

Article

A Comparative Environmental Assessment of Heat Pumps and Gas Boilers towards a Circular Economy in the UK [†]

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Abstract: This research compares the potential environmental impacts of heat pumps with gas boilers and scenario analysis through utilising the life cycle approach. The study analyses the current situation with the baseline model and assesses future applications with Circular Economy (CE), Resource Efficiency (RE) and Limited Growth (LG) scenarios. Then, hybrid applications of low-carbon technologies and different manufacturing scenarios are investigated according to baseline and CE scenarios. Our results show that the use and manufacturing phases are responsible for 74% and 14% of all environmental impacts on average as expected. Even though the electricity mix of the UK has decarbonised substantially during the last decade, heat pumps still have higher lifetime impacts than gas boilers in all environmental categories except climate change impact. The carbon intensity of heat pumps is much lower than gas boilers with 0.111 and 0.097 kg CO₂e for air source heat pumps and ground source heat pumps, whereas the boiler stands as 0.241 kg CO₂e. Future scenarios offer significant reductions in most of the impact categories. The CE scenario has the highest potential with a 44% reduction for heat pumps and 27% for gas boilers on average. RE and LG scenarios have smaller potential than the CE scenario, relatively. However, several categories expect an increase in future scenarios such as freshwater ecotoxicity, marine ecotoxicity and metal depletion categories. High deployment of offshore wind farms will have a negative impact on these categories; therefore, a comprehensive approach through a market introduction programme should be provided at the beginning before shifting from one technology to another. The 50% Hybrid scenario results expect a reduction of 24% and 20% on average for ASHP and GSHP, respectively, in the baseline model. The reduction is much lower in the CE scenario, with only a 2% decrease for both heat pumps because of the reduction in heat demand in the future. These results emphasise that even though the importance of the use phase is significant in the baseline model, the remaining phases will play an important role to achieve Net-Zero targets in the future.

Keywords: built environment; circular economy; gas boilers; heat pumps; life cycle assessment



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1. Introduction

In 2018, 55% of the global population lived in cities, and this is expected to reach 68% by 2050 [1]. Cities are globally responsible for 75% of primary energy consumption [2] and 60–80% of greenhouse gas emissions [3]. Of all industrial sectors, the built environment is responsible for 36% of global energy consumption and 39% of energy-related greenhouse gas (GHG) emissions [4]. Use emissions such as heating, cooling, lighting, and cooking account for 72% of these emissions and the remaining comes from embodied emissions. Building-related emissions have decreased by 13% since 2013 and are around 20% below 1990 levels in the UK [5].

Heating is responsible for nearly half of UK energy usage and a third of carbon emissions, and currently 70% of heating purposes provided by natural gas [6]; therefore, electrification of the heating scheme is crucial via low-carbon technologies. In 2017, The Clean Growth Strategy was introduced in the UK, which was preceded by The Climate Change Act in 2008. The main proposals for the strategy aim to reduce UK emissions through energy efficiency in industry and housing, low-carbon transportation, clean power generation and enhancing natural resources, which account for 38%, 24%, 21% and 15% of UK emissions, respectively [6].

Efficiency improvements in buildings have been the major strategy during the last half-century. Very low heat conductivity in the building fabric is provided with low U-value insulation materials through passive strategies. Thermal mass also became a common topic in order to reduce heating and cooling loads and shifting peak demand. It is possible to limit the indoor temperature fluctuation to ± 4 °C with a heavyweight construction which helps to reduce discomfort in buildings [7]. On the other hand, ambitious building regulations have created a demand for low-exergy heating systems such as heat pumps. It is possible to reach energy and GHG emissions saving with a low-temperature hydronic heating system, even though it is a gas boiler. However, heat pumps maximise the saving as their efficiencies are higher in low temperatures [8].

A heat pump is a low-carbon technology that exploits heat from air, ground or water sources by heat transfer and provides heating, cooling, and domestic hot water (DHW). It could utilise electricity, mechanical or thermal energy in various applications such as residential, commercial, industrial or district heating. An electricity-driven heat pump could provide a three to four times higher amount of heat than the electricity consumed; therefore, it is expected to play a significant role in the decarbonisation of heating in buildings [9].

Heat pumps offer higher efficiencies than gas boilers; however, various refrigerants perform differently in various evaporator and condenser temperatures; therefore, choosing the right refrigerant according to system description and temperature requirements is crucial [10]. Current heat pumps in the UK market utilise R410A refrigerant, which has high global warming potential (GWP 2088); however, the use of R134a (GWP 1300) and R32 (GWP675) has also been increasing [11]. The number of studies investigating natural refrigerants such as ammonia (GWP 0.1) has increased, and the results show that ammonia could be used as a refrigerant in both large and small applications; however, the cost of the system is more expensive than traditional ones [12]. Therefore, more support is needed from the government in order to introduce the system to the market.

Energy efficiency through low-carbon heating is one of the key policies requiring the improvement of the standards of 1.2 million new boilers installed each year in England, including the installations of control devices to save energy. Moreover, reforming the Renewable Heat Incentive (RHI) and spending GBP 4.5 billion to support low-carbon heating technologies is expected between 2016 and 2021. GBP 184 million of investment has been scheduled for innovations in energy efficiency and low-carbon heating options [6]. However, the UK Government was planning to replace RHI according to the new Net-Zero target for 2050; therefore, RHI is extended until March 2022 and consultation for a new support scheme has been introduced [13]. It aims to support energy efficiency and low-carbon heating in buildings with a GBP 9bn investment during the next ten years.

The total share of renewables in heating and cooling has been increasing during the last decade in the UK; however, it was still only 7.5% in 2017 and the UK was at the end of the list among the EU member states with the Netherlands (5.9%) and Ireland (6.9%) [14]. The total number of heat pumps reached 9.5 million in the EU, which represented 4% of the building stock and the capacity of 82.7 GW [15]. The highest number of heat pumps sold in 2017 in the EU was for France (240,000 units), while only 20,000 units were sold in the UK. According to the Climate Change Committee [16], this number should have been 30,000 in 2020 and much more ambitious long-term targets should be set by the government. The number of heat pumps sold in the UK is still low and the UK Government have plans for

not only single heat pump applications but also hybrid use with gas boilers [17]. The CCC also suggested that new homes should not be connected to the gas grid after 2025 and hybrid applications of heat pumps should start and reach 10 million by 2035 [18].

Domestic RHI was introduced in 2014 and, according to Ofgem, in 5 years, 55,000 domestic heat pumps have been deployed [19]. According to the CCC (CCC, 2018), at least 2.5 million heat pumps need to be deployed by 2030 in order to continue further progress of decarbonisation [20]. New residential applications are the majority of the heat pump market, which was around 10,500 units per year. However, this represents a small proportion when it is compared with the number of new residential units completed, which is around 175,000 per year approximately [15]. Even though current numbers are quite limited for now, more incentives and advances in the manufacturing process could help to increase the deployment rate. The UK Government's ten-point Industrial Revolution plan aims to have 600,000 heat pump installations per year by 2028 [21]. Moreover, the UK Government started a consultation in 2019 for future home standards to upgrade Part L and Part F of the building regulations [22]. This consultation was concluded in January 2021 and proposed a timetable for the implementation of future home standards. A total of 70% of respondents to this consultation believe that heat pumps will play a significant role in this standard, and there is already support from stakeholders [23]. According to the UK Government, future buildings should have 75–80% fewer CO₂ emissions than current built ones with these standards [24]. The RIBA Council introduced a challenge for designers, architects and industry to reduce operational energy demand, embodied carbon and water use through higher benchmarks for buildings [25]. As space heating plays a significant role in operational energy and carbon emissions, the importance of heat pumps as a low-carbon technology becomes more crucial to reach these benchmarks. According to a study conducted by the Department of Energy and Climate Change, in a mass-market scenario, cost reductions of around 18% are expected compared to current costs for Ground Source Heat Pumps (GSHP) and 20% for Air Source Heat Pumps (ASHP) [26,27], which could lead to a higher deployment rate in the future. However, reuse and recycle options of these systems should be considered before moving to mass deployment. Therefore, there is a need for harmonisation of current built environment theory with the theory underpinning CE in order to achieve circular chains.

This study extends the analysis presented in two conferences [28,29]. The aim of this research is a comparison of different environmental impact categories for key technologies to decarbonise heating in domestic buildings in the UK. Heat pumps and gas boilers are key technologies in the decarbonisation of buildings and have been selected as a relevant case to test our hypotheses and methods. Their impacts on low-carbon heating targets have been assessed through a Life Cycle Assessment (LCA) analysis for the current year, and future scenarios have been developed to assess their environmental impacts through LCA to understand the impacts of the replacement of existing technologies with new ones. The functional unit of the study is decided as 'generating 1 kWh of thermal energy for domestic heating', but cumulative results have also been presented to investigate lifetime environmental burdens associated with these heating technologies. Hybrid applications of heat pumps with gas boilers also assessed as hybrid technologies will play a significant role in the future according to government targets.

2. Methods

Life Cycle Assessment (LCA) is an analytical tool to assess the environmental impacts of a product or process through analysing the entire life cycle (raw material acquisition, production, use and disposal phases). Its aim was to reduce cost while improving performance; therefore, it has been widely used during the last couple of decades [30]. A Life Cycle Assessment (LCA) approach has been undertaken to evaluate the environmental impacts of low-carbon heating technologies for the domestic sector in accordance with ISO 14,040 and ISO 14,044 standards [31,32]. The analysis has four stages: (i) defining goal and scope to identify the purpose of the study and products; (ii) inventory analysis to collect data of the

unit processes of products and analyse; (iii) impact assessment to identify environmental impacts; and (iv) interpretation to evaluate results and compare with potential solutions. The first step of this study focuses on the current situation of heating technologies, then, future scenarios try to evaluate their impact according to government plans and targets.

