Raw Material Needs for Heat Pumps in Germany until 2045

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Abstract

Heat pumps are crucial for meeting international climate mitigation targets in the heating sector. As deployment is projected to rise, the demand for raw materials will increase significantly. This study illustrates the material requirement for heat pumps in Germany from the year 2021 to 2045 and the regarding share of material availability for the German heat pump sector considering both short-term and long-term perspectives on the example of two types of heat pumps. The analysis estimates annual material demand for the German heat pump market against projected production capacities and cumulative demand against reserves, focusing on critical materials such as copper, nickel, aluminum, and rare earth elements (REE) used in magnets. The results show that demand for all examined materials is expected to exceed production capacities. In addition, for copper and nickel the cumulative demand could exceed the reserve budget which may lead to long-term shortages. By optimizing the heat pump design, material demand can significantly decrease, with potential reductions of 50% for copper and 85% for nickel. Overall, the findings underscore the importance of proactive material planning and targeted mitigation strategies to ensure a secure and sustainable supply of critical resources for Germany's heat pump deployment.

Keywords: Material availability; Ressource scarcity; Circularity.

1. Introduction

The Paris Climate Agreement aims to limit global temperature rise to "well-below" 2 degrees Celsius above pre-industrial levels by reducing greenhouse gas (GHG) emissions [1]. In response, nations worldwide are accelerating the transition from fossil fuels to clean energy technologies. Germany, as Europe's largest greenhouse gas emitter, has set ambitious climate goals, committing to achieve climate neutrality by 2045, with interim targets of a 65% emissions reduction by 2030 and 88% by 2040 [2, 3]. In line with these goals, the share of renewable energy in Germany's net public electricity supply reached a record share of 59.7 % in 2023 [2]. Despite these advancements in energy transition, the heating sector in Germany remains heavily reliant on fossil fuels. Heating in buildings, along with hot water provision, accounted for a significant portion of the country's energy consumption, representing 32.7% of total final consumption in 2021 [4]. Alarmingly, over 80% of heating demand is still met using fossil fuels, with natural gas dominating the heating supply in the building sector, constituting 60% of the newly installed heating systems in 2021 [5]. This reliance underscores the urgent need for a transition to renewable heating solutions to meet Germany's climate targets.

Germany has significantly increased heat pump installations in recent years, with 1.7 million units in operation by the end of 2022. However, achieving climate neutrality by 2045 will require 6 to 8 million heat pumps by 2030 and 10 to 17 million by 2050 [6]. Rapid deployment without proper resource management could lead to raw material bottlenecks, hindering the decarbonization of the heating sector. Given the critical role of heat pumps for Germany's energy transition, assessing material needs is essential to securing a stable and resilient supply chain.

The material availability for electric vehicles, solar panels, and wind turbines has been widely analyzed, with consistent evidence of growing resource constraints. The International Energy Agency (IEA) highlights that clean technologies are substantially more material-intensive than fossil-fuel-based systems: for example, an electric vehicle requires six times more mineral inputs than a conventional car, while an onshore wind plant requires nine times more than a gas-fired plant of similar capacity [7]. In Paris Agreement–aligned scenarios, clean energy technologies are projected to account for over 40% of global copper and rare earth demand, 60 – 70% of nickel and cobalt, and nearly 90% of lithium demand by 2040. Several studies confirm these trends: wind turbines are increasingly dependent on copper and dysprosium [8], photovoltaics face supply risks for elements such as indium and selenium [9,10], and battery technologies are expected to exceed Germany's resource budget for nickel, lithium, and cobalt by 2030 [11]. Together, these findings underscore that material availability is a critical factor shaping the scalability of clean energy transitions.

While fossil-fuel boilers primarily utilize low-alloyed steel, heat pumps require substantially greater quantities of copper and high-alloyed steel, materials that are projected to face increased demand across various clean energy applications [11]. In addition, heat pumps incorporate components such as semiconductors, rare earth magnets, and refrigerants, which are not required in conventional boilers [9]. These components often rely on critical raw materials. Notably, several key materials used in heat pump systems—including copper, aluminum, nickel, and rare earth elements (REEs)—are classified as critical or strategic raw materials by the European Commission due to their high economic importance and associated supply risks [12]. Several structural and environmental factors contribute to the supply risks of critical materials used in heat pumps. According to the IEA, copper faces significant supply challenges due to declining ore quality, rising production costs, and increasing exposure to climate risks—over 50% of Chilean copper production occurs in areas of high water stress [7]. In addition, nickel sourced from high-pressure acid leaching (HPAL) projects in Indonesia, which are capital-intensive, delay-prone, and environmentally controversial due to high emissions and waste disposal issues [7].

