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A UK foresight study of materials in decarbonisation technologies: the case of heat pumps.

Decarbonisation and Resource Management Programme

Open report

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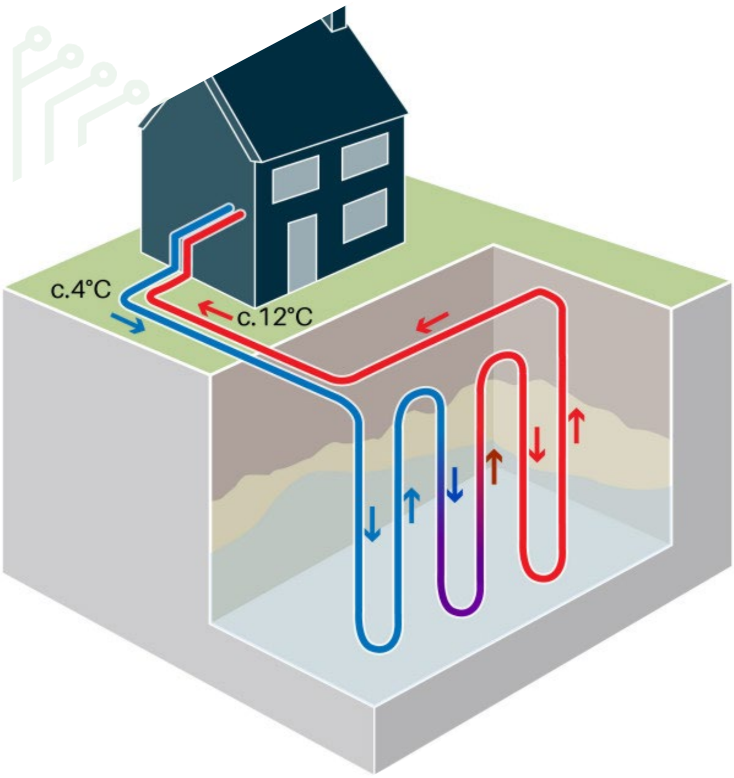

University of Exeter Business School

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BRITISH GEOLOGICAL SURVEY

Decarbonisation and Resource Management Programme

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A UK foresight study of materials in decarbonisation technologies: the case of heat pumps.

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British Geological Survey. Diagram of a typical vertical closed loop Ground Source Heat Pump. BGS © UKRI

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1. Introduction to heat pump technology

Low carbon heating technologies are a major building block in the UK's ambition to reduce emissions by 80 per cent by 2050. About 37 per cent of UK emissions in 2016 were attributed to heating, with space heating and hot water accounting for 21% of the total, amounting to 98 Mt CO_2e (WesternPower, 2022). Heating remains, therefore, one of the largest sources of the UK's greenhouse gas emissions (BEIS, 2018).

Heat pumps are an important low carbon heating technology, which, in conjunction with improved building insulation, are expected to play a significant role in decarbonisation of the heating and hot water provision in the UK. Achieving these objectives will require up to 600,000 new installations every year by 2028 (HPA, 2019, 2023; WesternPower, 2022). Heat pumps offer an attractive route to rapid decarbonisation. Given a short lead-time of 2 to 4 years to manufacture and install, heat pumps can be scaled significantly faster than other major decarbonisation technologies such as hydrogen technologies and wind power generation (EHPA, 2024; IEA, 2023).

Gas is currently the dominant heating source for more than 24 million homes and businesses in the UK (BEIS, 2018). Heat pumps have a lower lifecycle carbon footprint but are significantly more material intensive than gas boilers (IEA, 2023; WesternPower, 2022). Hence, given the current aggressive demand projections for heat pumps in the UK and overseas, a better understanding of the materials used in heat pumps and their supply chain challenges will help to inform policy decisions.

1.1. PRINCIPLES OF OPERATION

Heat pumps transfer heat from one place to another by using a small amount of energy. They are widely used for both heating and cooling purposes in residential and commercial settings. The functioning of a heat pump is based essentially on the laws of thermodynamics, particularly the principle that heat naturally flows from warmer to cooler spaces. The operation is based on a refrigeration cycle involving compression, condensation, expansion and evaporation of a refrigerant fluid. The cycle can be reversed to either absorb heat from the outdoor environment and release it indoors (for heating) or absorb heat from indoors and release it outdoors (for cooling) (Figure 1) (McQuiston et al., 2023):

- **Compression:** a compressor increases the pressure of the refrigerant, raising its temperature. The high-pressure, high-temperature gas then flows to the condenser.
- **Condensation:** in the condenser, the refrigerant gas releases its heat to the surrounding environment, thus warming the interior of a building.
- **Expansion:** the high-pressure liquid refrigerant then passes through an expansion valve, where its pressure decreases abruptly, cooling it down significantly.
- **Evaporation:** the cold, low-pressure liquid refrigerant absorbs heat from the surrounding environment (outdoors for heating, indoors for cooling) in the evaporator. As it absorbs heat, the refrigerant evaporates and turns back into a gas.

Heat exchangers that facilitate the transfer of heat between the refrigerant and the surrounding environment are key components in the condensation and evaporation stages of the heat pump operation.

To power this process electrical energy is required. Ideally this would be obtained from renewable resources such as wind or solar power. The ratio between the required electrical energy input to the generated heat output is expressed as the system's coefficient of performance (COP). The COP factor is commonly between 2 and 4: this compares favourably with traditional combustion-based heating solutions.

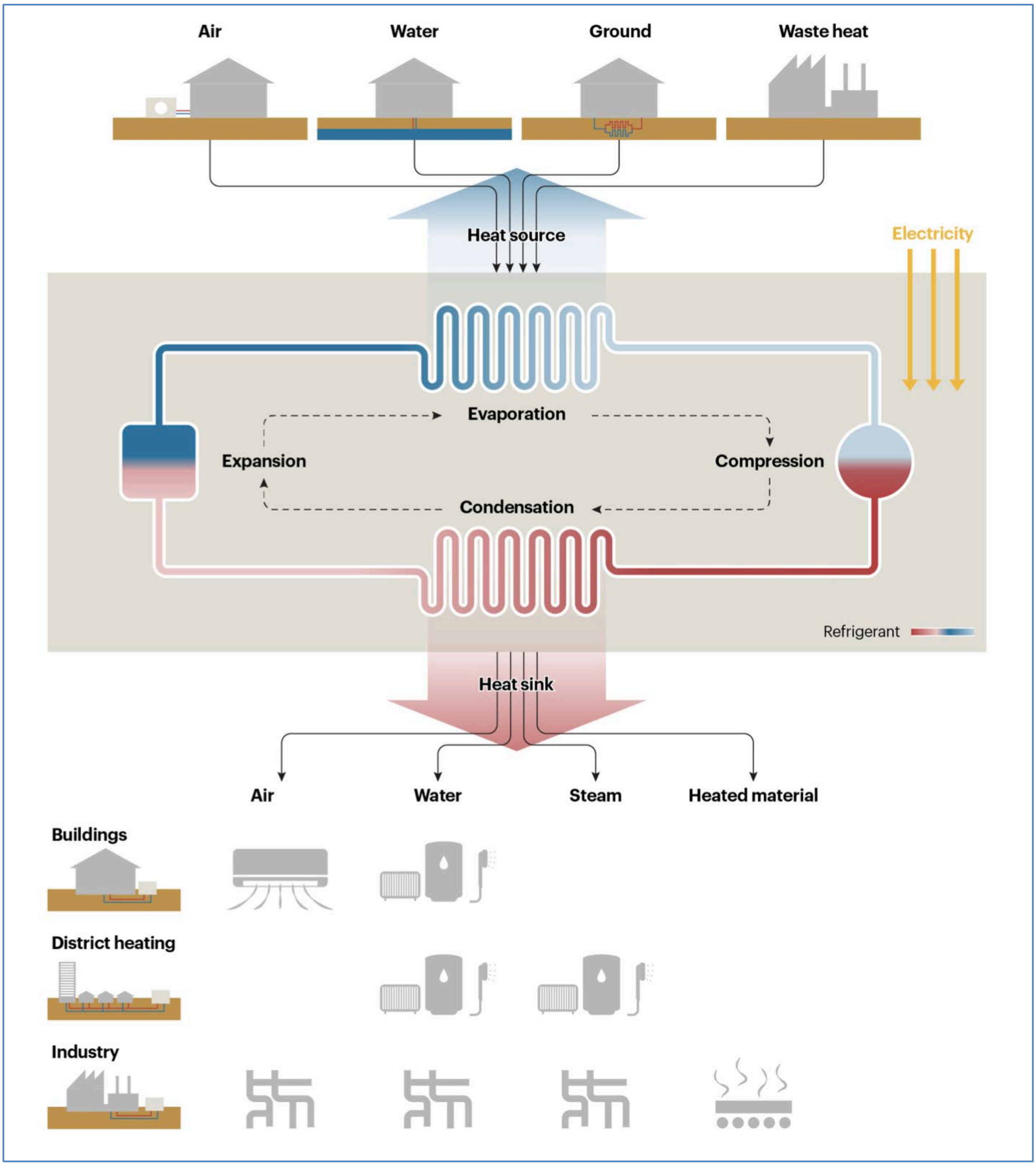

Figure 1 Principles of a heat pump (IEA, 2022b); HPs extract heat from a source, amplify and transfer the heat to a heat sink, which may air, water, steam or material. In buildings the heat can be delivered as hot air or hot water for space heating or sanitary purposes. Large scale HPs can deliver hot water or steam for district heating systems. In industry, HPs can be used to deliver hot air, water, steam or directly heat materials.

Heat pumps can be classified according to the source of the ambient heat (Energy Saving Trust, 2024; IEA, 2022b; McQuiston et al., 2023):

- **Air-Source Heat Pumps (ASHP)** are currently the most common type (globally 85%) and transfer heat from the outside to the inside of a building. They are the simplest designs and typically most cost-effective. However, they are less efficient in extremely cold climates and operations typically require additional heat sources (e.g. electrical boilers) where temperatures are below 15 - 20°C.