2.1. Goal and Scope

The goal of this study is to evaluate the potential environmental impacts of residential space heating in the UK through developing life cycle models for an air-source heat pump (ASHP), ground-source heat pump (GSHP) and natural gas boilers (NGB). This comprises a scenario analysis with the objective of achieving the Net-Zero target by 2050.

The functional unit of the study is decided as ‘generating 1 kWh of thermal energy for domestic heating’. However, cumulative results have also been presented to investigate lifetime environmental burdens associated with these heating technologies. The LCA software SimaPro 8.0.3 [33] has been used to model the products and the ReCiPe Midpoint (H) method [34] has been used to calculate environmental loads.

2.2. Inventory Data and Assumptions

2.2.1. System Description and Boundary

System specification and material requirements of heat pumps and gas boilers and data for these products have been taken from a previous study [35] that analysed the environmental implications of these products in the UK. Heat pumps are decided as air to water and ground to water, and heating is provided by underfloor heating. The underfloor heating system is designed as a screed system covering 150 m² area. Material requirements of heat pumps and gas boilers are illustrated (Table 1). The capacity of the systems and operation period have been assumed as 10 kW and 2000 h/year. The total space heating demand was assumed to be 20,000 kWh/year for both heat pumps and gas boilers, which represents an average UK household yearly heating demand. All technologies are considered maintenance free; however, it is assumed that the refrigerant needs to be topped up 6% yearly as losses occur. The total lifetime of both heat pumps and gas boilers was assumed as 20 years.

Table 1. Material requirements for heating technologies. Data source: [35].

Material	Unit	ASHP			GSHP			NGB	
		Heat Pump	Under-Floor Heating System	Maintenance	Heat Pump	Under-Floor Heating System	Heat Collector System		
Polyolester oil	kg	2.7			1.7				
R-134A	kg	4.9		5.9	3.1		3.7		
Rockwool	kg							8.0	
Low-alloyed steel	kg	32.0			20.0			115.0	
Reinforcing steel	kg	120.0			75.0		33.0		
Stainless Steel	kg	5.0						5.0	
Bentonite	kg				3.8				
Sand	kg		4650.0			4650.0			
Cement	kg		900.0			900.0			
Copper	kg	36.6			22.0			3.0	
Aluminium	kg		126.0			126.0		7.5	
Brass	kg						6.6	0.1	
Polyvinylchloride	kg	1.6			1.0				
HDPE	kg	0.5					301.2	0.9	
LDPE	kg		101.0			101.0	4.7		
Polystyrene	kg		66.0			66.0			
Elastomere	kg	16.0			10.0				
Ethylene Glycol	kg						167.0		
Total	kg	219.3	5843.0	5.9	136.6	5843.0	512.5	3.7	139.5

The system boundary of gas boilers and heat pumps includes extraction and production of raw materials, transportation of raw materials for assembly, manufacturing of

heat pumps and gas boilers, manufacturing of underfloor heating system for heat pumps, manufacturing of heat collector for GSHP, transportation of products to the distributor, transportation of products to the installation site, installation of GSHP as it requires drilling, operation period which includes natural gas processing for boilers and electricity generation for heat pumps, maintenance of refrigerant for heat pumps and disposal of materials (reuse, recycling, landfilling, etc.) (Table 2). The installation phase is only considered for GSHP as it requires drilling, which is an extensive installation when compared with ASHP and gas boilers. As two types of heat collector exist for GSHP (horizontal and vertical), this study only included the horizontal one for simplicity. The difference between the two types is the amount of pipework for heat collectors, the heat carrier liquid and the type of machines to dig the ground. The maintenance stage is only considered for heat pumps as there will be losses in refrigerant during the operation period; therefore, annual top-up is required. Additionally, the underfloor heating system is only included for heat pumps as replacing the gas boiler will require either resizing the radiators or the installation of an underfloor heating system to achieve higher efficiency. Therefore, in this study, the underfloor heating system is included in the system boundary of heat pumps. However, renewing the gas boiler does not require any system change; therefore, no new heating system is proposed.

Table 2. Processes in system boundaries included for heat pumps and gas boilers.

Processes in System Boundaries	ASHP	GSHP	NGB
Extraction and production of raw materials	•	•	•
Transportation of raw materials for assembly	•	•	•
Manufacturing of heating technologies	•	•	•
Manufacturing of underfloor heating system	•	•	
Manufacturing of heat collector		•	
Transportation of products to the distributor	•	•	•
Transportation of products to the installation site	•	•	•
Installation of the products		•	
Operation period including natural gas processing and electricity generation	•	•	•
Maintenance	•	•	
Disposal of products	•	•	•

2.2.2. Transport

Heat pump installations in the UK market heavily rely on imports. A total of 69% of ASHP and 59% of GSHP are manufactured outside of the UK [13]. Europe is the dominant market as 70% of imported products are manufactured there. When individual countries are investigated, Sweden has the highest imported heat pump amount followed by South Korea, Spain, Italy, Czech Republic, and Germany. This study, therefore, selects Europe as the manufacturing location for heat pumps. Ecoinvent generic values (100–200 km) have been used for raw materials and assembly transport assumptions [36]. Heat pumps are assumed to be manufactured in Europe and transported to the UK (Table 3). Within this process, raw materials are transported 200 km by railway and 100 km by a large truck (16–32 tonne). After the assembly of the heat pump, it is transported to the distributor 500 km by railway and 200 km by a large truck (16–32 tonne). Then, the installation site distance has been assumed as 200 km and the products have been transported by a small truck (3.5–7.5 tonne). The underfloor heating system (UHS) and heat collectors (HC) are assumed to be manufactured in the UK; therefore, transport distances for manufacturing have been assumed as 200 km by railway and 100 km by a large truck (16–32 tonne), and installation distance has been assumed as 200 km. Natural gas boilers are assumed to be manufactured in the UK; therefore, transport for raw materials has been assumed as 200 km by railway and 100 km by a large truck (16–32 tonne). Distances from manufacturer to distributor and installation site have been assumed as 200 km.

Table 3. Transport assumptions. Data source: [36].

Transport of;		Rail	Truck (Large)	Truck (Medium)	Truck (Small)
Heat Pumps	raw materials to manufacturer	km 200	100		
	products from manufacturer to distributor	km 500	200		
	products for installation	km			200
Gas Boiler	raw materials to manufacturer	km 200	100		
	products from manufacturer to distributor	km		200	
	products for installation	km			200
Underfloor Heating System	raw materials to manufacturer	km 200	100		
	products for installation	km		200	
Heat Collectors	raw materials to manufacturer	km 200	100		
	products for installation	km	200		

2.3. Scenario Analysis

The study offers a scenario analysis to assess the environmental impacts of heat pumps and gas boilers through LCA to understand the implications of the replacement of existing technologies with new ones. In this section, three scenarios have been developed for the year 2050. In the next section (Section 2.4), three more alternative scenarios have been developed for hybrid applications of technologies and another transport scenario. The latter is separated from the first three because they are assessed according to both the baseline model and also the Circular Economy (CE) scenario.

Circular Economy (CE) scenario: High technology development and high consumer engagement are supported by policies; therefore, more efficient houses and low-carbon technologies expect a reduction in energy demand. The decarbonisation of electricity is provided by increased offshore wind capacity, and the share of natural gas is nearly eliminated. Larger roles for heat pumps are provided and gas boilers are replaced with low-carbon technologies such as stand-alone heat pumps (10.7 million) or hybrid heat pumps (7.1 million). The number of gas boilers will reduce to 5 million and the remaining heating demand will be provided by district heating and biomass. A reduction in material demand and better waste treatment options are assumed with high policy support (Table 4).

Table 4. Summary of system specifications and assumptions for scenarios.

Drivers	Baseline	Circular Economy (CE)		Resource Efficiency (RE)		Limited Growth (LG)		Sources
Recycling rates for materials	Steel	75%	Steel	100%	Steel	90%	Steel	80%
	Copper	61%	Copper	100%	Copper	85%	Copper	75%
	Aluminium	69%	Aluminium	100%	Aluminium	90%	Aluminium	80%
	Plastics	32%	Plastics	100%	Plastics	80%	Plastics	60%
	Refrigerant	80%	Refrigerant	100%	Refrigerant	90%	Refrigerant	80%
SPF and Efficiency	ASHP	2.8	ASHP	4.2	ASHP	4.0	ASHP	3.6
	GSHP	3.4	GSHP	4.6	GSHP	4.4	GSHP	4.2
	NGB	90%	NGB	95%	NGB	95%	NGB	95%
Efficiency improvements			25%		15%		8%	[19,20,27]
Heat pump deployment (million)	ASHP	0.126	ASHP	10.479	ASHP	5.731	ASHP	0.809
	GSHP	0.015	GSHP	0.178	GSHP	0.132	GSHP	0.089
	Hybrid HP	0.016	Hybrid HP	7.065	Hybrid HP	2.705	Hybrid HP	0.833
	Gas Boiler	21.989	Gas Boiler	5.196	Gas Boiler	5.861	Gas Boiler	22.138

Resource Efficiency (RE) scenario: A reduction in energy demand is expected but this decrease is lower than the CE scenario. The decarbonisation level of electricity is similar to the CE scenario. The deployment of heat pumps is limited (8.5 million), and the number of gas boilers is similar to the CE scenario; therefore, applications of hydrogen

play a significant role in this scenario. High technology development and policy support are expected, but consumer support is relatively limited compared to the CE scenario.

Limited Growth (LG) scenario: Limited energy efficiency and technology development is assumed; therefore, residential heat demand is expected to reduce with the lowest number among other scenarios. The decarbonisation of electricity is not finished, and the deployment of heat pumps is very limited; therefore, the majority of heating demand will be provided by gas boilers. Slow adaptation to circular economy principles and low consumer engagement are expected.

