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Domestic heat pumps: Life cycle environmental impacts and potential implications for the UK

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ABSTRACT

This paper presents the results of a life cycle assessment of domestic heat pumps in the UK in comparison with gas boilers. The study considers air (ASHP), ground (GSHP) and water (WSHP) source heat pumps. The results show that heat pumps have higher environmental impacts than gas boilers due to the use of electricity. On average, the impacts for the ASHP are 82% higher than from the boiler and 73% for the GSHP and WSHP. The exception to this are the global warming, fossil resource depletion and summer smog impacts which are lower for the pumps than the boilers. For example, up to 36% of CO_2 eq. can be saved with the WSHP and 6% with the ASHP in comparison with the boiler. Among the heat pumps considered, ASHP have the highest impacts due to lower efficiencies and higher material requirements for the system. The GSHP and WSHP have comparable impacts, with the latter being marginally better. The life cycle impacts of heat pumps may improve if the UK electricity mix is sufficiently decarbonised; however, they will still remain higher than for the gas boiler. Overall, their potential to contribute to the UK climate change targets is limited.

1. Introduction

The domestic sector in the UK currently accounts for one third of the national energy consumption [1]. Owing to its heavy reliance on fossil fuels, it contributes around one quarter of the UK CO_2 emissions [2]. To help towards meeting the UK CO_2 reduction targets of 34% by 2020 and 80% by 2050 [3], the Government has identified micro-generation as a key measure for reducing the carbon emissions from domestic energy use [2]. This has led to its inclusion, initially in the 2003 Energy White Paper and the 2004 Energy Act, and later in the Micro-generation Strategy [4] and the Climate Change and Sustainable Energy Act [3], which set out measures for increasing the uptake of micro-generation.

Among other micro-generation technologies, heat pumps have been identified as one of the key technologies that could play a significant role in achieving the UK's CO_2 emission targets [5–7]. At present, heat pumps have a relatively small share of the UK micro-generation market, compared to the rest of Europe and the USA. For example, in 2008 there were 650,000 heat pump units installed in Sweden [8] compared with 895–2150 in the UK [6]. However, the number of UK installations has grown since so that in 2010 there were 37,000 units installed (with 0.6 GWth of capacity), of which 28,000 are in the domestic sector (0.2 GWth), mainly installed in newly-built housing [9]. The uptake of heat pumps is now expected to grow faster [10,11] as consumers become more aware of financial incentives. These include capital grants, the RHI (renewable heat incentive) and RHPP (renewable heat premium payment), which offer payments for the renewable heat energy that users generate [6,9,12–14].

However, as heat pumps rely on electricity, their potential to reduce carbon emissions on a life cycle basis is not immediately clear; furthermore, it is unclear at present how their other environmental impacts compare with fossil fuel alternatives. Therefore, this paper sets out to examine a future role that heat pumps could play in a more sustainable energy supply in the UK domestic sector by estimating the life cycle environmental impacts and comparing them to their current alternative, heat from natural gas boilers. The potential of heat pumps to contribute to the UK climate change targets is also studied. Three types of heat pumps are considered: ground-, air- and water-source heat pumps. As far as the authors are aware, this is the first study of its kind for the UK.

2. Methodology

The LCA methodology used in this study follows the ISO 14040 and 14044 guidelines [15,16]. The LCA software GaBi v. 4.4 [17] has been used to model the heat pump and natural gas systems and the CML 2 Baseline 2001 methodology [18] has been used to estimate the environmental impacts.

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2.1. Goal and scope definition

The goal of this study is to estimate the life cycle environmental impacts of ground-, air- and water-source heat pumps for the domestic sector in the UK and compare them with their current alternative, natural gas boilers. A condensing boiler which in the UK is gradually replacing older conventional designs is assumed in this study. The typical design capacity of both the heat pumps and the gas boiler of 10 kW is assumed [19].

The functional unit is defined as 'generation of 1 kWh of thermal energy for domestic space heating'. The scope of the study is from 'cradle to grave' (see Figs. 1 and 2); the system boundaries for the heat pumps and natural gas boiler are summarised in Table 1.

2.2. System description, data and assumptions

2.2.1. Heat pumps

Heat pumps work by extracting low-grade heat from a source (air, ground or water) and converting it into high-grade heat for space heating. ASHP (Air-Source Heat Pumps) considered here are shown schematically in Fig. 3 and GSHP and WSHP (Ground- and Water-Source Pumps) in Fig. 4. As shown, the heat pump systems comprise:

- an air fan (ASHP) or a heat collector (GSHP and WSHP); and
- a heat pump unit which contains an evaporator, a compressor and a condenser.

The fan or heat collector is used to extract low-grade heat from a source; this heat is then used in the evaporator to evaporate the refrigerant. The gaseous refrigerant is then compressed, raising its pressure and temperature and this high-grade heat is transferred to water in the heat distribution system to provide space heating. In the process, the refrigerant cools and condenses and is then passed through an expansion valve to decrease its pressure before the cycle begins again. Thus, heat pumps operate using the reverse refrigeration cycle (they can also be used for cooling, but this cycle is not considered in this study).

Heat pump efficiency is measured by the CoP (Coefficient of Performance). This is a measure of the ratio of useful heat output by the heat pump to the amount of energy input for operation. The CoP is typically between 3 and 5 [20]. Efficiency can also be measured by the SPF (Seasonal Performance Factor) which can be regarded as an average CoP for the entire heating season. This takes into account variations in weather and is thus a more accurate measure of efficiency [20]. In this study, typical SPFs for the heat pumps in the UK have been assumed: 2.8 for ASHP and 3.9 for GSHP and WSHP [19,21].

As shown in Figs. 3 and 4, the three heat pump systems have a similar configuration, differing only in the way the heat is extracted from the source. The GSHP and WSHP use external heat collectors which are normally installed bellow the ground or submersed into the water body, respectively. The collectors consist or either a horizontal or vertical pipework loop with a heat-carrier working fluid. In this study, both configurations use a mixture of water and ethylene glycol as the working fluid. The ASHP uses an air fan rather than a heat collector, which is placed outside the house in open air. To compensate for the lack of heat collector, the ASHP systems have a larger evaporator to increase the efficiency of the system.

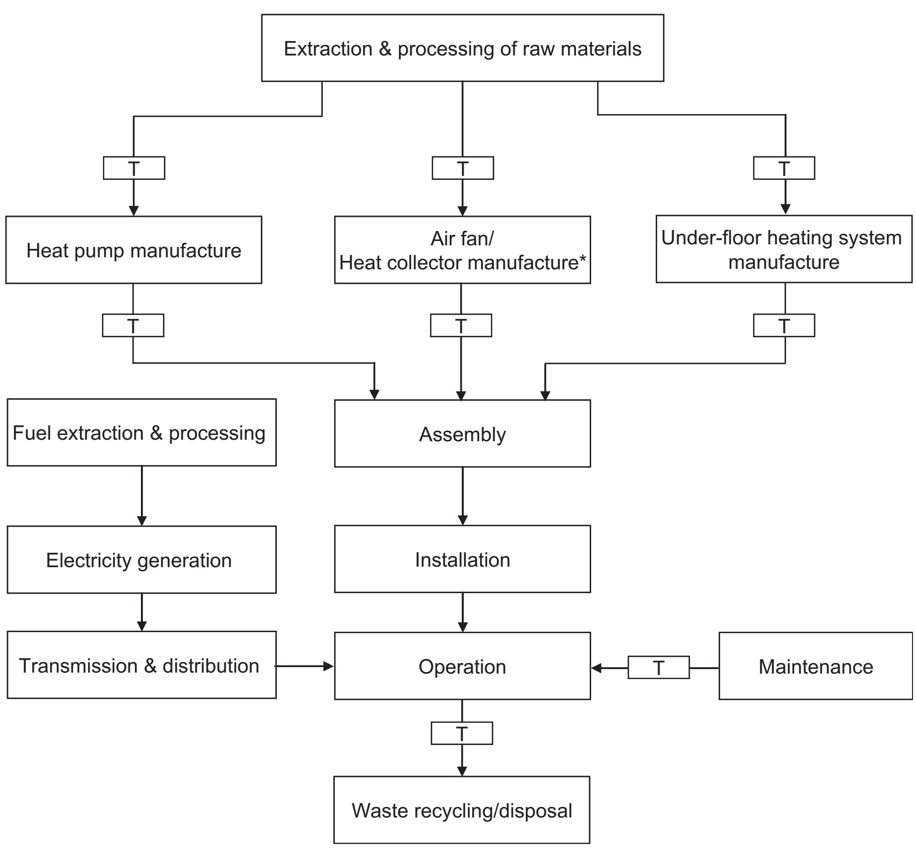

Fig. 1. The life cycle of heat pumps: air-, ground- and water-source systems (*Air fan: air-source heat pumps; heat collector: ground- and water-source heat pumps; T – transport; Operation includes the life cycle of electricity; Maintenance includes only refrigerant top-up).

