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Net-zero life cycle supply chain assessment of heat pump technologies

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ABSTRACT

In this study, a comparative life cycle assessment of different heat pump technologies based on multiple supply chain scenarios according to the UK market has been conducted. In addition to conventional heat pumps – air-source heat pump (ASHP), ground-source heat pump (GSHP), and water-source heat pump (WSHP) - a novel hydrogen-source heat pump (HSHP) has been studied from an environmental aspect. Different supply chain scenarios have been developed for all technologies based on the leading supplier of heat pump components in the UK. Results showed that the manufacturing and operation of heat pumps are the main causes of the environmental impacts. Among the four technologies studied, ASHP had the highest negative environmental impacts across most categories. HSHP stands out with notably lower carbon emissions compared to other cases. However, in certain impact categories, HSHP exhibited more significant consequences, especially concerning land use and land-related pollution. Regarding CO_2 emissions, ASHP is projected to achieve the most substantial reduction, with expected reductions of 23 %, 60 %, and 97 % by 2030, 2040, and 2050, respectively. GSHP, WSHP, and HSHP are also predicted to experience significant CO_2 emission reductions of 94 %, 95 %, and 59 % by 2050, aligning with the UK's net-zero goal.

1. Introduction and state-of-the-art

Governments around the globe are progressively adopting the Paris Agreement under the United Nations Framework Convention on Climate Change and incorporating it into their national strategies with the goal of achieving net-zero carbon emissions by 2050 [1]. Over the past few decades, the rise in global population and the growing need for energy have resulted in a surge in the utilization of fossil fuels. This has subsequently led to detrimental consequences such as global warming, depletion of the ozone layer, and pollution of the environment [2]. Recent research indicates that there is an anticipated 50 % increase in greenhouse gas (GHG) emissions, making it the primary and most influential factor contributing to climate change by the year 2050 [3]. Global warming or climate change is one of the most concerning matters for government and policymakers. Urgent actions should be done to control and lessen the environmental adverse effects. One of the main scalable solutions to curb GHG emissions is improving building heating and cooling systems. Various policies have been implemented to address the substantial GHG emissions associated with space heating. Heat pump technologies are an environmentally friendly energy efficiency measures that have the capacity to significantly decrease carbon emissions associated with building heat on a large scale [4]. The European Union's Renewable Energy Directive offers subsidies for eligible heat pumps that have GHG emissions below specific thresholds. In 2009, heat-related activities accounted for one-third of the United Kingdom's (UK) GHG emissions, with three-quarters of those emissions attributed to space heating in the residential sector [5].

Although heat pumps have been recognized as effective in significantly reducing GHG emissions at both the district and building level, their adoption in the UK is not widespread [5]. Heat pump technology has a significant potential in reaching the decarbonisation and net zero goal in a long term as this system applies natural resources as energy source. Currently, the prevalent heating system in residential buildings in the UK is central heating powered by a natural gas-fired boiler (around 92 % in 2017) [6]. As a result of the Future Homes Standard, the UK Government has established a national objective to phase out fossil-fuel heating systems in new houses starting in 2025 [7]. In the UK, the majority of units sold, accounting for 87 %, are air-source heat pumps (ASHPs), followed by ground-source heat pumps (GSHPs) and water-source heat pumps (WSHPs) at 9 %. Hybrid systems, which

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combine a heat pump with a traditional fossil boiler in a compact unit, make up the remaining 4 % of the market [8].

In addition, green hydrogen production via electrolysis has been considered one of the most promising options to provide lower carbon energy for different applications. Electrolysers serve as a central element in future green hydrogen supply chains, and their widespread adoption reflects the systemic challenges of simultaneously increasing renewable energy capacity, establishing transport infrastructure, and implementing hydrogen end-use applications [9]. Hydrogen stands out as one of the most favourable choices to assume the role of an energy carrier in the energy system [10]. Green hydrogen could be applied as an energy source to provide the required cooling and heating for the building sector. Coupling hydrogen production systems with boilers or heat pumps can contribute to decarbonisation purposes. However, a comparative life cycle assessment (LCA) should be done on any energy system that needs to be scaled up.

Deng et al. [11] did a Life Cycle Assessment (LCA) study of a heat pump considering a gas engine as an energy source to understand its damaging effects on three endpoint indicators. They proposed to diminish the adverse consequences of the system, consumption of natural gas should be minimized. They also compared it with an electric heat pump. Heikkilä [12] studied a GSHP unit to provide heating and cooling in comparison with a traditional air conditioner from environmental performance. The obtained results presented that the GSHP system could have lower damaging environmental impacts over its lifetime. Shah et al. [13] studied three heating and cooling providers including a furnace, boiler, for heating using air conditioner for cooling applications, and ASHP in four different locations in the United States. They found that 15–40 % of the grid network should be supported with renewable energies to reduce the environmental impact of heat pumps. Jenkins et al. [14] assessed the carbon reduction potential of the GSHP in the domestic sector in the UK. They evaluated some influential elements such as unit size, working temperature, and the grid network. They proposed that a deeper finding of the grid network situation is needed to assess the damaging environmental impact for the future scenario.

Saner et al. [15] conducted an LCA evaluation of the GSHP system from the environmental benefits view that came from applying this technology. They also calculate the carbon saving of geothermal energy application over the heat pump lifetime. They predicted a significant carbon dioxide saving from around 31 to 88 % compared with fossil fuel-based systems. The carbon footprint calculation of ASHP technology installed in domestic buildings in the UK has been studied by Johnson [16]. The main goal of this study was to understand the consequences of Hydrofluorocarbon implementation in heat pumps. The research outcomes showed that hydrofluorocarbon (HFC) could lead to 20 % more carbon footprint for this technology in the UK. Greening and Azapagic [17] carried out a comparative LCA evaluation of all kinds of heat pumps (GSHP, WSHP, and ASHP) with gas boilers used in residential buildings considered for the UK. Their study showed that due to using electricity, heat pumps have higher damaging impacts than boilers. They proposed the impact of heat pumps could be minimized by developing an adequately decarbonised energy mix in the UK. Genkinger et al. [18] compared an ASHP system with two solar systems, photovoltaic and collector from an environmental aspect using the LCA approach. They consider these systems to provide hot water for the domestic sector. Their results showed that there is no significant difference in the environmental performance of the two considered systems.

Bayer et al. [19] carried out a review study on the GHG emission saving potential of GSHP in residential buildings in Europe. They considered the carbon footprint decline of domestic heating production replacement by alternative low-carbon technologies such as GSHP in the past up to future effects. Environmental and economic evaluations of three heating unit applications for domestic complexes such as coal and gas-based boilers and WSHP were done by Chengmin et al. [20]. Their assessment showed lower environmental impacts of WSHP compared with other systems. Abusoglu and Sedeeq [21] performed an exergo-environmental and LCA investigations of three main heating technologies in the domestic sector in Turkey. Their considered systems are condensing gas boiler, coal-based boiler and GSHP. Their results showed that the GSHP has the highest efficient performance from an energetic point of view, however, it causes more environmental impact compared with the two other systems. A hybrid gas engine-assisted heat pump (GEHP) is assessed from an environmental aspect using the LCA approach is carried out by Wang et al. [22]. Their assessment showed that the environmental impact of hybrid system is lower than GEHP when systems work got more than 1778 h. Three main heating systems (gas boiler, electric, and absorption heat pumps) are compared using the LCA methodology by Nitkiewicz and Sekret [23]. They considered three indicator types, single score, damaging, and impact categories. They used geothermal as an energy source for heat pumps which proved the potential of geothermal energy in the environmental impact reduction of the heat pump.

Russo et al. [24] investigated an LCA comparison of a solar GSHP and liquefied petroleum gas-based hot air provider to apply for a greenhouse. They assessed the consumed energy and electricity and environmental condition inside the greenhouses based on these two systems. they reported that the carbon footprint was halved using solar GSHP. Eicher et al. [25] performed an LCA evaluation of solar heat pump (SHP) to provide hot water and heating for the domestic sector. They studied the electricity mix's impact on environmental impacts. Their assessed system was compared with two other systems with the same lifespan. Li [26] conducted a life cycle climate performance evaluation of ASHP for domestic building in hot and cold weather areas. The seasonal energy efficiency ratio and refrigerant recovery effects on environmental performance of the system have been investigated. Mattinen et al. [27] performed an LCA comparison of three systems to provide heating for the residential sector including the ASHP, GSHP, and direct electric heating. They assessed the heat pumps based on the different ambient temperature. The Monte Carlo method and sensitivity analysis were used for uncertainty assessment and dominant variables' impacts on the system's carbon footprint. Huang and Mauerhofer [28] conducted a LCA assessment of a GSHP case study in China. Their investigation proved that this system has approximately 40 % energy savings during its lifetime. The main operation phase impact is variation in soil temperature and production phase impact on global warming, eutrophication, and acidification. they also calculated the cost reduction arising from using this HP technology.

Two heat providers, ASHP and radiator heating units, are compared based on the LCA methodology to assess their environmental performance by Zheng et al. [29]. Their modelling proved that approximately 34 % of carbon dioxide emission was achieved using ASHP. Koroneos and Nanaki [30] performed a cradle-to-gate LCA evaluation of GSHP for a case study in Greece. They calculated the energy consumption and emission amount for this system. The obtained results proved that acidification is the main damaging impact. Zhao et al. [31] analysed a hybrid gas heat pump coupled with a solar system from an environmental view. They conducted an optimisation considering normalized environmental consequences as the objective function to reduce the damaging impact of the system. Zhao et al. [32] investigated an energetic performance of a solar-based hybrid gas heat pump to reduce the energy consumption to generate heating and cooling. They also conducted a LCA analysis to find the environmental impact of added solar unit. Furthermore, the most optimum environmental payback time was calculated. The Life cycle climate performance (LCCP) comparison of a cooling/heating heat pump unit and boiler has been conducted by Choi et al. [33]. They calculated the amount of carbon dioxide reduction using a heat pump system. Besides, they investigated this system's environmental operation, the effect of diverse refrigerants, and climate conditions. Coupling a GSHP unit with a solar system and battery to apply for residential buildings was assessed from environmental and techno-economic viewpoints by Litjens et al. [34]. They compared their supposed system with a base case including a condensing gas boiler (CGB) system. They calculated the payback period and avoided GHG emissions for all considered systems.