2.3.1. Electricity Mix

The use phase of heating technologies has a significant impact on LCA analysis, accounting for 74% of overall impacts; therefore, updating the electricity mix of the UK to the current situation would help to see more accurate results. The current electricity mix of the UK for the year 2018 has been identified for the use phase of heat pumps (Figure 1) [41]. In 2018, 40.2% of electricity was produced from natural gas. Nuclear and wind accounted for 19.9% and 17.4%, respectively. The remaining comes from bioenergy, solar and coal.

According to National Grid, more than one-third of UK electricity was produced from natural gas and offshore wind capacity, around 10 GW, in 2018 [19]; however, more deployment of wind energy is expected in the future. The UK Government has revised its offshore wind capacity target from 30 GW to 40 GW by 2030 [42]. Therefore, National Grid's electricity mix scenarios have been adopted for the UK's future electricity mix ('Community Renewables', 'Two Degrees', and 'Steady Progression' scenarios adapted to 'Circular Economy', 'Resource Efficiency' and 'Limited Growth' scenarios, respectively) (Figure 1). All three scenarios assume a significant increase in wind energy but in different shares. In 2050, the RE scenario assumes that 56% of electricity will be produced from wind energy and the remaining will come from nuclear, solar and bioenergy, which account for 19%, 8% and 7%, respectively. In the CE scenario, wind energy reaches 60% of total electricity production. Solar and bioenergy increase to 10% each; therefore, the share of nuclear energy reduces to 12%. The LG scenario, however, assumes the least wind energy share with 53%; therefore, natural gas still has a share of 10% of total electricity production.

2.3.2. Efficiency of Technologies

One of the main impacts on energy demand in heat pumps is the Coefficient of Performance (COP), which identifies the ratio of energy needed according to its efficiency. Seasonal Performance Factors (SPFs) represent the average COP for heat pumps during the heating season. According to the Department for Business, Energy and Industrial Strategy (BEIS) monthly reports since 2014, average ASHP and GSHP efficiencies are calculated as 3.2 SPF and 3.5 SPF [39]. These values vary for legacy applications and new installations. Legacy ASHP applications have an average of 2.5 SPF and new installations have 3.4 SPF. Legacy GSHP installations, on the other hand, have an average of 2.9 SPF and the new ones have 3.8 SPF. Field trials in the UK and Europe show similar results with an average SPF of 2.6 and 3.2 for ASHP and GSHP, respectively [17]. Therefore, average SPFs for heat pumps have been considered as 2.8 for ASHP and 3.4 for GSHP. The efficiency of NGB is considered as 90% for the baseline model (Table 4).

Current heat pump efficiencies vary between manufacturer test data and field trials. Correct sizing and better installation of heat pumps provide higher efficiencies; thus, it could be possible to reach manufacturers' test efficiencies in the future. Over the years, the efficiency of heat pumps is expected to increase with the help of advances in the market. The CCC assumes a 0.5 increase in the COP of heat pumps between 2020 and 2030 [40]. Therefore, future scenarios in this study assume higher efficiencies varying between 3.6–4.2 for ASHP and 4.2–4.6 for GSHP (Table 4). GSHPs are expected to have a lower increase in COP than ASHPs due to their high outlet temperature and modest difference in the ground temperature around the heat collector [43]. Therefore, efficiency improvement in GSHP is expected to be lower than in ASHP.

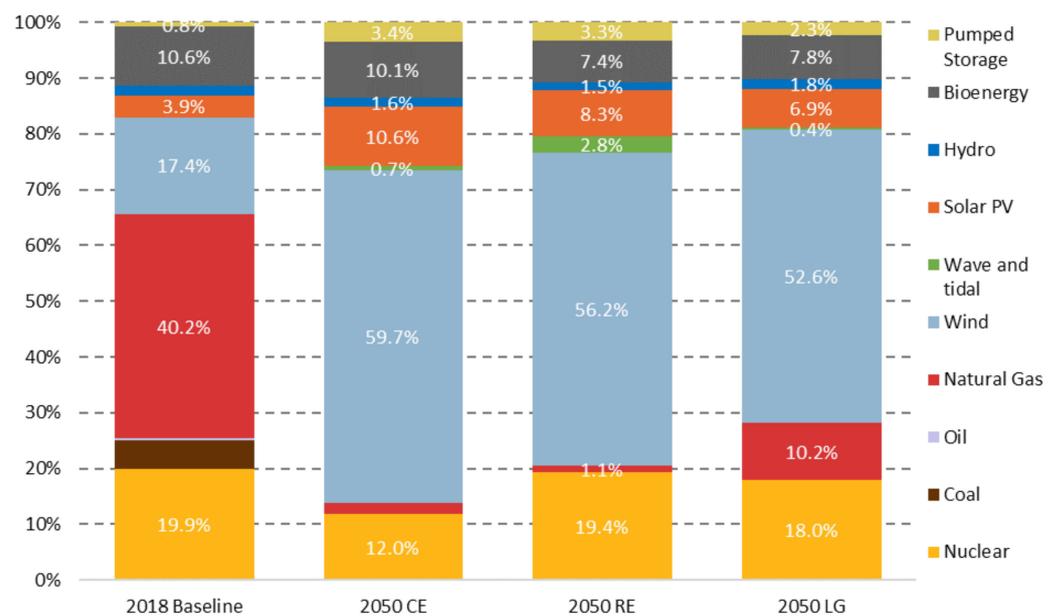


Figure 1. Electricity mix of UK in different scenarios used in LCA analysis. Data sources: [19,41].

2.3.3. Decommissioning

The lifetime of both technologies has been assumed to be 20 years, and at the end of their life cycle metal components are recycled and the rest is landfilled. UK and Europe recycling rates have been reviewed, and steel, copper, aluminium and plastics have been assumed as 75%, 61%, 69% and 32% recycled [37]. A total of 80% of refrigerants are assumed to be reused after 20% losses during the decommissioning [35].

Gas boilers and heat pumps are electrical and electronic equipment (EEE) covered by the WEEE Regulations under category 1 and category 12. They both have similar targets as 85% recovery and 80% recycling rates [38]. However, these benchmarks will likely increase if the UK continues to progress towards Net-Zero targets. Therefore, all scenarios expect an increase in the recycling rate; however, the CE scenario assumes the highest recycling rates with 100% for all components. High policy support and public engagement could help to achieve 100% recycle and recovery options.

2.3.4. Efficiency Improvements in Residential Sector

The need for space heating could be less in the future. Thermal efficiency improvements through retrofitting existing houses and setting higher benchmarks for new buildings mean that by 2050, domestic buildings could use up to 26 per cent less energy for heat compared to today [19]. The CCC [20] assumes a 15% reduction in energy consumption in the residential sector by 2030 through energy efficiency improvements in existing buildings. The Royal Institute of British Architects [27] has set a challenge for designers to reach at least a 75% reduction in operational energy in domestic buildings by 2030. Therefore, different measures have been taken for future scenarios. RE and CE scenarios assume a 15% and 25% reduction in heat demand in an average household. The LG scenario, however, does not consider any energy improvement measures as the economy faces limited economic growth (Table 4).

2.4. Hybrid and Transport Scenarios

In the previous section, model simulations are conducted based on individual heating technologies without focusing on hybrid applications. However, the UK Government and National Grid have decarbonisation targets for heating, and scenarios show that there will be a need for hybrid options in the future. Additionally, Asia is a dominant market, and some companies manufacture their heat pumps in Asian countries. Moreover, South Korea is the second country that the UK has the highest heat pump imports from [13]. Therefore,

this section investigates the impact of changing the manufacturing location and hybrid options according to the baseline scenario and CE scenario, which was modelled in the previous section. Three scenarios are investigated as:

- Transport (SK) scenario assumes that heat pumps are manufactured in Asia and average ROW (rest of the world) production values have been used in SimaPro. South Korea has been chosen as a manufacturing country to identify the main shipment method and distance as a transoceanic freight shipment of 12,400 nm (22,965 km). Table 5 shows the remaining transport methods and distances. In this scenario, the manufacturing location of the underfloor heating system and heat collectors has not been changed.
- 50% Hybrid scenario assumes half of the energy required for heating has been produced by ASHP or GSHP and the remaining comes from NGB.
- 75% Hybrid scenario assumes 75% of heating energy has been provided by heat pumps and the remaining 25% produced by the gas boiler.

Table 5. Transport assumptions of manufacturing in Europe and Asia [36].

Transport of;			Rail	Truck (Large)	Truck (Small)	Sea Freight
Transport (Europe)	raw materials to manufacturer	km	200	100		
	products from manufacturer to distributor	km	500	200		
	products for installation	km			200	
Transport (Asia)	raw materials to manufacturer	km	200	100		
	products from manufacturer to distributor	km		200		22,965
	products for installation	km			200	

The changes for these three scenarios are applied to both the baseline and the CE model to compare the impacts of these scenarios in the current year and an alternative of the year 2050.

3. Results

3.1. Baseline Results

The simulation results have been illustrated per functional unit, and the lifetime results are divided into the amount of total space heating demand for both heat pumps and gas boilers as the functional unit is decided as ‘generating 1 kWh of thermal energy for domestic heating’. However, lifetime environmental impacts are also provided in the graphs to show the impact of technologies during their lifetime.

Environmental impacts of the baseline scenario for air source heat pump (ASHP), ground source heat pump (GSHP) and natural gas boiler (NGB) have been illustrated in Figure 2. ASHP has the highest impacts on average, and GSHP and NGB have 17% and 51% lower results than ASHP on average, respectively. When individual impact categories were investigated, the results illustrated that NGB has the lowest impact in all categories except Climate Change (CC)—(CC (Climate Change), OD (Ozone Depletion), TA (Terrestrial Acidification), FEU (Freshwater Eutrophication), MEU (Marine Eutrophication), HT (Human Toxicity), POF (Photochemical Oxidant Formation), PMF (Particulate Matter Formation), TE (Terrestrial Ecotoxicity), FE (Freshwater Ecotoxicity), ME (Marine Ecotoxicity), IR (Ionising Radiation), ALO (Agricultural Land Occupation), ULO (Urban Land Occupation), NLT (National Land Transformation), WD (Water Depletion), MD (Metal Depletion), FD (Fossil Depletion))—and Fossil Depletion (FD) categories.