- **Ground-Source Heat Pumps (GSHP),** or geothermal heat pumps, transfer the heat from the ground into buildings. This system is more efficient than ASHP as the heat sourced from the ground is more constant than the external air temperature. However, installation cost is generally higher due to the need for excavation or drilling, which frequently also requires permission from the planning authorities.
- **Water-Source Heat Pumps (WSHP)** source the heat from water bodies such as lakes, rivers and aquifers. While their efficiency is similar to GSHP, their deployment is restricted by the need for accessible water bodies.

In practice these different heat pump technologies can be combined into hybrid heat pumps by mixing the source of ambient heat. They can also be integrated into bivalent heat pumps, which use other forms of traditional heat generation for peak demand or to deal with unfavourable conditions, such as periods of extreme cold. If electricity as the input energy is substituted with other forms of energy (e.g. gas or geothermal energy) heat pumps are classified as absorption heat pumps. These are typically installed in situations where access to electricity is restricted or excess energy is available from waste or other industrial processes. (IEA, 2022b)

In terms of size and application, heat pumps are commonly categorised into residential and commercial heat pumps. In residential heat pumps small systems produce up to 5 kW suitable for small apartments, while medium-sized systems, between 5 and 15 kW, are appropriate for average-sized homes. Large systems, above 15 kW, are suitable for bigger homes or buildings with high heating or cooling demands. In commercial applications heat pumps less than 25 kW are classified as small, 25 - 70 kW as medium and greater than 70 kW as large.

1.2. ESSENTIAL COMPONENTS AND MATERIALS

The heat-pump technologies discussed above consist of essentially similar components requiring similar functional materials. The total quantities needed are mainly a function of the size of the heat pump.

The core functional components of a heat pump are a compressor, a condenser and an evaporator (Figure 2):

- **Compressors** consist essentially of an electric motor, which increases the pressure and temperature of the refrigerant, enabling the heat pump system to effectively gather and transfer heat. Functional materials used in compressors include copper (Cu) in motor windings and aluminium (Al) which may be used to improve thermal conductivity. Some compressors use high-strength neodymium-iron-boron (NdFeB) permanent magnets (PM) in which rare earth elements (REE) are essential constituents. These are mostly found in high performance scroll and rotary compressors, where they contribute to relatively high operational efficiency. (Kostora, 2017). The REE utilised in these PM are neodymium (Nd), dysprosium (Dy) and, in some cases, praseodymium (Pr) and terbium (Tb) (Yang et al., 2017). The REE content in permanent magnets has been estimated to be less than 1 per cent of the total heat pump weight (BRE Global, 2023; Kiwa-Ecobility Experts, 2021)

- **Condensers and evaporators** are heat exchangers which are key to the operational efficiency of the heat pump system. Hence, the main materials used are copper and aluminium which have high thermal conductivity and are resistant to corrosion.

- **Expansion valves** make a small contribution to the overall weight of the heat pump but play an important role in regulating the flow of refrigerant between the high-pressure and low-pressure sides of the system. Hence, the materials used are mainly brass and stainless steel because they perform well at high pressure and are resistant to corrosion from refrigerants. Brass is an alloy which consists predominantly of copper (Cu) and zinc (Zn).

- **Other important functional components** include a control unit, which comprises printed circuit boards (PCBs) and other electrical units, although these do not contribute significantly to the weight of a heat pump. Materials used in the control unit are, therefore, excluded from this analysis.

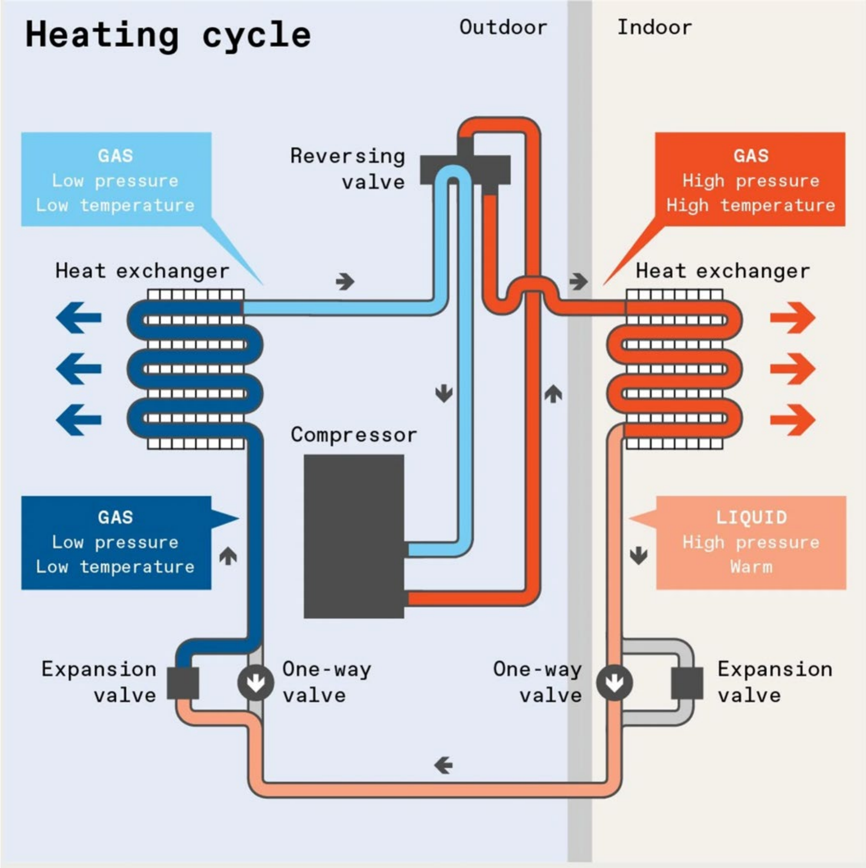

Figure 2: Technical schematic showing the major components of a heat pump (Schneider, 2023)

Structural materials, such as steel, plastic and insulation, used in the casing and for the piping within the heat pump, are not included in this analysis. Table 1 summarises the key materials used in the main functional components of a heat pump.

Table 1: Key elements used in heat pump technologies. UK critical elements based on Lusty et al. (2021).

Component	UK critical elements	Other
Compressor	Dysprosium (Dy), neodymium (Nd), praseodymium (Pr), terbium (Tb)	Iron (Fe), copper (Cu), aluminium (Al), boron (B), steel
Condenser / Evaporator		Copper (Cu), aluminium (Al)
Expansion Valve		Copper (Cu) and zinc (Zn) (in brass), stainless steel
Elements in red are excluded from the analysis because: (i) they are used in structural components; or (ii) they are not used in the most common configuration of the technology.		

Given the large variation in material quantities used, the approach taken in this study has been to use selected 'signature HPs' where bill of materials (BoM) data is available from environmental production declarations (EPD for models by Vaillant, Mitsubishi and Gebwell). EPD BoM data were complemented, where required, by other BoM materials derived from the literature. The signature HPs are used to reflect the material quantities used in the material demand analysis. Three types of signature heat pumps were used to estimate the overall demand mix at the material level by creating a BOM-table for the different types. In terms of HP capacity sizing, we used the average installation size as per the original National Grid forecast:

- **A 6 kW domestic heat pump without REE** permanent magnets for the compressor;
- **A 6 kW domestic heat pump with REE** permanent magnets for the compressor;
- **A commercial heat pump without REE** permanent magnets for the compressor, sized at 40-100 kW flexible capacity range.

As a result, two different BOMs for domestic heat pumps were consolidated and used in the analysis. It was assumed that 80 per cent of the heat-pumps would contain REE PM compressors, with 20 per cent using non-REE PM compressor technology. This split was based on expert assumptions that the higher energy efficiency of REE-PM-magnets compressor will improve the efficiency of the heat pumps with a positive impact on the economic viability (Efficiency for Access, 2021; Gauß et al., 2021). Interviews conducted with industry representatives as part of this study (e.g. from the UK Heat Pump Association, HPA) further supported the view that the use of REE PMs in HPs is likely to increase in the future as part of a drive to increase their efficiency.

Table 2: Bill of material (BoM) assumptions for the two domestic and one commercial signature HPs used in the material demand modelling.

	Domestic Heat Pump with REE PM in compressor		**Domestic heat Pump without REE PM in compressor**		**Commercial heat pump without REE PM in compressor**	
Element	mass %	mass (kg)	mass %	mass (kg)	mass %	mass (kg)
Copper	20.6%	39.6	21.1%	40.5	3.8%	32.72
Zinc	1.4%	2.6	1.4%	2.7	0.3%	2.64
Aluminium	2.0%	3.8	2.0%	3.8	2.6%	22.39
Dysprosium (REE)	0.018%	0.04				
Neodymium (REE)	0.125%	0.24				
Praseodymium (REE)	0.019%	0.04				
Terbium (REE)	0.003%	0.01				
Boron	0.005%	0.01				
Total	**24%**	**46.4**	**25%**	**47.0**	**7%**	**57.7**
Other (including steel and polymers)	76%	145.6	75%	145.0	93%	803.3

2. Supply chain mapping of heat pumps

The heat pump supply chain across the full life cycle can be divided into a number of key stages: 1) raw material extraction; 2) material processing; 3) pre-cursor material and sub-component manufacturing; and 4) component manufacturing and product assembly. As heat pumps require installation on site during construction or during energy retrofit operations, in practical terms the installation step can be seen as a 5th stage following product assembly, with a usage phase (6) and post-use decommissioning and revalorisation phase (7). The focus of this study will be the material supply chain leading to product assembly and hence the first 4 stages. The analysis will consider the key raw materials identified in Table 1.

Figure 3 shows the different stages of the heat pump supply chain, the key materials selected for the analysis at each stage as well as the components for the final product assembly.