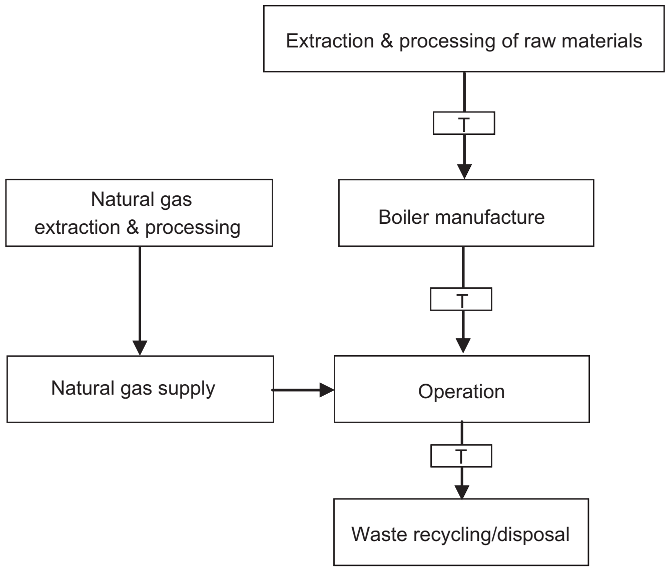

Fig. 2. The life cycle of natural gas boiler (Operation includes the life cycle of natural gas; T – transport).

The system specification and the data for the three types of heat pump and their differences are summarised in Table 2. The data for the heat collector materials, installation and ASHP infrastructure have been collected from manufacturers [22–24], contractors [25], operators [26] and from own laboratory investigations of an ASHP. Further data for heat pump infrastructure and operation have been sourced from Heck [21] and the Ecoinvent database [27]. All data reflect the current UK electricity mix (see Fig. 5) and the UK waste management for different materials [28,29].

The assumptions for different parts of the life cycle are summarised below.

2.2.1.1. Heat pumps manufacture and operation. The heat pumps are assumed to be manufactured in Europe, as is generally the case, and shipped to the UK [24]. The compressor and housing are made from reinforced steel and the evaporator and condenser from low-alloyed steel. The pipework, electrical cables and expansion valve are all made from copper, with the pipework insulated with a polymer (elastomere) and the cables insulated with PVC (polyvinylchloride). The refrigerant used is R-134a (1,1,1,2-tetrafluoroethane), assuming losses of 3% during manufacture and 6% during operation (annually) [21]. The units are considered maintenance free, only requiring a top up of refrigerant.

2.2.1.2. Installation. This stage is considered only for GSHP and WSHP. The installation process for ASHP is not included due to minimal installation work compared to the latter two systems which require extensive drilling and/or digging over a large area.

The GSHP and WSHP heat collectors are connected to the heat pump unit by a brass manifold and two 4 m long HDPE (high density polyethylene) pipes, insulated with LDPE (low density polyethylene) to reduce heat loss. The specific collector designs and installation requirements considered here are as follows:

- GSHP horizontal collector: the 500 m long pipework is placed in an 1 m deep trench covered with soil. A diesel excavator (Caterpillar 330L) is used to dig the trench; the digging takes 12 h to complete and requires 20 l/h of diesel [31].
- GSHP vertical collector: the pipework is 300 m long and the collector is located in a 150 m deep borehole, back-filled with a mixture of cement and bentonite. A borehole drilling machine (DCR 12/14 Beretta T44) is used to drill the borehole by the flush drilling technique, consuming 1.5 l of diesel per metre [25].
- WSHP horizontal collector: identical to the horizontal GSHP configuration but it requires four cast-iron weights to submerge the collector below the water surface.
- WSHP vertical collector: the pipework is 320 m long and requires a cast-iron weight to keep the collector submerged upright in the water source. Borehole drilling is required to reach the water source 10 m below ground.

The under-floor heating system consists of a multi-layer aluminium and polyethylene pipes covering a 150 m^2 floor area. The pipes are insulated with PS (polystyrene). Sand and cement form a screed for compacting around and over the pipework.

2.2.1.3. Decommissioning. A life time of 20 years has been assumed for the heat pumps. At the end of the life cycle, metal components are recycled assuming the current UK recycling rates, as shown in Table 2 [28,29]. The rest of the waste is landfilled. The screed used for the under-floor heating system is assumed to be left in situ. The remaining refrigerant is reused, assuming losses of 20% during this extraction process [21]. The heat-carrier liquid from the collectors (ethylene glycol) is treated in a wastewater treatment plant.

2.2.1.4. Transport. Generic transport distances of 100 or 200 km have been assumed for different parts of the heat pump system (see Table 3). These are based on the data in Ecoinvent [27]. An average distance of 700 km has been assumed for the transport of heat pumps from mainland Europe to the UK.

Table 1
System boundaries for heat pumps and gas boiler.

System boundaries	Heat pumps	Gas boiler
Included within system boundaries:	• Extraction and processing of fuels and raw materials • System manufacture: heat pump, heat collector (where applicable), under-floor heating system, refrigerant and assembly • Installation: drilling of boreholes and digging of trenches where appropriate • Operation • Maintenance (refrigerant top-up) • Decommissioning: metal recycling, inert material landfill disposal, re-use of the refrigerant and wastewater treatment • All relevant transport	• Extraction and processing of fuels and raw materials • Boiler manufacture • Operation • Decommissioning: metal recycling and inert material landfill disposal • All relevant transport
Excluded from system boundaries:	• The cooling cycle of the heat pump operation as it is not currently relevant for the UK • Water heating since the majority of heat pumps on the market are utilised for space heating only • The rest of the heating system (i.e. the radiators, pumps etc.).	• Installation and maintenance • The rest of the heating system (i.e. the radiators, pumps etc.)

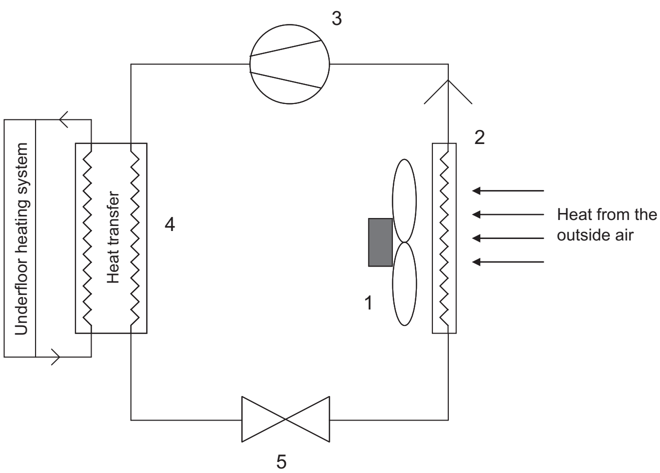

Fig. 3. A schematic representation of the air-source heat pump system (1. Axial fan; 2. Evaporator; 3. Compressor; 4. Condenser; 5. Expansion valve).

2.2.2. Natural gas condensing boiler

The specification for the boiler can be found in Table 4. The data have been sourced from Ecoinvent [27]. Further assumptions are given below.

2.2.2.1. Boiler manufacture and operation. The boiler is assumed to be manufactured in the UK. The system is made predominantly from low-alloyed steel, which is used for the casing, expansion tank and balance of plant. The boiler also contains a brass gas burner and aluminium and stainless steel heat exchangers. The pipework and electrical cables are all made from copper. Rockwool and HDPE are utilised to insulate the boiler and pipework, respectively. The boiler operates with the efficiency of 90% [24]. As for the heat pumps, the boiler is assumed to be maintenance free.

2.2.2.2. Installation. Similar to the ASHP, this stage is not considered for the gas boiler as the installation work is negligible in comparison to GSHP or WSHP.

2.2.2.3. Decommissioning. The assumed life time of the boiler is 20 years. At the end of the life cycle, metal components are recycled assuming the current UK recycling rates, as shown in Table 2 [28,29]. The rest of the waste is landfilled.

2.2.2.4. Transport. Similar to the heat pumps, generic transport distances based on the data in Ecoinvent [27] have been considered. Raw materials are assumed to be transported 200 km by freight train and 100 km by lorry (<16 tonne). The boiler is transported 200 km by a van (<3.5 tonne) to the installation site.

3. Results and discussion

3.1. Overview of the results

The life cycle environmental impacts for the three types of heat pump and the boiler are given in Fig. 6. As shown, the ASHP has the highest and the natural gas boiler the lowest impacts for most categories. On average, the impacts from the ASHP are 82% higher than from the boiler, ranging from 69% for EP (Eutrophication Potential) to 96% for METP (Marine Eco-Toxicity Potential). The exceptions to this are GWP (Global Warming Potential), ADP fossil (Abiotic Depletion Potential, fossil) and POCP(Photochemical Oxidation Creation Potential) for which the boiler is the worst option, with the ASHP pumps saving around 6%, 19% and 13% of these impacts, respectively.

