Environmental Life Cycle Assessment of heating systems in the UK: comparative assessment of hybrid heat pumps vs. condensing gas boilers

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Abstract

Residential space heating is one of the major contributors to greenhouse gas (GHG) emissions and hence a priority sector to decarbonise in the transition to Net Zero target by 2050 in the UK. To assess environmental impacts of a current heating system and potential alternatives in the UK, this study conducted a comparative LCA of a condensing gas boiler and a hybrid heating pump for a common type of UK's existing houses (a semi-detached house). The functional unit of this study is defined as delivering space heating for the whole lifetime (20 years) of heating system. The results suggest that the hybrid heat pump potentially saves 30% of GHG emissions as compared to the condensing gas boiler in the core scenarios (4.5E+04 kg CO2-eq/FU vs 6.4 E+04 kg CO2-eq/FU respectively). The hybrid heat pump also shows 13% to 48% emission reduction as compared to the condensing gas boiler in terrestrial acidification, photochemical oxidant formation, particulate matter formation and fossil depletion. However, the hybrid heat pump emits 3 to 6 times more emissions in terms of human toxicity, water depletion and metal depletion than the condensing gas boiler. The production phase contributes around 50% of the impact for metal depletion and human toxicity in both core scenarios, while the use phase dominates in other selected impact categories. The combustion of natural gas and the electricity production are the major causes for the dominance of the use phase for all selected impact categories excepting metal depletion and human toxicity. The sensitivity scenarios support the robustness of the results. Further work is needed to understand the role hybrid heat pumps can play in the residential sector decarbonisation under different scenarios of residential uptake, household behaviour and wider UK energy system decarbonisation.

Keywords: LCA, gas boiler, hybrid heat pump, decarbonisation, sensitivity analysis, trade-offs environmental impacts.

Abbreviation:

ABS	Acrylonitrile butadiene styrene
ASHP	Air-source heat pumps
CC	climate change
CCC	Committee on Climate Change
CCS	Carbon captured and stored
CGB	Condensing gas boilers
DECM	Domestic energy and carbon model
EoL	End of life
EPDM	Ethylene propylene diene monomer
FD	Fossil depletion
FE	Freshwater eutrophication
FET	Freshwater ecotoxicity
GHG	Greenhouse gas
GSHP	Ground-source heat pumps
HDPE	High-density polyethylene
HHP	Hybrid heat pumps
HP	Heat pumps
HT	Human toxicity
LCA	Life cycle assessment
LHV	Lower heating value
MD	Metal depletion
ME	Marine eutrophication
MET	Marine ecotoxicity
OD	ozone depletion
ODS	Ozone-depleting substances
PMF	Particulate matter formation
POF	Photochemical oxidant formation
PVC	Polyvinyl chloride
SPF	Seasonal performance factor
TA	Terrestrial acidification
TET	Terrestrial ecotoxicity
WD	Water depletion
WSHP	Water-source heat pumps

1. Introduction

Many policies have been issued in different regions to deal with the significant amount of greenhouse gas (GHG) emissions caused by space heating, e.g. European Union's Renewable Energy Directive provides subsidies for eligible heat pumps that emit GHG emissions below specific thresholds. In the UK, the government legislated for a net-zero GHG emission target by 2050 [1]. One third of UK's GHG emissions in 2009 were emitted from heat-related activities, where three quarters were caused by space heating for the residential sector [2]. According to estimates for domestic energy and carbon model (DECM), space heating emitted around 3 times more CO_2 than the second emitter, i.e. lights and appliances, in UK's dwellings [3]. Hence, reducing GHG emissions for residential sector, especially those related to space heating, is necessary for reaching this net-zero target. With phasing out the inefficient room heaters, central heating with gas boilers has become the dominant method for space heating in the UK [4–6]. Residential heating by gas boilers increased from 80% in 1996 to 92% in 2017 [7]. Given that most people currently have gas boilers, the government issued schemes for the residential sector to reduce GHG emissions, targeting the improvement of gas boiler standards and the replacement of inefficient gas boilers [8]. On the other hand, the Committee on Climate Change (CCC), as an independent adviser to the UK government, suggests other alternatives, e.g. heat pumps and hybrid heat pumps. Heat pumps were underlined to reduce GHG emissions significantly at district and building level [9], but they are not widely spread in the UK. The number of heat pumps per capita in the UK ranked 16th among EU member states in 2013, and only 0.2% of UK's building heat demand was satisfied by heat pumps in 2015 [6,10]. Their large-scale deployment raises concerns as first it would increase the peak demand of electricity consumption and second they could have worse environmental performance than condensing gas boilers due to high carbon intensity of electricity [11,12]. As a technology combining gas boilers and heat pumps, hybrid heat pumps are considered as a transition to decarbonizing heating [13,14]. Recently, it has been claimed that between 18% and 55% of GHG emissions could be reduced by hybrid heat pumps compared to condensing gas boilers with two different heating habits, i.e. a continuous heating schedule where the system is switched on all day and a twice a day heating schedule where heating activity is divided into up to 4 hours in the morning and 4-10 hours for 'home-time' [15]. This study also stated that hybrid heat pumps could reduce the peak electricity demand compared to standalone heat pumps.

Many researchers have explored the environmental impacts of various heating systems based on quantitative methods, e.g. life cycle assessment (LCA). The World Energy Council compared GHG emissions of various heat devices such as heat pumps and natural gas boilers. The results emphasised that the environmental performance of condensing gas boilers (0.271 kg CO2-eq/kWh) was better than the non-condensing ones (0.302 kg CO2-eq/kWh), while, with hydro, nuclear and natural-gas based electricity, ground-source heat pumps had the best performance (0.029-0.105 CO2-eq/kWh) [16]. Researchers compared different heating systems in China, such as heat pumps, highlighting that the use phase was the main emitter of GHG emissions, contributing to over 84% of the total [17]. For the European Union, a published LCA report tested five types of heating systems, such as condensing gas boilers and gas-electricity heat pumps, finding that refrigerants contribute to one third of the total GHG emissions [18]. In Italy, two different types of natural gas boilers, i.e. a traditional combination gas boiler with 24 kW rated thermal input and an instantaneous condensing combination gas boiler with 24kW heat output for heating and 26 kW for sanitation, were explored [19]. They stated that condensing gas boiler emitted on average 23% less environmental impacts than traditional one for selected impact categories due to higher efficiency of fuel use and lower CO and NO_x emissions of natural gas combustion. In the UK, the environmental impacts of three various types of heat pumps, i.e. air-source (ASHP), ground-source (GSHP), water-source heat pumps (WSHP) and condensing gas boilers, were assessed, suggesting that electricity generation for heat pumps and natural gas combustion for condensing gas boilers in heating systems were the major contributors to the climate change impacts [12]. Another study compared the carbon footprint of an air-source heat pump in various house types and sizes, concluding that all phases were insignificant in terms of GHG emissions other than the use phase and pointing out that power, refrigerant and equipment caused 80-83%, 15-18% and 2-4% respectively for three targeted house types [20]. However, to our best knowledge, an LCA study for the environmental assessment of UK's hybrid heat pump is rarely found.

There are several UK assessments for hybrid heating systems, but they only focus on decarbonisation and lack evaluations for environmental impacts coming from the whole supply chain. In-situ domestic hybrid heat pump systems, gas boiler systems and heat pump systems were compared from three perspectives, namely the performance of hybrid heat pumps, cost-effectiveness and impact on the wider energy system [15]. Energy Systems Catapult assessed UK's transition to net zero emission for the residential heat sector [21]. One study evaluated the cost and strategic benefits of the hybrid heating technologies for Irish areas based on a linear programming investment model, suggesting that the hybrid technologies, e.g. a combination of heat pumps and gas boilers, can reduce the cost and CO_2 emissions as compared to the standalone gas boilers and heat pumps [22]. As hybrid heat pumps are seen as a key solution for the UK residential heat decarbonisation, this study complements previous studies by providing insights into the wider environmental performance of hybrid heat pumps as compared to the incumbent heating technology, combi gas boilers. To this end, a comprehensive comparative LCA of hybrid heat pump vs gas boiler is performed, including indicators in 14 impact categories. The whole life cycles of both heating systems include the production of the heating system, the use phase, the distribution and the end-of-life phase. The environmental impacts for both heating systems were evaluated for 14 different environmental impact categories, based on two core scenarios for condensing gas boilers (CGB) and hybrid heat pumps (HHP) operated in current UK's conditions. This study also explored the main sensitivities in the assessment, namely the degree of decarbonisation of the UK grid electricity, the efficiency and the end-of-life options for both heating systems, and the type of refrigerant used in the HHP. The paper is structured as follows: Section 2 presents the methods used for the assessment, including the main data assumptions and scenario analyses undertaken. Sections 3 and 4 present the results of the study and discuss them in the light of current residential heating decarbonisation literature. Section 5 concludes with a summary of findings and ways forward.