LCA investigation and achieving energy saving by substituting the electric boilers (EBs) in residential building with ASHP were conducted by Latorre-Biel et al. [35]. They supposed three different heat emitters in their study such as common and low-temperature radiators and underfloor heating. Ren et al. [36] performed an LCA investigation on the polyethylene and steel GSHP in seasonal performance and based on the experimental monitoring. Their assessment comprises environmental, economic, and social evaluation. The payback period, Coefficient of Performance (COP), and carbon saving were calculated in this research. A critical review of the sustainability assessment of heat pumps is conducted by Marinelli et al. [37]. They considered the applied assumptions and methods in system modelling and analysed the obtained results. Marinelli et al. [38] analysed a dual-source heat pump (DSHP) using both air and ground thermal potential as an energy source. They compared this system's environmental performance with conventional GSHP and ASHP. The influence of the type of energy use and mix on the environmental impact is studied. Tveit et al. [39] did an LCA analysis of heat pump working under high temperatures. They also conduct thermodynamic, and exergy modelling of the system. They consider ways to improve the installation of this system and lessen relevant damaging impacts. A cradle-to-gate environmental investigation of two GSHP systems (absorption solar GSHP and vapor compression vapor GSHP) has been done according to LCA principles by Li et al. [40]. They compared several impact factors during these systems' lifespan and suggested some potential impact reductions. Sevindik and Spataru [41] conducted an environmental analysis of heat pump technology with gas boiler considering different scenarios. They considered two hybrid scenarios based on 50 % and 25 % heating generation by gas boiler in hybrid HPs. The calculation showed that hybris scenarios lead to higher GHG damaging impacts, however had declining trends in other categories. Dai et al. [42] developed the LCA and thermodynamic models to assess the energy consumption and emission saving of applying a heat pump system for the drying process. They calculated the emission impact reduction using this system against EB.

Several energy systems to provide energy for the domestic sector have been studied by Bahlawan et al. [43] from an environmental point of view. The considered technologies are ASHP, GSHP, absorption chiller (ACH), solar system, solar collector, combined heat, and power (CHP), and biomass boiler (BB). Their evaluation included different ranges of power production. Wang et al. [44] proposed a LCA methodology based on the local policy and regulations for a case study in China. Besides, they combined their environmental assessment with economic and exergy analysis in their study. They considered different systems such as coal boiler (CB), gas boiler (GB), GSHP, gas-based absorption and heating units, and electric air conditioning (EAC). Famiglietti et al. [45] compared two units, a gas-driven absorption heat pump (GDAHP) and CGB, from an environmental aspect. Their results presented that 97 % of the total impact originated from the use phase in both systems. The damaging impacts have been reduced by around 22 % by using GDAHP. They also conducted uncertainty evaluation for both systems. Lin et al. [5] compared a hybrid heat pump (HHP) with CGB for a case study from environmental impact view in the UK. Their assessment illustrated that the HHP saves around 30 % more GHG emission than CGB, however, in some impacts such as human toxicity, water depletion and metal depletion, HHP impact is 3–6 times higher. Refrigerant leakage causes 17 % of GHG emissions in HHP. The effect of GSHP application from environmental and energetic views for a state in the USA based on different energy mix scenarios is performed by Smith et al. [46]. They aimed to find the emissions diminish the potential of this technology in the building sector. Implementing the GSHP showed an environmental benefit in both mid and endpoint impact factors compared to using the fossil fuel-based systems. They suggested it is a promising option for environmental impact and end-use energy consumption stage along with low carbon energy providing strategy.

A novel heat pump system coupled with solar and battery systems was designed by Llantoy et al. [47] to compare its environmental impacts with an ASHP unit to provide heating and hot water for a case study in Germany. They proposed that the novel system has lower adverse impacts. They also conducted a parametric evaluation to find the impact of refrigerants. Sevindik et al. [48] compared heat pump and gas boiler technologies from environmental based on circular economy prospects in the UK. Their evaluation showed that around 14 and 74 % of the total impact arising from the manufacturing and use phases respectively. They mentioned that supposing a circular economic approach can lead to a 44 % and 27 % impact diminish for the heat pump and boiler in order. Saoud et al. [49] investigated an LCA evaluation of ASHP in comparison with an electric heater and solar-based heater using SimaPro and the IMPACT 2002+ method. They selected 416100 L water at 60 C degree as a functional unit. They showed operation phase in all three cases is the cause of the majority of environmental impacts. They also calculated the carbon dioxide saving amount by using ASHP instead of two other units. LCA assessment of a solar-based reversible HP in comparison with other conventional systems has done for a case study in Italy by Riva et al. [50]. Moreover, they analysed the influence of solar panel numbers and unit location on the environmental performance of system. A comparative LCA study of a cascade heat pump and natural gas furnace was conducted by Addo-Binney et al. [51]. They aimed to analyse the environmental impacts, cost, and energy savings potential of heat pump technology. Obtained results presented that the significant damaging impact reduction could be achieved using HP instead gas-based system.

A comparative cradle-to-grave LCA evaluation of an ASHP and CGB for a case study in Germany is done by Naumann et al. [52]. Their analysis showed that the most damaging impacts are related to the operation phase for both systems and in 8 out of 11 impact categories, the gas system has a lower impact. Carbone intensity of CGB was 70 % higher than GSHP due to the limitation of carbon reduction of the gas-fired system. Comparative LCCP and energy assessment of boilers and GSHP and solar-based GSHP have been done by Lee et al. [53]. Different refrigerants are examined to understand their impacts on the environmental and energetic factors. Energetic, economic, and environmental assessment of ASHP and GB in both hot and cold climate conditions was done by Chen and Li [54]. This research aimed to calculate the energy saving, carbon and other pollutants diminish and operating costs of both units. A comparative cradle-to-grave LCA assessment of GSHP and ASHP has been conducted by Violante et al. [55]. Results showed the ASHP has a higher impact in the operation phase, however, the manufacturing and installation phase cause a higher impact in GSHP. They mentioned that geothermal probe has a long lifespan (around 100 years), in general, GSHP is a more efficient and environmentally friendly system considering its longer lifetime. A comparative analysis of three different systems - CGB, an air-source gas-driven absorption heat pump, and an air-source electric-driven heat pump - was conducted by Famiglietti et al. [56]. The study also explored the use of hydrogen as a potential energy source for gas-driven equipment.

According to a comprehensive literature review conducted on LCA on heat pump technologies, it can be found that there are some important and challenging points that have been studied rarely by other scholars. This study addresses several key gaps in the sustainability assessment of the heat pump industry. Most published research focused on the environmental impact assessment of one heat pump technology or comparing two or three conventional heat pump types (ASHP, GSHP, and WSHP). This means that previous research has primarily focused on evaluating the technological sustainability of heat pumps. In other words, a comprehensive life cycle sustainability assessment of the heat pump industry's supply chain has been limited. This study aims to fill that gap by conducting a comparative assessment of the environmental impacts of various heat pump technologies within the UK market. This research specifically examines the heat pump market from a supply chain perspective, considering the unique context of the UK, which has not been thoroughly analysed in earlier studies. Importantly, this study explores a novel heat pump technology known as the HSHP, which uses hydrogen as an energy source rather than relying on the electricity grid which to the best of our knowledge has not been defined and assessed before. For the HSHP system, the supply chain assessment includes both the heat pump unit and the electrolysis process. This study introduces this type of heat pump to evaluate its potential as a sustainable alternative to conventional heat pumps. In this study, different supply chain scenarios have been expanded based on the main supplier of heat pumps in the UK market. For each heat pump system, five different supply chain pathways have been analysed. For each supplier two different approaches have been considered, first based on the 100 % of component manufacturing in the base country and the second based on 50 % of manufacturing in the base country and 50 % of manufacturing in the UK. The second one has been evaluated to understand the environmental impacts of the entire supply chain with establishing or expanding companies in the UK based on the current energy mix situation. Another forecasting evaluation has been conducted based on the net zero roadmaps in the UK for each decade from 2030 to 2050. This predictive comparative environmental impact assessment of different heat pump technology supply chains is another novel aspect of this study. This comprehensive supply chain environmental impact study, focusing on the UK market, has not been done in previous published works. This research reviews 4 heat pump technologies, maps 56 scenarios of these heat pump supply chains to the UK, conducts comparative LCA of these scenarios including projections to 2030, 2040, and 2050, discovers environmental hotspots, and discusses the manufacturing and energy implications to the UK net-zero goals. New insights from the comparative LCA suggest future supply chain strategy to combine reshoring and phasing economic partnerships for mature technologies and investing in new technologies to build long-term net-zero innovation capability and a sustainable and resilient supply chain. In addition, a Techno-Environmental Sustainability (TES) index is defined to provide a structured approach to evaluating and comparing the environmental sustainability of heat pump technologies. By considering multiple facets of the supply chain, TES enables stakeholders to make informed decisions aimed at reducing the environmental impact of their heating solutions which is another novel edge of this study.

