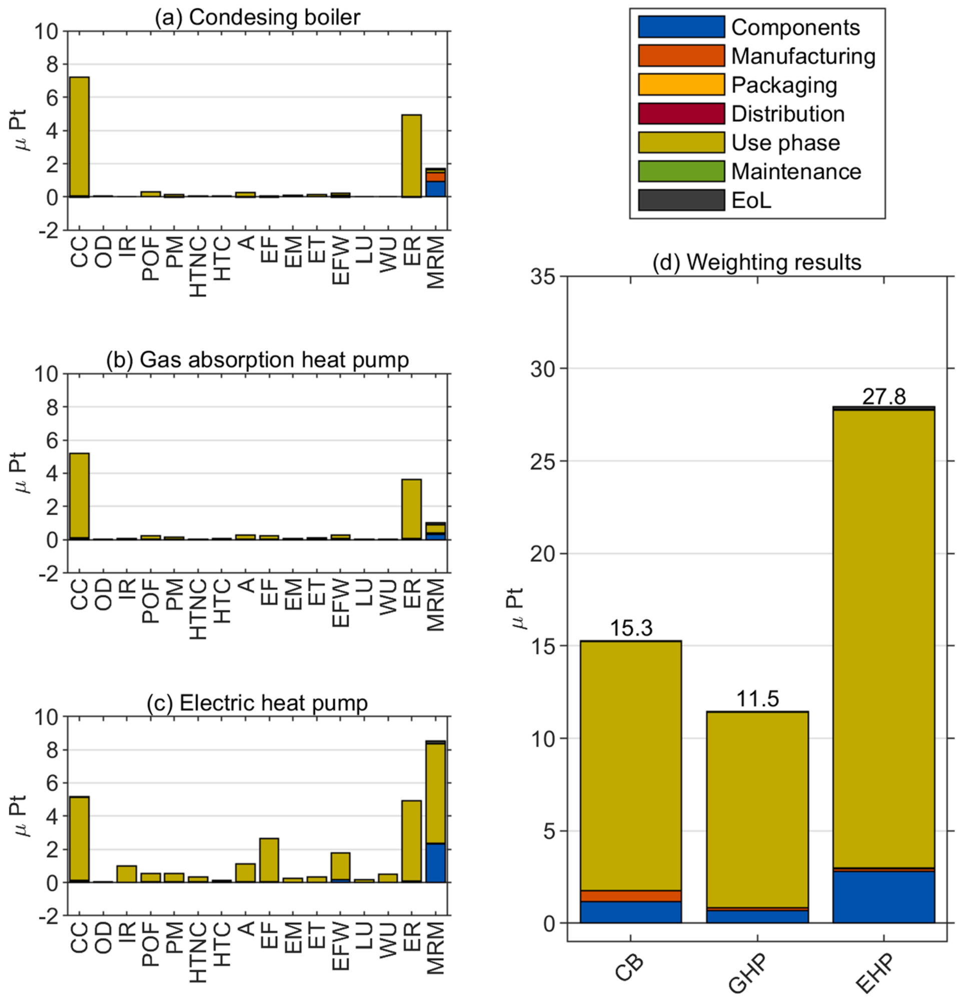

Fig. 6. Weighting results for FU (2020) – renovated building.

impact categories. It is confirmed in Fig. 6, where a better score for Climate Change (5.1 μPt / kWh_{th}) is found for the EHP, against 7.2 and 5.2 for CB and GHP, respectively, coupled with a higher single score impact (27.8 μPt / kWh_{th} against 15.3 and 11.5 of CB and GHP, respectively). When analyzing the impact of the different phases and comparing the results with previous works [24], some differences are found concerning component production. In particular, the component production phase for CB is higher than for GHP, even if the weight-to-power ratio of the CB is lower than one of the GHP. It can be explained by considering the different calculation models used in the two studies: the attributional model in [24] and the consequential model in this study. This difference leads to a higher environmental profile of copper, which penalizes the CB respect GHP due to the larger use of this material (4.2 kg vs. 0.6 kg per machine, respectively).