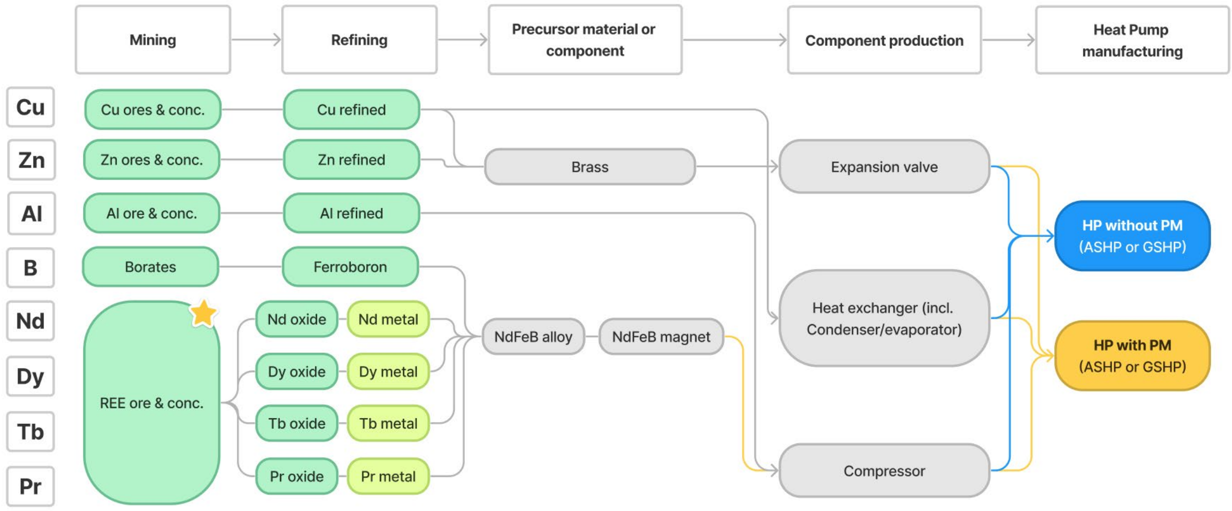

Figure 3: Simplified supply chain mapping of heat pump materials across the different stages from resource extraction to final product. The green shading indicates materials that have been included in the detailed analysis. A yellow star indicates a material produced as a co-product. The lime green shade indicates a material that was only partially analysed. Blue lines indicate flows to HPs without permanent magnets. Yellow lines indicate flows to heat pumps containing permanent magnets. (Cons., concentrates; REE, rare earth elements; PM, permanent magnets; ASHP, air source heat pump; GSHP, ground source heat pump).

In terms of key material requirements, bauxite and copper ores are mined in very large quantities (millions of tonnes per annum) in many countries. In contrast, the rare earth elements (neodymium, dysprosium, terbium and praseodymium) used in permanent magnets (PM) are produced in much smaller quantities (hundreds to thousands of tonnes of each) with the mining and processing activity restricted to a few countries. In some cases, REE are extracted as by-products from the mining of other commodities such as iron, tin and niobium (Wall, 2014). Consequently, the availability of the REE in these cases is linked to the production of the main parent material. It is also important to note that the REE have to be produced together as a group of co-products because they are chemically very similar to one another and cannot be easily separated from the minerals in which they occur. The availability of those REE used in permanent magnets, which are typically minor constituents of the ores, is, therefore, linked to the production of the other REE, such as lanthanum and cerium, which are generally more abundant and which determine the economic viability of the mining operations.

Boron, which is also used in permanent magnets is generally extracted as borates (boron oxides), which are refined to boric acid and subsequently into ferroboron (17-20 per cent boron) for permanent magnets. Refined rare earths and ferroboron are combined with iron to form NdFeB-alloy used to make sintered permanent magnets or NdFeB powder to make bonded permanent magnets via a different process. Only NdFeB alloys and sintered permanent magnets are here considered as it is the preferred magnet type for HPs and represents the majority of the NdFeB magnet market (Smith et al., 2022).

A recent analysis by the European Commission (Lyons et al., 2023) maps the raw and processed materials used in heat pumps and their components and notes that heat pumps use similar materials to the technologies they replace i.e. gas and electrical boilers. However, some critical raw materials are used, notably in the compressor motorised parts (which may include REE PM) and in the control unit.

3. Supply chain bottlenecks for heat pumps

In contrast to many other decarbonisation technologies, heat pumps do not require highly specialised manufacturing stages. Furthermore, global copper and aluminium value chains are well developed, and these materials are generally not considered vulnerable to supply restriction. In contrast, the geographical distribution of REE mining and refining operations is concentrated in only a few countries worldwide. This inevitably gives rise to increased risk of supply chain disruptions.

Given the stationary deployment of heat-pumps, potential shortages of REE-PM-motors could be alleviated by design changes that use potentially larger and less efficient installations that do not utilise REE. Similarly, in the event of prolonged shortages of the PCB-based control units, analogue designs requiring less critical materials could be used. Lyons et al. (2023) note that more widespread use of smart controls could increase vulnerability to semiconductor shortages. However, the chips used in HPs are not the most advanced and can be replaced relatively easily.

An overview of the materials and key components used in heat pumps and the location of the different supply chain stages is shown in Figure 4.

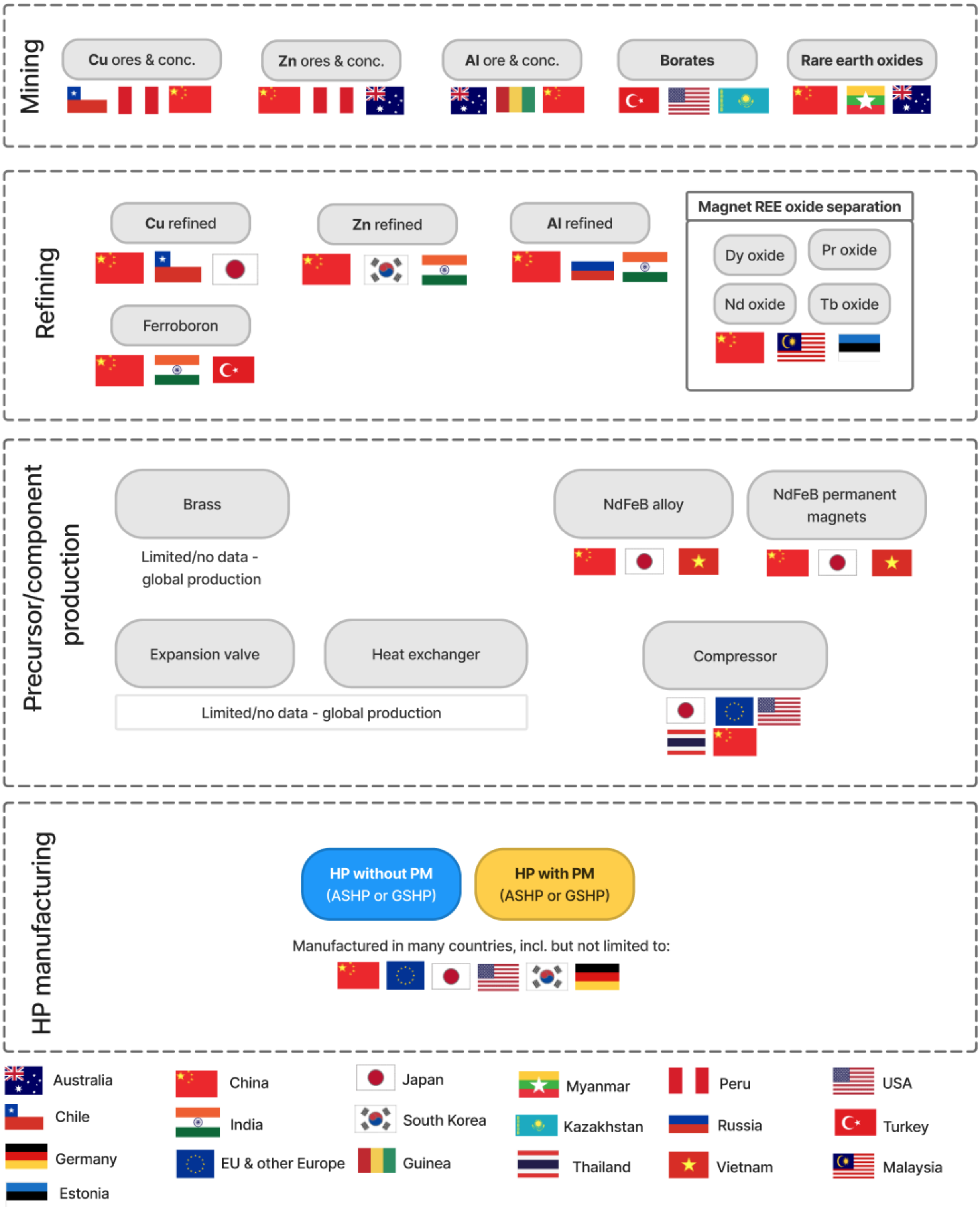

Figure 4: Geographical production concentration in the heat pump supply chain. At the mining and refining stages, the national flags show the top three producers, from left to right, based on quantitative data from the BGS World Mineral Statistics database (BGS, 2023). The top three producing countries of rare earth elements at the refining stage and the NdFeB alloy production are from (Adamas Intelligence Inc., 2022) and magnet manufacturing are based on data from (Smith et al., 2022). At the heat pump component and cell manufacturing stages, the flags highlight the location of selected key producers, but their order does not reflect their respective market share (data compiled and interpreted from various sources including (Carrara et al., 2023; GMI, 2023; IEA, 2023) and several company websites.

3.1. MINING AND REFINING

The global production share of key materials used in heat pumps was derived by aggregating the volumes of the three top producing countries in the mining and refining stages of the supply chain.

The global distribution of mine production of the key functional materials used in heat pumps is shown in (Figure 5).