The GSHP and WSHP perform much better than the ASHP on these three impacts, saving on average 36% of the GWP, 44% of the ADP fossil and 37% of the POCP relative to the boiler. For all other categories, the impacts from GSHP and WSHP are on average 73% higher than from the gas boiler.

The average difference in environmental performance between the ASHP and the other two types of pump is 32% in favour of the latter due to the lower efficiency and higher usage of electricity by ASHP. The GSHP has marginally (<0.1%) greater environmental impacts than the WSHP due to the larger excavation requirements (i.e. borehole drilling to greater depths and trench digging). Horizontal collectors for both types of pump have negligibly (0.2–0.4%) higher impacts than the vertical due to the longer pipework, larger volumes of ethylene glycol used and, in the case of the WSHP system, the need for cast iron weights for submersion.

The main contributor to most impacts from the heat pumps is their operation, contributing on average 84% to the total, mainly due to the electricity used. Manufacturing of raw materials contributes around 10% while maintenance, disposal and transport contribute relatively little (see Fig. 6). The only exception to this is ODP (Ozone Layer Depletion Potential), the majority of which is due to chlorinated emissions arising from the production of the refrigerant.

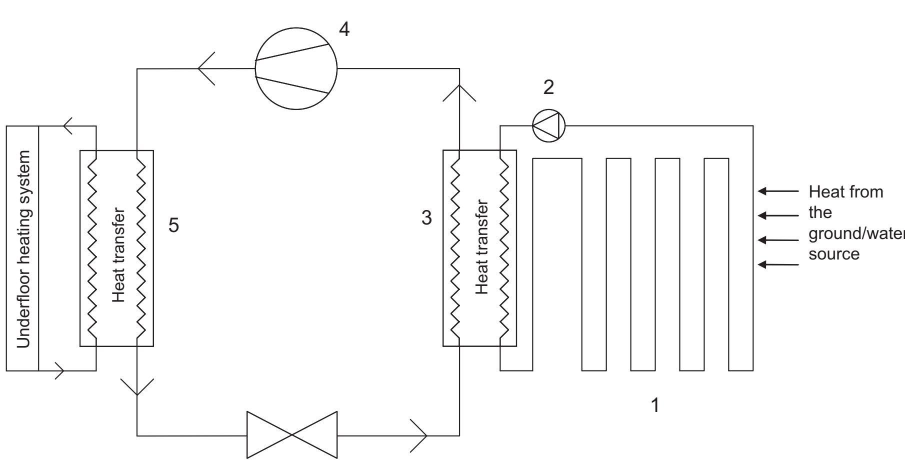

Fig. 4. A schematic representation of the ground- and water-source heat pump systems (1. Heat collector; 2. Circulating pump; 3. Evaporator; 4. Compressor; 5. Condenser; 6. Expansion valve).

Table 2
Summary of heat pump specifications.

Component, system or life cycle stage	Air-source heat pump	Ground-source heat pump	Water-source heat pump
Evaporator and condenser	• Low-alloyed steel: 32 kg	• Low-alloyed steel: 20 kg	• Low-alloyed steel: 20 kg
Housing and compressor	• Reinforcing steel: 120 kg	• Reinforcing steel: 75 kg	• Reinforcing steel: 75 kg
Wiring, piping and expansion valve	• Copper: 35.2 kg	• Copper: 22 kg	• Copper: 22 kg
Pipework insulation	• Elastomere: 16 kg	• Elastomere: 10 kg	• Elastomere: 10 kg
Wiring insulation	• Polyvinylchloride: 1.6 kg	• Polyvinylchloride: 1 kg	• Polyvinylchloride: 1 kg
Lubricating oil	• Polyolester oil: 2.7 kg	• Polyolester oil: 1.7 kg	• Polyolester oil: 1.7 kg
Air fan	• Copper: 1.4 kg • HDPE: 0.5 kg	N/A[a]	N/A
Refrigerant	• R-134a: 4.90 kg • Losses: 3% (manufacture) & 6% (operation, annually)	• R-134a: 3.09 kg • Losses: 3% (manufacture) & 6% (operation, annually)	• R-134a: 3.09 kg Losses: 3% (manufacture) & 6% (operation, annually)
Assembly of pump units	• Medium-voltage electricity (European mix): 504 MJ • Natural gas: 1400 MJ	• Medium-voltage electricity (European mix): 337 MJ • Natural gas: 875 MJ	• Medium-voltage electricity (European mix): 337 MJ • Natural gas: 875 MJ
Under-floor heating system	• Sand: 4650 kg • Cement: 900 kg • Aluminium: 126 kg • LDPE: 101 kg • Polystyrene: 66 kg	• Sand: 4650 kg • Cement: 900 kg • Aluminium: 126 kg • LDPE: 101 kg • Polystyrene: 66 kg	• Sand: 4650 kg • Cement: 900 kg • Aluminium: 126 kg • LDPE: 101 kg • Polystyrene: 66 kg
Heat collector pipework	N/A	• HDPE (horizontal heat collector, HHC): 301.2 kg • HDPE (vertical heat collector, VHC): 183.1 kg	• HDPE (HHC): 301.2 kg • HDPE (VHC): 194.9 kg
Heat collector pipework insulation	N/A	• LDPE: 4.7 kg	• LDPE: 4.7 kg
Heat carrier liquid	N/A	• Ethylene glycol (HHC): 167 kg • Ethylene glycol (VHC): 100.2 kg	• Ethylene glycol (HHC): 167 kg • Ethylene glycol (VHC): 106.9 kg
Weights	N/A	N/A	• Cast iron (HHC): 34 kg • Cast iron (VHC): 8.5 kg
Manifold	N/A	• Brass: 6.6 kg	• Brass: 6.6 kg
Back-fill	N/A	• Cement (VHC only): 19.1 kg • Bentonite (VHC only): 3.8 kg	• Cement (VHC only): 1.3 kg • Bentonite (VHC only): 0.3 kg
Scaffolding, rods, supports	N/A	• Reinforcing steel: 33 kg	• Reinforcing steel: 33 kg
Installation	N/A	• Diesel (vertical heat collector): 810 MJ • Diesel (horizontal heat collector): 9720 MJ	• Diesel (vertical heat collector): 540 MJ
Operation	• UK electricity: 0.357 kWh/kWh heat generated	• UK electricity: 0.256 kWh//kWh heat generated	• UK electricity: 0.256 kWh//kWh heat generated
Maintenance	• Refrigerant: 0.294 kg (annually)	• Refrigerant: 0.185 kg (annually)	• Refrigerant: 0.185 kg (annually)
Decommissioning	• Steel: 61.7% recycled; 38.3% landfilled • Aluminium: 90% recycled; 10% landfilled • Copper: 41% recycled; 59% landfilled • Refrigerant: 80% reused • Ethylene glycol: 100% to wastewater treatment • Plastics, sand, brass and cement landfilled: 100% landfilled	• Steel: 61.7% recycled; 38.3% landfilled • Aluminium: 90% recycled; 10% landfilled • Copper: 41% recycled; 59% landfilled • Refrigerant: 80% reused • Ethylene glycol: 100% to wastewater treatment • Plastics, sand, brass, bentonite and cement: 100% landfilled	• Steel: 61.7% recycled; 38.3% landfilled • Aluminium: 90% recycled; 10% landfilled • Copper: 41% recycled; 59% landfilled • Refrigerant: 80% reused • Ethylene glycol: 100% to wastewater treatment • Plastics, sand, brass, bentonite and cement: 100% landfilled

[a] N/A – not applicable.

The following section gives a brief overview of the main environmental burdens contributing to the individual impacts; the discussion refers to the results shown in Fig. 6.

3.2. Contribution analysis

3.2.1. ADP (Abiotic Depletion Potential) elements and fossil

The values for the depletion of elements range from 0.12 for the boiler to 0.47 mg Sb eq./kWh for the ASHP. In comparison, this impact for the GSHP and WSHP is 0.32 mg Sb eq./kWh. The major source of this impact for the heat pumps is the operation stage, contributing 77% to the total, due to the depletion of copper resources in the life cycle of electricity. The manufacturing stage contributes around 23% from the use of resources for the pipework, expansion valves etc. By contrast, the majority of elements in the life cycle of boiler (75%) are depleted in the manufacturing stage because of the use of molybdenum for steel production.

The ADP fossil is estimated at 2.6 MJ/kWh for the water and ground-source pumps, 3.7 for the ASHP and 4.6 MJ/kWh for the boiler. This impact is almost exclusively from the operation stage due to the depletion of coal and natural gas used in the UK electricity mix for heat pumps and natural gas combusted in the boiler.