2. Methods

To quantify the environmental impacts of selected heating systems, this study adopts the Life Cycle Assessment (LCA) method and follows principles set by the ISO 14040:2006 standard guidelines [23]. The LCA method can be used to quantify the consumption of resources and the environmental impacts of various emissions, throughout the whole life cycle of a product or a service from its production, use, transport and end-of-life phases (i.e. from cradle to grave) (ibid). This study uses the SimaPro 8.0 software [24] with Ecoinvent database v3 [25] to assess the environmental impacts.

2.1 Goal and scope of life cycle assessment

The goal in this study is to assess and compare the environmental impacts of a condensing gas boiler and a hybrid heat pump for an existing semi-detached house in the UK rather than assess the performance of selected heating systems. The study aims to quantitatively identify advantages and disadvantages of both targeted heating systems for semi-detached houses in the UK from an environmental perspective. The geographical scope is the United-Kingdom, and it aims at being current-technologies compliant, i.e. being as representative as possible of the 2019 stock. The scope of this study is from cradle to grave, which includes production, use, transport and end-of-life phases of heating systems. An attributional approach is used to evaluate the environmental impacts of both heating systems over their supply chain and end-of-life value chain, hence the consequences of changing the current heating systems is not included. The system boundaries of both heating systems are presented in fig. 1.

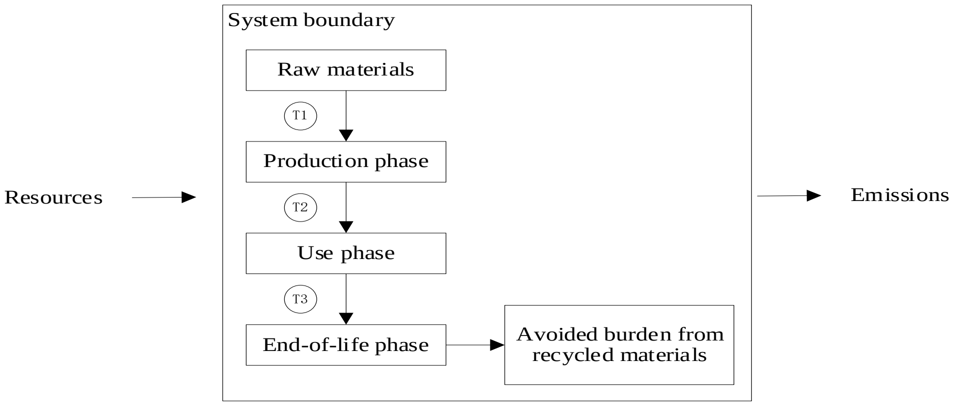

Fig. 1. System boundaries of the two heating systems under study. Note: T1, T2, T3 refer to transportation processes; T1 is for raw materials, T2 is for heating devices and T3 is for end-of-life devices and materials.

This study considers a semi-detached house with a size of 90 m^2, including 2 floors, 3 bedrooms, 2 bathrooms, 1 kitchen, dining room and living room [26]. The annual average heat demand of existing homes in the UK for space heating (140 kWh/m^2 per year) is adopted for estimating the heat demand over the lifetime [27]. Although current heating systems usually deliver both space heating and hot water supply, this study only considers space heating. The hot water supply is provided by the gas boiler in both heating systems, hence the environmental impacts caused by hot water supply would be the same for both heating systems. Given that this study compares both systems from an environmental impact perspective rather than performance of heating systems, it is safe to make such an assumption. With a lifetime of the heating systems of 20 years, the total heat demand over the whole lifetime is assumed to be 252,000 kWh. Therefore, the functional unit in this study is generating 252,000 kWh of space heat over 20 years.

2.2 Data collection and assumptions

According to DECM housing stock database, most semi-detached houses were built between 1930 and 1966, and the house layouts and construction method were unchanged during this period [3,28]. Un-furbished semi-detached houses built in 1930s were equipped with 30-kW condensing gas boilers (ibid). Due to the data availability and potential improvement for the houses, a condensing gas boiler with 24-kW capacity is adopted in this study. The specifications of the condensing gas boiler are illustrated in table 1.

Table 1. The specifications of the condensing gas boiler assumed in this study, including the sources of data.

Life cycle stage/system	Material /disposal	Amount	Unit	Source
Production phase	Copper	2.66	kg	[19]
	Brass	3.22	kg	
	Aluminium	1.91	kg	

	Steel	22.9	kg	
	Stainless steel	6.74	kg	
	Silicone	0.12	kg	
	EPDM	0.06	kg	
	ABS	1.17	kg	
	PVC	0.005	kg	
	Electronic components	0.25	kg	
Assembly	Medium-voltage electricity (UK mix)	294	MJ	[12]
	Natural gas	472	MJ	
	Light fuel oil	249	MJ	
Transport	Freight train	7.80	tkm	
	Lorry (<16 tons)	7.80	tkm	
	A van (<3.5 tons)	7.80	tkm	
Use phase	Natural gas	1.081	kWh/kWh heat generated	[29]
End-of-Life phase (recycling rates)	Aluminium	90.0	%	[18,30]
	Steel	90.0	%	
	Stainless steel	90.0	%	
	Brass	90.0	%	
	Copper	90.0	%	
	Silicone	23.0	%	
	EPDM	23.0	%	
	ABS	23.0	%	
	PVC	23.0	%	

A hybrid heating system (i.e. hybrid heat pumps) usually comprises a gas boiler and a heat pump in principle controlled by smart hybrid logic, which can select the most efficient or cost-effective heating mode over the heating season. According to the simulation of standalone heat pump size with the TRNSYS model for UK's detached house, heat pumps with at least 12 kW capacity were suitable for the house size of 88 m^2 [31]. Due to data availability, A 10-kW air-source heat pump and a 10-kW condensing gas boiler were selected to make up the hybrid heat pump and meet heat demand for the house, while the gas boiler element would provide heat at peak demand times. The specifications of this hybrid heat pump are presented in table 2, again based on different literature sources.

Table 2. The specifications of the hybrid heat pump assumed in this study, including the sources of data.

Life cycle stage	Material /disposal	Amount	Unit	Source
Production phase	Copper	39.6	kg	[12]
	Brass	0.05	kg	
	Aluminium	7.50	kg	
	Stainless steel	5.00	kg	
	Steel (low alloyed)	147	kg	
	HDPE	1.40	kg	
	Rock wool	8.00	kg	
	Reinforcing steel	120	kg	
	Elastomer	16.0	kg	
	Polyester oil	2.70	kg	
	R410A	6.42	kg	
Assembly	Medium-voltage electricity (European mix)	504	MJ	
	Medium-voltage electricity (UK mix)	294	MJ	
	Natural gas	1872	MJ	

	Light fuel oil	249	MJ	
Transport	Freight train	177.9	tkm	
	Lorry (<16 tons)	49.3	tkm	
	Lorry (>16 tons)	107.1	tkm	
	A van (<3.5 tons)	27.9	tkm	
Use phase	Low voltage electricity mix UK	0.37	kWh/kWh heat generated	[15]
	Natural gas	1.081	kWh/kWh heat generated	[29]
Maintenance	R410A (recharge yearly)	6	%	[20]
End-of-Life phase (recycling rates)	Steel	90.0	%	[18,30]
	Aluminium	90.0	%	
	Copper	90.0	%	
	Brass	90.0	%	
	Plastics	23.0	%	
	Rubber	23.0	%	
	R410A	90.0	%	