Figure 2. Lifecycle environmental impacts of heat pumps and gas boilers for baseline scenario (HP: Heat pump, NGB: Gas boiler, UHS: Underfloor heating system, HC: Heat collector).

This study illustrates that emissions for ASHP and GSHP are reduced to 0.111 kg CO₂e/kWh and 0.097 kg CO₂e/kWh (Figure 2), respectively, compared with the literature [35], where there was a reduction from 0.276 kg CO₂e/kWh and 0.189 kg CO₂e/kWh. This is mainly because of the decarbonisation of the electricity mix through the high deployment of wind energy to replace coal and some part of natural gas during the last decade. The carbon intensity of the gas boiler is more than double both heat pumps with 0.241 kg CO₂e/kWh. NGB has 96.2 t CO₂e lifetime emissions, much higher than ASHP (42.3 t CO₂e) and GSHP (38.8 t CO₂e).

The two highest contributor phases of life cycle analysis are the ‘use’ and ‘manufacturing’ phases, which are responsible for 74% and 14% of all environmental impacts on average. The manufacturing of heating technologies, underfloor heating systems and heat collector phases accounts for 17%, 20% and 12% for ASHP, GSHP and NGB, respectively. It is important to keep in mind that the manufacturing of heat pumps occurs outside of the UK, which does not have an impact on the UK’s territorial emissions; however, it will have an impact on consumption-based emissions of the UK or global emissions. The disposal phase accounts for 6%, 7% and 3% of total impacts for ASHP, GSHP and NGB, respectively; however, these impacts are negative due to contributions from the reuse of refrigerants and recycling of materials at the end of their life cycle. The refrigerant and maintenance phases account for only 3% for both heat pumps and no impact for the gas boiler as there is no refrigerant use in boilers. The transport phase, on the other hand, is only responsible for 1% of total environmental impacts.

When heat pumps are compared, GSHP has 17% lower results than ASHP as it requires less electricity because of its higher efficiency. The impact of heat collectors is relatively low in most of the categories, except the Terrestrial Acidification (TA), Photochemical Oxidant Formation (POF) and Particulate Matter Formation (PMF) categories. The reduction in the use phase in these categories is higher than the impact of manufacturing the heat collectors, so overall the environmental impact of GSHP remains lower than ASHP. The POF category is the only category in which GSHP has 3% higher results than ASHP because the impact of the manufacturing of heat collectors is greater than the reduction in the use phase. The highest difference between heat pumps occurs in the Ozone Depletion (OD) category with 36% because of lower refrigerant requirements. Metal Depletion (MD), Freshwater Eutrophication (FEU), Marine Eutrophication (MEU), Human Toxicity (HT) and Freshwater Ecotoxicity (FE) are the remaining categories that have more than 20% difference. Even though the disposal phase does not have a significant impact overall, there are several categories in which the disposal phase has higher impacts for heat pumps, such as TA, POF, PMF and ULO categories, accounting for 29%, 18%, 35%, and 22%, respectively.

3.2. Results from Future Scenarios

Scenario analysis aims to investigate the impact of changes planned in line with the government’s targets and national policies. The Circular Economy (CE) scenario results expect the highest reductions for all heating technologies, and the Limited Growth (LG) scenario expects the lowest. Overall reductions in CE, RE and LG scenarios are 44%, 42% and 31% for heat pumps and 27%, 18% and 12% for the gas boiler (Figure 3).

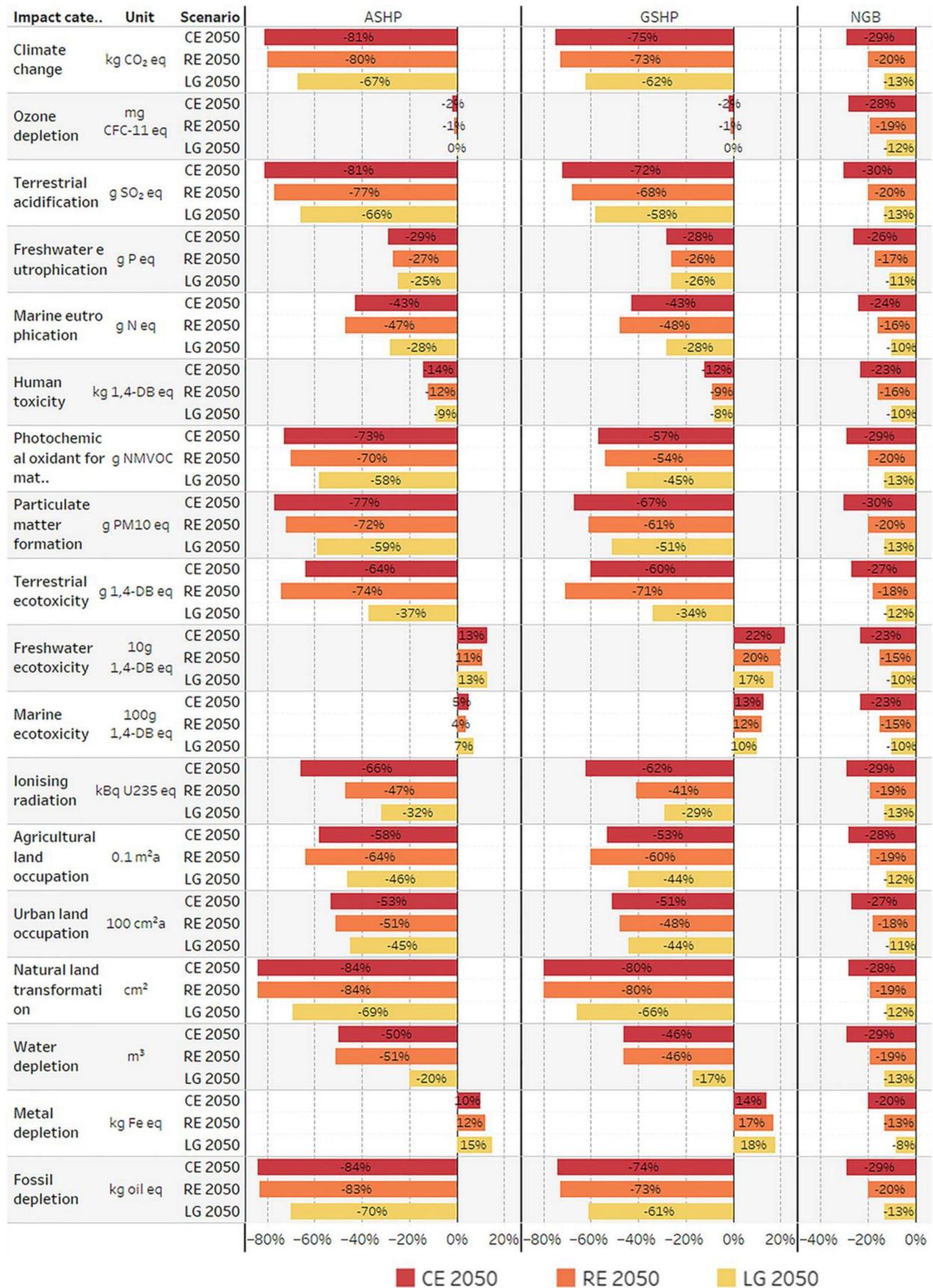


Figure 3. Lifecycle environmental impact change of future scenarios according to the baseline scenario.

In the CE scenario, the highest changes are in CC, TA, POF, PMF, NLT and FD categories with an average of 75% reduction in heat pumps. The lowest change occurs in the OD category with a 2% reduction only as the amount of refrigerant is the same in future scenarios. Even though the RE and LG scenario have lower results than the CE scenario, trends are the same. However, several categories expect an increase for all scenarios such as FE, ME, and MD. The main source of this impact is the heavy metals utilised in the high deployment of wind energy that will be provided by offshore wind farms; therefore, emissions to the water will be expected. Another toxicity category, human toxicity, also expects a lower reduction for all scenarios from 8% to 14% for heat pumps. Additionally, the major source of metal depletion comes from the life cycle of electricity because the high deployment of renewables requires more metal resources. On the other hand, there are several categories in which the RE scenario performs better than the CE scenario, such as MEU, TE, FE, ME and ALO. The main reason for this impact is that the CE scenario has the highest renewable share in the electricity mix and this has higher toxicity and land occupation results; however, the RE scenario has a lower renewable share and higher nuclear energy in the electricity mix. Therefore, negative impacts created by renewable energy are greater in the CE scenario. The LG scenario still has natural gas in the mix; therefore, the LG scenario still performs worse than both scenarios.

The reductions in NGB are very limited when compared with heat pumps. This is due to limited efficiency in the gas boiler. The reductions come from efficiency improvements in houses which will require less heat demand; therefore, the gas boiler expects similar reductions in all phases.

When the contributors to changes in future scenarios are investigated, only the use and disposal phases have an impact on categories. Figure 4 shows their weighted results, illustrating the importance of the use phase. Even though some categories are expecting significant increases in the disposal phase (ranging from 535–1286%), their weighted results are less than 1% when they are compared with the use phase. The highest disposal phase impact occurs in the OD category, with an increase of 20% and 9% for CE and RE scenarios and a decrease of 3% for the LG scenario.

3.3. Transport and Hybrid Scenarios

3.3.1. Results from Baseline Model

The Transport (SK) scenario results illustrate that changing the manufacturing location does not have a significant impact on most categories according to the baseline scenario. ASHP results show that even though the average change is less than 1%, there are some categories that have higher results (Figure 5). The highest impact category is MEU with a 30% decrease from the baseline scenario. TA, HT and PMF categories are other high impact categories with 13%, 11% and 8%, whereas with an increase, unlike the MEU category.