3.2.2. AP (Acidification Potential)

ASHP has the highest AP and the boiler the lowest, estimated respectively at 0.86 and 0.25 g SO_2 eq./kWh. The value for the WSHP and GSHP is 0.59 g SO_2 eq./kWh. The major contributors for both systems (95%) are the emissions of SO_2 and NO_x from electricity generation and natural gas combustion, respectively.

3.2.3. Eutrophication Potential (EP)

Similar to the AP, this impact is highest for the ASHP (0.08 g PO_4 eq./kWh) and lowest for the boiler (0.02 g PO_4 eq./kWh). The ground- and water-source heat pumps emit on average 0.07 g PO_4

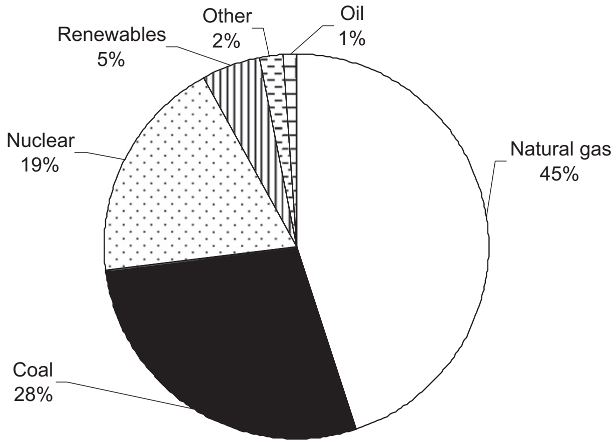

Fig. 5. The UK electricity mix [30].

eq./kWh. NO_x emissions in the life cycles of electricity and natural gas are the main contributor (>90%) to the EP for both types of the heating system.

3.2.4. FAETP (Fresh water Aquatic Eco-Toxicity Potential)

This impact ranges from 0.14 g DCB (dichlorobenzene) eq./kWh for the boiler to 0.91 g DCB eq./kWh for the ASHP. The value for the other two types of heat pump is 0.62 g DCB eq./kWh. Heavy metals, including vanadium, nickel, copper, molybdenum, selenium and arsenic, emitted in the life cycle of electricity and gas, contribute over 90% to this impact.

3.2.5. GWP (Global Warming Potential)

The WSHP and GSHP have the lowest carbon equivalent emissions, estimated at 0.189 kg CO_2 eq./kWh. The equivalent value for ASHP is 0.276 kg CO_2 eq./kWh, relatively close to that for the boiler (0.294 kg CO_2 eq./kWh). For all the systems, CO_2 emissions from electricity generation and natural gas combustion are the main contributor to GWP, causing over 95% of the impact.

3.2.6. HTP (Human Toxicity Potential)

Ranging from 0.03 kg DCB eq./kWh for GSHP and WSHP to 0.05 kg DCB eq./kWh for ASHP, this impact is mainly due to the arsenic and hydrogen fluoride emissions to air from electricity generation. The lowest HTP is for the boiler, estimated at 0.009 kg DCB eq./kWh. Benzene emissions during gas combustion and chromium emissions during manufacture are the main contributors to HTP from the boiler.

Table 3
Summary of transport modes and distances for heat pumps.

Transport stage	Mode of transport	Distance (km)
Heat pump manufacture	Freight train	200
(raw material transport)	Lorry: > 16 tonne	100
Refrigerant manufacture	Lorry: > 16 tonne	100
Heat pumps	Freight train	500
	Lorry >16 tonne	200
Installation	Lorry: >16 tonne (heat pump to site)	200
	Van: <3.5 tonne (drilling equipment to site)	200
	Lorry: 3.5–20 tonne (underfloor heating to site)	200
	Lorry: 3.5–20 tonne (heat collector to site)	200
Underfloor heating	Freight train	200
manufacture (raw material transport)	Lorry: >16 tonne	100

Table 4
Summary of natural gas boiler specifications [27].

Component/system/life cycle stage	Natural gas boiler
Pipework and electrical cables	• Copper: 3.03 kg
Gas burner	• Brass: 0.05 kg
Heat exchangers	• Aluminium: 7.5 kg
	• Stainless steel: 5 kg
Casing, expansion tank and balance of plant	• Steel (low alloyed): 115 kg
Pipework insulation	• HDPE: 0.9 kg
Boiler Insulation	• Rock wool: 8 kg
Assembly	• Medium-voltage electricity (UK mix): 294 MJ
	• Natural gas: 472 MJ
	• Light fuel oil: 249 MJ
Operation	• Natural gas: 1.11 kWh/kWh heat generated
Decommissioning	• Steel: 61.7% recycled; 38.3% landfilled
	• Aluminium: 90% recycled; 10% landfilled
	• Copper: 41% recycled; 59% landfilled
	• Plastics and brass: landfilled

3.2.7. MAETP (Marine water Aquatic Eco-Toxicity Potential)

This impact ranges from 5 kg DCB eq./kWh for the boiler to 123 kg DCB eq./kWh for the ASHP. The value for the other two types of pump (83 kg DCB eq./kWh) is also relatively high compared to the boiler. Hydrogen fluoride emissions to air in the life cycles of electricity and natural gas contribute to the majority of MAETP for both systems.

3.2.8. ODP (Ozone Layer Depletion Potential)

Although R-134a is chlorine free and therefore does not contribute to ODP, other substances emitted in its life cycle contribute to this impact, including monochlorotetrafluoroethane (R-124) and trichlorotrifluoroethane (R-113). ASHP has the highest ODP value of 0.3 mg R11 eq./kWh due to the higher refrigerant requirements. By comparison, the value for the natural gas boiler is 0.05 mg R11 eq./kWh due to the emissions of Halon 1211 (bromochlorodifluoromethane) emission during the extraction and processing of natural gas.

3.2.9. POCP (Photochemical Oxidant Creation Potential)

The lowest POCP is for the water- and ground- followed by the air-source pumps, with the values of 0.039 and 0.055 g C_2H_4 eq./kWh, respectively. The equivalent impact from the boiler is 0.063 g C_2H_4 eq./kWh. The large majority (over 90%) of this impact is due to the emissions of NO_x, CO and VOC emissions to air during electricity generation and gas combustion.

3.2.10. TETP (Terrestrial Eco-Toxicity Potential)

The gas boiler is the best option for this impact, with 0.29 g DCB eq./kWh. The values for the heat pumps are an order of magnitude higher, ranging from 2.6 g DCB eq./kWh for WSHP and GSHP to 3.8 g DCB eq./kWh for ASHP. Chromium emissions to soil in the life cycle of electricity and natural gas are the major contributor to this impact.

3.3. Validation of results

These results compare well with other published data. Most studies, however, only report the GWP results with no data for the other impacts. For example, a previously reported value for ASHP in the UK of 0.26 kg CO_2 eq./kWh [32] is in close agreement with the estimate in this study of 0.276 kg CO_2 eq./kWh. A study in Germany [33] estimates the GWP of GSHP at 0.15 kg CO_2 eq./kWh which is relatively close to the value of 0.189 kg CO_2 eq./kWh in this study, with the difference related to the electricity mix in the UK and Germany.