For rare earth elements (REEs), particularly neodymium and dysprosium used in permanent magnets, supply risks are exacerbated by China's dominance across the value chain—from mining and processing to magnet production—which accounts for nearly 90% of global REE refining capacity. This high concentration increases the sector's exposure to trade restrictions, environmental regulations, and policy shifts in key producing regions [7]. Aluminum, while more geographically diversified in production, remains vulnerable to climate-related supply disruptions, such as drought-induced power shortages in regions like Yunnan Province in China, which is a key hub for aluminum smelting [13].

These converging risks highlight the need for a dedicated assessment of material availability specific to heat pump technologies, to support effective resource planning and ensure a secure and resilient transition in the building sector. Without adequate planning, material shortages could hinder large-scale deployment and delay progress toward climate targets. This study evaluates the material availability for heat pump deployment in the German building sector through 2045. It identifies key materials required, assesses whether projected production capacities and reserves can meet future demand, and explores mitigation strategies to reduce material use and improve availability. Specifically, the study addresses three research questions: (1) What is the total material demand for heat pumps in Germany until 2045? (2) Will current production and reserves be sufficient to meet this demand? (3) Can heat pump design help to overcome material scarcities?

2. Methods

This study estimates the availability of key metals required for heat pumps in Germany through 2045, with a focus on the manufacturing stage while excluding energy sources such as electricity and heat. The analysis considers direct metal and mineral usage while omitting synthetic compounds like oil, refrigerants, and plastics. The selected timeframe aligns with Germany's carbon neutrality target, necessitating the accelerated deployment of heat pumps. Given the dominant market share of air-source heat pumps (ASHPs), propane ASHPs have been chosen as proxy for the calculations in this study [14].

The heat pump deployment pathway is derived from the energy system model REMod [15], which evaluates Germany's energy transition and simulates different energy system deployment pathways. In this analysis, two scenarios from REMod are used. The *Reference* Scenario serves as a baseline, assuming a cost-optimal energy system transformation without significant social or policy-driven changes. It targets a 65% reduction in CO_2 emissions by 2030, 88% by 2040, and net-zero by 2045. The *Sufficiency* Scenario represents an improvement scenario, assuming significant societal behavioral changes that lead to reduced energy consumption through efficiency and minimalism [15]. Heat pump sales include both new installations and replacements of end-of-life (EoL) units. Replacements are considered using historical sales data from the Bundesverband Wärmepumpe (BWP) for the years 2004–2020 assuming an average lifespan of 20 years.

2.1.1. Inventory and Material Composition of Heat Pumps

Table 1 presents the technical details of two ASHP models used in the analysis. A *current market heat pump* serves as the baseline, representing industry-standard technology, while the *compact propane heat pump* is analyzed as an alternative design scenario to exemplify the impact of heat pump design. Data for the current market heat pump model was mainly obtained from Saoud et al. [16]. The data for the permanent magnet is based on direct measurements, while electronic components, oil, pipework insulation, and wiring insulation were scaled according to weight, using inventory data from Kägi et al. [17]. The compact propane heat pump is currently in a prototype stage, inventory data are directly drawn from the prototype by the authors [18]. The compact design is to optimize efficiency while minimizing refrigerant charge, specifically using propane (R290). Although R290 has a low Global Warming Potential (0.02), its flammability necessitates charge reduction for safety. This design adjustment enhances environmental compliance and reduces overall material use in the heat pump system. However, the compact design leads to slightly lower efficiency.

Table 1 Technical data for the current market heat pump and the compact propane heat pump.

	Unit	*Current market heat pump*	*Compact propane heat pump*
Technologies		Air to water heat pump	Air to water heat pump
Capacity	kW	30	40
Refrigerant		R407C	R290
Lifespan	years	10 to 20	10 to 20
Total weight of a single unit	kg	618	460

Table 2 presents the specific material demand for a single unit of both the *current market heat pump* and the *compact propane heat pump*. The raw material demand is then determined based on the weight percentage of different components. The composition of low and high alloyed steel, brass, and aluminum alloy are based on life cycle inventory data from the database ecoinvent 3.10. The rare earth elements used in the magnets, including neodymium, praseodymium, and dysprosium, are summed and analyzed as rare earth elements (REE). Furthermore, among the raw materials used in heat pumps, copper (Cu), aluminum (Al), nickel (Ni), and rare earth elements (REE) are selected for further investigation in the material availability assessment, as they are classified as critical raw materials (CRMs) and strategic raw materials (SRMs) by the European Commission [12].