2.2.1 Production phase of the heating systems

This study assumes that the condensing gas boiler is manufactured in the UK. Stainless steel is the main material for the burner, internal coils, combustion chamber and some plates. The gas boiler also contains some non-ferrous metals such as copper, aluminium and brass. Other materials such as polyvinyl chloride (PVC), acrylonitrile butadiene styrene (ABS), and ethylene propylene diene monomer (EPDM), are assessed as well [19]. No secondary material is assumed to be used for components of the condensing gas boiler. For assembly, energy and material consumption are covered, e.g. natural gas, light fuel oil and UK's medium-voltage electricity mix [12]. The production phase of the hybrid heat pump includes manufacturing two major components, i.e. a 10-kW condensing gas boiler and a 10-kW air-source heat pump. For the gas boiler, it is assumed to be produced and assembled in the UK. The boiler is made principally from low-alloyed steel, the main material for the casing and expansion tank [12]. The gas burner is made up from brass, while aluminium and stainless steel are the major materials for heat exchangers, and copper is used for the pipework and cables. The gas boiler also contains rock wool and high-density polyethylene (HDPE) as insulation for the boiler and pipework. The air-source heat pump is assumed to be made in the EU such as Remscheid (Germany). Reinforced steel is made up for the compressor and housing while copper is for various parts such as the pipework, cables and expansion valve. Some insulation materials are also included, e.g. polyvinylchloride (PVC) and polymer (elastomer). R410A, as one of prevalent refrigerants for heat pumps in the UK, is used in this study. The production of R410A is also assessed in the production phase as well as UK's electricity mix, see section 2.3.

2.2.2 Use phase of the heating systems

Energy consumption and resources are assessed for the use phase in this study. Natural gas is the main input for the standalone condensing gas boiler in the use phase. The lower heating value (LHV) efficiency of the gas boiler is assumed to be 92.5%, which is an average space heating seasonal efficiency of condensing gas boilers [29]. Based on the functional unit (i.e. generating 252,000 kWh heat for 20 years), the amount of natural gas consumed during the whole life is calculated as 272,432 kWh (27,627 m3 calculated with LHV [32]). To test the sensitivity of results to the assumed gas boiler efficiency, a sensitivity analysis was conducted for a gas-boiler efficiency of 100%.

Electricity and natural gas are the main inputs for the hybrid heating system during its use phase. There are many operation modes for the hybrid heat pump to achieve most efficient or cost-effective heating but manufactures expect heat pumps to provide the larger share of the heat demand. The hybrid heat pump manufacturers recommend a heat demand share in a range between 70:30 and 85:15 between the heat pump and gas boiler in hybrid heat pump systems [15]. This study considers a share of 80%:20% for the hybrid heat pump in core scenario, i.e. 80% of the overall heat demand is met by the heat pump and 20% by the gas boiler. With 252,000 kWh total heat demand, 201,600 kWh heat (80%) is generated by the heat pump while 50,400 kWh heat (20%) by the gas boiler. With an efficiency of 92.5% for the gas boiler and the seasonal performance factor (SPF) of 2.7 for the heat pump (ibid), 51,692 kWh electricity and 58,947 kWh (5111 m^3) natural gas are consumed. According to [33], the charge level of the R410A is 0.3 kg/kW, hence the hybrid heat pump with a 10-kW air-source heat pump requires 3 kg of R410A in the use phase. Maintenance for the hybrid heat pump includes the recharge of the R410A with 6% of annually leakage rate and recharge rate [20]. No installation is assessed for both heating systems in this study. To explore the sensitivity of the results to the above assumptions, this study also assesses scenarios in which the share of the heat pump to the total heat demand ranging 60%:40% to 90%%:10%, the efficiency of the condensing gas boiler is 100%, and the SPF for the heat pump is of 3.9 respectively.

2.2.3 Transport of the heating systems

For the standalone condensing gas boiler, 200-km distance by freight train and 100-km distance by lorry (<16 tons) are assumed for raw materials' transport [12]. The standalone gas boiler is assumed to be transported 200 km through a van (< 3.5 tons) to customers' homes. During the end-of-life phase, the boiler is transported 100-km distance by lorry (<16 tons) from the installation site (i.e. customers' homes) to the treatment site. For the hybrid heat pump, the transport of the condensing gas boiler is assumed the same as for the standalone gas boiler. For the air-source heat pump, 200-km distance by a freight train and 100 km by a lorry (>16 tons) are assumed for transporting raw materials. From manufacturing sites in the EU to the UK, 500-km distance by a freight train and 400-km distance by a lorry (>16 tons) are assumed. To dispose of the heat pump, 100-km distance is assumed to be undertaken by a lorry (<16 tons).

2.2.4 End-of-Life phase of the heating systems

The recycling of heating systems' components is probably available in the UK due to some statements and policies of recycling announced by the UK government such as policy for recycling refrigerant [34]. However, the statistics of recycling heating systems are currently unavailable. Although recycled materials are likely to be used to produce new heating systems or other products, no data can be found to support this hypothesis.

With incentives from the UK government and the obligation for equipment suppliers to replace inefficient boilers for customers, old boilers could be recycled and disposed properly. Due to the unavailability of specific data, this study considered material-specific heating systems recycling rates. A recycling rate of 90% for metals was assumed, such as copper, steel and brass [18]. The recycling rate of UK's packaging plastics from household waste was 46% in 2017 [30]. However, the recycling rate of plastics for gas boilers or hybrid heat pumps is expected to be lower since final treatment is more likely to focus on value recovery of metals. Therefore, the recycling rate of other materials, such as plastics and rubber, is assumed as the average (i.e. 23%) between zero and the recycling rate of household plastic waste (46%). Components that are not recycled are assumed to be directly landfilled. The recycling of the refrigerant is also considered in this study. It is reported that 90% of refrigerator was sent to the recyclers while ozone-depleting substances (ODS) were required to be recovered during dismantling by the law (i.e. Controls on Ozone-Depleting Substances) in the UK [35]. As results, the high recycling rate (90%) is assumed for R410A in this study. It is also assumed that no loss would be generated when processing recycled contents, so the waste materials could be entirely turned to recycled contents. It is also assumed that the substitute of raw materials by recycled contents is 1:1, meaning that no loss exists during processes. The contents are used to produce other products such as packaging materials. The impacts of recycling processes are also included in this study. The credits (avoided burdens) from the recycling process are attributed to producers of other products rather than to producers of waste, due to the existing market for many materials such as LDPE and HDPE market [36]. This study assumes that it is the average available product in the market which is substituted. To identify the difference of environmental impacts between landfilling process and recycling process, end-of-life scenarios with 100% landfilled rate are created for sensitivity analysis. In this end-of-life phase, all materials are directly landfilled without any process and energy consumption.

2.3 Electricity mix and refrigerant production

2.3.1 Electricity mix in the UK

The UK's electricity mix in this study is modelled based on the electricity supply mix in the heating season of 2018 [37], see table 3. The amounts of electricity produced by renewable sources in heating season are slightly different from the annual electricity production in 2018. As the decarbonisation of electricity in the UK continues, the impacts, such as GHG emissions, caused by hybrid heat pumps might decrease. Therefore, a future electricity mix in the UK is considered as a sensitivity analysis. There are several studies assessing the development of the electricity mix in the future to meet the net-zero emission target by 2050. Three scenarios were simulated for the future electricity mix to achieve net-zero GHG emissions by 2050 [14]. A set of scenarios were proposed, where the UK could reach a net-zero carbon emission by 2050 [38]. Some of the CCC and NG ESO scenarios include carbon captured and stored (CCS) technologies, which are not available in Ecoinvent databases v3. Here, a net-zero scenario without CCS was selected from the NG ESO report. The decarbonized annual electricity mix in 2050 is presented in table 3, where the renewable generation share reaches 68% of the total.

Table 3. Projected electricity mix in heating season in 2018 and 2050.