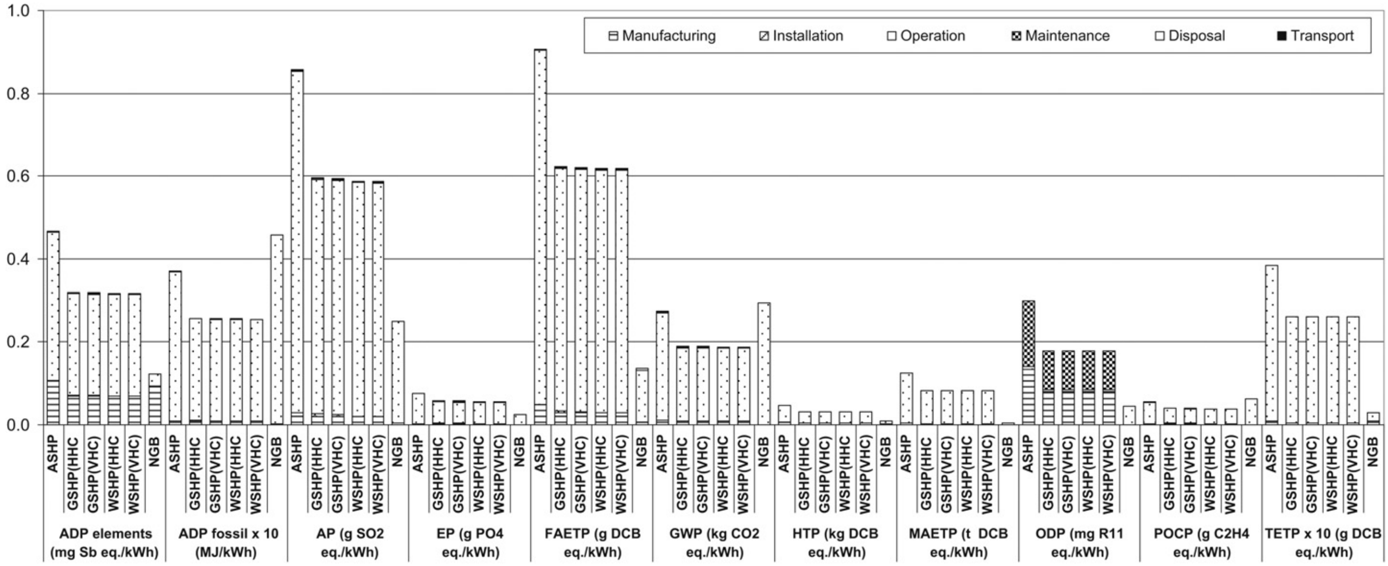

Fig. 6. Life cycle environmental impacts of heat pumps and gas boiler. [*Legend*: ASHP: air-source heat pump; GSHP (HHC): ground-source heat pump (horizontal heat collector); GSHP (VHC): ground-source heat pump (vertical heat collector); WSHP (HHC): water-source heat pump (horizontal heat collector); WSHP (VHC): water-source heat pump (vertical heat collector); NGB: condensing gas boiler. *Impact categories*: ADP elements: Abiotic resource depletion of elements; ADP fossil: Abiotic resource depletion of fossil fuels; AP: Acidification potential; EP: Eutrophication potential; FAETP: Fresh water aquatic ecotoxicity potential; GWP: Global warming potential; HTP: Human toxicity potential; MAETP: Marine aquatic ecotoxicity potential; ODP: Ozone layer depletion potential, POCP: Photochemical ozone creation potential; TETP: Terrestrial ecotoxicity potential].

Most other studies also found that electricity mix influences significantly any GWP savings from heat pumps over the alternatives. In countries with a low carbon electricity mix such as Switzerland, France and Norway, a GWP saving of 81–87% can be achieved compared to oil and 76–83% relative to gas heating [34]. A German study, assuming high (regional) penetration of nuclear (55%) and renewable power (15%), found similar savings (72%) for gas boilers over GSHP [33]. By contrast, in countries with the most carbon intensive electricity mixes such as Greece and Poland, conventional gas boilers are favourable because the GHG emissions for the GSHP system are 2% and 21% higher, respectively [34].

Heat pump efficiency has been also identified as an important factor affecting GWP of heat pumps [32–35]. For example, increasing CoP from 2.9 to 3.9 reduces GWP of ASHP from 0.26 to 0.21 kg CO_2 eq./kWh [32]. Therefore, due to the significant influence of electricity mix and pump efficiency on the environmental impacts identified in this and other studies, the next section explores the potential effects of future UK electricity mix as well as the anticipated improved system efficiencies.

4. Improvement opportunities

4.1. Future UK electricity mix

Renewables currently contribute around 5% to the UK electricity mix (see Fig. 5 and Table 5) [30]. If the UK is to meet its carbon reduction targets, this proportion will have to increase significantly in the future. Here we consider different potential levels of penetration of renewables into the electricity mix, ranging from 20 to 80%, with the lower value being the EU target by 2020 [36] and the higher value an assumed maximum. Table 5 gives the assumed breakdown of the individual sources contributing to the total mix. For illustration purposes, the relative split between the renewables (biomass: 30%; hydro: 55%; and wind: 15%) is kept constant for all levels of the renewables penetration. Similarly, the relative split between the non-renewable options (gas: 47.4%; oil: 1%; coal: 29.5%; nuclear: 19%; imports: 2.1%) also remains constant and their total contribution to the mix is scaled down proportionally as the share of renewables increases.

The results suggest that the environmental sustainability of all heat pump systems improves with the greater penetration of renewables in the electricity mix. This is illustrated in Fig. 7; the same trends are found for all the pumps. Increasing the percentage of renewables to 80% reduces the environmental impacts of the heat pumps on average by 42%, ranging from an 1% decrease for ODP to a 71% decrease for the TETP. The GWP decreases by 50%.

As mentioned earlier, similar GWP trends have been found by other studies. For example, Blum et al. [33] and Saner et al. [34] report the GWP savings of 72–83% relative to gas heating for electricity mixes with 58–89% of renewables and nuclear power. Similarly, Shah et al. [37] find that replacing 47% of coal electricity with wind would reduce the GWP of heat pumps by 49% compared to gas boilers.

However, despite the improved environmental performance of the heat pumps with the increasing penetration of renewables compared to the current electricity mix, the results in this study indicate that most environmental impacts remain higher than those from gas boilers for all types of the pump. The exception to this are GWP, ADP fossil and POCP. As shown in Fig. 8 for ASHP, the GWP saving relative to the boiler is 20% for a 20% share of renewables and 53% for the share of 80%. The equivalent saving of

Table 5
Assumed electricity mix for different levels of penetration of renewable energy.

	Contribution of renewables to the total electricity mix (%)				
	5%[a]	20%	40%	60%	80%
Biomass	1.5	6.0	12.0	18.0	24.0
Hydropower	2.8	11.0	22.0	33.0	44.0
Wind	0.8	3.0	6.0	9.0	12.0
Subtotal	5.0	20.0	40.0	60.0	80.0
Natural gas	45.0	37.9	28.4	19.0	9.5
Oil	1.0	0.9	0.7	0.4	0.2
Coal	28.0	23.6	17.7	11.8	5.9
Nuclear	19.0	16.0	12.0	8.0	4.0
Imports	2.0	1.6	1.3	0.8	0.4
Total	100	100	100	100	100

[a] Current UK electricity mix.

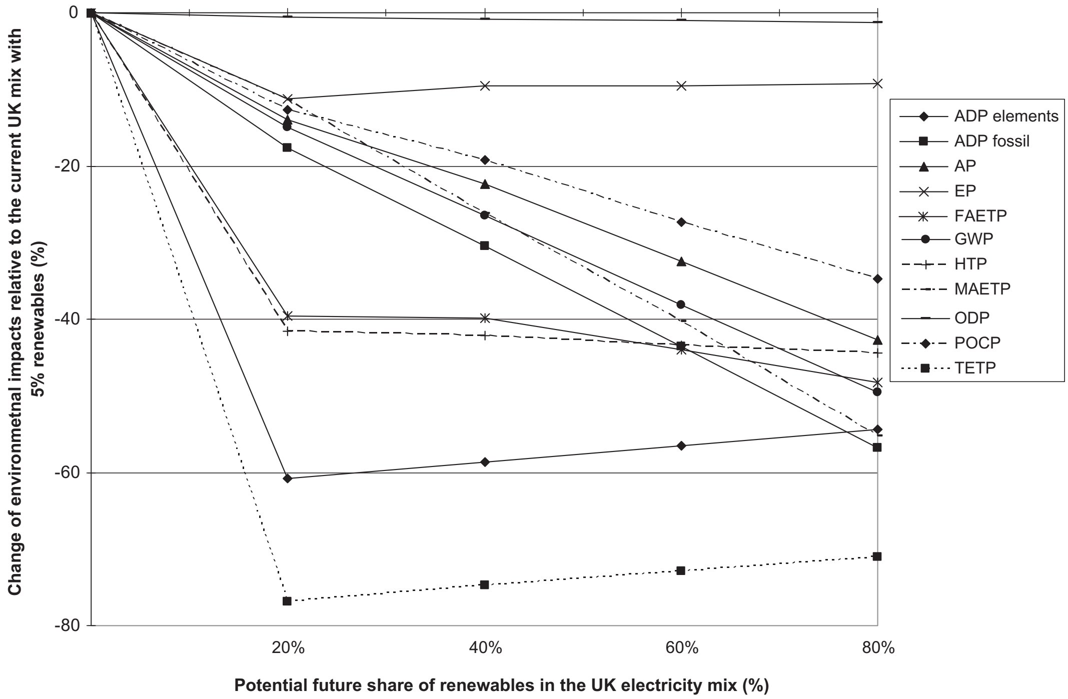

Fig. 7. The influence of renewables share in the electricity mix on the environmental impacts of heat pumps (average for all pump types).

fossil fuels (ADP fossil) is 33% and 65% for the 20% and 80% penetration of renewables, respectively. The decrease in the POCP ranges from 24 to 43% for the same share of renewables. All other impacts remain on average 68% higher for all levels of the renewables penetration. Similar trends are noticed for the GSHP and WSHP (Fig. 9).