Material demand is calculated by multiplying annual heat pump sales by the raw material demand per unit.

Table 2 Specific material demand for a single unit of the current market heat pump and the compact propane heat pump.

Heat pump Component	Material	Unit	*Current market heat pump*	*Compact propane heat pump*
Evaporator	Aluminum alloy	kg	49.28	63.36
	Copper tube	kg	20.52	13.54
	Brass	kg	0.21	0.20
Compressor	Polyols	kg	4.02	4.02
	Low alloy steel	kg	98.98	36.59
	Magnet	kg	0.41	0.41
	Oil	kg	3.72	1.86
Condenser	High alloy steel	kg	44.16	7.70
Expansion valve	Glass fibre reinforced plastic	kg	0.21	0.21
	Magnet	kg	0.03	0.03
Economizer	High alloy steel	kg	6.40	-
Refrigerant		kg	7.50	1.75
4-way reversing valve	Glass fibre reinforced Plastic	kg	1.17	1.17
Non-return check valve	Brass	kg	0.18	0.18
	Copper	kg	0.02	0.02
Filter dryer	Low alloy steel	kg	1.04	3.12
	Copper	kg	0.20	0.60
Pipes	Copper	kg	85.00	38.00
Suction fan	Aluminum	kg	10.00	10.00
	Low alloy steel	kg	10.00	10.00
Outside shell	Low alloy steel	kg	250.00	250.00
Pipework insulation	Elastomer	kg	20.00	12.00
Wiring insulation	Polyvinyl chloride	kg	2.00	2.00
Electronic control unit		kg	3.34	3.34

2.2. Projection of material supply

For the short-term availability analysis, the annual primary material demand for heat pumps is compared against mining production, which refers to the extraction of raw materials from the earth. Mining production projections for Cu, Ni, and REE are based on the IEA's Global Critical Minerals Outlook 2024 [13], while Al projections follow the net-zero scenario outlined in the IEA's Net-Zero Roadmap [13, 14]. The base case production scenario includes output from existing assets, projects under construction, and those with a high likelihood of advancement.

For long-term availability analysis, potential shortages are identified when cumulative demand approaches or exceeds global reserves. "Raw Material Reserves" refer to known, economically extractable material quantities, with reserve data sourced from the USGS [19]. Table 3 presents supply data for Cu, Al, Ni, and REE, including production figures for 2021, 2023, 2030, and 2040, alongside their respective reserves.

To assess material availability relative to natural resources, primary material demand is further calculated and compared with mining production and reserves using the global secondary material use rate [13].

Table 3 Supply data global mining production and reserves of Cu, Al, Ni, and REE for magnets.

Material	Unit	2021 Production	2023 Production	2030 Production	2040 Production	Reserves
Copper	kt	21.426	22.508	22.412	14.889	1.000.000
Aluminum	kt	67.840	69.440	74.400	76.440	7.500.000
Nickel	kt	2.649	3.451	4.304	4.439	130.000
REE	kt	55	75	107	114	23.571

Since production and reserve data are available only at the global level, but the demand is specific to heat pumps in Germany, the global data must be allocated to each material's 2023 market share for the German heat pump sector. This share is calculated as the proportion of raw material demand for heat pumps in Germany relative to global demand in 2023 (Table 4).

Table 4 Material demand for the German heat pump market, the global demand and the resulting relative market share for German heat pump in 2023.

	Demand for the German heat pump market in 2023 (kt)	Global demand in 2023 (kt)	2023 market share (%)
Copper	35.8342	25855	0.1386
Aluminum	19.1317	96900	0.0197
Nickel	1.3577	3104	0.0437
REE	0.061	96	0.0634

Finally, Table 5 presents the mining production and reserves allocated to the German heat pump sector.

Table 5 Allocated mining production and reserves for German heat pump sector.