Source	Supply (TWh)	Proportion (%)
Electricity mix in heating season in 2018 [37]		
Coal	13.1	6.4
Gas	69.0	33.9
Oil	0.59	0.3
Hydro (Run-of river)	3.4	1.7
Hydro (pump storage)	0.5	0.2
Nuclear	28.3	13.9
Onshore wind	33.8	16.6
Offshore wind	16.8	8.2
Solar PV	11.5	5.7
plant biomass	14.7	7.2
Energy from waste generation	2.8	1.4
French net import	6.1	3.0
Netherlands net import	2.9	1.4
Ireland-Wales net import	0.05	0.02
Electricity mix in 2050 ([38]**; scenario Consumer Evolution)**		
Biomass	11.0	2.7
Gas	81.6	20.1
Hydro	7.1	1.8
Interconnectors	40.6	10.0
Marine	0.1	0.02
Nuclear	32.6	8.0
Offshore Wind	105	25.9
Onshore Wind	63.5	15.7
Other Renewables	19.0	4.7
Other Thermal	0.1	0.02
Solar	33.6	8.3
Waste	11.7	2.9

2.3.2 Refrigerant

For the refrigerant, the only available data in Ecoinvent database v3 is R134a, which is also one of the common refrigerants adopted in UK's refrigeration systems. However, hybrid heat systems use the R410A refrigerant in the UK, hence a new process was built for R410A based on data available in the literature, see table 4. The usage of the refrigerant is considered as a contributor for climate change (CC) and ozone depletion (OD) [39]. As a primary substitute for R22, The R410A is made up of R32 and R125, offering zero emission for ozone depletion in practice [40]. Therefore, this study considers GHG emissions for the R410A in each phase. At the production phase, producing 1kg R410A emits 78-268 kg CO_2-eq emissions, so the mean value (173 kg CO_2-eq) is selected [20]. Based on the guidelines from the UK government, GHG emissions of the R410A is 2088 kg CO_2-eq/kg R410A [41]. Therefore, the GHG emissions of leaking 1 kg R410A is calculated as 2088 kg CO2-eq, which is the same value for disposing 1 kg R410A in landfills. The detail amount of R410A in each phase can be found in table 4. To evaluate the sensitivity of refrigerant-related assumptions, two scenarios are created, i.e. hybrid heating systems using R134a and the production of R410A with the maximum factor of 268 kg CO_2-eq emissions/kg.

Table 4. Inventory of the R410A refrigerant for the heat pump element in hybrid heat pumps, including data source.

Stage	Procedure	Amount (kg)	GHG emission (kg CO_2-eq/kg)	Source
Production phase	Production	6.42	173.0	[20]
Use phase	Operated in the system	3.00	-	[33]
End-of-life phase	Leakage	3.42	2088	[41]
	Recycling	2.70	-	-
	Landfill	0.30	2088	[41]

2.4 Methods for Life Cycle Impact Assessment

The method adopted to calculate the impacts is ReCiPe Midpoint (Hierarchist) [42]. Based on the literature review, 14 impact categories are selected, i.e. Climate change (CC), Ozone depletion (OD), Terrestrial acidification (TA), Freshwater eutrophication (FE), Marine eutrophication (ME), Human toxicity (HT), Photochemical oxidant formation (POF), Particulate matter formation (PMF), Terrestrial ecotoxicity (TET), Freshwater ecotoxicity (FET), Marine ecotoxicity (MET), Water depletion (WD), Metal depletion (MD) and Fossil depletion (FD). 9 out of 14 impact categories, excluding Freshwater eutrophication (FE), Marine eutrophication (ME), Terrestrial ecotoxicity (TET), Freshwater ecotoxicity (FET), Marine ecotoxicity (MET), are analysed in this study while full results are presented in Appendix.

2.5 Scenario design

To test the robustness of the results, sensitivity analyses were done for five key assumptions, i.e. low carbon electricity, end-of-life treatment, efficiency of heating elements, refrigerant type, and different shares of gas boiler: heat pump in meeting the heat demand for hybrid heat pump. Table 5 illustrates the key elements of these sensitivity scenarios. In the case of low carbon electricity, the electricity consumed by the heat pump is assumed to be low carbon, based on [38]. All the other assumptions are kept the same with core scenarios for both targeted heating systems. For the end-of-life case, it is assumed as the worst case of fully landfilled heating systems at the end of their life (100%-landfill). For the efficiency case, assumptions are made, i.e. a case of 100% of efficiency for condensing gas boiler in both standalone gas boiler and HHP, and a SPF of 3.9 is assumed for the heat pump element in the HHP system. The refrigerant assumptions in the HHP system are also tested by assuming a sensitivity case with a different refrigerant (R134a), and a case with a higher GHG factor for the production of R410A. Finally, the share of gas boiler to heat pump in the use phase of the HHP is tested, considering cases from 60%:40% to 90%:10%, i.e. 60% of heat demand is met by the gas boiler, and 40% by the heat pump, to 90% met by the gas boiler and only 10% by the heat pump.

Table 5. Details of cases for sensitivity analysis and core scenarios. CGB: condensing gas boiler; HHP: hybrid heat pump.

		Assumption types			
Case/Scenario	Heating elements	Specification of electricity mix	Specification of heating equipment	Specification of the refrigerant	Specification of the end-of-life phase
Core	CGB	-	Efficiency of 92.5% for the condensing gas boiler	-	With recycling and landfilling process
	HHP	Electricity mix in 2018 heating season	SPF of heat pump with 2.7; Efficiency of 92.5% for the condensing gas boiler; Share of heat demand 80:20 (80% provided by the HP, 20% by the CGB).	R410A with mean GHG emissions in production.	With recycling and landfilling process
Low carbon electricity	CGB	Same as core	Same as core	Same as core	Same as core
	HHP	Electricity mix in 2050	Same as core	Same as core	Same as core
Landfill type	CGB	Same as core	Same as core	Same as core	100%-rate landfill
	HHP	Same as core	Same as core	Same as core	100%-rate landfill
Efficiency	CGB	Same as core	100%-efficiency condensing gas boiler	Same as core	Same as core
	HHP	Same as core	100%-efficiency condensing gas boiler; SPF of heat pump with 3.9	Same as core	Same as core
Refrigerant	CGB	Same as core	Same as core	Same as core	Same as core
	HHP	Same as core	Same as core	Use of R134a instead of R410A; Production of R410A with higher GHG emissions	Same as core
Share of heat demands	CGB	Same as core	Same as core	Same as core	Same as core
	HHP	Same as core	Share of heat demand (varying from 60:40 to 90:10 ratios HP to CGB in the HHP)	Same as core	Same as core

3. Results

3.1 CGB vs HHP, core scenarios

Fig. 2 presents the comparison between the environmental impacts potentially caused by a condensing gas boiler (CGB) vs a hybrid heat pump (HHP) providing a functional unit of 252,000 kWh heat, corresponding to the heat demand for a typical UK semi-detached house over 20 years. The HHP shows lower environmental impacts than the CGB in five out of nine impact categories, i.e. climate change (CC), terrestrial acidification (TA), fossil depletion (FD), photochemical oxidant formation (POF) and particulate matter formation (PMF). The results suggest that the use of the HHP could reduce FD by 50% and GHG emissions by 30% as compared to using the CGB over 20 years. For TA, POF and PMF impact categories, the HHP shows 13% to 26% less impacts as compared to the CGB. The CGB shows significantly better environmental performance (3 to 6 times smaller values) in 3 out of 9 impact categories, i.e. human toxicity (HT), water depletion (WD) and metal depletion (MD). For ozone depletion (OD), the HHP and CGB show similar environmental impacts.