It can also be observed that the ADP elements, TETP and EP increase with the increasing share of renewables, after an initial drop for a 20% contribution of renewables (Figs. 7–9). The former two impacts increase due to the increasing importance of the construction of new renewable electricity plants with the growing contribution of renewables. This results in a higher depletion of abiotic elements – particularly copper and molybdenum – used to produce the copper and steel components of the plants. It also results in higher heavy metal emissions, in particular chromium which contributes to the TETP. The EP increases due to the increasing contribution of biomass to the mix and the associated emissions of nutrients from biomass cultivation.

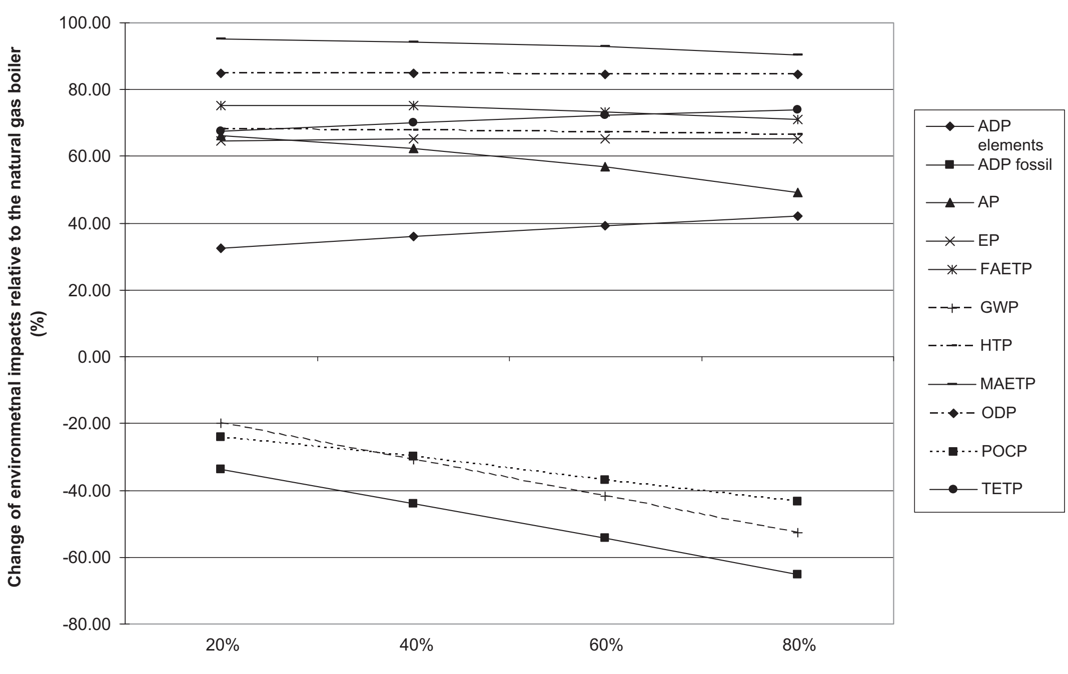

Fig. 8. Comparison of environmental impacts of ASHP with the gas boiler for different penetration of renewables in the UK electricity mix.

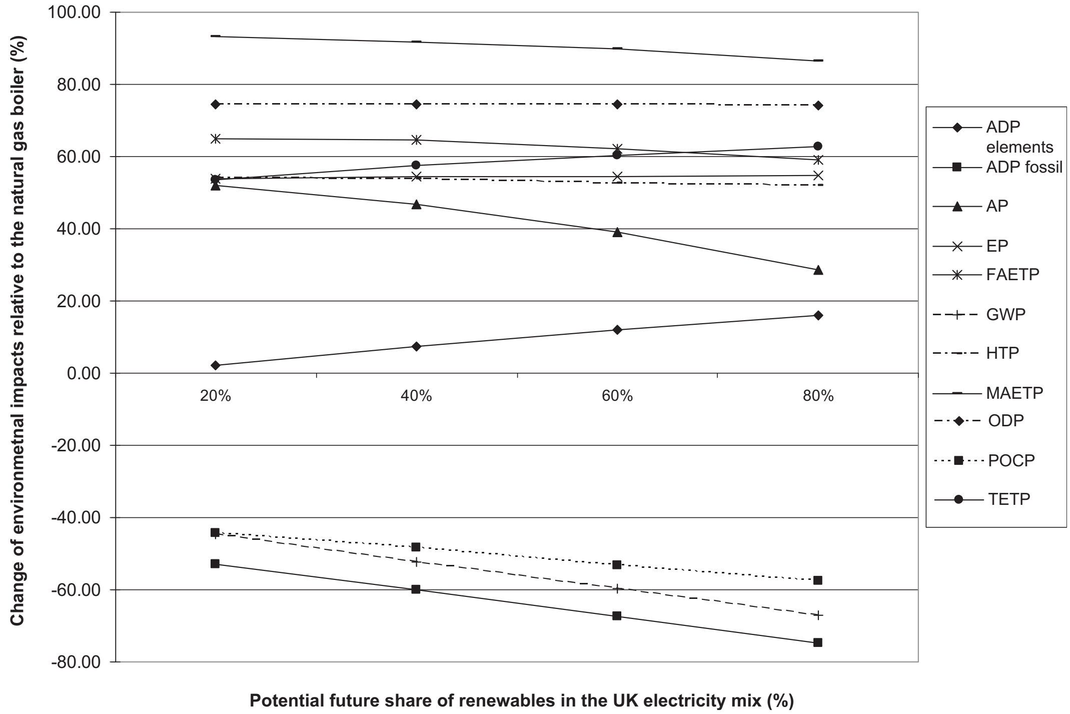

Fig. 9. Comparison of environmental impacts of GSHP and WSHP with the gas boiler for different penetration of renewables in the UK electricity mix.

4.2. Heat pump efficiency

This section examines the influence on the environmental impacts of the seasonal performance factors (SPF) using the values reported for the UK [38] and considering the current UK electricity mix. For ASHP, the SPF values considered range from 3.5 to 5. The SPF values for GSHP and WSHP are slightly higher than for ASHP as ground and water have generally higher temperatures than the ambient air.

The results show that any increase in SPF value would improve the environmental performance of heat pumps since the amount of electricity used to operate the pumps decreases. For example, increasing the current SPF value of the ASHP from 2.8 to 5.0 reduces the environmental impacts on average by 38% (see Fig. 10). Increasing the SPF value of the GSHP and WSHP systems from the current 3.9 to 6.5 reduces the environmental impacts on average by 30–33%. However, despite these reductions, the majority of impacts remain higher than for the gas boiler: on average by 70%

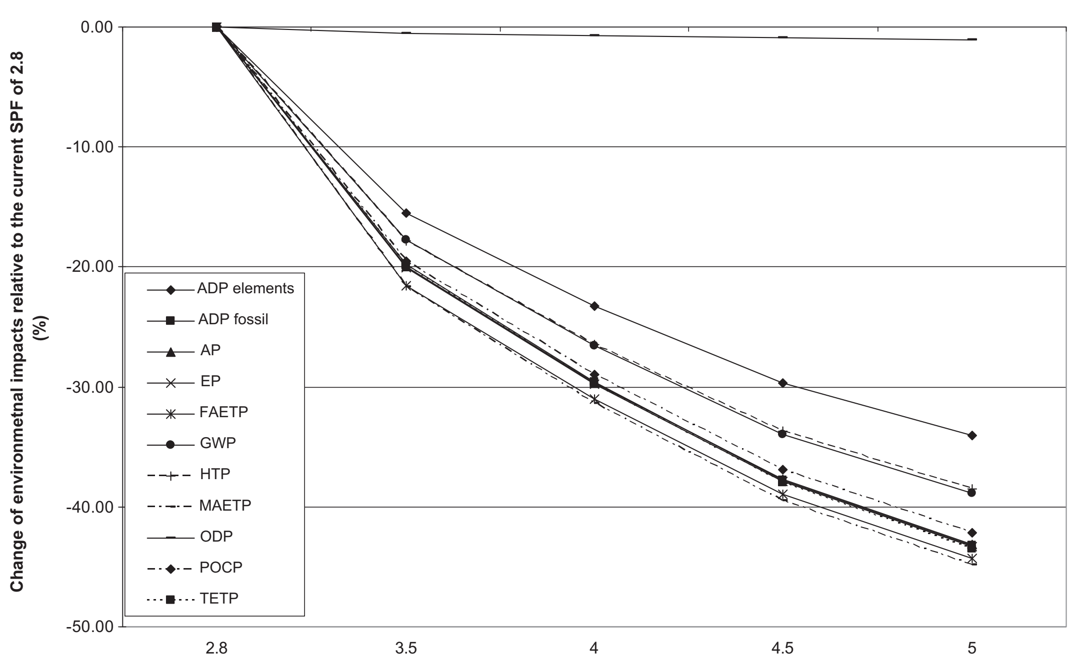

Fig. 10. The influence of seasonal performance factor (SPF) on the environmental impacts of ASHP.

for ASHP and 60–62% for GSHP and WSHP. This is illustrated in Fig. 11 for the example of ASHP. The exception to this trend are GWP, ADP fossil and POCP which decrease for all the heat pumps across all the increased SPF values. For example, the GWP from ASHP decreases by 43% relative to the boiler for the SPF of 5; ADP fossil and POCP go down by 54% and 50% (see Fig. 11).