Material	Unit	2021 Production	2023 Production	2030 Production	2040 Production	Reserves
Copper	kt	29.70	31.20	31.06	20.64	1385.97
Aluminum	kt	13.39	13.71	14.69	15.09	1480.78
Nickel	t	1158.72	1509.53	1882.64	1941.70	56,864.20
REE	t	34.88	47.56	67.86	72.30	14,948.11

3. Results

3.1. Material demand for the German heat pump sector

Figure 1 presents the annual material demand for iron (Fe), aluminum (Al), and copper (Cu) in heat pumps for the German market from 2021 to 2045 under the REMod [15] *Reference* and *Sufficiency* scenarios, with other materials aggregated due to their relatively small quantities. Under the *Reference* scenario, total material demand is projected to increase to 300% by 2030 compared to 2023 and to 190% by 2045. In the *Sufficiency* scenario, material demand is expected to rise to 269% between 2024 and 2030 and to 186% between 2024 and 2045.

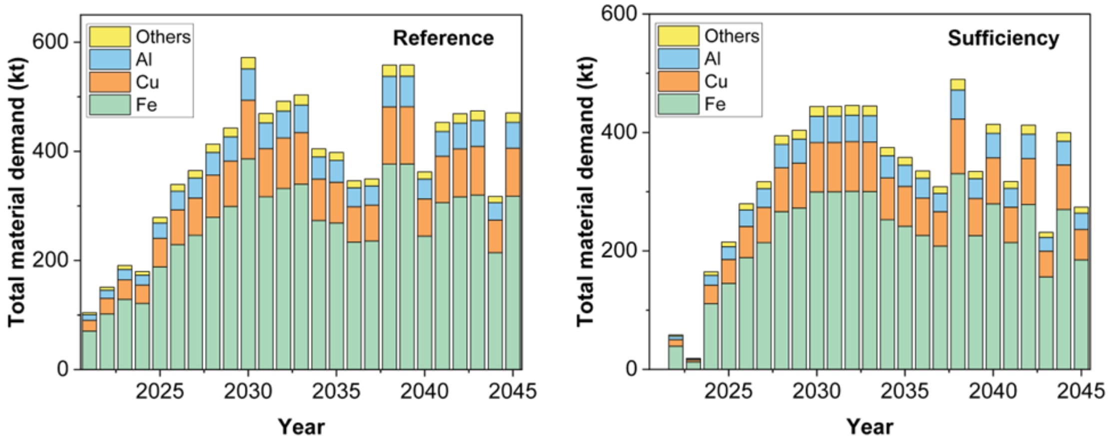

Figure 1 Total material demand for heat pumps in Germany under the Reference and Sufficiency scenarios [15] from 2021 to 2045.

Figure 2 illustrates the cumulative material demand over the same period for both scenarios, highlighting Fe, Al, and Cu while aggregating other materials for clarity. The *Sufficiency* scenario reduces overall cumulative

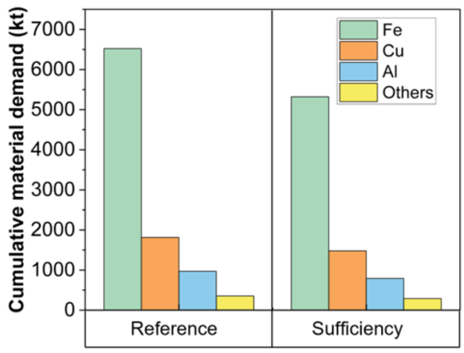

Figure 2 Cumulative material demand for heat pumps in Germany from 2021 to 2045 under the Reference and Sufficiency [15] scenario.

material demand by 20% compared to the *Reference* scenario, reflecting the impact of behavioral changes on resource consumption.

3.2. Material Availability Assessment

The material availability is assessed at short-term, which compares annual material demand with annual mining production, and at long-term, which compares cumulative material demand from 2021 to 2045 with known reserves. If demand exceeds production or reserves, a supply risk is identified.