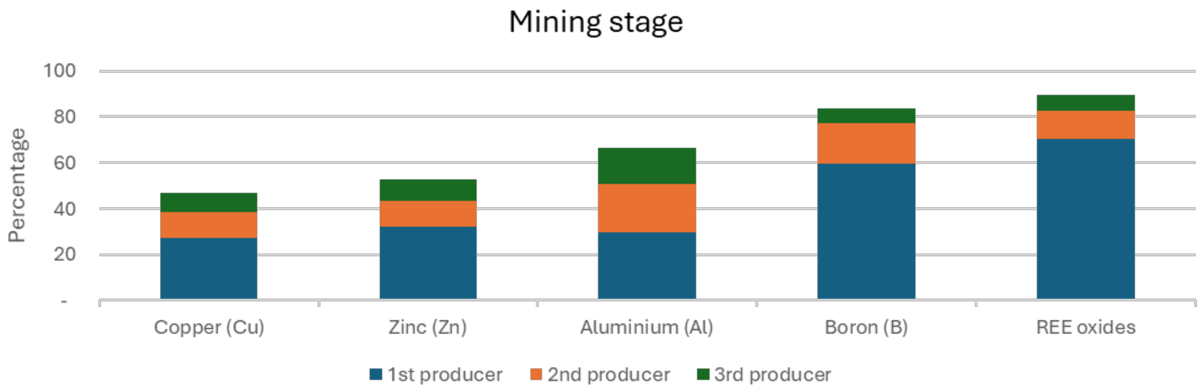

Figure 5: The distribution of g(lobal mine production of key functional materials used in heat pumps. (Data from the British Geological Survey World Mineral Statistics database BGS, 2023).

The production of boron and REE oxides is highly concentrated geographically with more than 80 per cent the global total derived from the top three producing countries. The production of copper is the least concentrated, with 56 per cent from the top three producers.

Although production data for the individual REE are unavailable, work conducted by the British Geological Survey focusing on the geochemical signature of REE deposits, indicates that global mine production consists of approximately 5 per cent praseodymium, 15 per cent neodymium, 0.1 per cent terbium and 1 per cent dysprosium by mass. In contrast the mass of contained cerium (Ce) and lanthanum (La) is about 25–43 per cent. This highlights an additional challenge in mine supply, as not all deposits contain viable economic concentrations of all the REE. Many deposits are rich in cerium and lanthanum, but have lower concentrations of terbium, dysprosium, praseodymium and neodymium.

The refining stage concentrations for the selected materials are shown in Figure 6 . Refining stage data is not available in the public domain for boron and REE oxides, so the assessment included only the production concentration of refined copper, zinc and aluminium. While it remains impracticable to quantify the production concentration of ferroboron, it is acknowledged that China, India, and Turkey are the foremost producers (Smith et al., 2022).

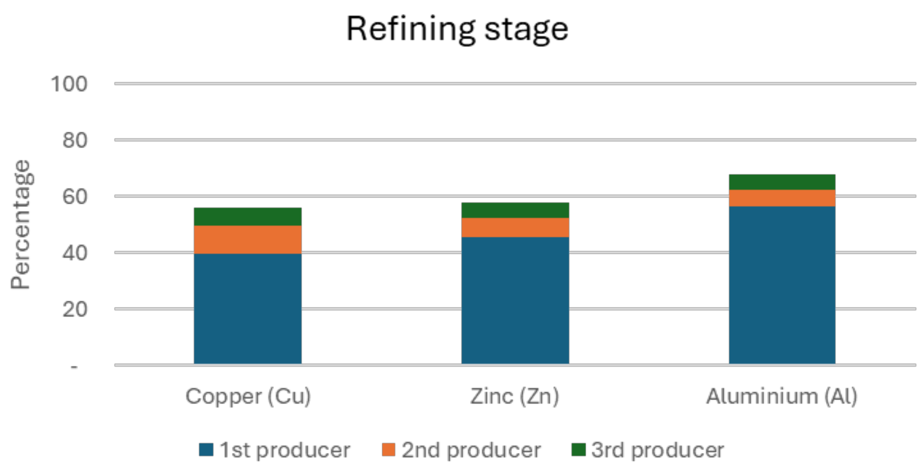

Figure 6: The distribution of global refinery production of key functional materials used in heat pumps. Data from the British Geological Survey World Mineral Statistics database (BGS, 2023).

Production concentration of copper, zinc and aluminium is higher than that of mining. The three largest producers for all three commodities account for less than 70 per cent of the global tota. China is the largest producer with more than 40 per cent of the refining total for the three materials evaluated. This highlights that the global refining capacity outside China, although widely distributed geographically, is relatively small and fragmented.

Ranked production concentration scores based on the indicator recommended in the revised methodology for UK criticality assessment (Josso et al., 2023) are shown in Figure 7. These are derived from the production shares of the leading producers modified by a factor that reflects the ESG performance of those countries. Based on this analysis the materials of greatest concern are REE and boron. Mining of REE is highly concentrated in China and Myanmar, both of which have poor ESG scores.

The mine production of the other materials is generally less geographically concentrated, hence the relatively poor ESG scores of the top producers carry less weight. At the refining stage the relatively poor score for aluminium can be attributed to the high proportion of the global total which is produced in China.

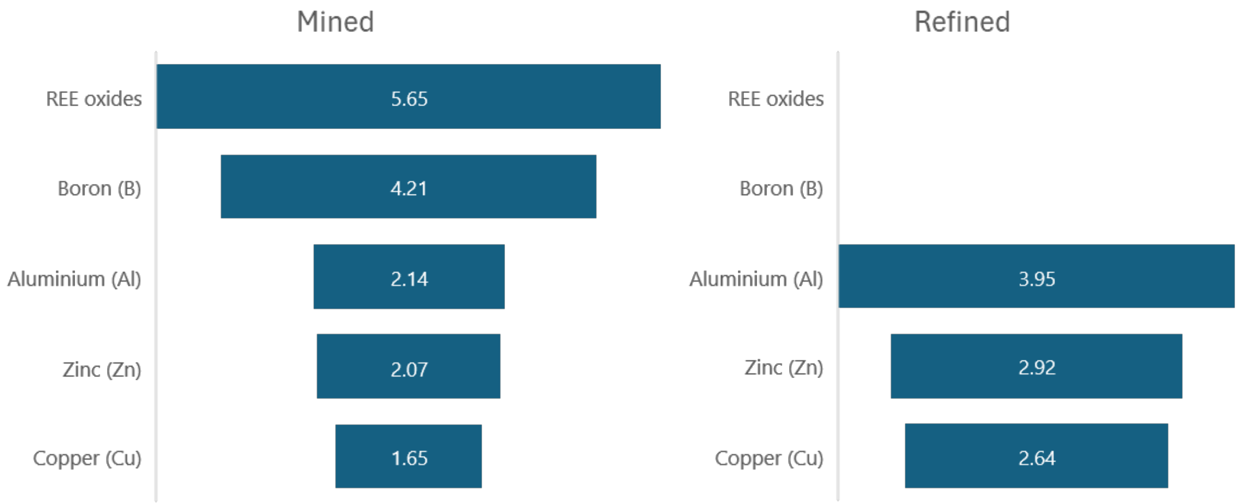

Figure 7: Ranked production concentration scores for key materials (mined and refined) used in heat pump technologies based on ESG-weighted HHI combined for the 3 top producing countries. No readily available data is available for refinery production of REE and boron/ferroboron.

3.2. GLOBAL TRADE CONCENTRATION AND TRADE RESTRICTIONS

Trade concentration is calculated from import and export data derived from the UN Comtrade database for the period 2017–2021 (UN Comtrade, 2023). An overview of the materials included in the analysis and their respective HS code is provided in Table 3.

Table 3: Elements and compounds included in the analysis of trade concentrations based on UN Comtrade data, and their respective HS codes.

SC stage	Material	HS code	HS code description of corresponding traded form
Mining	Copper (Cu)	260300	Copper ores and concentrates
Mining	Zinc (Zn)	2608	Zinc ores and concentrates
Mining	Aluminium (Al)	260600	Aluminium ores and concentrates
Mining	Boron (B)	252800	Natural borates
Refining	Copper (Cu)	740200	Copper, unrefined; copper anodes for electrolytic refining
Refining	Zinc (Zn)	7901	Zinc, unwrought
Refining	Aluminium (Al)	7601	Aluminium; unwrought (note: contains both alloyed and not alloyed)
Refining	REE oxides	284690	Compounds, inorganic/organic, of rare-earth metals/yttrium/scandium/mixtures of these metals, other than cerium comps.
Refining	REE metals	280530	Rare-earth metals, scandium and yttrium, whether or not intermixed or interalloyed

The top three net importing and exporting countries of the mined functional materials used in heat pumps is shown in Figure 8.