In Fig. 7, the weighting results are shown for the 2030 scenario. As mentioned, even in this case, the use phase was the most significant for the three appliances, ranging from (95 %, 97 %, and 88 %), followed by the component productions phase (3 %, 3 %, 11 %), and the manufacturing (2 %, 1 %, 1 %). The figure also emphasizes that, compared to Fig. 6, Material Resources Metals/minerals (MRM) become the most significant impact category for all the three appliances, accounting for 70 % of the single score result for CB, 67 % for GHP, and 36 % for EHP. MRM was followed by Climate Change (6 %, 7 %, and 16 %), which in 2020 was the most impacting category for CB and GHP, Ecotoxicity Freshwater (7 %, 7 %, and 6 %), and Energy Resource non-renewable (3 %, 4 %, and 17 %). These findings highlight that the Material Resources Metals/minerals will become strategic when it comes to increasing the environmental profile of an energy system. Therefore, the life cycle eco-design (i.e., extending the lifespan, reusing or recycling components, etc.) of both the appliances and the renewable plants utilized to produce electricity will be necessary to drive the decarbonization pathway of the European Union appropriately. This conclusion is emphasized by the scores of the two thermally driven systems, higher in 2030 than 2020, even if the Climate Change contribution was drastically reduced.

The major findings linked with the results reported in this section of the article can be summarized as follows:

- the use phase has the most significant impact, with an average contribution of 90.6 % across the investigated cases. The use phase is followed by the component productions phase (7.4 %) and the manufacturing phase (1.5 %). The other stages are negligible (lower than 1 %).
- Concerning the impact categories, in 2020, Climate Change (37 %), Energy Resources non-renewable (27 %), and Material Resources Metals/minerals (18 %) were the most important. In 2030, the most

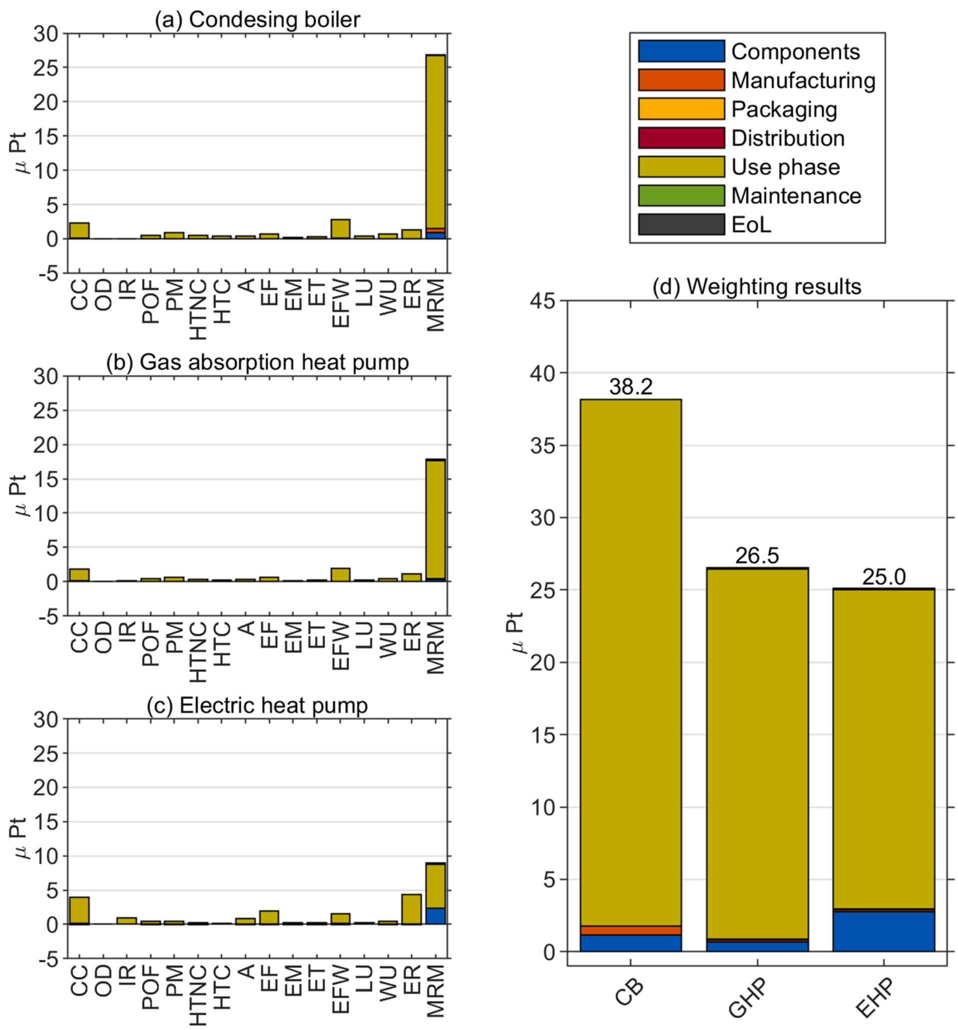

Fig. 7. Weighting results for FU (2030) – renovated building.