5. Possible implications for the UK

As the results discussed above demonstrate, while heat pumps have advantages with respect to the GWP, depletion of fossil fuels and POCP, they are much less sustainable for the other environmental impacts compared to the gas boiler. It is therefore important to estimate the potential implications for the UK of any future replacement of conventional heating systems by heat pumps. We first examine the life cycle implications, followed by an analysis of direct CO_2 emissions to find out what potential contribution the heat pumps could make towards achieving the UK's GHG emissions targets.

5.1. Life cycle emissions

At present, natural gas boilers are the main source of space heating in the UK, providing 83% of the heating demand [39,40]. In 2009, there were around 22.5 million gas boilers installed in the domestic sector [41]. Assuming an extreme hypothetical case where all the boilers are condensing and all are replaced by heat pumps, the total annual life cycle environmental impacts would be as given in Fig. 12. For example, the total estimated annual GWP from the boilers would be 132 Mt CO_2 eq./yr. The equivalent GHG emissions from ASHP are 124 Mt CO_2 eq./yr, representing a GWP saving of 6.2%. The GSHP and WSHP would provide much greater savings of up to 35.8%, emitting 85 and 84.7 Mt CO_2 eq./yr, respectively.

The heat pump systems would also reduce fossil fuel depletion: ASHP by 19% (from 206.2 to 166.4 PJ per year) and GSHP & WSHP by 44% (to 115.4 PJ). Finally, 13% and up to 39% of POCP would be saved, respectively, if ASHP and GSHP & WSHP replaced the gas boilers.

However, all other impacts would increase and some quite significantly. This is particularly the case for MAETP which increases 23 times for ASHP and 16 times for the other two types of pump. Similarly, TETP goes up 13 and 9 times, respectively while ODP and FAETP from ASHP increase 6.6 times. The increase in HTP is on average between 3.6 and 5 times while the other impacts increase on average 2.5–3 times.

Therefore, while on a life cycle basis they can save up to 36% of GWP, heat pumps are currently not a sustainable alternative to condensing boilers with respect to other environmental impacts as most are several-fold higher than for the boilers. Furthermore, it is not clear what potential they have to contribute to the UK climate change targets in the short to medium and long terms. This is discussed in the next section.

5.2. Direct GHG emissions

National GHG emissions and the reduction targets refer to direct rather than life cycle CO_2 eq. emissions. Therefore, to determine the potential contribution of heat pumps to the UK climate change targets, this section compares the direct CO_2 eq. emissions from the heat pumps and gas boilers.

In 2009, the GHG emissions from the domestic sector were 147.2 kg CO_2 eq. [40]. For the purposes of the discussion here, we assume an extreme case where all the boilers are condensing, so that the direct emissions from 22.5 million gas boilers in 2009 would have been 99 Mt CO_2 eq./yr (see Table 6 and the assumptions listed there). If they were to be completely replaced overnight by the ASHP, the direct emissions would increase to 118.4 Mt CO_2 eq./yr. Replacing the boilers with the GSHPs and WSHPs would decrease the direct emissions to 80.09 Mt CO_2 eq./year (see also Table 6). Therefore, the total emissions from the domestic sector would increase by 13% to 166.60 Mt CO_2 eq./yr for the ASHP. Using the GSHP and WSHP instead would reduce the emissions to 128.30 Mt CO_2 eq./yr, a saving of 12.8% on the condensing boilers.

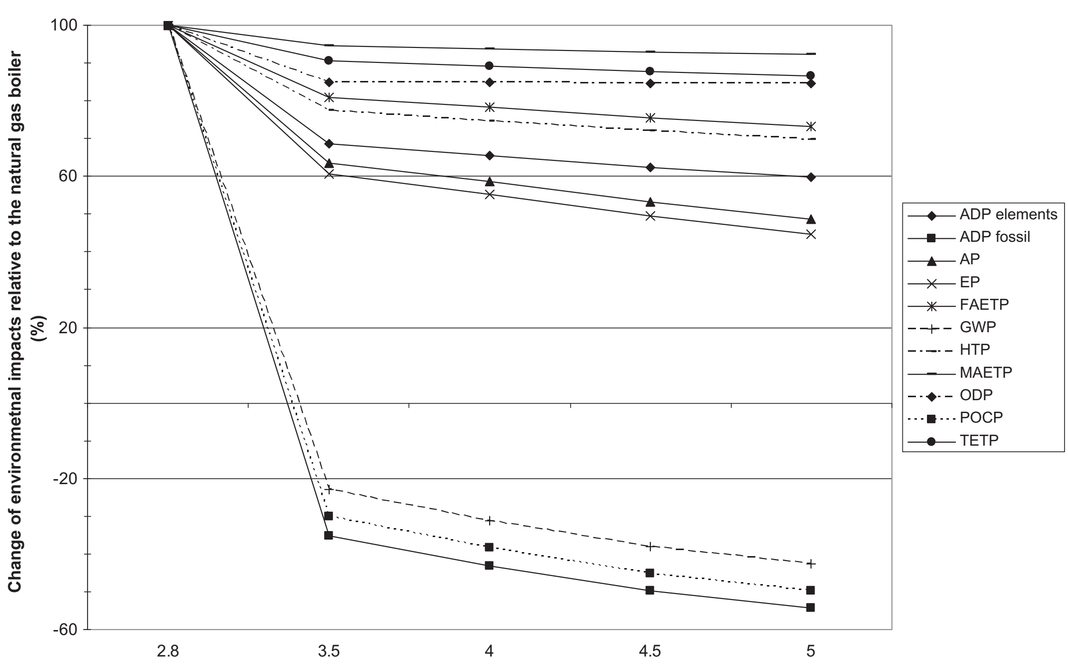

Fig. 11. Comparison of environmental impacts of ASHP with the gas boiler for different seasonal performance factor (SPF).

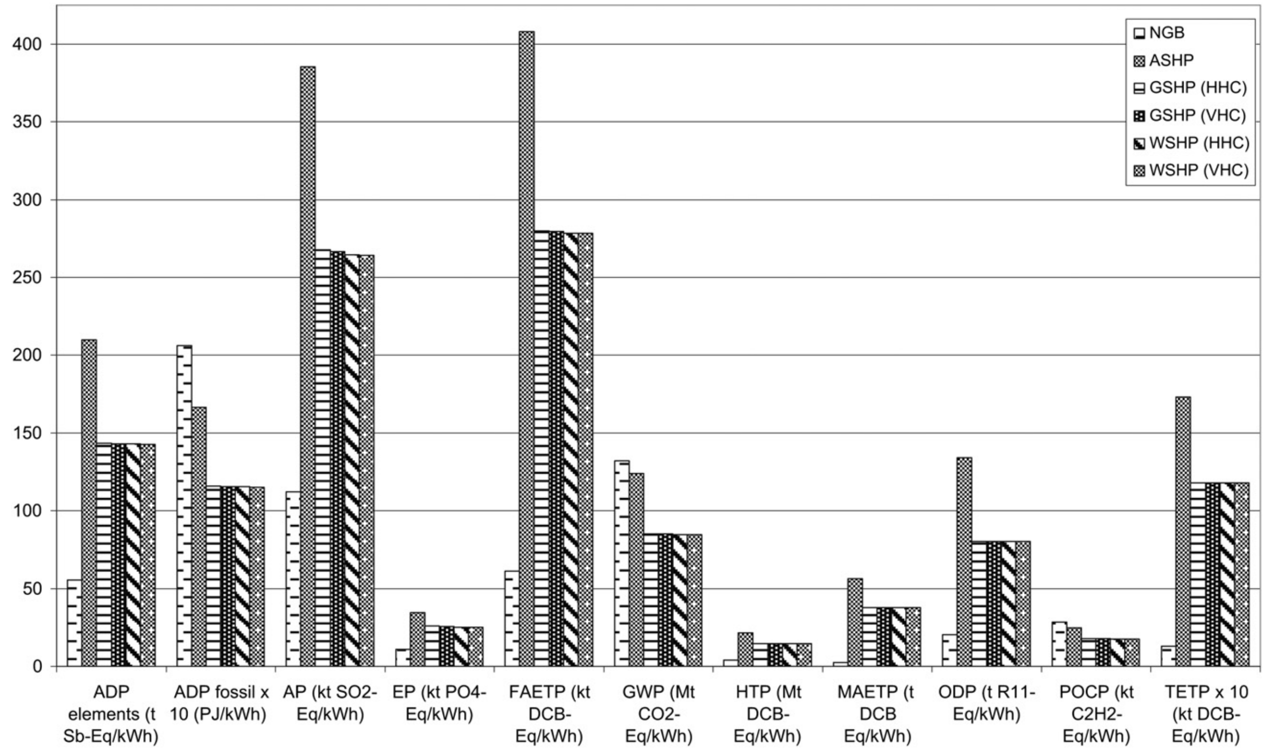

Fig. 12. Annual life cycle environmental impacts from heat pumps compared to natural gas boilers. [Impacts for 22.5 million boilers or heat pump units, assuming heat production of 20,000 kWh per unit per year. All the boilers are assumed to be condensing.].