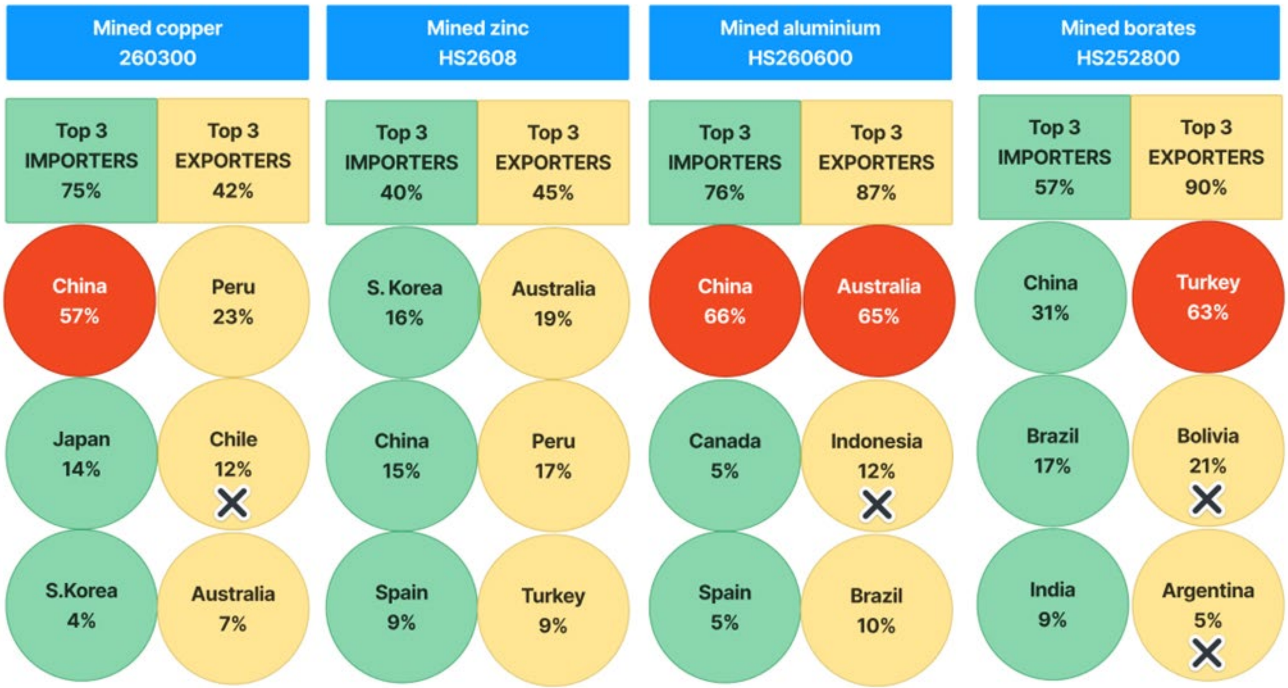

Figure 8: The top three net importing and exporting countries for mined materials used in heat pump supply chains. Countries highlighted in red are dominant exporters or importers (i.e. where global share exceeds 40 per cent) whilst countries with a black cross have active trade restrictions. Data on trade flows compiled from UN Comtrade (2023) based on 2017-2021 data, and active trade restrictions based on OECD (2022a) and associated dataset (OECD, 2022b) for the year 2021.

China is the dominant importer of mined copper (57 per cent of the global total), aluminium (66 per cent) and borates (31 per cent). The second and third largest importing nations have much smaller shares of the imports of all the mined materials evaluated.

Exports of mined copper and zinc are relatively diversified: Peru is the largest exporter of copper accounting for 23 per cent of the global total, while Australia is the leading exporter of mined zinc with 19 per cent of the total. For mined copper, the second largest exporter, Chile, applies export restriction in the form of fiscal tax on exports. Australia is the largest exporter of mined aluminium ore (65 per cent of total), followed by Indonesia (12 per cent) and Brazil (10 per cent). Indonesia applies trade restrictions on aluminium ore in the form of export prohibitions, export tax, licencing requirements. Export of mined borates is dominated by Turkey (63 per cent). The second and third largest exporters (Bolivia, 21 per cent, and Argentina, 5 per cent) both apply export restrictions to borates.

There are no suitable data for assessing the trade concentration of rare earth element ores and concentrates. At the six-digit level the trade code under which these materials are reported (i.e. HS253090) is highly aggregated and includes numerous mineral substances (e.g. alunite, pozzolana and mineral pigments), making it very difficult to extract data that specifically relate to rare earth element ores and concentrates. At the eight- and ten-digit level there are trade codes for rare earth element ores and concentrates (e.g. HS25309050). However, these data are not typically publicly available and not every country reports trade data at this level of detail. In effect these trade flows are ‘hidden.

An overview of refined minerals used in heat pump supply chains, showing the top three net importing and exporting countries, is given in Figure 9.

For refined copper, which is the most important functional material for heat pumps in terms of volume, China is the dominant net importer (48 per cent), followed by Belgium (11 per cent) and India (10 per cent). The largest exporting nation is Zambia (42 per cent), followed by Chile (20 per cent) and Bulgaria (8 per cent). Zambia and Chile have active trade restrictions (based on 2021 data); Zambia applies export tax (10-14 per cent) and licencing requirements and Chile applies fiscal tax on exports (10 per cent). For aluminium, trade concentrations are low, with the largest exporter, Canada, holding a share of 16 per cent of the global total of refined aluminium. The second largest exporter of refined aluminium (Russia) applies trade restrictions in the form of an export tax.

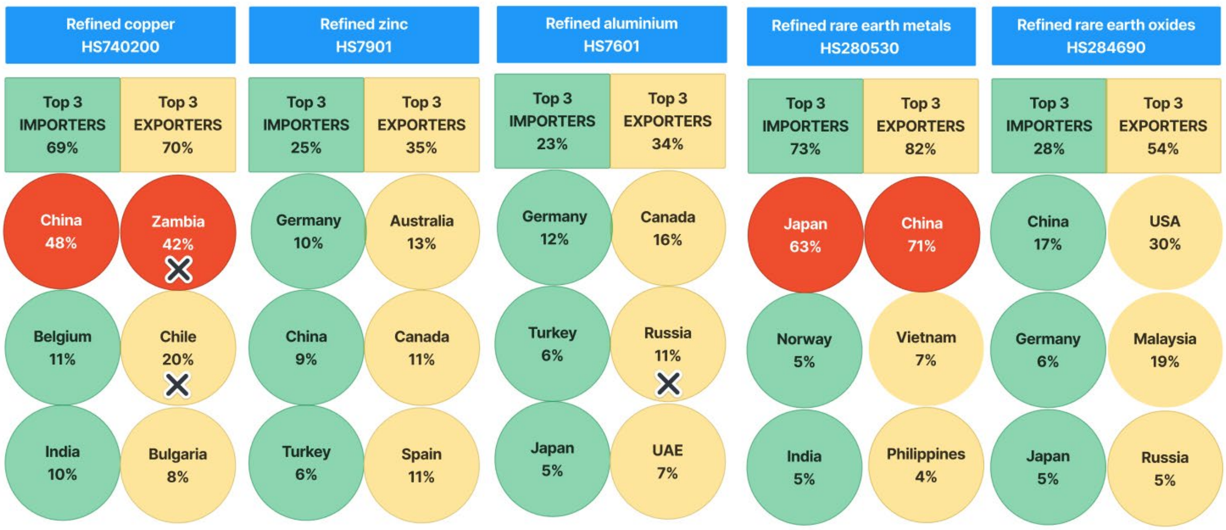

Figure 9: The top three net importing and exporting countries for refined materials used in heat pump supply chains. Countries highlighted in red are dominant exporters or importers (i.e. where global share exceeds 40 per cent) whilst countries with a black cross have active trade restrictions. Data on trade flows compiled from UN Comtrade (2023) based on 2017-2021 data, and active trade restrictions based on OECD (2022a) and associated dataset (OECD, 2022b) for the year 2021.

Two trade categories are shown for refined rare earth elements, one for refined metals (HS280530) and one for compounds (HS284690). HS284690 represents the separation stage of refining before refined metal production. The trade of refined (separated) rare earth compounds is moderately concentrated with the top three exporting nations (USA, Malaysia and Russia) accounting for 54 per cent of the global total. Of these the USA is the single largest exporter, accounting for 30 per cent of the total. Imports of rare earth compounds are less concentrated with the top three importers (China, Germany and Japan) accounting for only 28 per cent of the global total. Even though a significant amount of rare earth refining capacity exists in China, it does not appear as a top exporter of rare earth compounds. This is likely due to domestic consumption of these materials to manufacture magnets and refined rare earth metals, of which China is a major global exporter. China is the largest exporter of refined REE metals with 71 per cent of global exports, followed by Vietnam with 7 per cent of the total.

The key points derived from the analysis of the global trade in materials required for heat pumps are:

i. China is the largest net importing country for all the mined materials evaluated except for zinc.

ii. Trade of REE metals is exposed to the highest risk due to the relatively high export concentration in China and the fact that REE magnets are an important component to enable high energy efficiency of the heat pumps.

iii. In general, there seems to be relatively little risk to the supply of those materials used in large quantities in heat pumps, such as copper and aluminium. The global value chains and resulting trade links for these two metals are relatively diversified, particularly so for aluminium. In contrast, 70 per cent of global refined copper exports are sourced from three countries (Zambia, Chile and Bulgaria). However, given the vast production of these metals in relation to HP demand, this is unlikely to constitute a significant supply chain risk.

iv. It is difficult to assess the direct impact of a particular trade restriction as this will depend on its type, magnitude and duration. Imposition of a trade embargo or quota is likely to have a greater impact than levying an export tax for a short period. The dynamic character of export restrictions also contributes additional uncertainty to the supply chain, especially considering current geopolitical tensions.

3.3. COMPONENT AND PRODUCT MANUFACTURE

The manufacture of heat pumps does not require specialised technologies and hence they are commonly produced either locally or in Europe for installation in the UK (IEA, 2023). According to IEA the global production capacity in 2021 has been estimated to be about 110 GW, with the majority in China. However, Europe is expected to significantly increase its production capacity to meet the targets established for the deployment of heat pumps in the region.

While large international corporations are active in the manufacturing of heat pumps, such as Mitsubishi, Vaillant, Viessmann, Daikin, Nibe, Samsung, LG, Hitachi and Mitsubishi, many regional companies are also increasing their manufacturing capacities. These include, for example, Hoval and Saunier Duval (Carrara et al., 2023; IEA, 2023).

The compressors are of particular interest as they use the REE for their permanent magnets and represent the most complex engineering part of the heat pump. In this market a wide range of companies are active globally such as Daikin Industries, Atlas CopCo, Danfoss, Carrier, Panasonic, Johnson Controls and the Kulthorn Group. According to reports by BSRIA (2022) heat pumps account for about 1% of the global application of compressors, with refrigeration accounting for 41% and air conditioning for 58% of demand within the HP segment. China is estimated to provide more than half of the total market in 2021. For all other global markets, especially Europe, the Middle East, and Africa (EMEA), Americas and rest of world, it is expected that compressor manufacturing capacities will be expanded to meet local demand, to comply with regulation and to provide protection against potential geopolitical tensions (BSRIA, 2022).