Fig. 1 illustrates research on different heating and cooling systems for buildings, revealing that none of the studies have examined the HSHP to date. In the search for alternatives to carbon-heavy fossil fuels, hydrogen has proven to be a promising option because of its versatility for various applications. Hydrogen can function as an energy storage solution for heat and power generation, a feedstock in the chemical and processing industries, or a transportation fuel. Its potential in these various fields is considerable [57]. Additionally, there has been a marked rise in both academic and corporate interest in green and sustainable supply chain management [58].

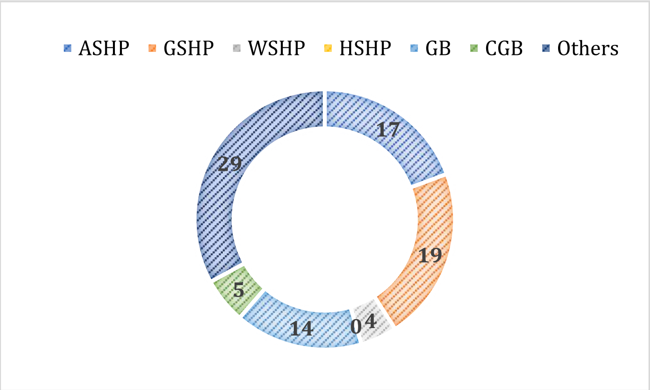

Fig. 1. Number of research on different domestic heating/cooling systems.

2. Different heat pump technologies

2.1. ASHP

The ASHP system is the most commonly utilized air conditioning system in the building sector [59]. The ASHP relies on outdoor air as a heat sink, and the performance of this system is greatly influenced by the outdoor temperature and humidity conditions. These factors play a crucial role in achieving optimal performance of the heat pump. The ASHP utilizes an air fan instead of a heat collector, which is positioned outside the house in the open air. To compensate for the absence of a heat collector, ASHP systems incorporate a larger evaporator to enhance system efficiency [17]. The main sections of analysed ASHP are evaporator, condenser, insulation applied in wiring and piping, compressor, air fan, lubricating oil, valve, and refrigerant which their relevant values are presented in tables present din supplementary information file. The ASHP employs an air fan instead of a heat collector, positioned outdoors in open air. ASHPs utilize ambient air to generate warmth indoors. Initially, the outdoor unit, containing a fan and refrigerant coil, draws in surrounding air. As the air passes over the refrigerant coil, the refrigerant absorbs its heat, transforming it into a low-pressure gas. A compressor then heightens the temperature and pressure of this gas. This warm refrigerant gas is transported to the indoor unit, where it releases its heat to warm indoor air through a heat exchanger. Upon expelling heat, the refrigerant returns to a liquid state and repeats the cycle. ASHPs can also function in reverse, extracting indoor heat to provide outdoor cooling. This flexibility makes ASHPs efficient solutions for both heating and cooling in various settings. A standard design capacity of 10 kW is assumed for each of the heat pumps. In this study, standard Seasonal Performance Factors (SPFs) have been assumed to be 2.8 for the ASHP commonly used in the UK [17]. The COP for the systems is around 3.5. Furthermore, R-134a is regarded as a refrigerant for all heat pump systems.

2.2. GSHP

A GSHP utilizes the renewable energy stored beneath the ground as a heat source to efficiently meet the heating and cooling needs of buildings. This sustainable approach involves extracting the stored energy through closed-loop heat collection pipes, which provide space heating/cooling and domestic hot water. Generally, a GSHP operates on electricity and has the ability to produce three to four times more heating energy than the amount of electrical energy consumed to power it [60]. Among the various renewable resources, geothermal energy is particularly promising because it can offer a stable and continuous energy supply without the challenges of intermittency [61–64]. The heat collector is employed to draw low-grade heat from a source, which is then utilized in the evaporator to vaporize the refrigerant. Subsequently, the compressed gaseous refrigerant undergoes an increase in pressure and temperature, transferring high-grade heat to water in the heat distribution system for space heating purposes. During this process, the refrigerant cools and condenses before passing through an expansion valve to reduce its pressure, thus restarting the cycle. SPF has been assumed to be 3.9 for the GSHP [17].

2.3. WSHP

A WSHP uses heat energy from water to generate residential heating and hot water. Like air source heat pumps, WSHPs can extract energy from water, even at lower temperatures than the desired indoor air, and convert it into heat. Both GSHP and WSHP use external heat collectors, typically installed underground for GSHP or submerged in a water body for WSHP [17]. SPF has been assumed to be 3.9 for the WSHP [17]. The principle of operation for WSHP is similar to that of GSHP, with the main difference lying in the utilization of distinct heat sources.

2.4. HSHP

A heat pump that relies on hydrogen as its primary fuel source for heat generation is known as a hydrogen-based heat pump. This system functions similarly to conventional heat pumps but utilizes hydrogen gas instead of electricity, or fossil fuel as its energy source. Hydrogen is typically generated via electrolysis, often utilizing renewable energy sources, and subsequently stored for later use. Once stored, the hydrogen is directed into a fuel cell embedded within the heat pump, where it reacts chemically with oxygen to generate electricity, heat, and water. This electricity powers the compressor and other essential components of the heat pump, while the generated heat can be utilized for heating purposes. The structure of the HSHP typically includes crucial elements like a hydrogen supply system integrating predictive technology like alkaline electrolysis, in addition to storage tanks or other methods for storing and distributing hydrogen to the heat pump. The conversion of generated hydrogen and oxygen into electricity, heat, and water, provides a sustainable and efficient energy source for powering the heat pump's operation. The heat pump unit component and structure are similar to the ASHP unit. Utilizing hydrogen as its energy source enables this system to function autonomously, detached from reliance on the electrical grid. This approach offers a sustainable and potentially carbon-neutral solution for heating and cooling needs, particularly when the hydrogen is derived from renewable resources. SPF has been assumed to be approximately 3.9 for the HSHP. This system has not been studied from an environmental point of view.

3. Methodology

3.1. Life cycle assessment

LCAs find extensive application in facilitating decisions for transformative strategies, such as the decarbonisation of energy systems, the adoption of circular economy practices, and the promotion of sustainable consumption in diverse energy and environmental-related contexts [65]. LCA takes into account all energy and material exchanges with the environment that occur throughout the entire life cycle [66]. LCA can serve as a valuable tool for making informed decisions by systematically monitoring a diverse range of environmental impacts throughout the entire product development value chain. LCA involves collecting and assessing the inputs, outputs, and potential environmental consequences of a product system throughout its entire life cycle [67]. To conduct LCA assessment and system modelling OpenLCA open-source software v1.11 has been applied. The main four phases of the LCA approach are shown in Fig. 2.

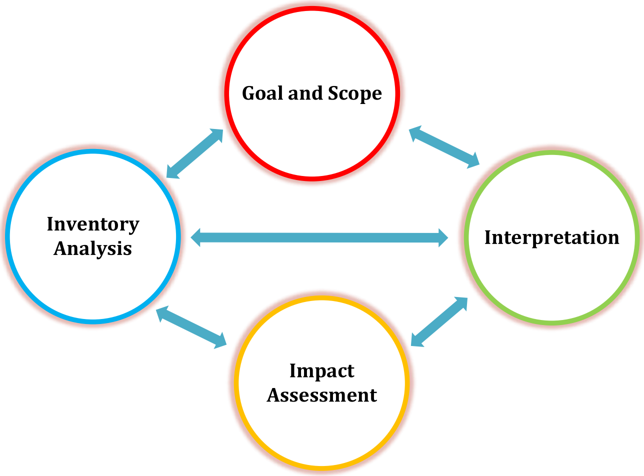

Fig. 2. Four main phases of LCA approach.

The main goal and scope of this life cycle supply chain assessment is comparing different heat pump technologies including HSHP during their life cycle from the environmental point of view based on the different heat pump supply chain schemes according to the UK market. It seeks to find the most sustainable supply chain environmental impact of the heat pump industry for the UK. The defined system boundary in this study includes raw material extraction, manufacturing, operation and maintenance (O&M), assembly and installation (A&I), and transportation and distribution as shown in Fig. 3. End-of-life phase has been excluded from this study due to the lack of complete data and its insignificant impact compared with other dominant phases. According to previous studies on the environmental impact assessment of heat pumps, the negative effects during the end-of-life phase of these technologies are substantially lower than those in other phases [17,52]. There are additional limitations besides the exclusion of end-of-life considerations due to data incompleteness. Technological advancements and improvements over time have not been taken into account in this study. External factors, including policy changes, market dynamics, and supply chain disruptions, can influence the environmental impact but are challenging to incorporate into the LCA. This study does not account for dynamic changes such as variations in market conditions or regulatory landscapes over time. Different impact assessment methods can produce varying results, and the chosen methodology can affect the interpretation of environmental impacts. In this study, consistent methods were applied across all technologies and scenarios.

Required data has been collected from different sources such as literature (detailed in the Supplementary Information), ecoinvent v3.9 database, ELCD database, and Environmental Footprint (EF). For the life cycle impact assessment, the ReCiPe 2016 midpoint has been applied to calculate the environmental impacts. The selected functional unit for all case studies is 1 kWh of produced energy by heat pumps. 25-year lifetime has been assumed for all systems.