significant impact categories were Material Resources Metals/minerals (58 %), Climate Change (10 %), Energy Resources non-renewable (8 %), and Ecotoxicity FreshWater (7 %). The outcomes show that the shift from natural gas to green hydrogen makes fuel-driven appliances more beneficial to the climate profile of electric heat pumps. However, it caused a burden-shifting from Climate Change to all other impact categories (a decrease in climate change vs. an increase in other impact categories) except Ozone Depletion and Energy Resources non-renewable.

4.3. Uncertainty analysis – Stochastic

In this section, the outcomes obtained from the stochastic analysis are presented and discussed. Fig. 8 and Fig. 9 show the distribution of the results by Monte Carlo (MC) simulations (1 000 runs) for climate change and weighting for each building typology and reference year. Besides the results of each run (colored markers), the mean (μ), the median ($\widetilde{x}$), and the standard deviation (σ) values are also reported. It should be observed that the resulting μ and $\widetilde{x}$ are higher than the outcomes of the deterministic analysis. E.g., for the renovated building with CB in the 2020 scenario 277 gCO_2eq / kWh_{th} were obtained with the deterministic approach, while a μ of 351 and $\widetilde{x}$ of 299 are found with the stochastic method. This issue is known in the literature and does not affect the ranking of alternatives [45].

For what concerns the impact of climate change, in the 2020 scenario, the lowest mean value was found for the EHP, the higher for the CB, with GHP as intermediate technology. Moreover, the order is confirmed for the three building typologies. The results of the comparison change when considering the weighing, for which the highest impact is for the EHP and the lowest for the GHP. This difference can be explained by the fact that with the given specific emission for natural gas and electricity and the resulting efficiency of the three technologies, the CO_2eq emissions of the EHP during the use phase (which is the dominant phase) are lower than the ones of GHP and CB. However, the use of electricity of EHP is associated with a larger impact in the categories: Energy Resource non-renewable, Eutrophication Freshwater, Ecotoxicity Freshwater, and Acidification, which leads to an increase in weighting.

The results change moving to 2030 - using hydrogen produced with excess renewables significantly reduces the Climate Change impact of the CB and GHP. The same does not happen to the EHP because, as discussed, the electricity used for this technology corresponds to the expected energy mix of 2030. On the other hand, the renewable energy and the infrastructure required to produce hydrogen have an environmental impact, reflecting an increase in the weighing for CB and GHP.

This analysis, based on the mean value, gives some indications. However, since the outcomes of the propagation obtained with the Monte Carlo method are very sparse, a better understanding can be obtained from a statistical analysis. As anticipated in section 2, two options were considered for the choice of one alternative over another:

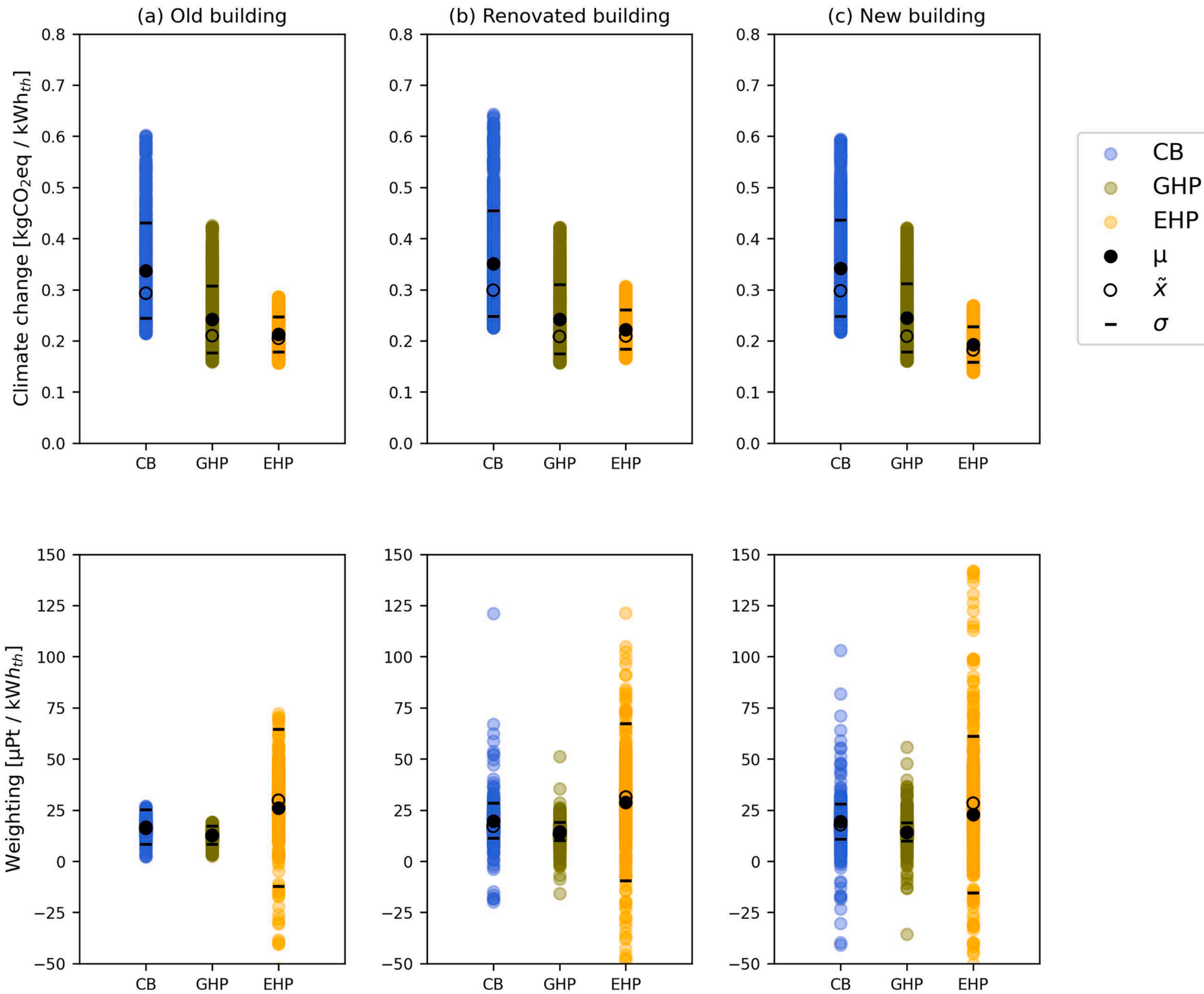

Fig. 8. Characterization results (2020 scenario).

- comparing the probability (P), where P represents the average probability that one appliance has a higher impact than the other on the given category;
- the null hypothesis testing, which analyzes the distribution of environmental profiles of alternative energy systems obtained with the Monte Carlo method, is essential to confirm the choice of an alternative.

Looking at the probability results, reported in Table 10 and Table 11 for 2020 and 2030, respectively, taking as an example the comparison between GHP and EHP for climate change (2020 scenario – renovated building), Table 10 shows 50.8 % positive values. It means that in 508 runs out of 1 000, the GHP had a higher impact in this category than EHP, while in the remaining 492, the GHP had a lower impact than EHP. This result suggests that the two technologies have a quite similar impact in terms of Climate Change for this application, with a small advantage for the EHP. In the old building, similar values are found, while in the new building, the EHP has a higher probability of performing better than a GHP, thanks to more suitable operating conditions. Similar results are found for Ozone Depletion, while for all the other categories, the probability that EHP is less impacting than a GHP is minimal. For the CB, results not far from the ones of the GHP are found (likely because they are driven by the same fuel) but slightly better for the manufacturing phase and worst for the use phase (due to the lower efficiency).

In 2030, it is confirmed what was observed looking at the mean value, i.e., that the two fuel-driven technologies most likely do not have a worse impact than the EHP. However, in other categories, such as the Particulate Matter formation, Human Toxicity Non-Carcinogenic, Ecotoxicity Freshwater, Water Use, and Material Resources Metals/minerals, the probability for CB and GHP to have a larger environmental impact than the EHP increases from negligible values to 60–80 %.