In general access to materials is seen as less of an issue for the scaling of this technology than the high volatility in the pricing of the materials used. This volatility can influence the cost of heat pumps and hence the relative cost advantages compared with combustion-based heating sources, such as gas in the UK.

4. UK supply chain in heat pump technology

Achieving the projections of the National Grid for the total number of installed heat pumps up to 2050 represents a growth opportunity for the UK. Companies with a presence in the UK are likely to benefit most from growth at the manufacturing step (Marketsandmarkets, 2024; company websites). These include:

- **Worcester Bosch** is one of the UK market leaders in the heating industries, with a product range including heat pumps, solar water heating, hot water cylinders as well as the controls and necessary accessories.
- **Grant UK** has been designing and manufacturing heating products in the UK for the last 40 years and has been recognised as heat pump producer of the year 2023 (Grant Aerona).
- **Ideal Heating** has a 100-year tradition of producing heating solutions in the UK and offers a wide range of heat pumps catering for the domestic and non-domestic deployment.
- **Calorex Heat Pump Ltd.** is a member of the Dantherm Group based in Essex with more than 30 years' experience in the development of heat pumps for different applications.
- **Vaillant** manufactures a large share of the products in the UK, although the design stems from Germany. Heat pump models have been adapted to the UK-specific weather conditions through the use of specialised coatings.

In addition, most of the large European and international corporations, such as Viessmann, Daikin, Nibe, Samsung, LG and Hitachi, maintain an active presence in the UK covering the full sales, distribution and after-sales value chain to ensure seamless access to heat-pump technology in the UK. There are also several SMEs active in the field of heat pumps in the UK which, given the strong growth trajectories of the industry, should be able to benefit and further diversify the heat pump supply chain (Carrara et al., 2023; Lyons et al., 2022).

The compressor represents the most complex engineering part of a heat pump. Most of the large European and international corporations in the compressor market, such as Daikin Industries, Atlas CopCo, Danfoss, Carrier, Panasonic, Johnson Controls and Kulthorn Group are present in the UK with distribution and service activities providing components and solutions to the UK heat pump market (Nowak & Westring, 2023)

On the component side the compressor technology and the semiconductor technologies are those, which require access to potentially critical raw materials, especially if REE PM motors are being increasingly deployed to provide greater energy efficiency. The heat exchanger relies heavily on copper and aluminium for their superior heat-transmission properties.

In summary, until 2021 Europe has been a net-exporter of heat-pump technology globally. With a sharp increase in demand in the region and the UK the region has been become a net-importer of heat-pump technology. However, the strong installed manufacturing base will ensure high accessibility to the technology in the UK going forward (Carrara et al., 2023; IEA, 2022b).

In addition to the manufacturing stage of the supply chain, the Heat Pump Association (HPA) also sees a significant demand in ramping up the installation capacities to achieve the targeted 600,000 installations per annum (HPA, 2019). In contrast to other decarbonisation technologies, the installation of heat pumps for domestic purposes does require careful planning to assess the necessary size of the heat pump, to access the required heat sources and to identify any consequent changes to the radiation system used within a dwelling.

5. UK future demand

5.1. MARKET SHARE SCENARIOS AND MODELLING CONDITIONS

The UK demand for materials embedded in heat pump technology has been estimated for each of the demand scenarios presented by National Grid (2023a, 2023b). In these scenarios the heat pump demand is both quantified in the number of homes with heat-pump installations as well as the annual heat-pump installations. The latter is understood to take into consideration the replacement demand as a heat-pump usage cycle of 10 to 15 years would require some exchange of the installed base up to the forecast time horizon of 2050.

To account for the differences in material intensity the study differentiated between the domestic and non-domestic forecast by assuming a different bill of materials and included this in the weighted average demand projections. If not stated otherwise, the material demand was derived from the most aggressive demand scenario, which for heat-pump is the “consumer transformation” as represented in Figure 10 for the domestic and Figure 11 for the non-domestic segment.

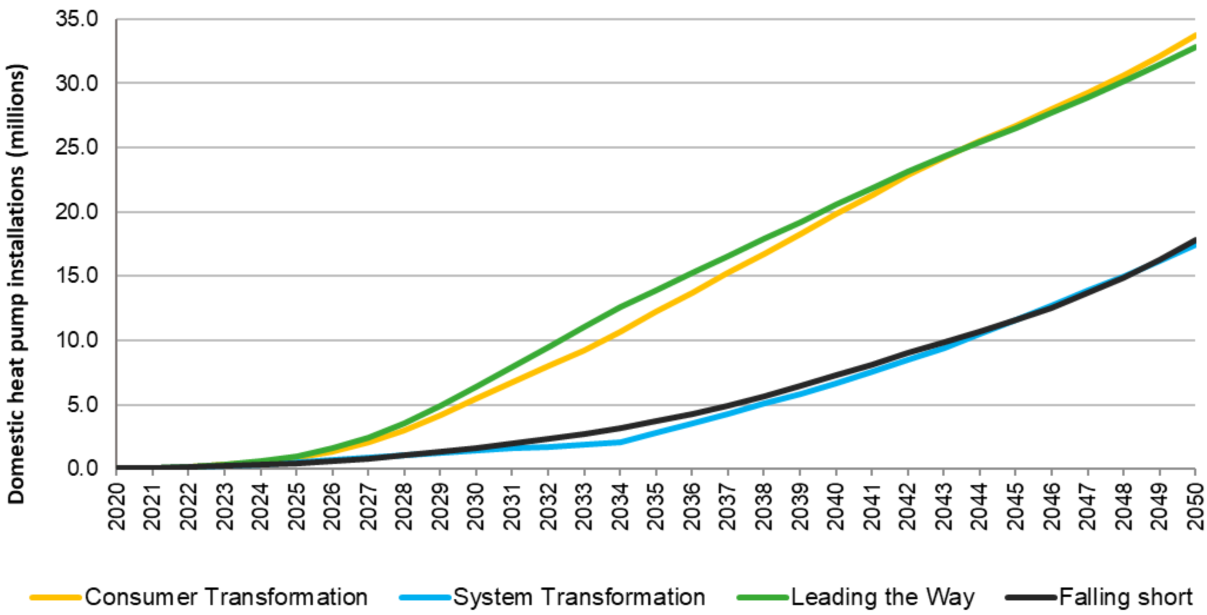

Figure 10: The cumulative installed number of domestic heat pumps in the UK based on four different scenarios (National Grid, 2023a, 2023b).

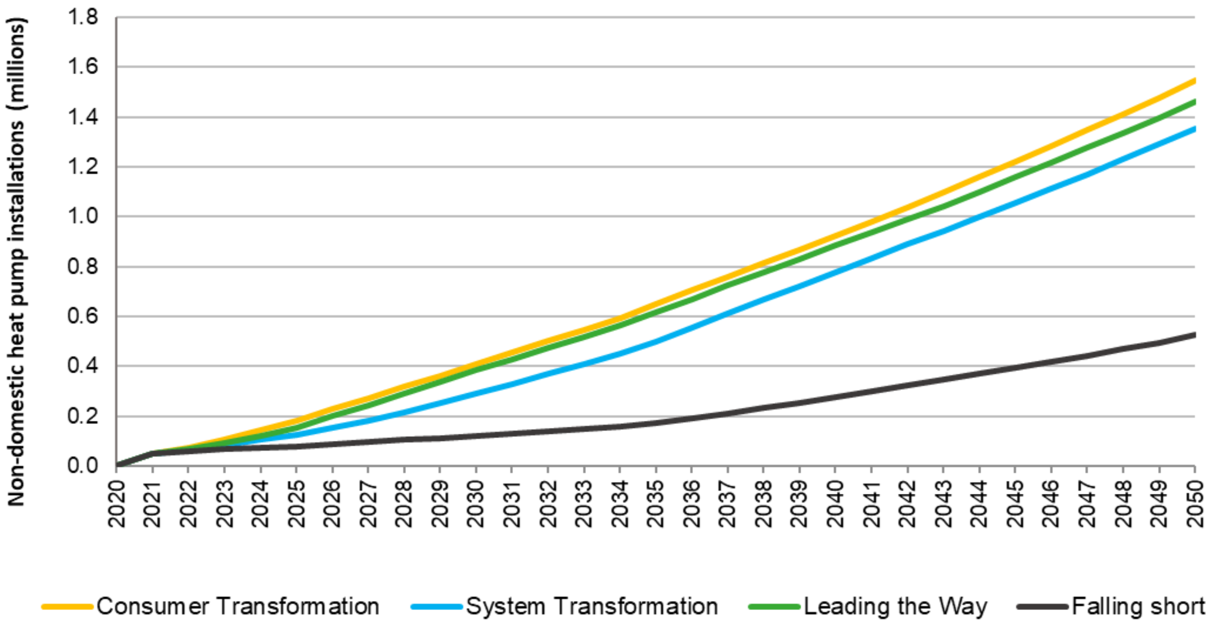

Figure 11: The cumulative installed number of heat pumps for the non-domestic, commercial sector in the UK based on four different scenarios (National Grid, 2023a, 2023b).

The material demand modelling was based on the total number of annual installations, which was explicitly given in the forecast by National Grid. It was further assumed that there will not be significant learning curves in terms of material mix optimisation, due to the mature state of the technology. Hence, current BOM-configurations were used to estimate the future demand over time.

5.2. FUTURE UK RAW MATERIAL NEEDS FOR HEAT PUMPS

The derived demand for future materials is depicted in the following overview. Figure 12 represents the cumulative demand up to 2050 for the selected materials together with their ramp-up for the years 2030 and 2040. An overview of the corresponding annual demand is included in Appendix B of this report.

Figure 12: Cumulative forecast UK heat pump demand (tonnes) for the materials considered in this study between 2020 and 2050 under four different scenarios: Leading the way (LW); System transformation (ST); Consumer transformation (CT); and Falling short (FS).

It is instructive to compare the estimated UK demand with the current global production of these materials (Table 4).