3.2. Defined scenarios

In this study, 14 different scenarios have been developed to compare various supply chain pathways to supply the heat pump market per heat pump technology. Four heat pump technologies have been considered, so a total of 56 scenarios have been modelled. The main supplier of the UK heat pump market has been chosen based on the government report and the main exporter of the heat pump component to the UK [8]. The base scenarios are expanded supposing 100 % of heat pump components are manufactured in the exporter country and shipped to the UK. Another scenario is considered assuming that 50 % of the component is manufactured in the exporter country and 50 % in the UK. For each heat pump technology, five main exporters have been considered. The final delivery point of all scenarios is considered to be in London except for Ireland where the final destination is assumed to be in Manchester. Included in the calculation, it should be mentioned that the distribution is considered from the point of manufacturing in the exporter country and then transporting components to the mentioned port for export. The destination ports in the UK are selected based on the location of the exporter country. Regarding the electrolysis for HSHP, three main countries are considered as manufacturers; for the China case, it has been assumed that electrolysis is manufactured in China and exported with the heat pump to the UK; for the Germany case, we considered electrolysis manufactured in Germany and export with considered heat pump to the UK, and for other cases we considered electrolysis manufactured in France.

The base scenarios which are numbered from 1 to 5 with a letter before the number (A for ASHP, G for GSHP, W for WSHP, and H for HSHP), have been developed according to 100 % of the manufacturing

Fig. 3. Considered phases of heat pump life cycle supply chain assessment.

of heat pump components in the exporter country and then transporting them to the UK. Other scenarios which have numbered from 6 to 10 have been developed assuming 50 % of heat pump component construction in the exporter country and the remaining 50 % manufactured in the UK. These modelled scenarios are compared with a future supply chain scheme assuming 100 % of heat pump components are manufactured in the UK which has been numbered with 11. In addition, the scenarios numbered 11 to 14 represent the forecasting of 100 % of manufacturing of components in the UK for the future (2030, 2040, and 2050) according to the net-zero goal in the UK. The summaries of distribution and supply chain scenarios are presented in Tables 1 and 2. In this analysis, we assume that lorries intended for regional and cross-country transport have a capacity of 32 tonnes. Similarly, we assume that cargo ships used for international sea transport typically have a capacity of around 7500 Twenty-foot Equivalent Units (TEU).

3.3. *Life cycle inventory*

During the life cycle inventory phase, it is essential to quantify the system's inputs, such as energy and material requirements, as well as the system's outputs [68]. Assessing data quality is a crucial procedure to ensure the data's accuracy, reliability, and relevance for the study. The collected data is evaluated based on key criteria, including reliability, completeness, temporal relevance, geographical relevance, and technological relevance. All data applied in life cycle modelling are presented in the Supplementary Information file. The data presented includes different phases (system manufacturing, O&M, and A&I). It has been assumed that the timeframes for data collection and analysis are consistent across all heat pumps to enable fair comparison. End-of-life is excluded from this study due to limited data availability for all technologies and to avoid uncertainty increment of results. It is essential to acknowledge and communicate these assumptions transparently to ensure the validity and reliability of the study results. Table 3 provides a condensed overview of the specifics of the LCA study.

4. Results and discussion

A comparative life cycle supply chain study of four different heat pump technologies including ASHP, GSHP, WSHP, and HSHP is carried out in this study using LCA methodology. The modelling is expanded using OpenLCA software v1.11. Several databases are applied to model these systems based on the secondary data. This study seeks the more sustainable solution for heat pump supply chain in the UK to reduce the carbon footprint and other pollutant elements over the system's lifetime. The base scenarios were based on the assumption that all heat pump components would be manufactured in the exporting country and then transported to the UK. Alternative scenarios were also considered, assuming that 50 % of the component production would take place in the exporting country and the remaining 50 % would be manufactured in the UK. These scenarios were compared to a supply chain model where 100 % of the heat pump components were manufactured in the UK. In addition, three more scenarios for all technologies are forecast for 2030, 2040, and 2050 aligning with the net zero plan in the UK supported by the heat pump supply chain environmental impact variations based on this plan. To validate and assess the viability of our model, we compared it with a previous study, and the results are presented in Table 4.

4.1. *Life cycle environmental impact of ASHP*

Fig. 4 displays the 18 mid-point impact category values for all the considered ASHP (Air Source Heat Pump) scenarios. Among these scenarios, A4 stands out with the highest environmental impacts in all categories. This can be primarily attributed to China's higher reliance on coal and fossil fuel-based energy, leading to more detrimental effects during the manufacturing of heat pump components. Additionally, the transportation of these components from China to the UK contributes to increased pollution compared to other scenarios. Offshoring heat pump production to countries with lower labour costs, may result in cheaper end products for consumers. However, from an environmental standpoint, it would be more beneficial to reshoring the heat pump industry or establish new manufacturing facilities within the UK instead of importing from China. This transition would require incentives from the UK government to subsidize production costs and make them more affordable and competitive with Chinese products. Comparing the environmental impacts of heat pump production across various

Table 1
Summary of transportation and distribution for each supply chain scenarios.

NO	Exporter country	From	To	Distribution centre in	Transportation way
ASHP					
1	Sweden	Gothenburg port	Southampton port	London	Lorry and cargo ship
2	South Korea	Busan port	Southampton port	London	Lorry and cargo ship
3	Ireland	Dublin port	Liverpool port	Manchester	Lorry and cargo ship
4	China	Shenzhen port	Southampton port	London	Lorry and cargo ship
5	Spain	Barcelona port	Southampton port	London	Lorry and cargo ship
GSHP, WSHP and HSHP					
1	Sweden	Gothenburg port	Southampton port	London	Lorry and cargo ship
2	Germany	From factory to German port	Dover port (UK)	London	Lorry and cargo ship
3	Austria	From factory to Austrian port	Dover port (UK)	London	Lorry and cargo ship
4	Italy	From factory to Italy port	Dover port (UK)	London	Lorry and cargo ship
5	China	Shenzhen port	Southampton port	London	Lorry and cargo ship
Electrolysis					
1	France	From factory to Calais port in France	Dover port (UK)	London	Lorry and cargo ship
2	Germany	From factory to German port	Dover port (UK)	London	Lorry and cargo ship
3	China	Shenzhen port	Southampton port	London	Lorry and cargo ship

Table 2
Summary of considered scenarios for all technologies.

ASHP		GSHP	
Scenario	Manufacturing	Scenario	Manufacturing
A1	100 % in Sweden	G1	100 % in Sweden
A2	100 % in South Korea	G2	100 % in Germany
A3	100 % in Ireland	G3	100 % in Austria
A4	100 % in China	G4	100 % in Italy
A5	100 % in Spain	G5	100 % in China
A6	50 % in Sweden & 50 % in UK	G6	50 % in Sweden & 50 % in UK
A7	50 % in South Korea & 50 % in UK	G7	50 % in Germany & 50 % in UK
A8	50 % in Ireland & 50 % in UK	G8	50 % in Austria & 50 % in UK
A9	50 % in China & 50 % in UK	G9	50 % in Italy & 50 % in UK
A10	50 % in Spain & 50 % in UK	G10	50 % in China & 50 % in UK
A11	100 % in UK	G11	100 % in UK
A12	100 % in UK (2030)	G12	100 % in UK (2030)
A13	100 % in UK (2040)	G13	100 % in UK (2040)
A14	100 % in UK (2050)	G14	100 % in UK (2050)

WSHP		**HSHP**	
Scenario	**Manufacturing**	**Scenario**	**Manufacturing**
W1	100 % in Sweden	H1	100 % of heat pump in Sweden and 100 % of electrolysis in France
W2	100 % in Germany	H2	100 % of heat pump and electrolysis in Germany
W3	100 % in Austria	H3	100 % of heat pump in Austria and 100 % of electrolysis in France
W4	100 % in Italy	H4	100 % of heat pump in Italy and 100 % of electrolysis in France
W5	100 % in China	H5	100 % of heat pump and electrolysis in China
W6	50 % in Sweden & 50 % in UK	H6	50 % of heat pump in Sweden and 50 % of electrolysis in France & 50 % of heat pump and electrolysis in UK
W7	50 % in Germany & 50 % in UK	H7	50 % of heat pump and electrolysis in Germany & 50 % of heat pump and electrolysis in UK
W8	50 % in Austria & 50 % in UK	H8	50 % of heat pump in Austria and 50 % of electrolysis in France & 50 % of heat pump and electrolysis in UK
W9	50 % in Italy & 50 % in UK	H9	50 % of heat pump in Italy and 50 % of electrolysis in France & 50 % of heat pump and electrolysis in UK
W10	50 % in China & 50 % in UK	H10	50 % of heat pump and electrolysis in China & 50 % of heat pump and electrolysis in UK
W11	100 % in UK	H11	100 % of heat pump and electrolysis in UK
W12	100 % in UK (2030)	H12	100 % of heat pump and electrolysis in UK (2030)
W13	100 % in UK (2040)	H13	100 % of heat pump and electrolysis in UK (2040)
W14	100 % in UK (2050)	H14	100 % of heat pump and electrolysis in UK (2050)

Table 3
Summary of implemented LCA assessment.

Item	Information
Defined goal and scope	• Conducting a comparative life cycle sustainability assessment of various heat pump technologies. • Introducing HSHP as a sustainable solution substitutable with conventional residential heating systems. • Comparing different international scenarios for the heat pump supply chain to meet the demand in the UK market. • Evaluating the impact of the UK's net-zero target on the environmental supply chain of the heat pump industry.
Studied systems	ASHP, GSHP, WSHP and HSHP
Functional unit	1 kWh of produced energy by heat pumps
System boundary	Cradle-to-gate (including raw material extraction, manufacturing, operation and maintenance (O&M), assembly and installation (A&I), transportation and distribution phases)
Software	OpenLCA v1.11
Gathered data	Secondary data (literature and ecoinvent v3.9 database, ELCD database, and Environmental Footprint (EF))
Chosen impact categories	18 midpoints
Life cycle impact assessment method	ReCiPe 2016

Table 4
Comparison of our model with previous study.