In 2020, the substantial equivalence between GHP and EHP (for the renovated scenario) is confirmed by the pairwise Wilcoxon Rank Sum test (used because data were not-normally distributed), which shows that there is no significant difference in the climate change impact category between GHP and EHP ($\mu = 241$, $\tilde{x} = 209$, $\sigma = 130$ gCO_2eq / kWh_{th} for the GHP and $\mu = 222$, $\tilde{x} = 209$, and $\sigma = 71$ gCO_2eq / kWh_{th} for the EHP, with a p-value = 7.97E-02). It means the data do not allow the identification of a preferred alternative in this comparison because the null hypothesis cannot be rejected. Looking at all the combinations with this approach, in Table 12, the cases where it is impossible to identify a preferred alternative are reported for the different impact categories and the two temporal scenarios. These are the cases where no statistical difference is found ($p > 1.67E\text{-}02$) between two energy systems for the building typology indicated next to each comparison.

Two significant findings reported in Table 12 are worth mentioning:

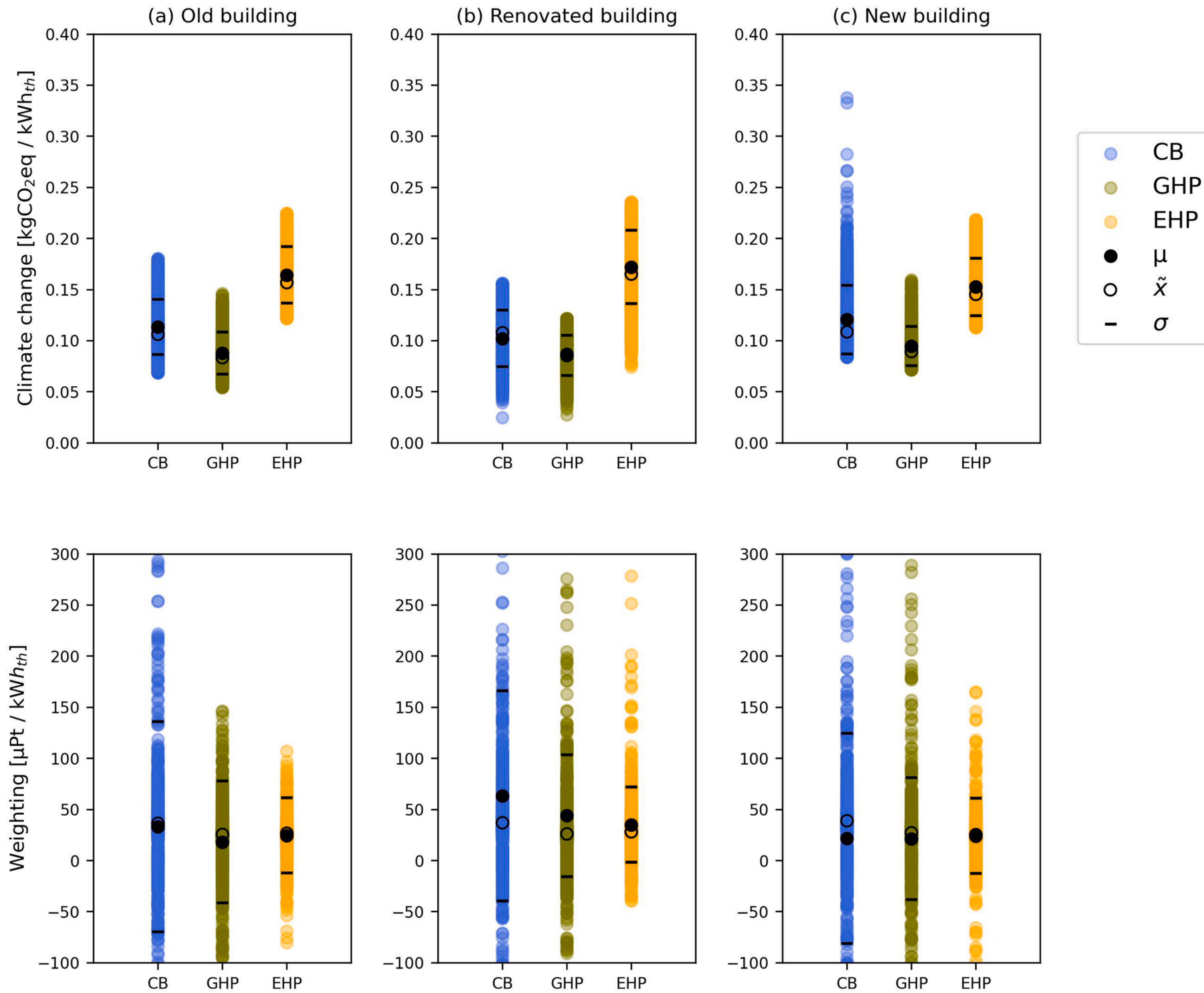

Fig. 9. Characterization results (2030 scenario).

- in 2020 renovated building, it is not possible to state which technology has the better climate profile (Climate Change) between GHP and EHP;
- for all three building typologies, it is impossible to state which technology has a better environmental profile (weighting) between GHP and EHP.

For the comparisons not listed in Table 12, it is reasonable to conclude that one of the appliances has a higher impact than the other in the given category. Complete results of the statistical testing are provided in the supplementary data (see Microsoft Excel files "Hypothesis testing 2020" and "Hypothesis testing 2030").

Looking at the two most important categories, which together account for a fraction of the overall impact (weighting) between 50 and 76 %, the p-values confirmed by the null hypothesis testing (not weak significance) are:

- in 2020, the electric heat pump (EHP) always has a better climate profile (CC) than the boiler. The same cannot be stated with the GHP in the renovated buildings because EHP can only be indicated as the preferred alternative for the old and new buildings. In 2030, the outcomes are always the opposite – the fuel-driven appliances have a very low climate profile thanks to the shift from natural gas to green hydrogen, permitting them to be suggested as the preferred alternative;