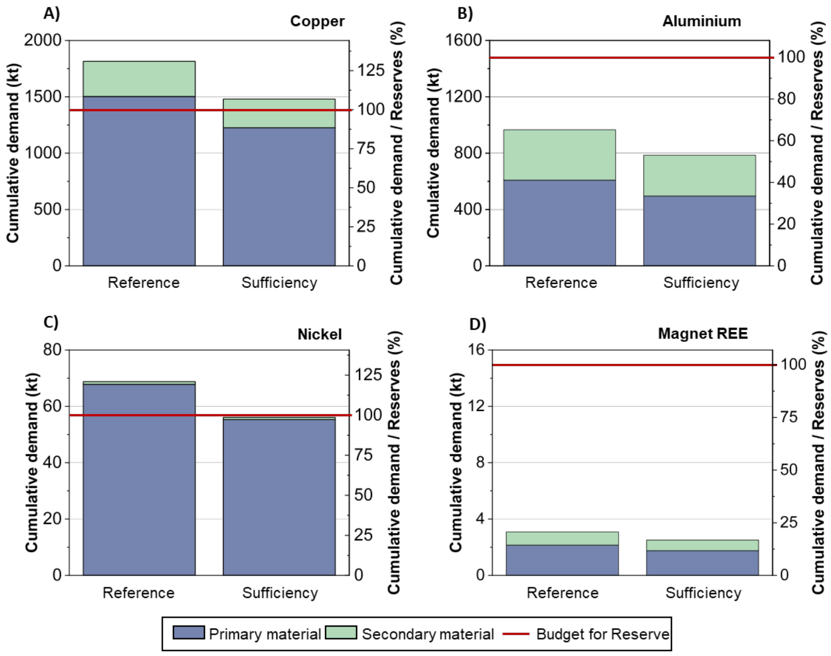

Figure 3 Long-term perspective: Cumulative demand for heat pumps in Germany from 2021 to 2045 for Copper (Cu), Aluminum (Al), Nickel (Ni), and Rare Earth Elements (REE) across different energy pathways (Reference and Sufficiency [15]). The blue bars represent primary demand, while the green bars indicate secondary demand for each material, and the red line represents the German heat pump budget of reserves.

Figure 3 illustrates the cumulative material demand for heat pumps in Germany from 2021 to 2045 alongside the allocated reserve budget for copper, aluminum, nickel, and rare earth elements. Cumulative primary material demand for Cu under the *Reference* scenario exceeds the budget allocated to the German heat pump market by 108%, indicating a long-term shortage risk (Figure 3 A). In contrast, in the *Sufficiency* scenario, Cu demand reaches 88% of the reserve budget.

Similarly, nickel demand under the *Reference* scenario exceeds the reserve budget by 119%, while in the *Sufficiency* scenario, it reaches 97%, suggesting a potential supply risk (Figure 3 C).

In contrast, cumulative primary material demand for Al and REE remains within reserve limits. Under the *Reference* scenario, Al demand accounts for 43% of the reserve budget (Figure 3 B), while REE demand accounts for 14% (Figure 3 D). These findings suggest that Cu and Ni may face long-term supply constraints, whereas Al and REE reserves are sufficient under both scenarios.

Figure 4 presents the annual primary material demand for the German heat pump market in 2023, 2030, and 2040 for copper, aluminum, nickel, and rare earth elements, alongside the allocated production budget for the German heat pump market under the *Reference* and *Sufficiency* scenarios [15]. In the *Sufficiency* scenario, material demand is notably lower in 2023, due to a temporary reduction in heat pump installations. However, demand recovers in 2024 and beyond, following a more typical trajectory as heat pump deployment increases.

Copper exhibits the highest short-term shortage risk, with primary demand significantly surpassing the allocated production budget for the German heat pump market. In 2030, primary copper demand is at 280% of the budget in the *Reference* scenario and at 218% in the *Sufficiency* scenario.

By 2040, mining production is expected to decline further, with a growing reliance on secondary material production to address the shortfall. However, primary copper demand still is at 230% of the production budget in the *Reference* scenario and at 263% in the *Sufficiency* scenario.

Aluminum demand also exceeds production budgets in both scenarios. In 2030, primary aluminum demand surpasses the production budget by 242% under the *Reference* scenario and 188% under the *Sufficiency* scenario. By 2040, demand continues to outstrip production, exceeding the budget with 134% in the *Reference* scenario and 153% in the *Sufficiency* scenario.

Nickel demand in 2030 exceeds German heat pump budgets of mining production with 209% under the *Reference* scenario and 163% under the *Sufficiency* scenario. By 2040, primary demand still surpasses the production budget with 120% in the *Reference* scenario and 137% in the *Sufficiency* scenario.