System	Parameter	Unit	Ref. model [17]	Our model
ASHP	CC	Mt CO_2 eq/kWh	122	121.2
WSHP	CC	Mt CO_2 eq/kWh	80	79.81
GSHP	CC	Mt CO_2 eq/kWh	80.5	80.32

countries, the UK performs better than South Korea and China in most impact categories but lags behind other considered European countries. This suggests that the UK's energy mix requires more proactive measures to become greener, such as developing renewable energy-based electricity generation and adopting less pollutant technologies.

Moreover, Sweden's adoption of a greener energy mix has minimized the environmental impact of heat pump production compared to other scenarios, resulting in a lower overall environmental footprint throughout the entire supply chain. For example, in the A1 scenario, production emits 0.15 g/kWh less CO_2 than A4, 0.13 g/kWh less than A2, 0.7 g/kWh less than A3, 0.06 g/kWh less than A4, and 0.07 g/kWh less than A11 over the system's lifetime. These findings highlight the significance of a more sustainable electricity grid network in the manufacturing of heat pumps. Comparatively, the production of heat pumps in China exhibits significantly higher impacts in certain categories such as PMF, POF, TE, NLT, ULO, and WD. These disparities primarily stem from the utilization of fossil fuels in both the manufacturing and transportation phases. However, considering the A9 scenario, the impacts on TE and ULO are roughly halved compared to those in China. This improvement is primarily due to the UK's grid network emitting fewer pollutants in this scenario.

In specific instances, pollutants like ALO and ULO show lower values in scenario A6. This is primarily attributed to Sweden's increased use of renewable energy sources, such as solar, wind turbines, and biomass, for electricity generation, resulting in reduced land use-based impacts. Conversely, air pollutant impacts like CC, POF, and PMF demonstrate higher values in scenario A6, largely due to the UK grid network's heavier dependence on energy sources that emit more pollutants. Overall, it can be noted that the heat pump supplied from Ireland and Spain exhibits similar impacts across most categories.

4.2. Life cycle environmental impact of GSHP

Fig. 5 illustrates the 18 mid-point environmental impact categories of GSHP based on various defined supply chain scenarios catering to the UK market. Similar to previous cases, China consistently exhibits higher impacts across most categories compared to other supply chain schemes for GSHP. However, in certain categories, sourcing the entire heat pump component from Italy leads to higher damaging impacts than China. These categories include TE, ULO, WD, and OD, primarily due to Italy's higher reliance on fossil fuel-based energy mix and the use of pollutant materials in the manufacturing process. Additionally, it's worth noting that transportation from Italy involves longer distances compared to other considered European routes. In the context of the examined supply chain plans, Sweden has the lowest level of emitted CO_2. This is

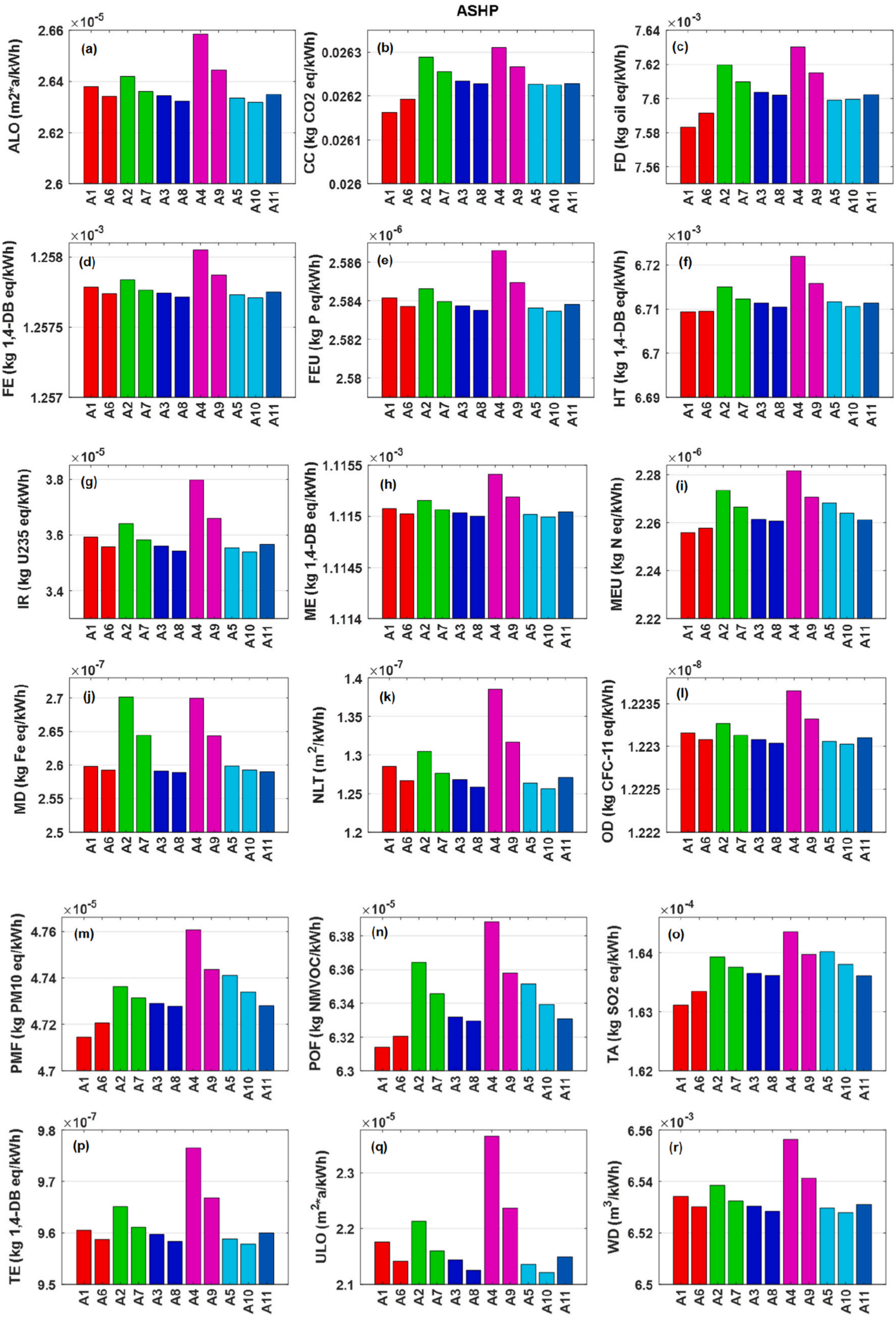

Fig. 4. Impact categories comparison for all defined ASHP supply chain scenarios, (a) agricultural land occupation, (b) climate change, (c) fossil depletion, (d) freshwater ecotoxicity, (e) freshwater eutrophication, (f) human toxicity, (g) ionising radiation, (h) marine ecotoxicity, (i) marine eutrophication, (j) metal depletion, (k) natural land transformation, (l) ozone depletion, (m) particulate matter formation, (n) photochemical oxidant formation, (o) terrestrial acidification, (p) terrestrial ecotoxicity, (q) urban land occupation, (r) water depletion.