- the benefit of the fuel-driven appliances achieved for the climate change impact category from 2020 to 2030 is not confirmed for Material Resources, Mineral/metals (MRM). In 2020 the boiler and the gas heat pump show a lower impact than the electric heat pump on MRM, but the opposite occurs in 2030. The use of green hydrogen increases this potential impact for fuel-driven appliances, making them more impactful than the electric heat pump.

Based on these considerations, it can be stated that using green hydrogen for running a GHP provides favorable results in decarbonizing the domestic heating in all three building typologies selected. This option is better than a condensing boiler due to its higher efficiency. Moreover, the combination of hydrogen plus GHP in the 2030 scenario

Table 10
Probability results (2020).

Impact category	Building	CB > GHP [%]	CB > EHP [%]	GHP > EHP [%]
CC	Old	69.0	75.3	51.6
	Renovated	71.1	74.1	50.8
	New	68.7	81.5	61.8
OD	Old	78.7	88.1	67.5
	Renovated	79.5	76.7	53.7
	New	76.3	74.7	54.4
IR	Old	0.0	0.0	0.0
	Renovated	0.0	0.1	0.1
	New	0.0	0.0	0.0
POF	Old	69.2	24.0	11.0
	Renovated	65.4	21.3	10.6
	New	65.5	29.5	15.6
PM	Old	48.7	0.4	0.3
	Renovated	44.5	0.4	0.1
	New	33.3	1.0	0.7
HTNC	Old	49.8	1.1	0.7
	Renovated	61.2	1.0	0.8
	New	51.4	1.5	0.9
HTC	Old	25.7	9.3	13.2
	Renovated	17.7	9.0	15.0
	New	12.3	7.7	19.4
A	Old	55.6	1.6	0.8
	Renovated	58.6	2.7	0.6
	New	50.5	2.7	1.3
EF	Old	2.1	0.9	1.1
	Renovated	5.7	1.4	1.5
	New	5.6	1.1	1.5
EM	Old	62.3	11.5	6.3
	Renovated	58.4	9.5	3.4
	New	56.2	14.2	7.4
ET	Old	62.8	14.5	6.9
	Renovated	60.3	14.4	7.5
	New	55.0	16.7	9.8
EFW	Old	30.2	1.3	1.3
	Renovated	40.5	1.0	1.2
	New	30.6	1.4	1.4
LU	Old	5.7	1.0	1.0
	Renovated	6.9	0.6	0.7
	New	4.8	1.5	1.8
WU	Old	1.0	0.1	0.0
	Renovated	1.7	0.1	0.1
	New	0.8	0.0	0.0
ER	Old	75.9	48.8	23.7
	Renovated	78.4	44.3	19.4
	New	75.7	58.3	31.7
MRM	Old	56.2	19.8	20.0
	Renovated	69.0	21.6	21.4
	New	61.1	19.7	19.1
Weighted	Old	75.1	13.9	10.5
	Renovated	76.7	16.0	11.9
	New	72.6	17.8	13.1

Table 11
Probability results (2030).