During life cycle phase analysis, only changes in the manufacturing of heat pumps, refrigerant and transport phases were considered. The manufacturing phase increases with an average of 27% in all categories, and the highest change occurs in the TE category with a 358% increase for ASHP (Figure 6). TA and PMF categories show increases of 226% and 58%, respectively. There are also several categories with negative impacts such as MEU and OD categories with a 92% and 19% decrease, respectively. The transport phase, on the other hand, increases 17% on average in all categories and the highest contribution comes from TA, PMF, MEU and POF categories with 77%, 49%, 40% and 39%, respectively. The refrigerant phase, however, has a negative impact, and results decrease only 2% on average and the highest change occurs in IR, NLT and TE categories with a decrease of 18%, 8% and 7%, respectively. PMF and TA categories have also seen a 4% increase.

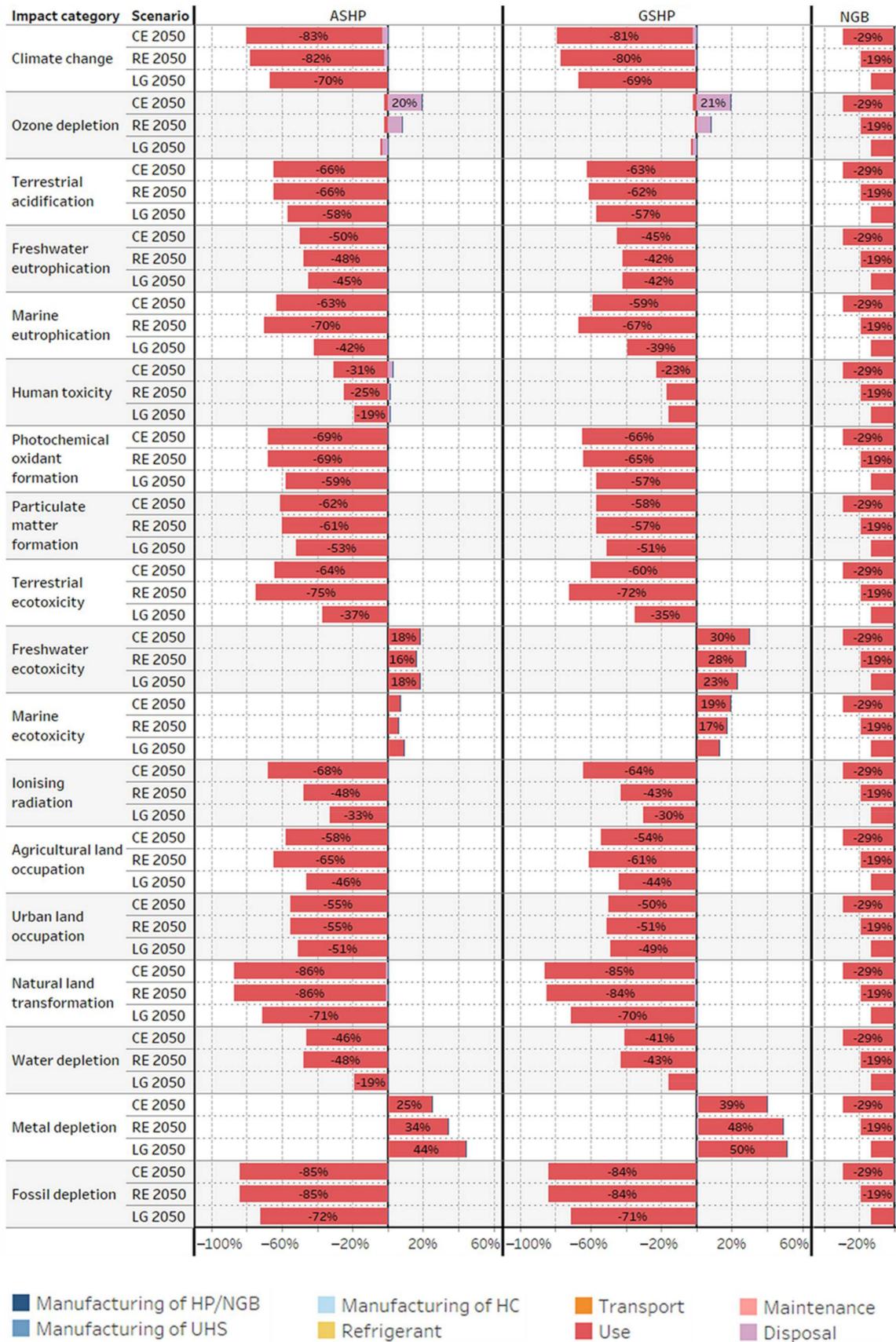


Figure 4. Lifecycle environmental impact change of phases in future scenarios.

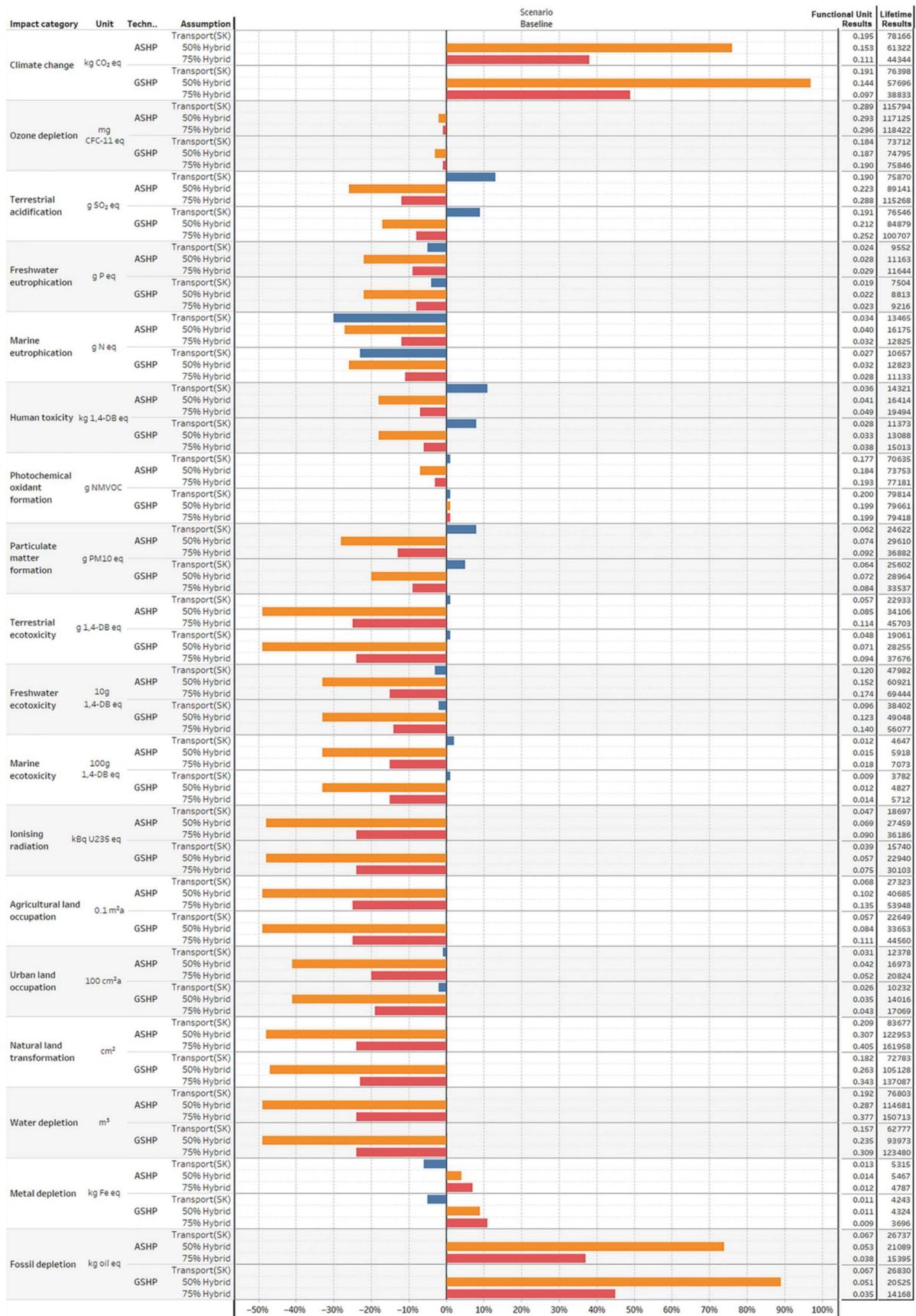


Figure 5. Lifecycle environmental impact change of Transport (SK) and Hybrid scenarios according to baseline scenario.