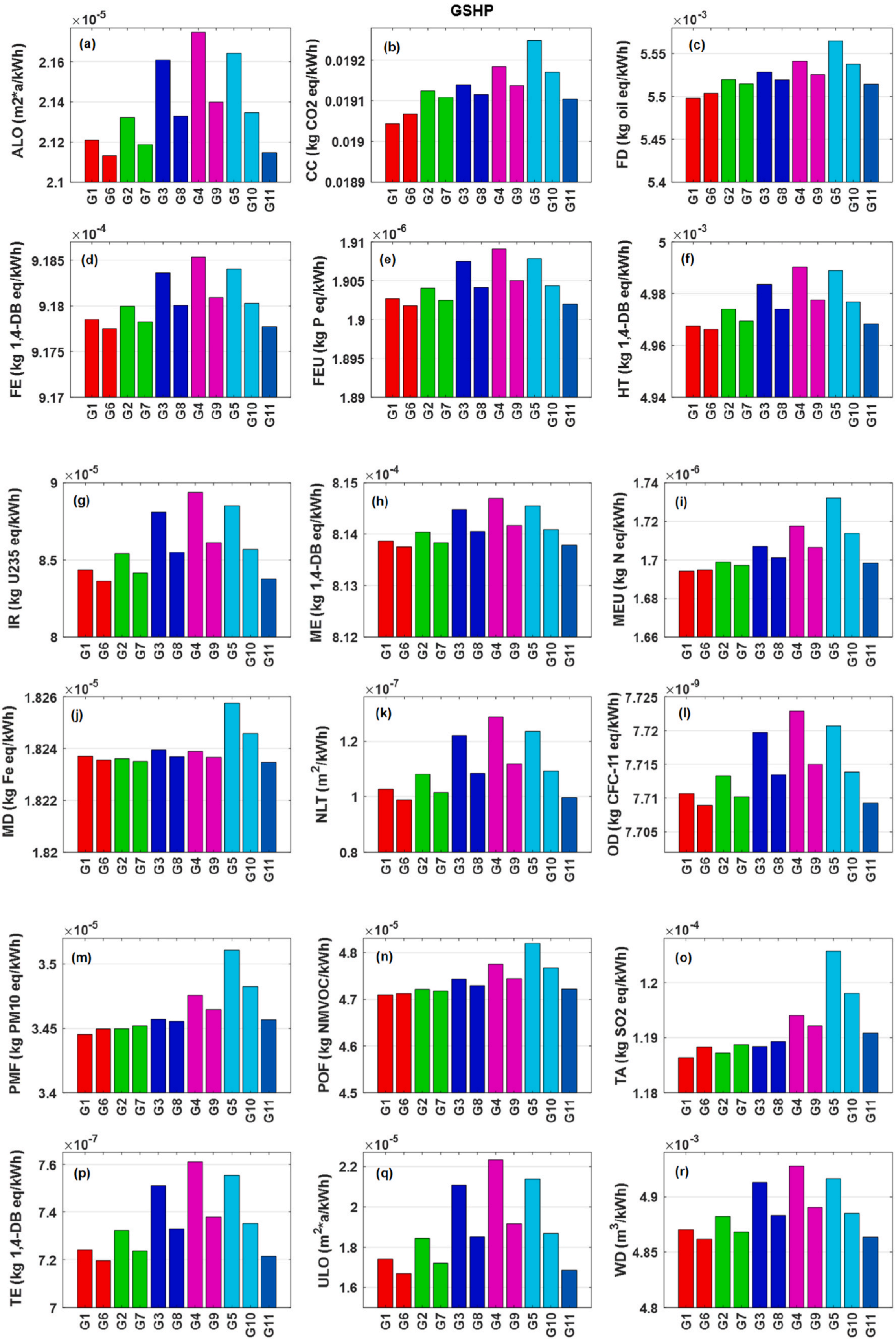

Fig. 5. Impact categories comparison for all defined GSHP supply chain scenarios, (a) agricultural land occupation, (b) climate change, (c) fossil depletion, (d) freshwater ecotoxicity, (e) freshwater eutrophication, (f) human toxicity, (g) ionising radiation, (h) marine ecotoxicity, (i) marine eutrophication, (j) metal depletion, (k) natural land transformation, (l) ozone depletion, (m) particulate matter formation, (n) photochemical oxidant formation, (o) terrestrial acidification, (p) terrestrial ecotoxicity, (q) urban land occupation, (r) water depletion.

attributed to the fact that Sweden's electricity grid relies less on fossil fuels compared to other countries. Notably, the CO_2 emission impact for W1 and H1, which involve manufacturing in Sweden for two different systems - WSHP in Fig. 6 and HSHP in Fig. 7 - also shows the lowest values.

Nevertheless, it can be observed that the manufacturing of GSHP in the UK is less polluting in several impact categories, such as ALO, FE, and IR, compared to other countries, even lower than Sweden. Opting for a scenario where 50 % of the manufacturing takes place in the UK and the remaining 50 % in the exporting country leads to a reduction in damaging impacts due to less transportation and distribution-related pollution. However, in some categories (like CC, FD, and TA), higher environmental consequences occur, indicating that the dominance of reduced transportation pollution is outweighed by the impact of the grid network. In other words, despite eliminating the transportation of heat pumps to the UK, the manufacturing systems in the UK with higher grid network pollution cause an increase in the mentioned impact pollution.

4.3. Life cycle environmental impact of WSHP

Fig. 6 presents the environmental impact category values for WSHP based on the midpoint results for all specified scenarios. The impact pattern for WSHP closely resembles that of GSHP because these two technologies share similar materials. Additionally, the supplier considered for WSHP and the heat pump part of HSHP aligns with the defined scheme for GSHP, owing to their technological similarities.

4.4. Life cycle environmental impact of HSHP

Fig. 7 displays the environmental impact values across all midpoint categories based on the expanded supply chain scenarios for HSHP (Hybrid Source Heat Pump) aimed at serving the UK market. Some categories show slight variations from the previously considered heat pumps due to the inclusion of excess components related to the hydrogen production system. As seen in earlier cases, the scenario where the entire system is manufactured in China (H5 scenario) results in the highest environmental consequences across most categories. In this Chinese scenario, both electrolysis and heat pump manufacturing take place in China, leveraging the country's significant economic capabilities to support the UK market. Nevertheless, in a scenario where manufacturing is split equally between the UK and China (H10 scenario), the negative effects are reduced by half across most categories compared to H5. The results show that the UK market has great potential to bring industries back to its shores and lessen the environmental impact of the heat pump and electrolysis supply chain. This can be achieved through the establishment of manufacturing facilities in the UK or by expanding existing companies' product lines and capacities to meet the UK market's needs effectively.

After Sweden, Germany emerges as a more sustainable solution, exhibiting lower environmental impact in some impact categories as the H2 and H7 supply chain schemes. On the other hand, supply chain scenarios involving Austria and Italy lead to higher pollution rates compared to the UK, Sweden, and Germany. Nevertheless, it is worth noting that the environmental impact of H11 is nearly equivalent to or even lower than the damaging impact observed in other countries, underscoring the significant influence of eliminating transportation and cross-border distribution by manufacturing the component entirely in the UK. It should be noted that the energy mix in some of these countries is not substantially different from the proportion of fossil fuel-based electricity in the UK's network.

4.5. Normalized environmental impact results

Fig. 8 illustrates the normalized impact values for the 18 mid-point environmental impact categories and technologies under the assumption of the A11 scenario. The computations reveal that ecotoxicity-related impacts have a more significant adverse effect on the environment compared to other impacts throughout the lifespan of all technologies. The ecotoxicity impact is associated with the manufacturing phase of heat pumps. Since the main materials used in the construction process of all technologies are similar (though with slightly varying values), a comparable pattern is observed across all studied technologies. Certain materials, such as copper and steel, in the production of heat pumps are the main causes of this toxicity impacts. These materials have the potential to induce ecotoxicity impacts in freshwater due to their capacity to release toxic substances into the water. When heat pumps are manufactured or used, these metals can be discharged into freshwater ecosystems through different pathways. Since the majority of materials used in all types of heat pumps are similar, the primary contributors to pollution are largely the same. Nonetheless, the results for HSHP exhibit some variance due to the different use of materials (such as steel and aluminium) in the construction of electrolysis. Furthermore, the normalized value for ASHP exceeds that of the other systems under consideration.

Based on the normalized results calculated for all technologies and scenarios, a TES index has been defined and measured to compare the sustainability of each technology. This index is derived from the average of all normalized results across all scenarios, considering values from 18 impact categories to provide an overall sustainability index. The environmental impact weighting is based on the normalized results for five main impact contributors (FE, FEU, HT, ME, and FD). The final TES index for the four technologies is presented in Table 5. A higher value indicates a more sustainable technology, while a lower value indicates a more polluting one. According to the TES results, HSHP scores 88, making it the most sustainable technology among all systems. The lowest rank belongs to ASHP with an index of 38. Additionally, after HSHP, GSHP, with a score of 82, is the next most sustainable option.

4.6. Life cycle supply chain environmental impact reduction based on the UK net-zero target

Fig. 9 represents the environmental impact reduction of the heat pump supply chain considering the net zero goal in the UK which is mainly due to expanding the share of renewable energy in the UK grid network over 2021, 2030, 2040, and 2050. From the results, it is evident that the ASHP has a higher damaging impact in most categories compared with other technologies. As previously mentioned, the concept of utilizing green hydrogen as an energy source for the HSHP entails generating hydrogen from renewable energy sources. Consequently, impact categories linked to land use or agricultural fields (e.g., ALO and ULO) exhibit higher values for HSHP when compared with other technologies. Notably, the climate change impact of HSHP is significantly lower than that of other technologies until 2040. However, by the time the net-zero goal is achieved in 2050, the CO_2 emissions from all technologies will converge to similar levels. In certain categories such as FE, FEU, and HT, the pollution level of HSHP exceeds that of GSHP and WSHP due to the excess impact resulting from the electrolysis section of HSHP. Moreover, in 2050, which aligns with the UK's net zero plan, the environmental impact of HSHP surpasses that of other technologies, whereas, until 2040, the detrimental impact of HSHP was lower, similar to HT. However, from 2021 to 2050, HSHP exhibits a higher damaging impact in certain categories, suggesting the need for technological or material improvements to ensure the sustainability of the electrolysis part of HSHP. It is important to note that this study does not consider technological developments that may occur over the specified period. Some impact categories have insignificant changes over this period which should be investigated from different aspects. It should be considered that developing some renewable technologies such as solar, geothermal, biomass, and wind may have some environmental pollution supposing the current technological situation which shows the importance of improving the technical performance, and sustainability of renewable technologies. The impacts are mainly on water pollution