Impact category	Building	CB > GHP [%]	CB > EHP [%]	GHP > EHP [%]
CC	Old	73.2	21.0	6.4
	Renovated	70.0	14.0	5.3
	New	70.0	26.4	11.6
OD	Old	67.3	44.8	30.7
	Renovated	59.6	36.7	26.6
	New	54.3	47.5	41.8
IR	Old	2.0	0.0	0.0
	Renovated	1.9	0.0	0.0
	New	2.5	0.0	0.0
POF	Old	74.6	71.4	52.5
	Renovated	74.8	70.6	48.3
	New	75.5	79.3	57.2
PM	Old	78.3	88.3	74.1
	Renovated	79.4	86.6	70.1
	New	79.7	92.3	81.8
HTNC	Old	80.2	92.1	77.6
	Renovated	81.8	91.8	73.2
	New	82.9	95.9	80.3
HTC	Old	59.8	75.8	75.2
	Renovated	59.1	74.7	74.6
	New	58.9	77.5	79.0
A	Old	68.9	15.9	5.4
	Renovated	69.1	16.5	5.9
	New	69.3	25.4	11.2
EF	Old	60.3	19.1	9.9
	Renovated	60.3	16.8	6.6
	New	58.3	21.5	12.4
EM	Old	74.8	53.9	29.3
	Renovated	73.9	52.4	28.1
	New	73.7	65.1	42.6
ET	Old	73.6	59.2	34.2
	Renovated	72.9	56.3	33.0
	New	73.0	68.8	46.2
EFW	Old	77.2	81.4	62.6
	Renovated	78.9	80.6	58.2
	New	82.7	90.1	70.1
LU	Old	73.2	67.0	57.9
	Renovated	73.9	67.0	57.0
	New	74.3	69.8	59.7
WU	Old	77.3	77.1	56.3
	Renovated	78.0	78.0	52.2
	New	78.0	86.5	69.2
ER	Old	61.1	1.3	0.4
	Renovated	57.3	0.6	0.2
	New	57.5	1.6	0.5
MRM	Old	69.7	80.3	79.5
	Renovated	68.8	78.6	78.5
	New	69.0	78.7	78.7
Weighted	Old	77.2	72.9	49.4
	Renovated	77.5	69.9	38.6
	New	77.9	76.3	54.8

has a better climate profile than the EHP running with electricity from the grid, which is currently considered the reference heating system for that time horizon. The use of a solution for storing renewable energy to be used in an EHP (batteries or fuel cells driven by green hydrogen) is out of the scope of this work. However, this would likely decrease the EHP's impact on Climate Change while increasing other categories, increasing the weighting. It has to be mentioned the results of this study would be even more in favor of gas heat pump appliances if, in the 2030 scenario, the potential benefit of producing oxygen as hydrogen co-product in the electrolyzer was considered. In fact, as anticipated, following a conservative approach, the oxygen was supposed to be vented into the air, while most likely, in the considered scenario, it would be used for other applications, with benefit for the environmental profile of hydrogen production and consequently of the GHP and CB.

Looking at the evolution of the impact of the GHP technology, the reduction of climate change from 2020 to 2030 due to the use of green hydrogen comes with an increase of other categories, increasing the weighting. It confirms the findings of Laurent et al. [60] and [61] for electricity production, i.e., that a potential burden shift may occur in the path of decarbonization. The findings also confirm that energy planning based only on Climate Change provides recommendations to policy and decision-makers that could either be too optimistic about the outcome of measures or lead to solutions with the worst environmental profile. Moreover, the breakdown of the impacts under different categories beyond Climate Change highlights the importance of the Material Resources Mineral/metals (MRM) in the decarbonization pathway scenarios for hydrogen and electricity production. The outcomes obtained for the MRM impact category emphasized the relevance of photovoltaic

Table 12
Cases with weak significance ($p > 1.67E-02$).