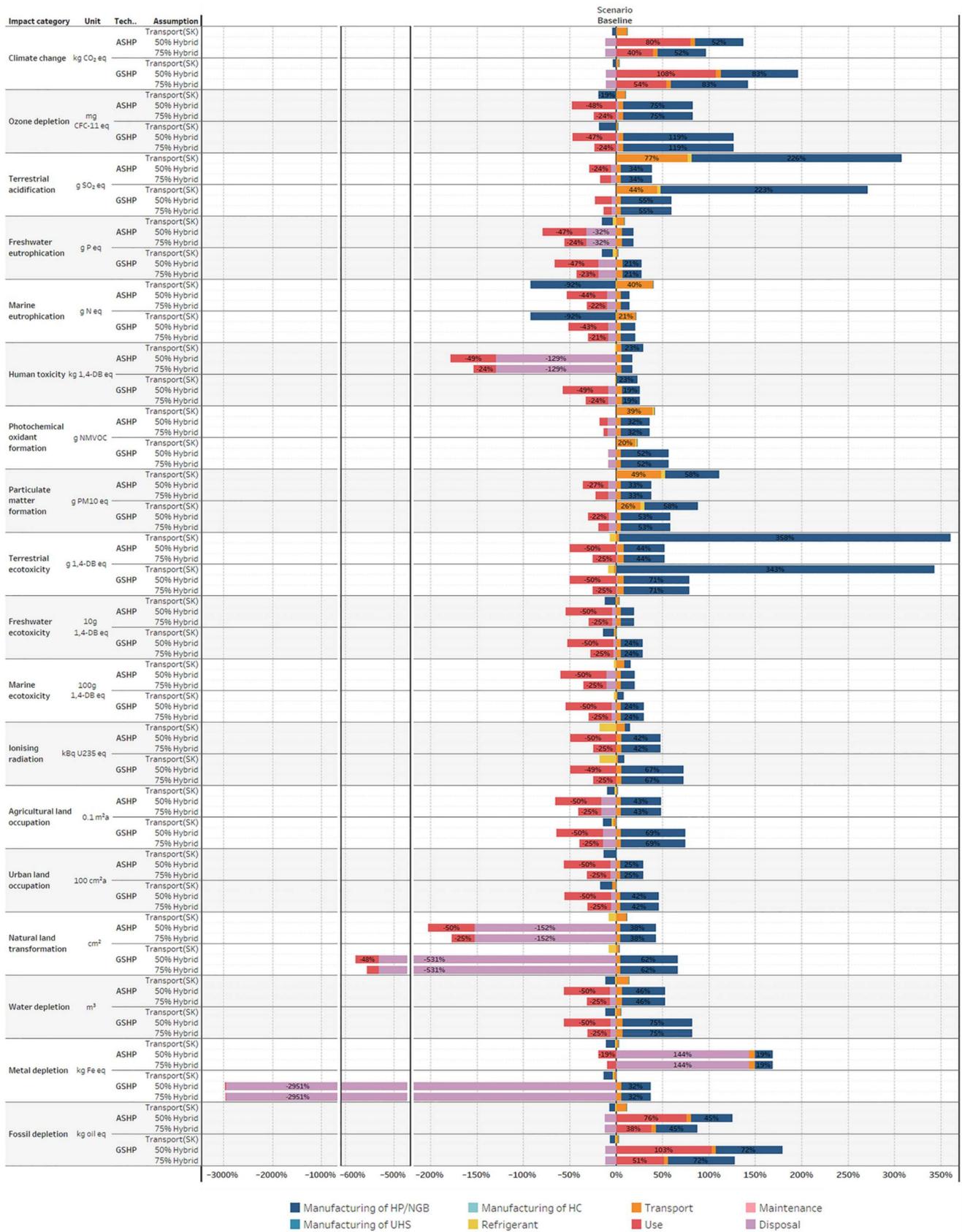


Figure 6. Lifecycle environmental impact change of phases for Transport (SK) and Hybrid scenarios according to baseline.

The results of GSHP show similarities with ASHP, with a decrease of 1% on average (Figure 5). The highest impact category is MEU with a 23% decrease, followed by a 9% and 8% increase in TA and HT categories, respectively. The changes in GSHP are relatively lower than ASHP as heat collectors in GSHP will still be manufactured in Europe in this scenario; therefore, the weight of the change becomes smaller in this technology.

The results of phases are also similar in manufacturing and refrigerants with a 26% increase and 2% decrease on average for GSHP (Figure 6). The highest impact categories are TE, TA, PMF and MEU categories in the manufacturing phase, and IR, TE, NLT, PMF and ULO categories in the refrigerant phase, like the ASHP results. The main difference between ASHP and GSHP occurs in the transport phase and the average change is 7%. Even though the highest categories are the same, the changes are less than ASHP.

The 50% Hybrid scenario results expect an increase of 32% and 20% on average in ASHP and GSHP, respectively (Figure 5). GSHP offers a lower increase or less reduction in all categories, resulting in fewer advantages than ASHP. The highest change occurs in CC and FD categories with a 76% and 79% increase for ASHP, and 97% and 89% increase for GSHP, respectively. The MD category also expects an increase of 3% and 7% for heat pumps. The remaining categories result in a decrease, and the highest decrease occurs in TE, IR, ALO, NLT, and WD categories, varying between 49% and 38% for both heat pumps. Some categories have a less than 5% impact change, such as OD, FEU and HT categories.

In the 50% Hybrid scenario, the highest changes occur in the disposal phase with an average of 15% and 200% decrease for ASHP and GSHP (Figure 6). Even though the overall change is greater in GSHP, most of the contribution comes from MD and NLT categories with a decrease of 2951% and 531%. The reason for this reduction is that the amount of metals required for ASHP is greater than GSHP; therefore, this value is a positive value for ASHP. Thus, negative metal depletion values coming from NGB reduce the impact of ASHP. When other phases are analysed, the use phase expects a decrease of 33% and 29% for ASHP and GSHP, and the manufacturing phase expects an increase of 33% and 53%, respectively. The transport phase has an average change of 5% increase for both heat pumps.

Even though the use phase offers a reduction in all categories, the CC and FD categories expect an increase in all phases except the disposal phase. As gas boilers perform worse than heat pumps only in this category in the baseline scenario (Figure 2), the hybrid scenario offers the worst results in these categories. Moreover, the MD category also expects an increase even though it is less than 10%. However, in other categories, the use phase eliminates the increases created by manufacturing and transport phases as the weight of the use phase is very large and creates negative results overall in all categories.

The 75% Hybrid scenario results offer less reduction than the half-hybrid scenario with an 11% and 9% decrease in ASHP and GSHP (Figure 5). Similarly, GSHP performs worse than ASHP in this scenario with an increase in CC and FD categories and a decrease in other categories; however, this scenario offers less decrease overall as the contribution of the gas boiler is less than the 50% Hybrid scenario. The highest changes occur in CC and FD categories with a 38% and 37% increase for ASHP, and 49% and 45% increase for GSHP, respectively. The highest decreases occur in TE, IR, ALO, and NLT categories, varying between 24% and 19% for both heat pumps.

3.3.2. Results from CE 2050 Model

The Transport (SK) scenario results show that changing the manufacturing location could increase the environmental impacts on average 3% and 1% for ASHP and GSHP, respectively, according to the CE 2050 model (Figure 7). The highest changes for ASHP occur in TA and PMF with a 68% and 34% increase. Additionally, results suggest a decrease in several categories with less than 3% except the MEU category, which has a 53% reduction in the CE 2050 model. GSHP results show lower values than ASHP in all categories, but the highest contributors are the same impact categories.

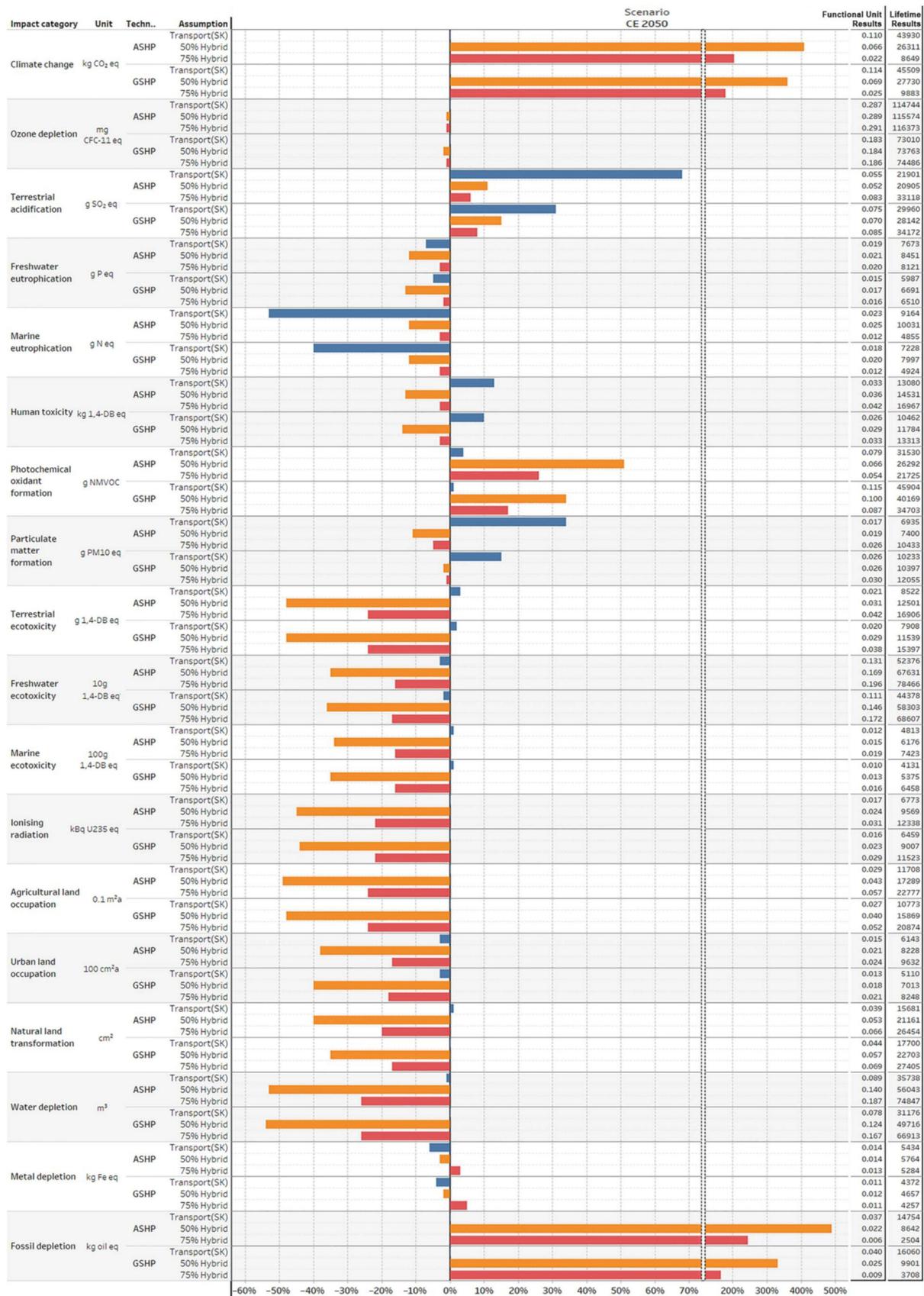


Figure 7. Lifecycle environmental impact change of Transport (SK) and Hybrid scenarios according to CE scenario.