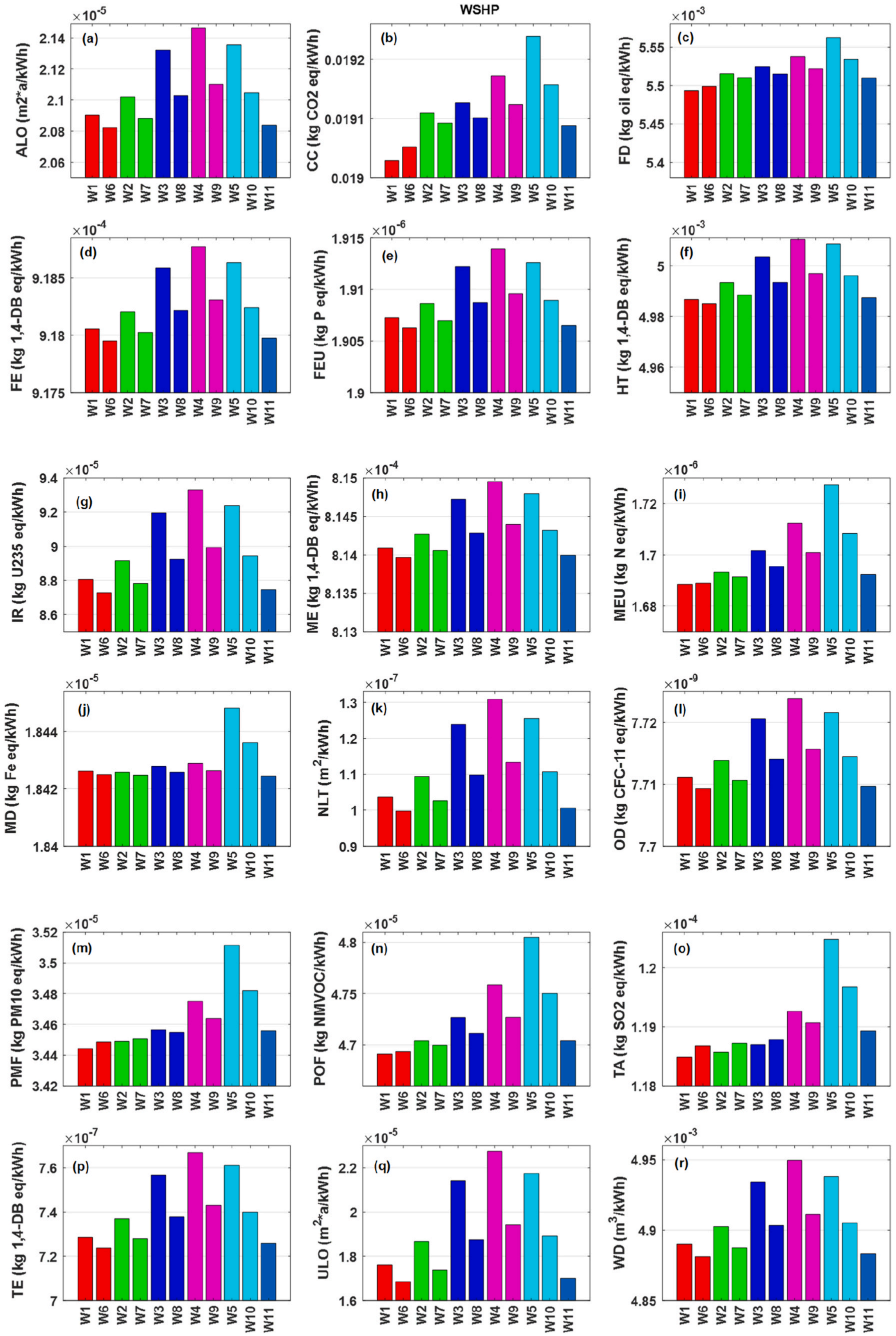

Fig. 6. Impact categories comparison for all defined WSHP supply chain scenarios, (a) agricultural land occupation, (b) climate change, (c) fossil depletion, (d) freshwater ecotoxicity, (e) freshwater eutrophication, (f) human toxicity, (g) ionising radiation, (h) marine ecotoxicity, (i) marine eutrophication, (j) metal depletion, (k) natural land transformation, (l) ozone depletion, (m) particulate matter formation, (n) photochemical oxidant formation, (o) terrestrial acidification, (p) terrestrial ecotoxicity, (q) urban land occupation, (r) water depletion.

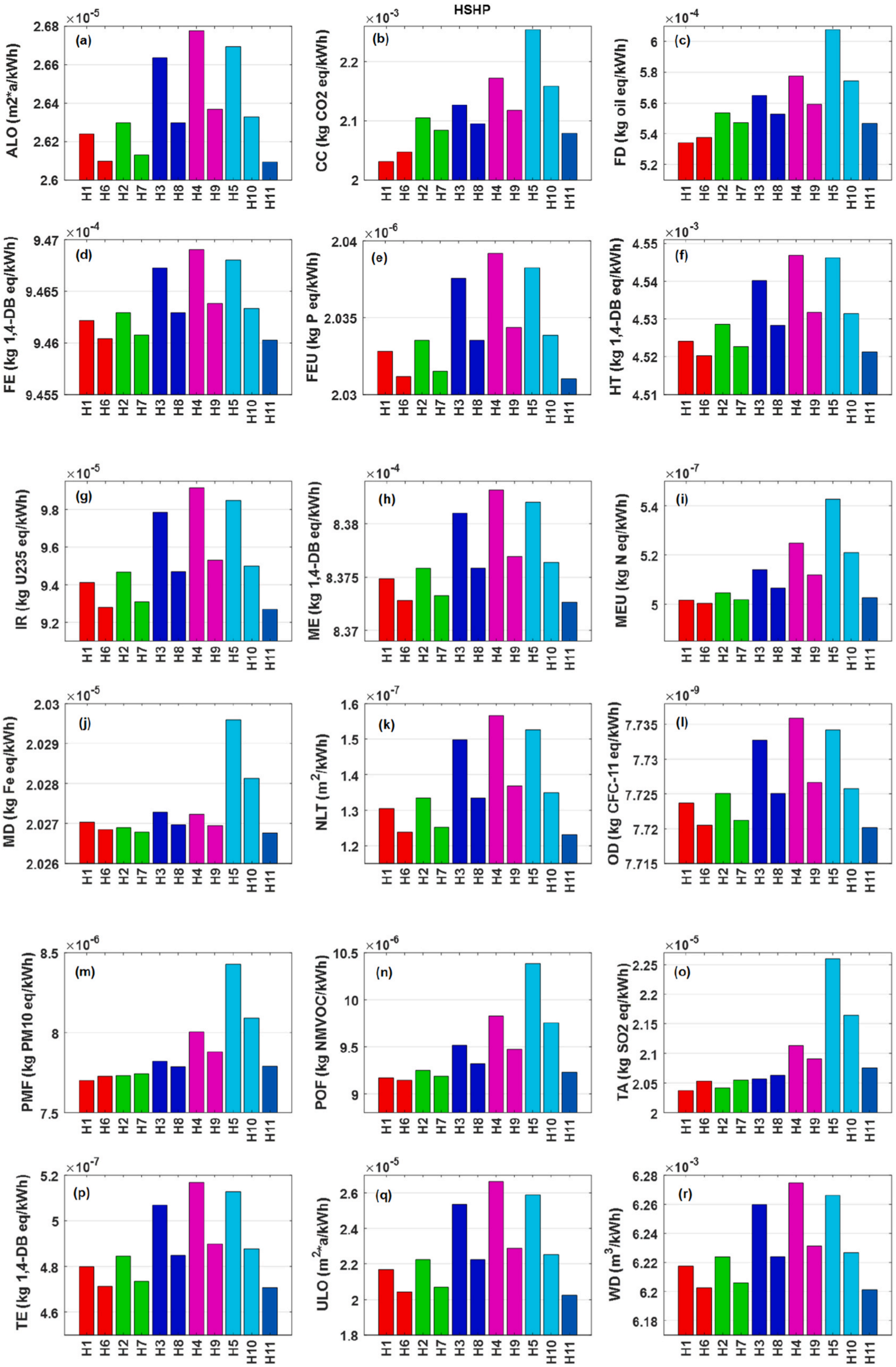

Fig. 7. Impact categories comparison for all defined HSHP supply chain scenarios, (a) agricultural land occupation, (b) climate change, (c) fossil depletion, (d) freshwater ecotoxicity, (e) freshwater eutrophication, (f) human toxicity, (g) ionising radiation, (h) marine ecotoxicity, (i) marine eutrophication, (j) metal depletion, (k) natural land transformation, (l) ozone depletion, (m) particulate matter formation, (n) photochemical oxidant formation, (o) terrestrial acidification, (p) terrestrial ecotoxicity, (q) urban land occupation, (r) water depletion.

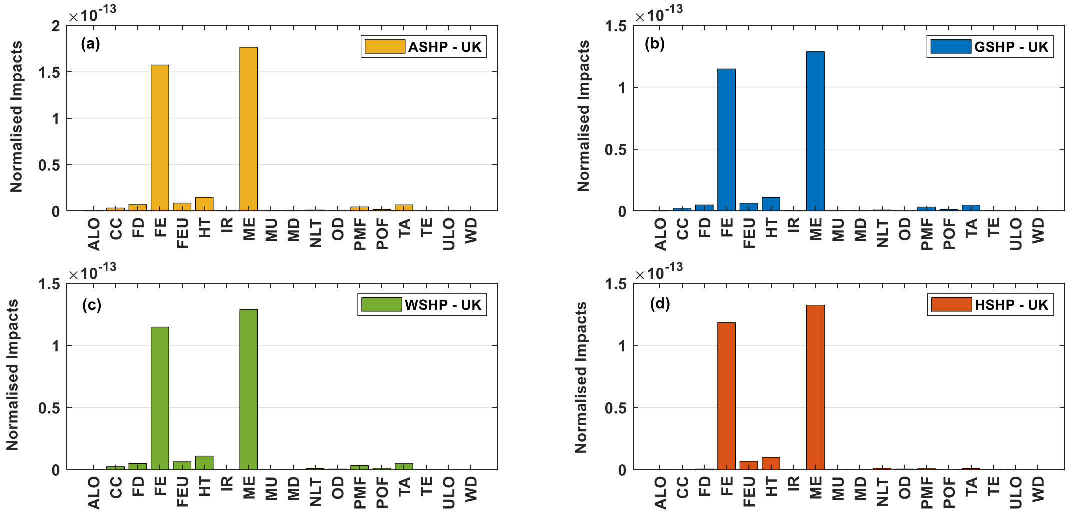

Fig. 8. Normalized environmental impacts for all technologies based on the UK, (a) ASHP, (b) GSHP, (c) WSHP, (d) HSHP.

Table 5
TES index values for all considered technologies.