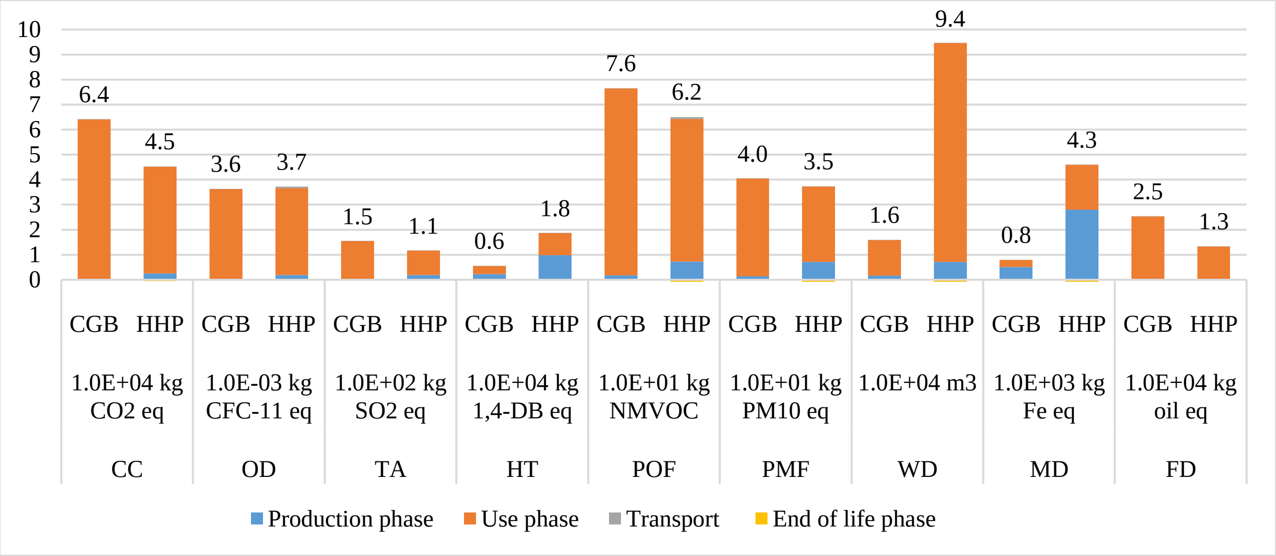

Fig. 2. Comparison between CGB and HHP core scenarios in selected impact categories. CC: Climate change; OD: Ozone depletion; TA: Terrestrial acidification; HT: Human toxicity, POF: Photochemical oxidant formation; PMF: Particulate matter formation; WD: Water depletion; MD: Metal depletion; FD: Fossil depletion.

With a few exceptions, the use phase is the main contributor to all impact categories for both heating systems, for which energy consumption is the reason. For example, for climate change (CC), the combustion of natural gas is the major cause for the CGB scenario, while electricity production based on natural gas and hard coal for electricity mix in the UK contributes around 40% of the total emissions of the use phase in the HHP scenario. The leakage of R410A in the use phase also leads 17% of GHG emissions in the use phase for the HHP scenario. The metal depletion (MD) is dominated by the production phase (around 66% of the total) with a large amount of metal consumption in both scenarios. The production phase also contributes to between 40% and 50% for human toxicity (HT) for CGB and HHP. For both MD and HT impact categories, producing electronic components and copper in the production phase for both heating systems contributes the largest amount of impacts. The environmental impacts caused by transport in both scenarios are negligible, amounting to less than 2% of total emissions. The end-of-life phase has also negligible influence on the results, with less than -5% contribution. The minus sign (negative emissions) is caused by modelling choices, where recycling is counted as avoided burden.

3.2 Sensitivity analysis

The results for a low carbon electricity case are shown in fig. 3. Compared with the CGB core scenario, when powered with a low carbon electricity mix, the impacts of the HHP are further reduced across 5 out of 9 impact categories. In particular, the HHP could potentially save 45% of GHG emissions and 34%-60% of impacts for terrestrial acidification (TA), photochemical oxidant formation (POF), particulate matter formation (PMF) and fossil depletion (FD). However, the HHP performs worse in the impact categories where the HHP had higher impact than the CGB in the core scenario, i.e. HT (human toxicity), WD (water depletion) and MD (metal depletion). This suggests that the environmental impacts of the HHP are strongly influenced by the environmental profile of the electricity mix, but the hierarchy between the CGB and the HHP remains the same.

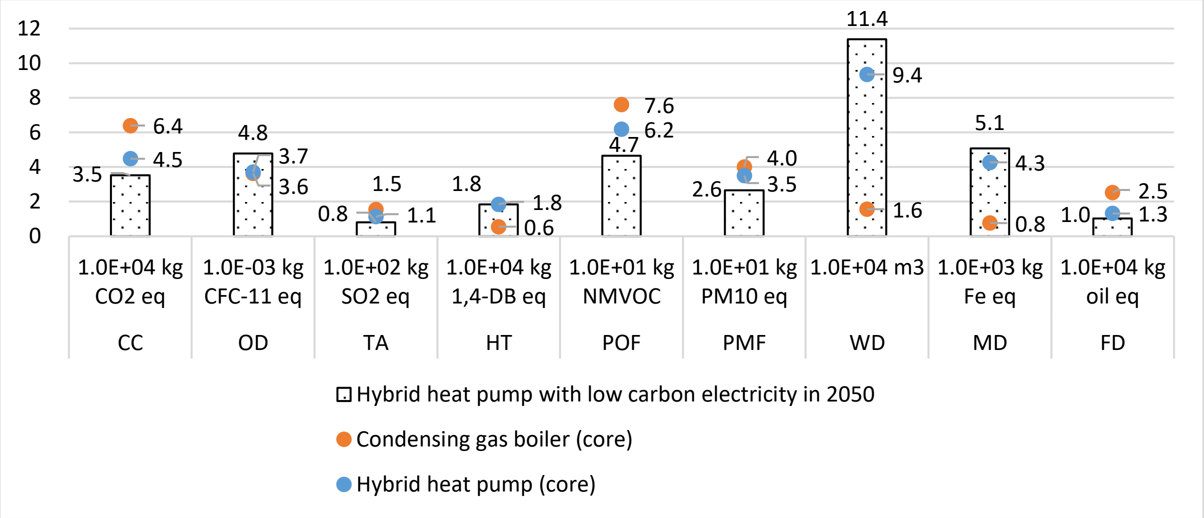

Fig. 3 Sensitivity results for the case of low carbon electricity in 2050. Note that this sensitivity only affects HHP results, while the CGB impact values are the same as in the Core scenario. CC: Climate change; OD: Ozone depletion; TA: Terrestrial acidification; HT: Human toxicity, POF: Photochemical oxidant formation; PMF: Particulate matter formation; WD: Water depletion; MD: Metal depletion; FD: Fossil depletion.

The sensitivity results for the end of life (EoL) phase, show that a worst-case scenario of full landfilling of the heating systems at the end of their life does not affect the ranking between the HHP and the CGB, see fig. 4.

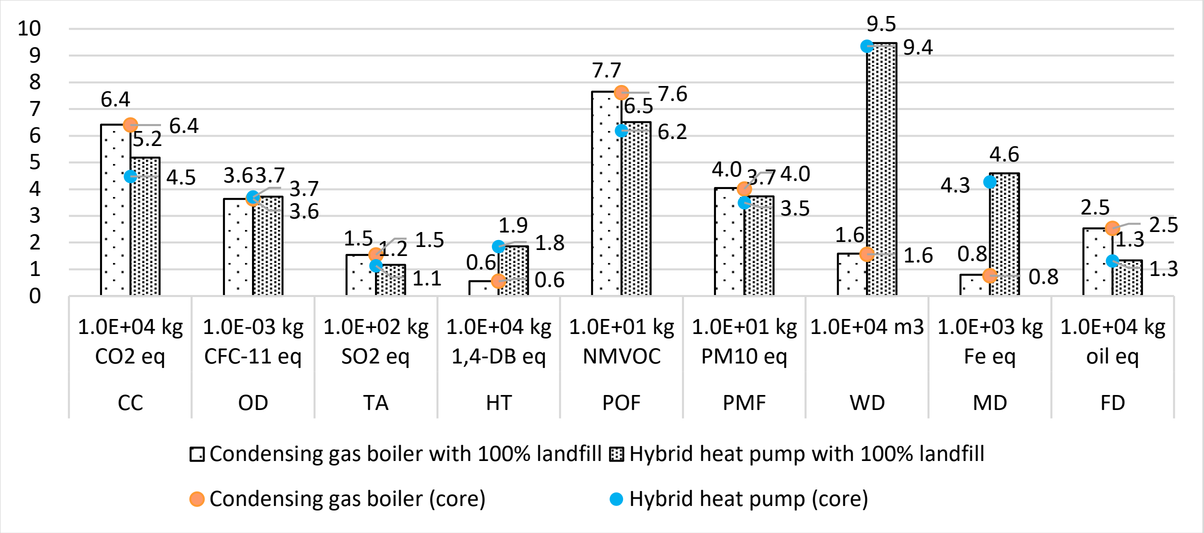

Fig. 4 Sensitivity results for EoL with 100% landfill compared to core scenarios. CC: Climate change; OD: Ozone depletion; TA: Terrestrial acidification; HT: Human toxicity, POF: Photochemical oxidant formation; PMF: Particulate matter formation; WD: Water depletion; MD: Metal depletion; FD: Fossil depletion.