Table 6
Direct GHG emissions from boilers and heat pumps.

Technology	Emissions (kg CO_2 eq./kWh)[a]	Annual emissions from each technology[b] (Mt CO_2 eq./year)	Annual UK emissions from the domestic sector[c] (Mt CO_2 eq./year)	Total annual UK emissions in 2009[d] (Mt CO_2 eq./year)
Gas boiler	0.220	99.00	147.20	566.30
ASHP	0.263	118.40	166.60	585.70
GSHP & WSHP	0.178	80.09	128.30	547.39

[a] Direct emissions for heat pumps include emissions from the leakage of refrigerants and direct emissions associated with electricity generation. Source: Ecoinvent [27] and own estimates.

[b] Each unit size 10 kW, operating 2000 h/yr and generating 20,000 kWh/yr.

[c] These values represent total UK annual emissions from the domestic sector, assuming in turn that different technologies replace all gas boilers which are assumed all to be condensing. The values are calculated as follows (example given for ASHP):

- Emissions from non-domestic heat use = Total domestic emissions with boilers (147.2 Mt CO_2 eq./year) − Emissions from gas boilers (99 Mt CO_2 eq./year) = 48.20 Mt CO_2 eq./year.
- Total annual emissions from the domestic sector with heat pumps: Emissions from non-domestic heat use (48.20 Mt CO_2 eq./year) + Emissions from heat pumps (118.40 Mt CO_2 eq./year) = 166.60 Mt CO_2 eq./year.

[d] These values represent total UK annual emissions, assuming in turn that different technologies fully replace gas boilers. The values are calculated as follows (example given for ASHP):

- UK emissions from non-domestic sectors = Total UK emissions (566.3 Mt CO_2 eq./year) − Emissions from the domestic sector (147.2 Mt CO_2 eq./year) = 419.1 Mt CO_2 eq./year.
- Total UK annual emissions with heat pumps: UK emissions from non-domestic sectors (419.1 Mt CO_2 eq./year) + Emissions from heat pumps (166.60 CO_2 eq./year) = 585.70 Mt CO_2 eq./year.

Put in the context of total national GHG emissions, in 1990 the UK emitted 778.3 Mt CO_2 eq./year [39]. In 2009, a 27.24% reduction in emissions (566.3 Mt CO_2 eq./yr) had been achieved [39]. If the ASHP replaced all the boilers (still all assumed to be condensing), the total emissions would decrease by 24.8% on the 1990 levels, leading to the total emissions of 585.70 Mt CO_2 eq./yr. However, compared to the gas boilers, this represents an increase of 2.5% on the 2009 levels. The GSHP and WSHP are a slightly better alternative, achieving a decrease of 29.7% on the 1990 levels or 2.4% (547.4 Mt CO_2 eq./yr) on the 2009 levels.

Therefore, these results show that replacing gas boilers with ASHP is not a sustainable option – not only would it not help to meet the climate change targets, it would also contribute substantially to other environmental impacts. Using GSHP and WSHP would help towards the targets only marginally but would also increase other impacts significantly. Note that this simplified analysis considers an extreme case where the heat pumps replace completely the gas boilers. This is obviously unrealistic, particularly as even the most optimistic scenarios to 2020 project generation of only 48,600 GWh/yr by domestic heat pumps [19]. Whilst this represents a phenomenal growth from the current 200 GWh/yr, it is still 9 times lower than assumed in this analysis, meaning that any GHG savings would also be roughly 9 times lower than estimated here. The GWP reduction prospects would improve in the longer term with the increasing decarbonisation of the energy sector and increasing SPFs, but as discussed in the previous section, most of the impacts would still remain higher than from the gas boilers.

Thus, with little contribution to the climate change targets in the short to medium term (up to 2020) and marginal contribution in the longer term (2050), while at the same time incurring significant other environmental impacts and requiring huge replacement costs, it is doubtful whether heat pumps can contribute to a more sustainable domestic energy supply in the UK.

6. Conclusions

The findings of this study show that currently heat pumps do not offer significant environmental advantages over condensing gas boilers for the UK conditions as the boiler has lower impacts for most impact categories. Among the heat pumps, ASHP has the highest and WSHP (VHC) the lowest impacts. The average relative difference in the impacts in favour of the gas boiler compared to the ASHP is 82%, ranging from 69% for the EP to 96% for the METP. The exceptions to this are the GWP, depletion of fossil resources (ADP fossil) and POCP for which the boiler is the worst option, with the ASHP pumps saving around 6%, 19% and 13% of these impacts, respectively. The GSHP and WSHP pumps perform much better than the ASHP on these three impacts, saving on average 36% of the GWP, 44% of the ADP fossil and 37% of the POCP relative to the boiler. For all other categories, the impacts from GSHP and WSHP are on average 73% higher than from the boiler.

The average difference in environmental performance between the ASHP and the other two types of pump is 32% in favour of the latter due to the lower efficiency and higher usage of electricity by ASHP. The GSHP has marginally (<0.1%) greater environmental impacts than the WSHP and horizontal collectors for both types of pump have negligibly (0.2–0.4%) higher impacts than the vertical.

The main contributor to most impacts from the heat pumps is their operation, contributing on average 84% to the total. Manufacturing of raw materials contributes around 10% while maintenance, disposal and transport contribute relatively little. The only exception to this is ODP, which is mainly due to the manufacture of the refrigerant.

The results indicate that the environmental sustainability of all heat pump systems improves with the greater penetration of renewables in the electricity mix. Increasing the percentage of renewables to 80% reduces the GWP of the heat pumps by 50% and other environmental impacts on average by 42%. However, most environmental impacts remain higher than those from gas boilers for all types of the pump. The exception to this are GWP, ADP fossil and POCP. The GWP saving relative to the boiler is 53% for the share of renewables of 80%. The equivalent saving of fossil fuels (ADP fossil) is 65% and POCP from 24 to 43%. All other impacts remain on average 68% higher for all levels of the renewables penetration considered.

The results also show that increasing the SPF of the ASHP from 2.8 to 5.0 reduces its environmental impacts on average by 38%. For the GSHP and WSHP, up to a 33% decrease in the impacts can be achieved by improving the SPF from 3.9 to 6.5. Nevertheless, the majority of impacts remain higher than for the gas boiler: on average by 70% for the ASHP and 60–62% for the GSHP and WSHP. The exceptions to this trend are GWP, ADP fossil and POCP which decrease for all the heat pumps across all the increased SPF values.

Replacing all gas boilers with ASHP at the UK level would save around 6% of GWP on a life cycle basis. The equivalent saving from GSHP and WSHP would be much greater – up to 36%. However, other impacts would increase significantly including MAETP - by 23 times and 16 times for the ASHP and the other two types of pumps, respectively. Similarly, TETP goes up 13 and 9 times, respectively, while ODP and FAETP from ASHP increase 6.6 times. The increase in HTP is on average between 3.6 and 5 times and the other impacts increase up to 3 times.

However, considering only direct GHG emissions, the total CO_2 eq. emissions from the domestic sector would increase by 13% for the ASHP. Using the GSHP and WSHP instead would save 12.8% compared to the condensing gas boilers. With respect to the total UK emissions, using the ASHP would increase the direct GHG emissions by 2.5% compared to the gas boilers while the GSHP and WSHP would lead to save 2.4% of the emissions.

Therefore, these results show that replacing gas boilers with the ASHP is not a sustainable option – not only would it not help to meet the climate change targets, it would also increase substantially the other impacts. Using the GSHP and WSHP would help only marginally towards reducing the direct GHG emissions and meeting the climate change targets but would increase other life cycle impacts significantly. The GWP reduction prospects would improve with the increasing decarbonisation of the energy sector and increasing SPFs, however, most of the impacts would still remain higher than from the gas boilers.

Thus, with little contribution to the climate change targets in the short to medium term (2020) and a marginal contribution in the longer term (2050), while at the same time incurring significant other environmental impacts and requiring huge replacement costs, it is doubtful whether heat pumps can contribute to a more sustainable domestic energy supply in the UK.

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