Technology	TES index
ASHP	38
GSHP	82
WSHP	77
HSHP	88

and land use changes. Nevertheless, technological advances are expected to improve the sustainability of these technologies to mitigate the aforementioned impacts. It is predicted that the future supply chain of heat pump technology will tend to be more sustainable. This can be reached by several main interventions and critical actions such as improving the technological aspects of the heat pump and relevant components, increasing the renewable energy portions in the UK energy mix, establishing or restoring new companies, or expanding current production lines in the UK to increase the construction portion of heat pump components in the UK, eliminating or reducing the distribution and transportation-related pollution by using greener transportation and fewer distances.

5. Conclusion

This study aims to compare the environmental impacts of various heat pump supply chain scenarios for the UK market. The different scenarios are based on the primary supplier catering to the UK market demand. The LCA involves modelling the supply chain of defined heat pump technologies using the OpenLCA tool. Data from different databases are used for inventory analysis, and the ReCiPe 2016 midpoint impact assessment method is applied. In addition to conventional heat pump types, this research considers a novel hydrogen-based heat pump as a potential green alternative to currently installed boilers and other heat pumps that rely on the grid network for operation from an environmental perspective. The research also evaluates how the UK's net-zero goal impacts the environmental footprint of the heat pump industry supply chain.

The results indicate that manufacturing of the entire heat pump component in Sweden and then importing them to the UK emerges as the most sustainable solution in terms of reducing CO_2 emissions. On the other hand, scenarios involving Chinese suppliers for all technologies in most categories are found to be the most pollutant supply chain scenarios. This is primarily attributed to the reliance on fossil fuel-based grid networks and electricity for component manufacturing, as well as increased transportation and distribution pollution. It should be noted that, in some impact categories, manufacturing of the entire heat pump component within the UK is more sustainable than other scenarios. This highlights the importance of minimizing cross-border transportation consequences, especially for impact categories directly related to the electricity grid network. These impacts are predominantly associated with the manufacturing and operation of heat pumps, which are the primary sources of environmental pollution. Overall, the findings emphasize the significance of adopting a green electricity mix to mitigate the environmental impact of heat pump manufacturing and operation, which are identified as the main contributors to environmental pollution in this context.

The most prevalent pollutant impacts observed in all analysed systems are related to ecotoxicity, such as ME, FE, and toxicity to humans. These impacts are primarily caused by the manufacturing processes and the use of certain materials like copper. Among the four studied heat pump technologies, ASHP exhibits the highest damaging environmental impacts across most categories. However, in certain impact categories, HSHP displays the most significant consequences, particularly in terms of land use and land-related pollution, due to the utilization of more renewable resources (e.g., solar, wind, biomass) for generating electricity in the grid network. One notable impact category where ASHP has a higher damaging impact compared to other systems is OD, primarily due to the higher refrigerant usage in this heat pump type. The refrigerant applied in the heat pump industry is a major contributor to damaging OD impacts, both during the manufacturing process and potential loss and leakage throughout the O&M phase.

The study forecasts the impact of the UK's net-zero plan on carbon emissions reduction. ASHP is projected to achieve the highest CO_2 emission reduction, with reductions of 23 %, 60 %, and 97 % expected by 2030, 2040, and 2050, respectively. The CO_2 emissions related to GSHP, WSHP, and HSHP are predicted to decline by 94 %, 95 %, and 59 % by 2050, aligning with the UK's defined net-zero goal. However, it should be noted that HSHP may cause higher damaging impacts in some categories until 2050, indicating the need for technological or material improvements to enhance the sustainability of the electrolysis part in HSHP.

Recommendations

Based on the results obtained from the assessments conducted, certain interventions could be suggested to enhance the sustainability of the heat pump industry and its supply chain. To reduce the environmental footprint of the heat pump industry's supply chain stemming

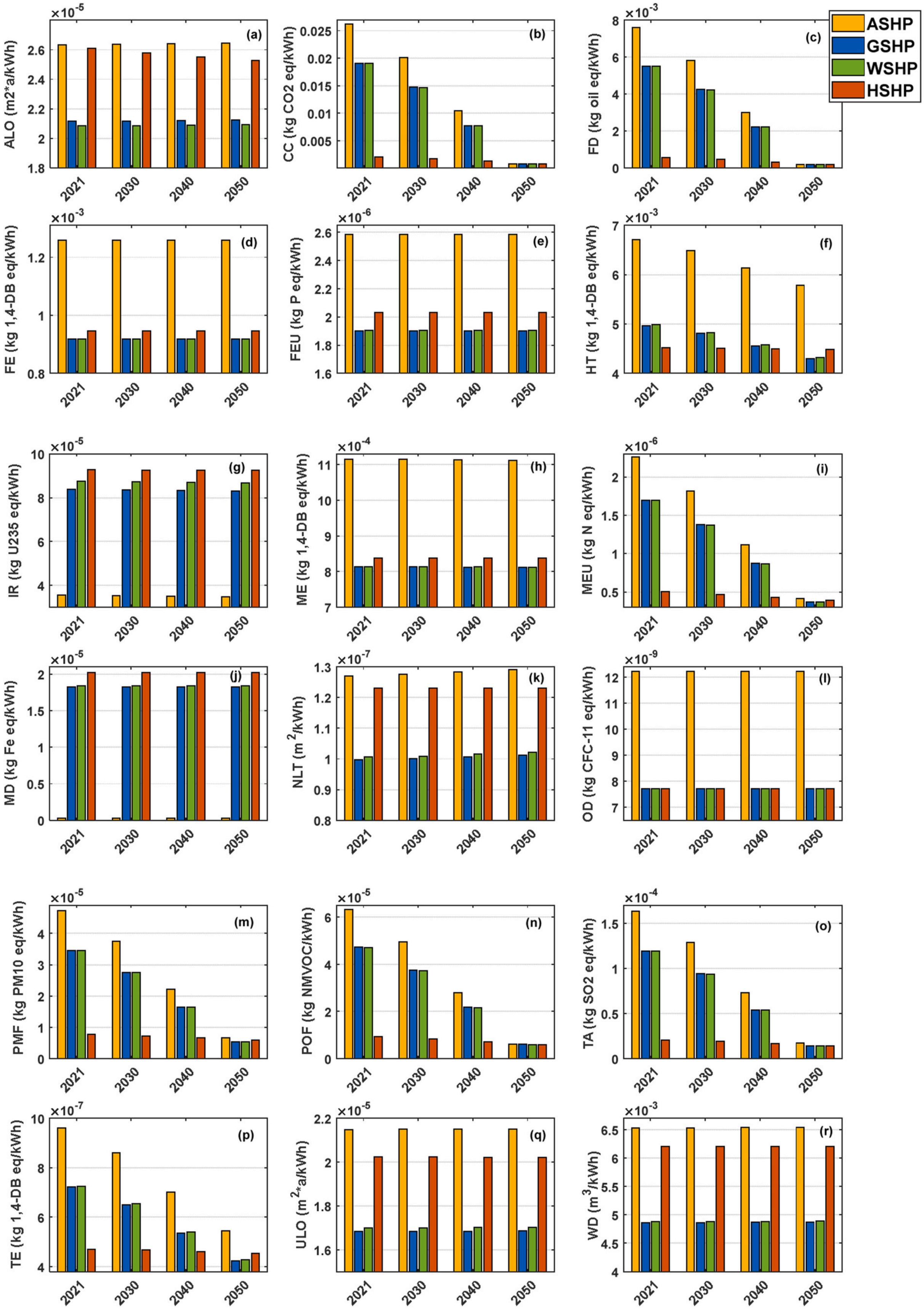

Fig. 9. The UK heat pump supply chain environmental impact based on net zero plan forecast, (a) agricultural land occupation, (b) climate change, (c) fossil depletion, (d) freshwater ecotoxicity, (e) freshwater eutrophication, (f) human toxicity, (g) ionising radiation, (h) marine ecotoxicity, (i) marine eutrophication, (j) metal depletion, (k) natural land transformation, (l) ozone depletion, (m) particulate matter formation, (n) photochemical oxidant formation, (o) terrestrial acidification, (p) terrestrial ecotoxicity, (q) urban land occupation, (r) water depletion.

from the manufacturing section, adopting more sustainable and less polluting materials is recommended. In addition, developing a reshoring policy in line with the net-zero plan will yield both economic and environmental benefits for the UK. To address any supply chain gaps in the UK, training skilled labour and workforce aligned with other policies is essential, as reshoring and infrastructure expansion require qualified personnel throughout all phases, from manufacturing to installation. Furthermore, increasing the share of renewable-based electricity in the energy mix has a significant impact on reducing the environmental consequences of the heat pump supply chain, as it can mitigate pollution arising from the O&M phase, which is a primary contributor to the life cycle pollution impact. It is important to consider that making improvements in systems from energetic, efficient, economic, and environmental perspectives through research and development (R&D) in both academic and industry sectors can expedite the reduction of environmental consequences in the heat pump supply chain.

CRediT authorship contribution statement

Moein Shamoushaki: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft. **S.C. Lenny Koh:** Formal analysis, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

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

Data availability

The lists of data inventory have been presented in the Supplementary Information file.

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Abbreviations

ACH	Absorption chiller
ASHP	Air-source heat pump
BB	Biomass boiler
CB	Coal boiler
CHP	Combined heat, and power
CGB	Condensing gas boiler
COP	Coefficient of performance
DSHP	Dual-source heat pump
EAC	Electric air conditioning
EB	Electric boiler
GB	Gas boiler
GDAHP	Gas driven absorption heat pump
GEHP	Gas engine heat pump
GHG	Greenhouse gas
GSHP	Ground-source heat pump
HFC	Hydrofluorocarbon
HHP	Hybrid heat pump
HSHP	Hydrogen-source heat pump
LCCP	Life cycle climate performance
SHP	Solar heat pump
WSHP	Water-source heat pump

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2024.133124.

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