Increasing the efficiency of the gas boiler to 100% in both heating systems has marginal effects on the ranking of the HHP vs CGB, i.e. it slightly reduces impacts for all selected impact categories compared to core scenario, but does not change the ranking between the CGB and the HHP. However, increasing the SPF of the heat pump in the HHP from 2.7 to 3.9 contributes to a substantial reduction of HHP impacts across all categories, resulting into 41% reduction in GHG emissions as compared to the CGB, 21% -58% less impacts for OD, POF, PMF, and FD, and between 1.9 and 3.9 times more impacts in HT, MD, and WD as compared to 3 to 6 times more in the core scenario.

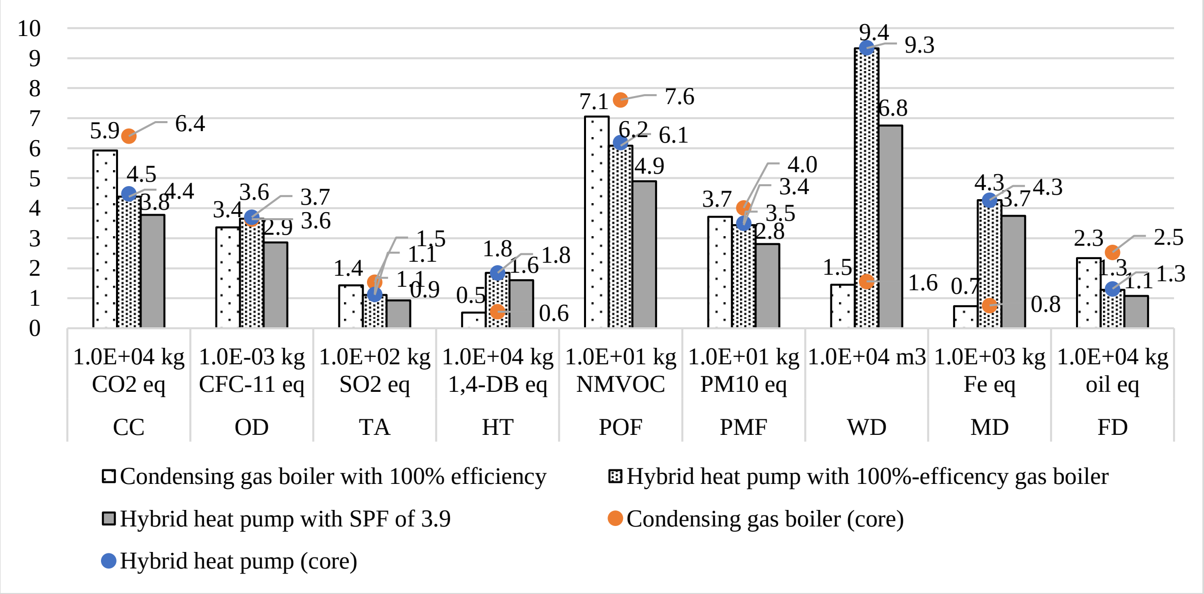

Fig. 5 Sensitivity results for 100% efficiency of heating elements compared to core scenarios. CC: Climate change; OD: Ozone depletion; TA: Terrestrial acidification; HT: Human toxicity, POF: Photochemical oxidant formation; PMF: Particulate matter formation; WD: Water depletion; MD: Metal depletion; FD: Fossil depletion.

Results in the core scenario are also robust to a worsening of impacts from the R410a production, see fig. 6. The change of the refrigerant from R410a to R134a contributes 20% more of OD (ozone depletion) impacts compared to core HHP scenario while only 2% more are contributed in the rest selected impact categories.

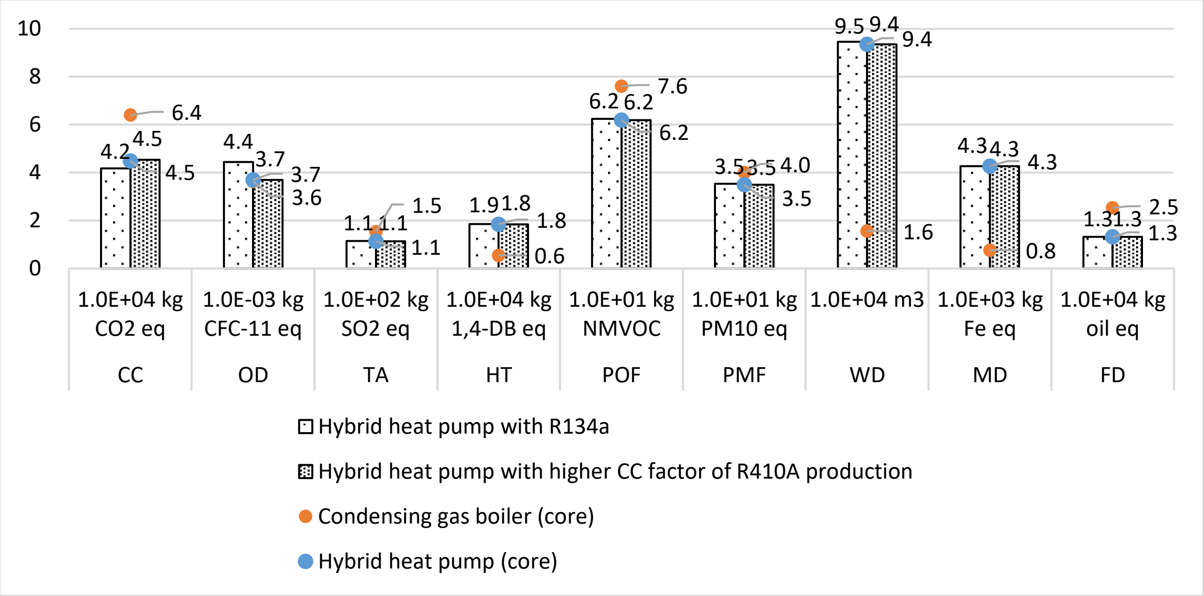

Fig. 6 Sensitivity results for HHP refrigerant compared to core scenarios. CC: Climate change; OD: Ozone depletion; TA: Terrestrial acidification; HT: Human toxicity, POF: Photochemical oxidant formation; PMF: Particulate matter formation; WD: Water depletion; MD: Metal depletion; FD: Fossil depletion.

Varying the share of HP:CGB in the HHP from 60:40 to 90:10 (vs 80:20 in the core scenario) shows negligible effects on the comparison between the CGB and the HHP, see fig. 7. The highest changes are observed for WD, for which a 10% increase can be seen as compared to the core scenario.

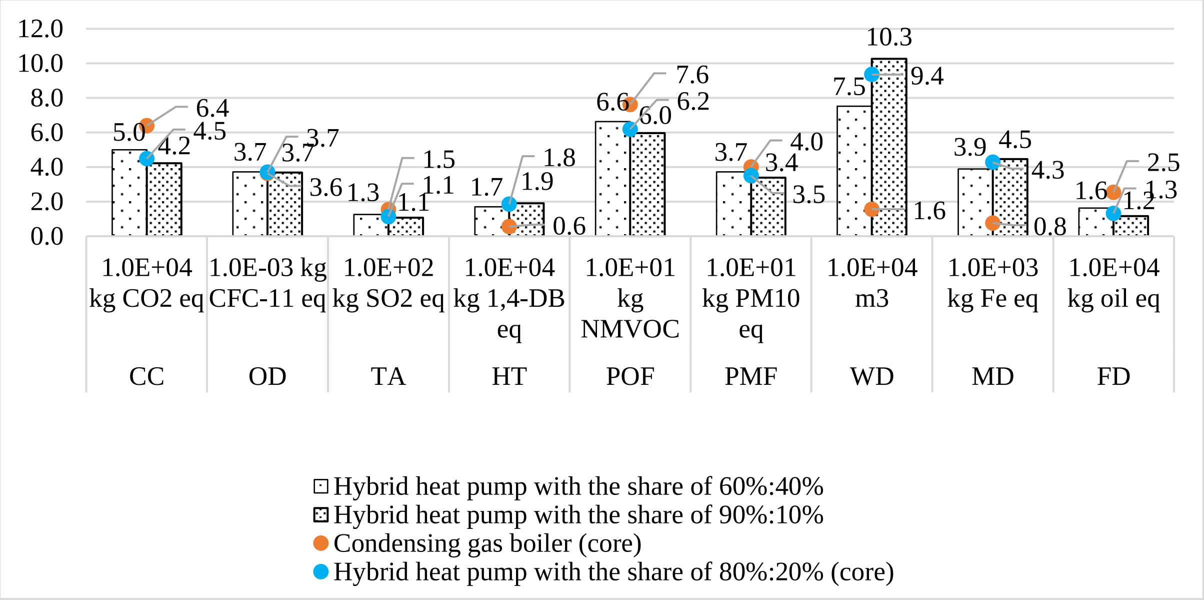

Fig. 7 Sensitivity results of cases for share of heat demands varying from 60%:40% to 90%%:10% compared to core scenarios. CC: Climate change; OD: Ozone depletion; TA: Terrestrial acidification; HT: Human toxicity, POF: Photochemical oxidant formation; PMF: Particulate matter formation; WD: Water depletion; MD: Metal depletion; FD: Fossil depletion.