Table 4: Global metal production compared with UK cumulative material demand to 2050 and UK peak annual demand in a high demand scenario ('consumer transformation'). Production data are 5-year averages (2017-2021) (data from World Mineral Statistics database (BGS, 2023; Idoine et al., 2023). The year in which peak UK demand is forecast is also shown.

Element	Global production (5-year average) (tonnes)	UK cumulative demand in 2050 (consumer transformation Scenario) (tonnes)	UK peak annual demand in 2020-2050 (Consumer transformation) (tonnes (*year*))
Copper	20,821,680	1,394,661	67,846 (2050)
Aluminium	64,334,168	164,335	7,919 (2050)
Zinc	12,572,822	93,623	4,553 (2050)
REE oxides	244,723	8,561	417 (2050)
Boron	7,370,822	259	13 (2050)

Given that heat pumps do not rely as heavily on raw materials as some other decarbonisation technologies, the overall share of material demand as a fraction of annual global demand is relatively limited. For instance, in the high demand scenario the share of copper required for heat pumps in the UK in 2050 would equate to 0.33% of global annual production (based on the 5-year production average from 2017 to 2021). The REE material demand for permanent magnets used in heat-pumps would account in 2050 for 0.17% of current global annual production (Figure 13). In essence, this confirms that, despite the significant increase in expected heat-pump deployment, access to adequate amounts of raw materials is unlikely to inhibit the scaling up of heat pump usage in the UK.

However, several industry experts have suggested that the relatively high price of materials required for heat-pump construction, notably copper and REE, could impact on the speed of scaling up heat pump deployment. High material prices would directly impact the up-front investment costs of heat-pumps in comparison to current fossil-fuel based installations, which have lower material, production and installation costs (HPA, 2023; IEA, 2023).

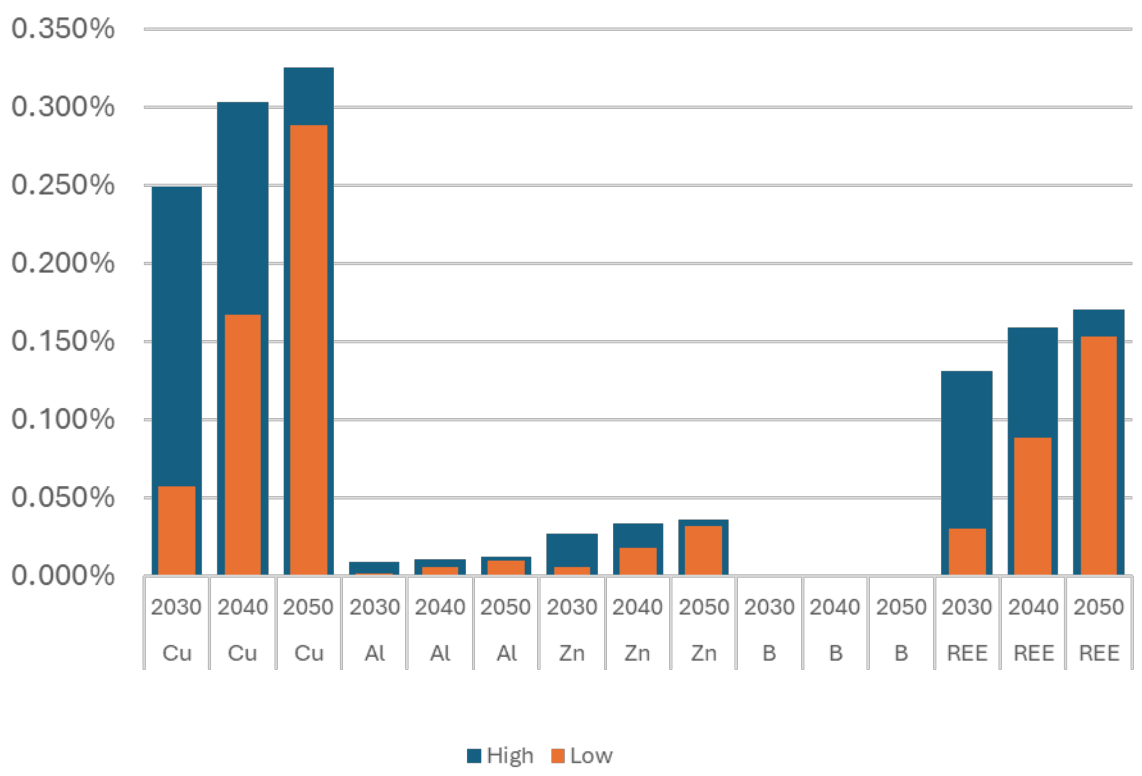

Figure 13: The estimated annual UK demand in 2030, 2040 and 2050 as a percentage of current global annual metal production. The global metal production figures used (5-year average, 2017-2021) are shown in Table 4.

5.3. GLOBAL DEMAND VS UK DEMAND PROJECTIONS

For a better understanding of the future share of the UK demand relative to global demand projections several reports were consulted (Carrara et al., 2023; IEA, 2022b, 2022a, 2023). While there is variance in the speed of ramp-up, these studies conclude that there will be a substantial increase in heat-pump deployment globally.

The expectation is that government policies will be a driver for accelerating the heat pump transition across all major regions. In the US several national and regional legislations are in the pipeline, where heat pumps are integrated as baseline technology for the building code and some states are banning gas-powered heating for buildings above a certain size. In Europe the REPowerEU programme aims to double heat pump deployment rates, which would add 30 million installations alone between 2020 and 2030. In China regulatory measures have been implemented into HVAC (heating, ventilation, air-conditioning) regulation for new build. China is aiming to accelerate the manufacturing capacity for energy-efficient products including heat pumps.(Carrara et al., 2023; IEA, 2023).

The international Energy Agency (IEA) estimates that global annual heat pump sales in the space heating market may reach up to 600 GWth by 2050 (IEA, 2023) and that global heat pump capacity to cover heating needs may reach 6,000 GW globally in 2050 (IEA, 2022b). Assuming an average heat pump size of 6 kW, this equals approximately one billion heat pump units.

An EU foresight study also estimates the development of global heat pump sales up to 2050 in high demand (HDS) and low demand (LDS) scenarios and estimates associated material demand for key materials; steel and copper. It indicates that global HP related demand for copper in 2050 may be in the range of approx. 3-6% of total current global supply in LDS and HDS scenarios, respectively. For steel in 2050, the HP related demand is estimated to be well below 1% of current global supply in both HDS and LDS scenarios. The report also notes that permanent magnets are a potential risk due to supply chain dependency on China. (Carrara et al., 2023).

To provide context for the UK material demand analysis, the same bill of material composition and similar average heat-generation capacity (6 kW) as in the UK demand analysis was used to estimate the global demand, applying the following global scenarios:

1. **IEA NZE scenario**: linear increase in global heat pump installations reaching 1 billion installed heat pumps by 2050, based on the IEA estimate of 6000 GW installed capacity in a NZE scenario (assuming 6 kW per heat pump)
2. **EU foresight - World – LDS**: global annual heat pump sales based on approximation of the LDS data reflected in Figure 16 (cumulative HP sales up to 2050: 425 million)
3. **EU foresight - World – HDS**: global annual heat pump sales based on approximation of the HDS data reflected in Figure 16 (cumulative HP sales up to 2050: 846 million)

Figure 14 compares the estimated UK material demand (‘consumer transformation’ ‘high’ scenario) with the selected global projection scenarios. The comparison varies slightly according to the material. Overall however, the UK material demand ranges from approximately 2 per cent of global HP related demand in 2030 to approximately 4 per cent in 2050.