The life cycle phase results illustrate that the highest contributor phases to the changes from the CE 2050 model are the manufacturing of heat pumps, refrigerant, and transport phases, similar to the baseline model (Figure 8). The results of changes in these phases are the same with the baseline model; therefore, the changes in these phases have the same impacts in both the baseline and CE 2050 model.

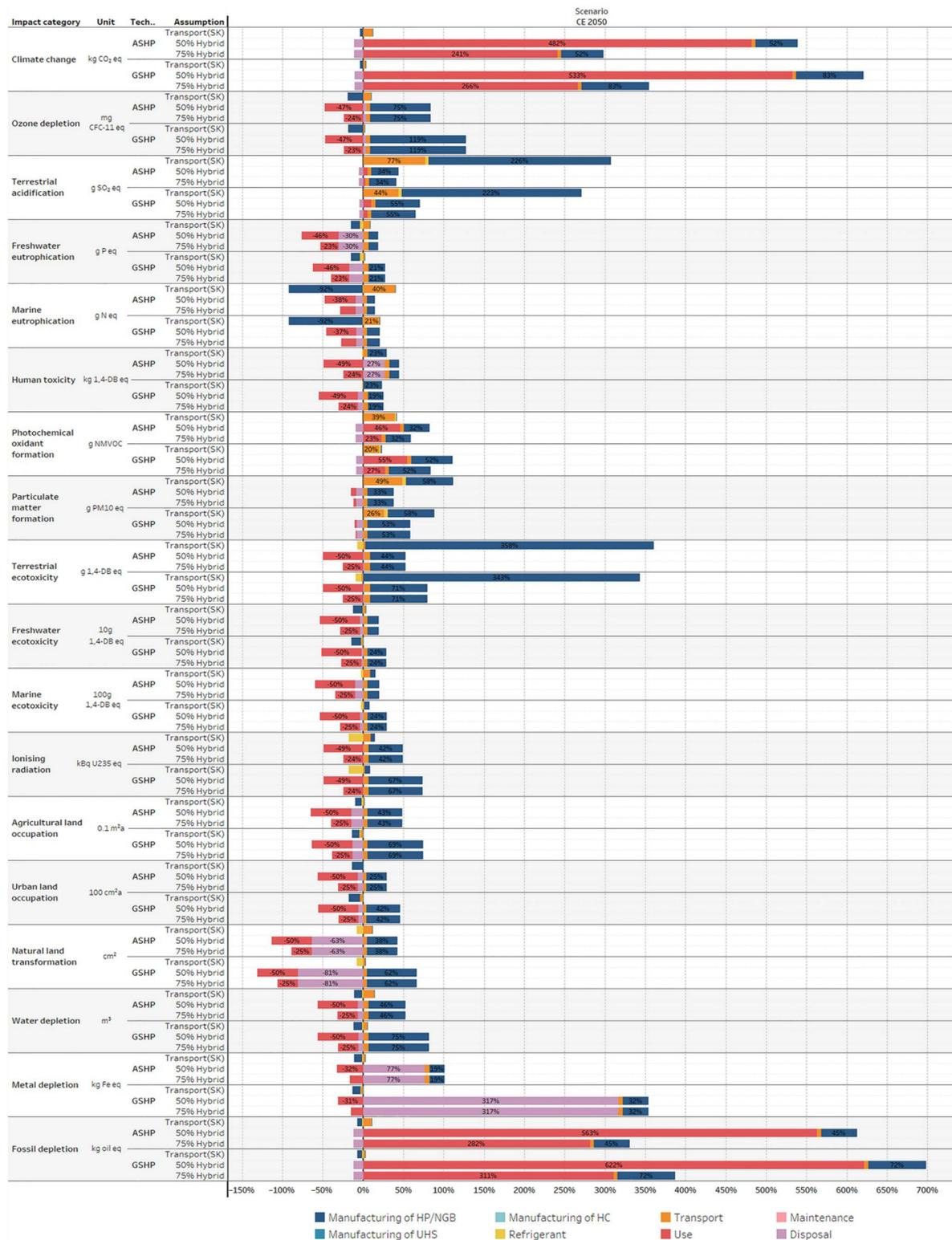


Figure 8. Lifecycle environmental impact change of phases for Transport (SK) and Hybrid scenarios according to CE scenario.

Even though hybrid scenarios in the CE 2050 model have similar results as the baseline model in most of the categories, there is a significant difference in CC and FD categories as they are very sensitive to the use phase results. In the 50% Hybrid scenario, the highest changes occur in the FD category with a 490% and 333% increase for ASHP and GSHP, similar to the baseline model (Figure 7). The other category suggesting an increase is CC with 409% and 360% for both heat pumps. The impact of the MD category is lower than the baseline model in the CE model. Most of the remaining categories have a reduction of around 16–47%.

The results of phases in the 50% Hybrid scenario illustrate that the highest changes occur in the manufacturing phase, with a 33% and 53% increase on average for both heat pumps (Figure 8). The transport phase creates an increase of 5% and 6% for ASHP and GSHP, respectively. The disposal phase, on the other hand, expects a decrease of 4% for ASHP and an increase of 8% for GSHP. However, the use phase suggests a decrease of around 5% on average for both heat pumps. Similar to the baseline model, the use phase offers a reduction in all categories and an increase for CC and FD categories with 482% and 563% for ASHP, and 533% and 622% for GSHP, respectively. The only exception is for the POF category, which was expecting a reduction in the baseline model but expecting an increase in the CE 2050 model. The main reason for this is that the result of NGB for this category is lower than heat pumps in the baseline model; however, in the CE 2050 model, NGB has a higher value and increases the average of hybrid results.

TA, FEU, and PMF categories have a reduction varying between 9% and 18%, whereas the remaining categories expect higher reductions varying between 30% and 48%. In the CE 2050 model, hybrid scenarios offer an overall increase in contrast to the baseline model mainly because the change in the CC category is greater than the baseline model and the weight of the use phase is lower in the CE 2050 model.

Similar to the baseline model, the 75% Hybrid scenario results offer less increase than the half-hybrid scenario with a 4% and 10% increase overall in ASHP and GSHP, respectively. The highest change occurs in CC and FD categories with a 205% and 246% increase for ASHP, and 181% and 167% increase for GSHP, respectively. The highest decreases occur in TE, IR, ALO and WD categories, varying between 19% and 22% for both heat pumps.

The changes in manufacturing, transport and disposal phases are similar to the baseline model in both hybrid scenarios, so there is no difference between the baseline and CE model and 50% and 75% Hybrid scenarios in these phases, except the use phase.

The results of hybrid scenarios offer a benefit to reduce the negative impacts caused by heat pumps in most of the categories. Even though this creates an increase in CC and FD categories and GHG emissions, negative consequences could be prevented. Moreover, replacing gas boilers with heat pumps requires a transition period, and hybrid applications could help to create a smoother transition.

3.4. Data Quality and Limitations

In order to validate the study, results are compared with the adopted study [35]. Impact categories vary between different calculation methods, but several impact categories are common in most of the studies so only these categories are compared. The CC impact result of ASHP is 0.225 kg CO₂e/kWh in the baseline model, which is 18% lower than the adopted study (0.276 kg CO₂e/kWh). The GSHP result is 0.168 kg CO₂e/kWh for the baseline model and the result from the adopted study is 0.189 kg CO₂e/kWh, which is lower around 11%. The OD category of the adopted study was 0.3 mg R11eq, which is 2% higher than this study (0.294 mg CFC-11eq). Additionally, TA category results for ASHP and GSHP were 0.86 and 0.59 g SO₂eq, which is 2% and 8% lower than this study's results, respectively (0.842 and 0.638 g SO₂eq). FEU and HT categories have higher differences that vary between 20% and 47%. The major reason causing these differences is the different methodology used for the models. This study used ReCiPe Midpoint (H) methodology;

however, the adopted study used CML 2 Baseline 2001 methodology. Moreover, the adopted study used GaBi software, and this study used SimaPro software.

The limitation of the Transport (SK) scenario is that even though South Korea is used as a manufacturing location, rest-of-the-world (RoW) data for production assumptions and input data have been used in SimaPro due to the lack of data availability. Transport simulations are specific to South Korea; however, manufacturing data are not specific.

The impacts of the electricity mix, heat demand, efficiencies of technologies, lifetime of the products and disposal phase have been assessed for a sensitivity analysis. The parameters have been decided as:

- Doubling renewable share in the electricity mix;
- 50% increase in SPF (in this analysis, the efficiency of the gas boiler has been increased from 90% to 95%);
- 25% reduction in heat demand;
- 25% increase in product lifetimes;
- 25% increase in recycling rates of materials.

The results of sensitivity analysis indicate that electricity use has a significant impact on heat pump results. Doubling the renewable share in the electricity mix creates positive and negative impacts in several categories for ASHP (Figure 9). The highest influences occur on IR, NLT, FD, and CC categories with a decrease of around 41%, 41%, 40% and 34%, respectively. However, it could increase the results of TE, ALO, WD, FE, MEU and ME categories with 97%, 95%, 76%, 52%, 42% and 42%. The renewable share has no impact on NGB as it uses natural gas only.

A 50% increase in SPF creates an average of 29% reduction overall, and the highest changes occur in TE and ALO categories, accounting for 70% and 50%, respectively. The remaining categories expect a reduction range from 8% to 39%. Increasing boiler efficiency from 90% to 95% reduces all impact categories by an average of 4%.