Fig. 8 summarises the results of all the sensitivity analyses as compared to the core scenarios. Although individual performances are driven by some of the assumptions, Main finding of this study is that the sensitivity analyses performed here do not change the overall conclusions on the comparison between the two heating systems, although they might be important parameters for each individual performance. For impact categories for which the CGB scenario has worse performance than the HHP scenario, i.e. CC (Climate change), TA (Terrestrial acidification), POF (Photochemical oxidant formation), PMF (Particulate matter formation) and FD (Fossil depletion), maximum impacts of HHP sensitivity analysis scenarios are still lower or stay at the same level compared with the minimum environmental impacts of CGB. Meanwhile, for human toxicity (HT), water depletion (WD) and metal depletion (MD), the HHP shows worse impacts across all the sensitivity scenarios analysed here. However, for ozone depletion (OD), although core scenario shows slightly worse performance for the HHP than the CGB, the HHP could potentially perform better than the CGB if the SPF is increased to e.g. 3.9, as analysed here. A higher SPF would also contribute to significantly reducing the WD impacts of the HHP, i.e. by a third as compared to the core scenario.

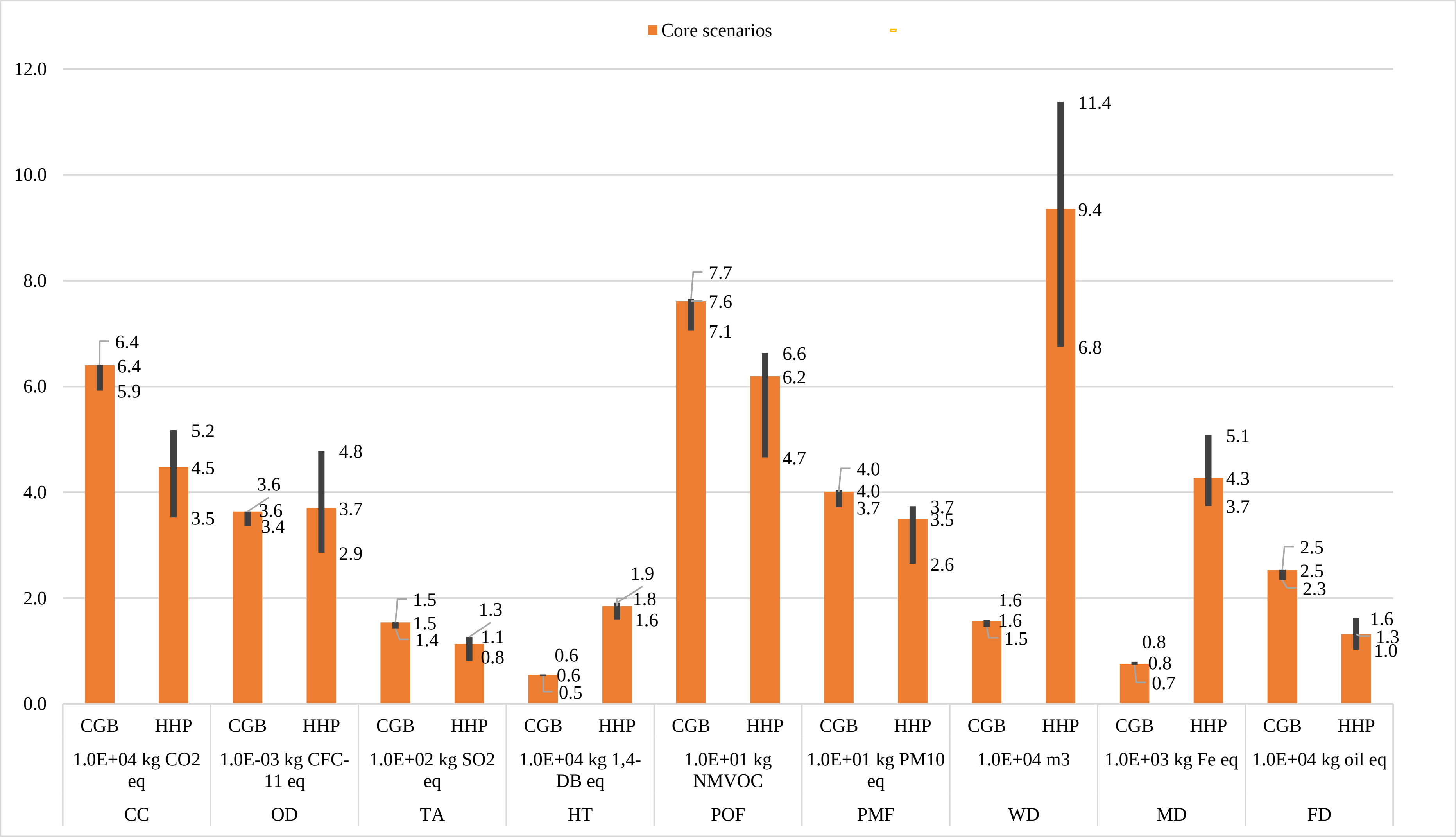

Fig. 8. Results of sensitivity analysis compared with the core scenarios. CGB: core scenario of condensing gas boiler; HHP: core scenario for hybrid heat pump; CC: Climate change; OD: Ozone depletion; TA: Terrestrial acidification; HT: Human toxicity, POF: Photochemical oxidant formation; PMF: Particulate matter formation; WD: Water depletion; MD: Metal depletion; FD: Fossil depletion.

3.3 Comparison to literature results

Due to the prevalence of carbon footprint analyses in the existing LCA literature for gas boilers, figure 9 compares the total GHG emissions of both heating systems in this study with the literature in terms of CO_2-eq emissions per kWh heat. While many studies provide modelled GHG emissions associated with heat generated by CGB [12,15,16,18], only one study reports the GHG emissions of real gas boilers in the UK [43], and no study reports HHP emissions in the UK. Summarising all the literature reported data, GHG emissions of gas boilers in most studies are ranging between 210 and 300 gCO_2-eq/kWh heat, see fig. 9. In this study, the GHG emissions of the CGB in the core scenario and sensitivity scenarios range between 235 and 254 gCO_2-eq/kWh heat, which is consistent with the literature. In comparison, the GHG emissions of the HHP in core scenario in this study range between 150 and 205 gCO_2-eq/kWh heat.