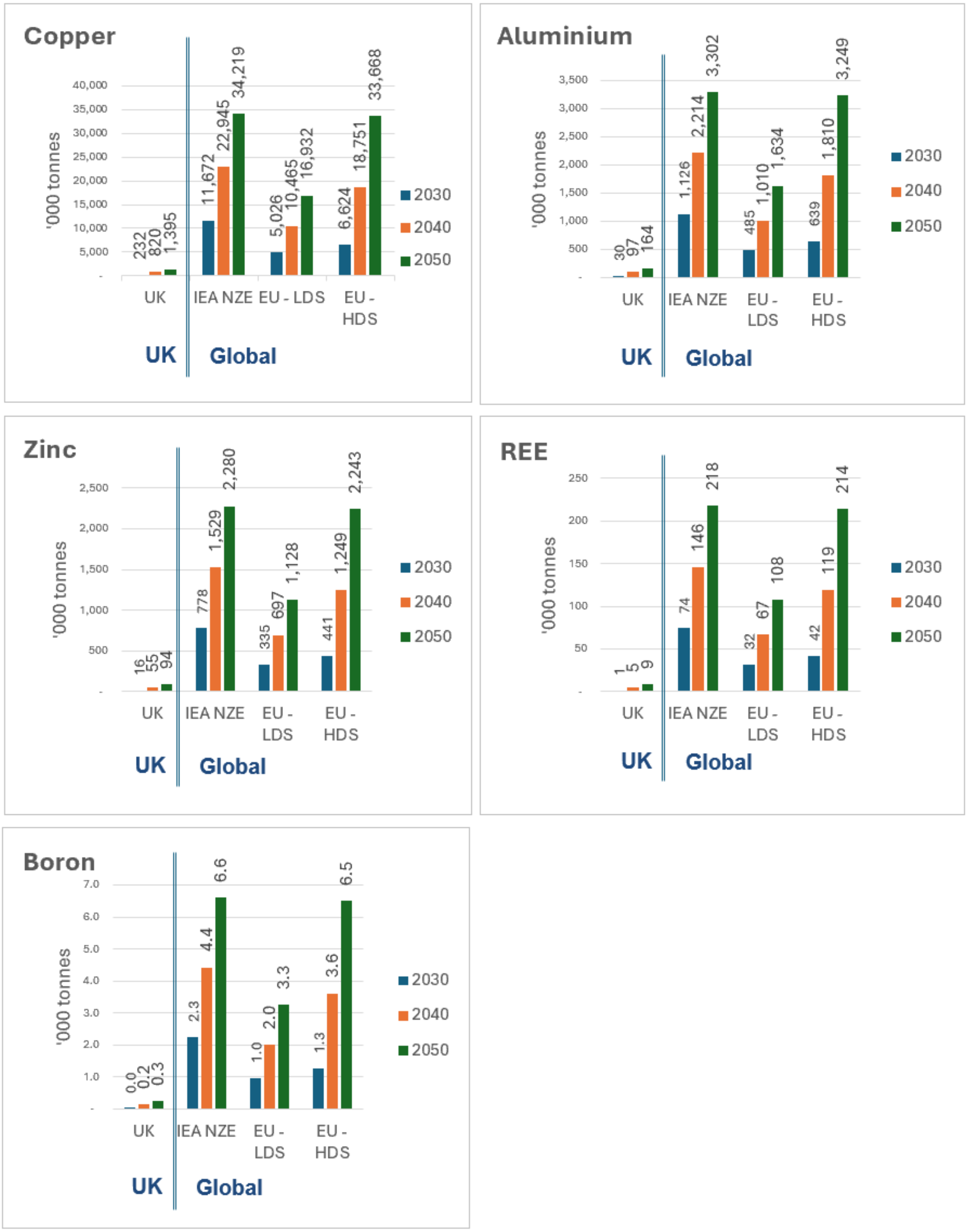

Figure 14: Comparison of estimated UK ('consumer transformation') and global cumulative material demand for the analysed heat pump materials in 2030, 2040 and 2050.

6. Discussion and conclusions

Heat pump technology offers significant potential to provide net-zero decarbonisation contributions by replacing fossil-fuel based feedstocks for heat generation, especially if the required electric energy is provided by renewable sources. While heat pump technology is relatively mature and follows a long known principle, it does require a range of materials, several of which are already considered to be critical to the UK. Most notable are those materials needed for high performance compressors and motors using REE permanent magnets.

This study analysed the global supply chains and UK material demand requirements up to 2050 for different heat pump components. For the compressor REE permanent magnets containing dysprosium (Dy), neodymium (Nd), praseodymium (Pr), terbium (Tb) and boron (B) are of particular importance for the delivery of significant improvements in energy efficiency of most heat pump technologies. The efficiency of the condenser and evaporator depend on materials with high heat transmission capabilities and consequently most designs require significant amounts of copper (Cu) and, to a lesser degree, aluminium (Al). Expansion valves are mostly made from brass, which is produced from copper and zinc (Zn), as these components require higher strength and durability than copper to accommodate the high pressure in the heat pumps.

Materials which fulfil a structural rather than a functional role in the heat pump have not been evaluated in this study. Similarly, HP control units and associated materials have been excluded from the study.

Given the wide variety of designs and sizes on the market three signature heat pumps were selected; a domestic size (6 kW heat pump without REE permanent magnets, a similar size domestic heat pump with permanent magnets, and a commercial size (40-100 kW) heat pump without REE permanent magnets.

The study conducted an analysis of the HP supply chain in the context of key materials, exploring material specific value chains across several distinct steps from mining and refining to component manufacture and final product assembly. For the mining and refining stages supply risks were evaluated based on global production and trade concentration moderated by the ESG ratings of key producing and trading nations and by the existence of trade restrictions on those materials required for the heat pump supply chain. Subsequently, the study quantified the resulting material demands for the UK by 2050, based on the National Grid Future Energy Scenarios (FES) for HP developments. The UK demand was then compared with forecast global material demand in heat pump technology for the same period.

The key insights derived from this analysis are:

- Future UK demand for materials for heat pump technologies as a share of global production levels is likely to be small, even for the most aggressive demand scenario.
- The highest UK shares of global production are for copper, and for the REE required for permanent magnets. However, even for these materials the UK share of global demand is small and does not exceed 0.33 per cent of current global supply of copper and 0.17 per cent for REE.
- Mining, refining and trade concentration are relatively low compared with other decarbonisation technologies requiring large amounts of a variety of specialised materials. REE are the main exception with production strongly concentrated in China.
- Imports of components (especially compressors) and finished products are likely to increase due to the expected faster adoption of heat pump technology in the UK and the EU than the rest of the world. However, it is expected that an increasing proportion of the component and final assembly will take place in the UK and Europe, reducing vulnerabilities from geopolitical supply chain risks.

- As heat-pump technology can also be used for air conditioning, there is potentially a high volatility in future trade volumes, as the much larger air-conditioning market is also expected to grow outside the UK and Europe.
- Overall concerns regarding access to materials are less significant for heat pump technology compared with other decarbonisation technologies.
- However, given the significantly higher material demand per GW produced compared with traditional heating sources in the UK (mostly gas), the high volatility and potential upward price pressure on materials, could negatively affect the comparative advantage of heat pump technology. As a result, the need for upfront investment is a potential barrier to rapid scaling up of heat pump technology in the UK.
- In addition, heat-pump installation requires careful planning and in many cases additional work, especially if implemented as a retrofit to an existing dwelling. To provide these services a substantial build-out of local, UK-based capacities for the planning and installation activities is essential to deliver against respective UK targets.
- Given the need for electrical energy to operate heat pumps, there is also substantial co-dependence on the power generation and power distribution networks in the UK. There is a particular need to improve access to the grid to fully reap the decarbonisation potential that heat-pump technology promises.

7. Recommendations

Several recommendations derived from this analysis could help to increase security of supply requirements to achieve the UK's ambitions for scaling up the installation of heat pumps.

Methodology recommendations

- **Increased HP proliferation combined with variance in design and manufacturing:**. As the technology is relatively simple many designs and heat pump variations are available. While EPD (environmental product declarations) were effectively used to collect and assemble bill of material data necessary for this analysis and to provide initial order of magnitude estimates, there are still relatively few EPDs available and those which are accessible report at different levels of granularity. This requires the application of estimates and in the current case the construction of "signature" BOMs to have the necessary inputs for back-casting predictions on material demand. Improved standardisation and interoperability of designs would simplify the maintenance and installation of heat pumps across the UK.
- **Reducing the visibility gap**: the analysis has shown that the estimation of material demand using a back-casting approach from product to component, and refined and raw materials, is difficult because the availability, quality and relevance of publicly available data is limited. This includes missing data on the bill of materials (BOM) and material composition; and the limited availability of data on refining and mining capacities, especially for by- and secondary products. These data deficiencies exist for both the present time but also, more importantly, for future scenarios.
- **Commercial appraisal of material values**: heat pump technology requires large amounts of materials, which are in high demand for competing technologies, notably copper and the REE. The price volatility of these materials affects the financial viability of heat pump technology compared with alternatives, such as gas boilers, where less upfront investment is required. Consequently, both material quantities and prices should be tracked because of their potential impact on the speed of adoption of heat pump technology.
- **Fast moving markets with competing applications:** The growth in the overall HP market across all regions, combined with competing demand for HP applications, especially for cooling and air-conditioning, could lead to significant shifts in global trade

volumes (e.g. as evidenced by the EU turning into a net-importer after being a major exporter of heat-pump technology).
- **Demand prediction uncertainty:** There remains substantial uncertainty around the predictions for heat pump installation in the UK. Given the high variance in sizing, design and potential material mixes of heat pumps there is a continuing need to monitor the uptake of this technology to project future material demands.

These methodology challenges should be addressed by further ongoing investment in material observatories to provide the necessary fact base for private and public sector decision making and policy development. This is particularly important at present where rapid technology development is taking place at a time of dynamic geopolitics and unstable market forces. Continual review of these foresight studies is pivotal to create a solid foundation for proactive and reliable decision making in the future.

Security of supply recommendations

The study has shown that:

- **Scale-up of heat pump technology** will require undisrupted supply of raw and refined materials. However, these materials are often sourced from jurisdictions with poor ESG-ratings and high geopolitical risk, many of which already impose trade restrictions via licencing and tax requirements.
- **To reduce relative dependencies** on those materials and to reduce the exposure to material price fluctuations options should be investigated for alternative material supplies, including revalorisation of existing stock in the UK via post-use circular revalorisation options. While potentially small in total value, they could play an important role in keeping peak-pricing down.

Hence, a concerted effort at a national level is required to explore policy options to ensure access to those materials and to incentivise improvements of ESG-performance in the source markets. Focus should be on trade-related partnering agreements at regional level. At the same time, effective schemes should be established to facilitate reuse and recycling to maintain necessary stocks within the UK (Hagelüken & Goldmann, 2022).

Domestic capability recommendations

The study has shown that:

- While there is already sufficient local capability in the manufacturing stage and the component market is competitive and not concentrated in geopolitically challenging markets, access to heat pump products is not believed to be an issue for the UK. However, the demand for installation capacity has been identified by many experts as a potential barrier to rapid upscaling of heat pump deployment in the UK (HPA 2023).

- Given the lack of indigenous resources of materials used in heat pump technologies and the long lead-times for developing those known overseas, it is important to focus on maximising the resource productivity of existing stocks. This can be achieved in part through optimised post-use revalorisation schemes including component reuse and material recycling. While this in principle applies to all key heat pump components, significant value may be retrieved through revalorisation of high value components, such as REE permanent magnets. These approaches would benefit from a UK-focused programme to incentivise private sector investment.

Hence, to further de-risk the dependence on imported feedstock an improvement of post-use revalorisation of the installed asset base should be a key priority for the UK. In addition further innovation in heat pump-technology, which also incorporates design for deconstruction, is required to achieve higher resource productivity of the embedded materials.

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Appendix A

Materials excluded from this analysis.

Component	Function	Reason for exclusion
Raw materials		
Steel	Heat pump casing	Structural material
Iron	Essential component in Neodymium iron boron (NdFeB) permanent magnets (PM).	Iron is manufactured in billions of tonnes annually. Hence, the small amount used in PMs is highly unlikely to be problematic from a supply perspective.

Appendix B

Estimated annual UK material demand for heat pumps for each of the national grid scenarios.