A 25% reduction in demand has both negative and positive impacts on categories. Even though the lifetime results expect a reduction in this analysis, functional unit results fluctuate as the lifetime results are divided into heat demand, which is 25% reduced. Therefore, some categories react differently in lifetime and functional unit results. The highest changes occur in TE and ALO categories, similar to SPF improvements for heat pumps. A similar issue occurs for the gas boiler and creates an increase of 4% overall, even though lifetime results are reduced.

Increasing the lifetime of products to 25 years increases the lifetime impact results as expected, with an increase of an average 16%, 15% and 22% for ASHP, GSHP and NGB. However, functional unit results expect a decrease of 7%, 8% and 2% for the technologies, respectively.

A 25% increase in the recycling rates of materials also has a significant impact in several categories for heat pumps such as TE, MEU and ALO categories, with a reduction of 56%, 26% and 25%, and the WD category with an increase of 36% for heat pumps. However, its impact is relatively low for gas boilers.

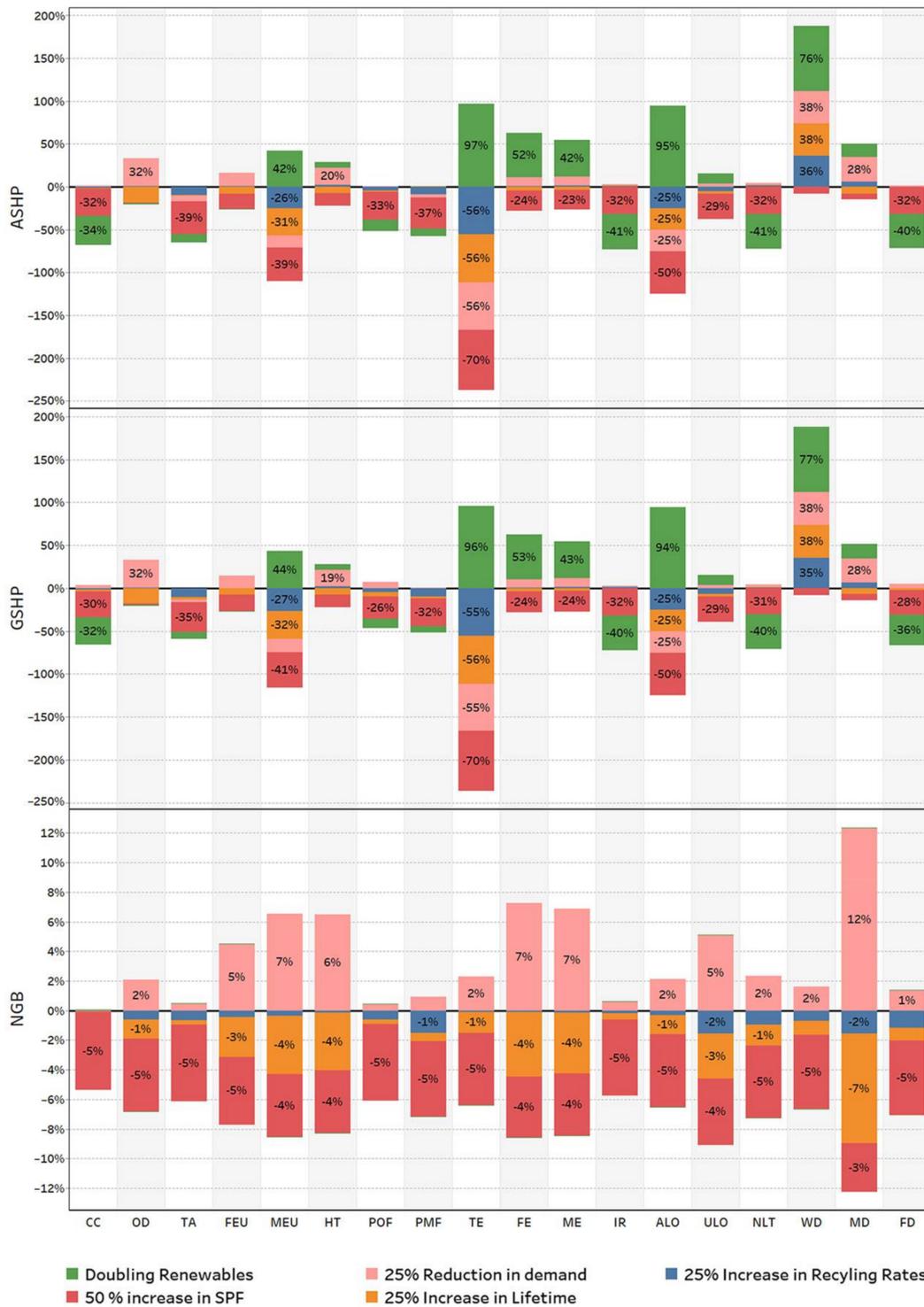


Figure 9. Impacts of different parameters on environmental results for heating technologies in sensitivity analysis.

4. Conclusions

This study assesses the environmental impacts of heat pumps vs. gas boilers through three main scenarios: Circular Economy (CE), Resource Efficiency (RE) and Limited Growth (LG), and three alternative scenarios: Transport (SK), 50% Hybrid and 75% Hybrid. The findings illustrate that replacing gas boilers with heat pumps could help to reduce lifetime GHG emissions by 78% (CE scenario), 77% (RE scenario) and 65% (LG scenario). The overall average impact is expected to be lower around 43% (CE scenario), 42% (RE scenario)

and 31% (LG scenario). However, the following categories MEU, TE, FE, ME, ALO and WD perform 5% lower in the CE than in the RE scenario.

Heat pumps provide significant reductions in GHG emissions and the fossil depletion category; however, they do not provide sustainable solutions in other impact categories. Moreover, future scenarios expect reductions in most of the categories; however, several categories expect an increase in contrast to remaining impact categories in all scenarios, such as freshwater ecotoxicity, marine ecotoxicity and metal depletion categories. It is important to point out that the high deployment of renewables, especially offshore wind farms, will have a positive impact in most of the categories, but also create toxicity problems and material scarcities.

Hybrid scenario results (50% Hybrid and 75% Hybrid) expect an increase in GHG emissions as boilers use fossil fuel, whereas the negative impacts coming from the remaining categories decrease. Therefore, a transition period that includes hybrid applications rather than replacing gas boilers individually should be provided in order to reduce negative impacts. In both hybrid scenarios, the overall results suggest a reduction in the baseline model (22% for 50% Hybrid scenario and 10% for 75% Hybrid scenario); however, the changes are 15% lower in the CE scenario. In the CC category, the changes are greater in the CE model as heat demand in the future will be relatively small; therefore, the importance of each phase will be higher to reduce the negative impacts. As the UK increases its ambitions to reach the 'Net-Zero' target, actions for each phase should be considered thoroughly.

In the Transport (SK) scenario, changing the manufacturing location from Europe to Asia creates a 1% reduction in the baseline model and a 2% increase in the CE model. The reason for this slight increase is that the weight of the use phase is lower in the CE scenario due to efficiency improvements in houses and low-carbon technologies, so the remaining phases comprise higher shares. As the main contributor to these changes is the manufacturing phase, better production lines through adapting CE principles could help to reduce the impact of the manufacturing phase. It is also important to reiterate that, even though the impact of the manufacturing phase is relatively smaller than the remaining phases (14% of the overall impact), the manufacturing of heat pumps has an impact in those locations where manufacturing takes place; therefore, this does not count in territorial emissions.

Future scenarios show how decision making could have a significant impact on environmental impacts. The CE scenario provides the best outcome among all scenarios without affecting economic growth. Reducing GHG emissions and preventing negative consequences are highlighted in the CE scenario. Achieving the Net-Zero target requires strong commitments, and the results of future scenarios emphasise that the importance of impacts proposed by changes will reduce in time. Therefore, quick implementation of changes and stronger commitments are required in other areas as well, mainly energy efficiency improvement in houses (insulation, etc.), better-installed heat pumps with higher efficiencies and greener manufacturing solutions.

High demand for specific materials could enhance scarcities and environmental degradation related to resource extraction and processing. Circular economy principles through reuse and recycle options become more important in these situations. However, new strategies are needed to reach the 'Net-Zero' target as it requires stronger commitments and more rapid market dissemination. Therefore, a comprehensive approach through a market introduction programme should be provided at the beginning before shifting from one technology to another. It is important to stress that different heating technologies require different material demands and waste streams. High deployment of heat pumps in the CE scenario (17.7 million) will require high demand for metals and minerals, even though they do not have significant impacts on GHG emissions in the manufacturing phase. It would be of utmost importance to develop CE standards for the production of heat pumps, e.g., through procurement or eco-design, and include the use of secondary materials and the re-usability of all components. Thus, a more comprehensive circular framework for decision-making tools could be created for sustainable design practice. A

holistic approach should be considered where both territorial and consumption-based emissions are considered together for policies and future planning.

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Abbreviations

ALO	Agricultural land occupation	MEU	Marine eutrophication
ASHP	Air source heat pump	NGB	Natural gas boiler
CC	Climate change	NLT	Natural land transformation
CCC	Climate Change Committee	OD	Ozone depletion
CE	Circular Economy	PMF	Particulate matter formation
FD	Fossil depletion	POF	Photochemical oxidant formation
FE	Freshwater ecotoxicity	RE	Resource Efficiency
FEU	Freshwater eutrophication	RHI	Renewable Heat Incentive
GSHP	Ground Source Heat Pump	RIBA	Royal Institute of British Architects
HC	Heat Collector	SK	South Korea
HP	Heat Pump	SPF	Seasonal performance factor
HT	Human toxicity	TA	Terrestrial acidification
IR	Ionising radiation	TE	Terrestrial ecotoxicity
LCA	Life cycle assessment	UHS	Underfloor heating system
LG	Limited growth	UK	United Kingdom
MD	Metal depletion	ULO	Urban land occupation
ME	Marine ecotoxicity	WD	Water depletion

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