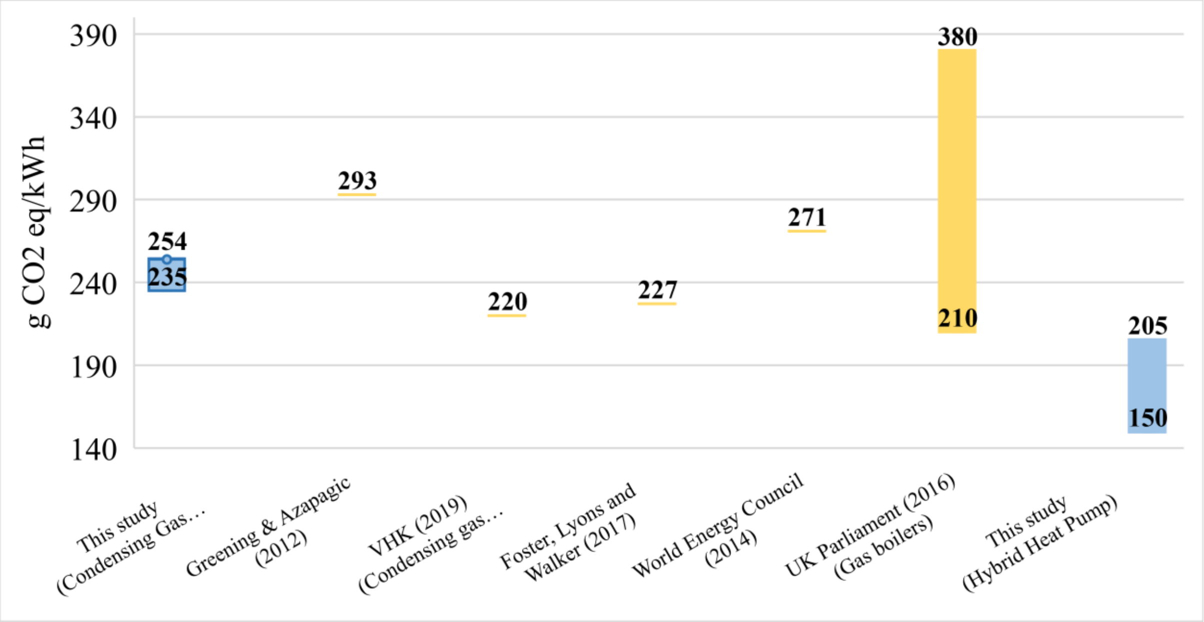

Fig. 9. GHG emissions of heating systems in this study and literature. Note that the ranges indicate values across different scenario analyses.

4. Discussion, limitations and future work

Results in this study show that a hybrid heat pump could lower household GHG emissions by up to 30% as compared to a condensing gas boiler, suggesting that the HHP could be a transition step for decarbonising residential space heating at individual house level. Those conclusions cannot be extrapolated directly at a national level, as the goal and scope of the study were not defined for such a purpose. It should be noted that if the hybrid heat pump had been compared to older less efficient gas boilers that are currently in place in existing homes the GHG emission reduction would have been larger, but the scope of this study was set on comparing two alternatives for new equipment. While in agreement with [14], results in this study highlight that the introduction of HHP may reduce residential UK GHG emissions, but it would not bring them to near zero, as required by the ambitious UK climate target of Net Zero GHG emissions by 2050 [1]. To further reduce GHG emissions, results found the use phase of the heating systems as the most impacting stage, which confirms findings of existing literature (e.g. [12,17,19]). Particularly, decarbonising the electricity mix is critical if the GHG reduction by a transition to HHP is to happen. Further GHG emission reduction could be achieved by the improvement of the seasonal performance factor (SPF) for heat pump elements in HHP, which would enhance the efficiency of HHP and hence further reduce GHG emissions. Sensitivity results suggest that further improving the efficiency of the gas boiler in the HHP would only lead to marginal GHG emission reduction, hence energy efficiency efforts should target increasing the SPF of heat pump elements.

Although this study does not model the effects changes in the UK legislation could have on the transition to HHP, the sensitivity analyses include two particular near-term changes which will affect the environmental profile of the HHP: (1) the replacement of the HHP refrigerant R410, and (2) the rapid out-phasing of fossil fuels. The results suggest that a replacement of R410 with R134a would marginally decrease GHG emissions but could potentially lead to a 20% increase in ozone depletion (OD). Given that here only one refrigerant alternative is considered, it is critical that more analyses are run with other refrigerants, e.g. the HFO (Hydrofluoroolefin) R1234ze, not covered in this study. The results of this study suggest that a lower carbon electricity mix could reduce GHG emissions by 45% as compared to using a CGB. Further policy options for phasing out fossil fuels in residential heating could include using renewable electricity for running heat pumps, conversion of conventional gas to low carbon hydrogen and biomethane, hydrogen boilers to replace gas boilers, or carbon capture technologies to provide a stepping stone for transition to the complete phasing out of fossils [14]. As all these options are in incipient development stages in the UK, they were not included this study, but should be object of further investigation.

This study focused on the energy production ways to decarbonize the heating sector, but the building consumption and household heating behaviour are also keys for reducing energy consumption and hence GHG emissions (see e.g. [15]). LCA studies investigating the impact different HHP running modes based on customers' habits are necessary.

Results in this study evidence that increasing the heat demand satisfied by the heat pump element in the HHP can further reduce GHG emissions at individual house level. However, consequences of a large deployment of such an equipment have not been assessed, as it would have been in a consequential life cycle assessment study (consequential LCA). Such a deployment could for instance increase the electricity peak demand. This calls for optimal share of heat demand satisfied by heating elements in hybrid heat pumps in the future, capable to lower electricity peak demand, especially in winter.

Consequential LCA methods would allow estimation of systemic changes induced by the wide adoption of HHPs in the UK: it would study the effects of the electricity peak consumption on the national grid, the consumer behaviours changes and potential rebound effects of such a deployment, that are not considered in this study.

Furthermore, this study is limited to the heating function; however, heating systems evolve rapidly, and some are increasingly starting to provide additional functions, e.g. cooling function. Hence, future studies should also consider the rapidly changing nature of these heating systems. The dimensioning of the heating elements in the HHP is also evolving. While the size of heat pumps in HHP is similar to standalone heat pumps, newer HHPs are expected to have a smaller size heat pump [15].

In addition to the use phase, results show that the production phase is also affecting metal depletion (MD) and human toxicity (HT), which suggests further research into the impacts from the electronic elements and metal production, e.g. copper. Policies for implementing circular economy principles could reduce the extraction of raw materials, eliminating the end-of-life phase and enhancing resource utilization efficiency. However, this requires further research to assess trade-offs between circular models of the heating systems (e.g. modular structures which could be re-used more readily reducing natural resource extraction) and potentially unintended consequences (e.g. increased environmental impacts due to the reconditioning of the older parts before they are used in new similar or different systems).

Data adopted in this study is collected from published literature, reports, government and companies' websites. Uncertainty analysis should be conducted to reveal the inherent uncertainties of modelling parameters and results. This should be conducted for all impact categories to enable better decision-making [44], i.e. ensuring that reduction of e.g. GHG emissions does not come at the cost of more polluted water streams, or penalties to human health.

Finally, this study focuses on the comparison of two types of heating systems for a typical semi-detached house in the UK. Although this house is one of the most common types in the UK, the results of this study cannot be extrapolated to national level and to the case of newly built houses. A large-scale transition from CGB to HHP would need to consider other types of houses (e.g. collective housing) and uses of the heating systems, together with wider system changes needed to support this transition. Again, a consequential LCA approach might be best fitted for these analyses, especially if trade-offs between different environmental categories need to be identified.

5. Conclusion

The results in this study show that the hybrid heating system has better environmental performance on CC, TA, POF, PMF and FD impact categories than the traditional combination condensing gas boiler. The savings induced by the hybrid heating system for TA, POF and PMF represent a reduction of around 20%, while 30% and 48% of GHG emissions and FD impacts are reduced compared to the condensing gas boilers. From the contribution analysis, the use phase is the main contributor for most selected impact categories except the MD and HT, where the production phase leads to around 50% of the total for the CGB and HHP scenarios. The combustion of natural gas and the electricity production based on natural gas and hard coal are the main causes for the high proportion of the use phase for CC impact category for both heating systems. Also, the leakage of the refrigerant (R410A) contributes to 17% of the total GHG emissions for the HHP scenario. Although the end-of-life phase with recycling materials offsets negative impacts for selected impact categories, contributions from this phase are negligible as well as the transport phase. With the sensitivity analysis, robustness of the results is verified. For further study, more pollution transfers need to be considered other than GHG emissions at the national level, although decarbonisation is the core objective for many countries nowadays. To improve the study, uncertainty analysis could be useful, and consequential LCA methods are suggested to assess the changes of heating systems by 2050. Policy-level influences are revealed for heating systems, i.e. refrigerant usage, out-phasing of fossil energies and circular economy practice. This study is aimed for comparison of two specific heating systems from environmental point of view with quantitative method (i.e. LCA). However, further studies are suggested for exploring environmental impacts of heating system at national level with LCA by including a wider range of types and conditions of houses and heating systems, and the use of alternative fuels such as biogas or hydrogen.

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