Impact category	p test (2020)	p test (2030)
CC	GHP vs. EHP (renovated)	–
OD	–	CB vs. EHP (old) CB vs. EHP (new)
POF	–	GHP vs. EHP (old) GHP vs. EHP (renovated)
PM	CB vs. GHP (old) CB vs. GHP (renovated)	–
HTNC	CB vs. GHP (old)	–
A	CB vs. GHP (new)	–
EM	–	CB vs. EHP (renovated)
WU	–	GHP vs. EHP (renovated)
LU	–	GHP vs. EHP (old) GHP vs. EHP (renovated)
ER	CB vs. EHP (old)	–
Weighting	–	GHP vs. EHP (old) GHP vs. EHP (renovated) GHP vs. EHP (new)

panels and wind turbines. The supply chain of metals such as copper, steel, and aluminum should be improved (i.e., increasing the circularity and reducing energy consumption) to ease the additional environmental impact associated to the transition from fossil fuels to renewables. Additionally, precious and rare metals, such as platinum, iridium, niobium, etc. under investigation to increase the efficiency of electrolyzers (in alkaline and polymer electrolyte membrane) will also need to be evaluated with life cycle approach [62].

The authors moreover highlight that the use of error propagation on LCA inventories has a significant limitation: the covariance between parameters is not considered (e.g., between fuel consumption and direct emissions during the combustion), leading to either over or underestimating the results' uncertainties, as previously analyzed by Pizzol [45] and Groen et al. [63].

5. Conclusions

In this work, the environmental performance of a condensing boiler, an air source gas-driven absorption heat pump, and an air source electric-driven heat pump for residential space heating and domestic hot water were compared through the consequential life cycle approach. Two scenarios were considered: 2020, with the actual energy mix for electricity production and natural gas as fuel for the gas-driven machines, and 2030, with the expected energy electricity mix and green hydrogen from renewables as fuel. The calculation was performed for an old building, a renovated one, and a new building, deriving the following conclusions:

- The use phase is the most impacting in all the investigated cases. In fact, for the renovated building, a share of the overall impact equal to 88 %, 92 %, and 89 % can be assigned to this category for condensing boiler, gas absorption, and electric heat pump, respectively in the 2020 scenario and 95 %, 97 %, and 88 % in 2030.
- The use of green hydrogen to power gas-driven units, besides providing storage capability for renewable electricity, reduces the Climate Change impact of space heating and domestic hot water from about 0.20–0.28 to 0.07–0.09 kg CO_2eq per kWh. The lower limit of the two ranges is for gas absorption heat pump, while the upper is for condensing boiler, confirming that using a more efficient technology assures lower emissions in both the 2020 and 2030 scenarios.
- The impact on Climate Change of hydrogen-driven (condensing boiler and gas absorption heat pump) is significantly lower per unit of energy delivered than that of the electric-driven heat pump by the expected mix for energy production in 2030.
- The production of renewable energy and its conversion into green hydrogen, while reducing the Climate Change of gas-driven heating appliances, increases their impact in other categories and the weighting. It underlines that the eco-design of photovoltaic panels and wind turbines will be crucial to improve the environmental profile of green hydrogen related to impact categories and prevent the mentioned burden shift.
- The need for breaking down the impacts under different categories, as it allows the investigation of further aspects, such as the effects of variation of the renewable share in the electrical and gas networks, which would be neglected otherwise.

Additionally, this work provides data and results which can be of use for further studies on the environmental profile of heating systems and their decarbonization. In particular, the detailed life cycle inventory data of the European electricity decarbonization scenario and production of green hydrogen, used in the study for the life cycle assessment of the three appliances, provides the future environmental profile of boilers and heat pumps for space heating and domestic hot water in the European residential buildings based on a holistic analysis.

Moreover, the outcome of this work could be further improved with higher quality primary data for hydrogen production, currently limited by the small number of studies available in the literature. Moreover, other aspects beyond the environmental perspective could be included to the investigation: adding the Life Cycle Cost and the Social-Life Cycle Assessment 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, Investigation. **Tommaso Toppi:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Investigation. **Davide Bonalumi:** Writing – review & editing, Investigation. **Mario Motta:** Supervision, Project administration, 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.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enconman.2022.116527.

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