REE primary demand in 2030 exceeds the German heat pump budget mining production with 196% in the *Reference* scenario and 153% in the *Sufficiency* scenario. By 2040, primary demand remains above production capacity, exceeding the budget with 115% in the *Reference* scenario and 130% in the *Sufficiency* scenario.

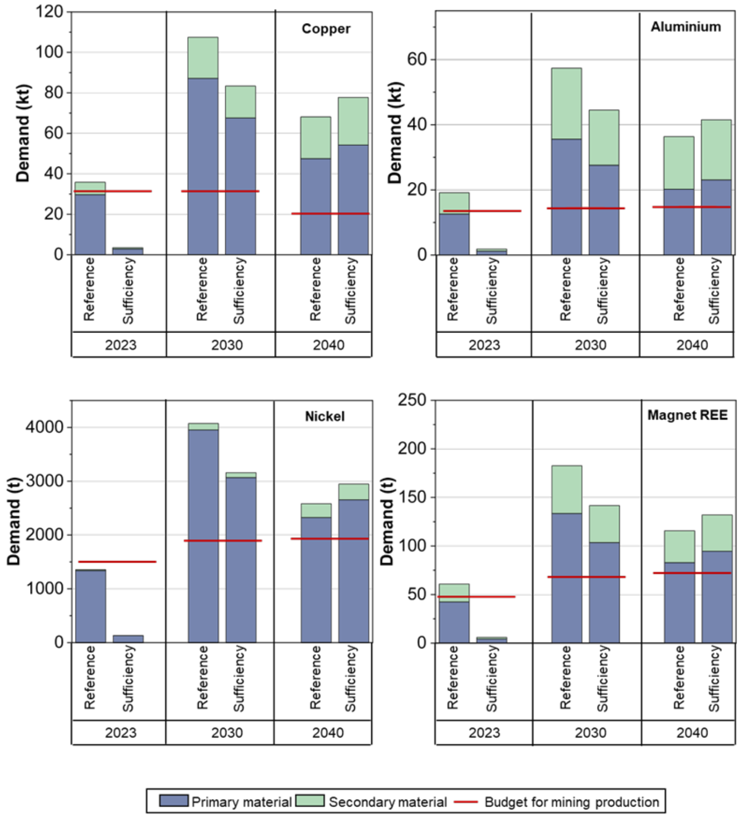

Figure 4 Short-term perspective: Annual material demand for heat pumps in Germany (2023, 2030, and 2040) for Copper (Cu), Aluminum (Al), Nickel (Ni), and Rare Earth Elements (REE) across different energy pathways (Reference and Sufficiency Scenarios). Purple bars indicate primary material demand, green bars represent secondary material contributions, and the red line illustrates the allocated production budget for the German heat pump market.

These findings suggest significant short-term supply constraints across all materials, with copper facing the highest risk, followed by aluminum, nickel, and rare earth elements.

3.3. Impact of Heat Pump Design

Heat pump design can influence material availability. Figure 5 illustrates the material requirements for iron (Fe), chromium (Cr), manganese (Mn), nickel (Ni), copper (Cu), and aluminum (Al) for a single unit of the current market heat pump and the compact propane heat pump. Other materials or components that maintain the same quantity are not included in this figure.

The compact propane heat pump demonstrates reduced usage of certain materials compared to the current market heat pump. Notably, chromium (Cr) and nickel (Ni), experience the largest material reductions with a decrease of 85%, particularly in high alloy steel used for the condenser. Additionally, copper usage is reduced by 50%, primarily due to decreased copper tubing in the evaporator and copper piping. However, the demand for Al in the evaporator increases by approximately 30% to maintain efficiency.

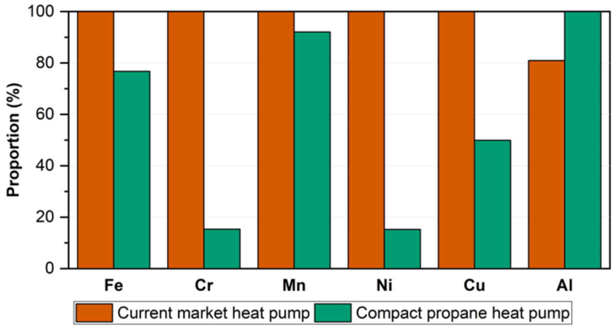

Figure 5 Material requirements for iron, chromium, manganese, nickel, and aluminum in a current market heat pump and a compact propane heat pump.

A market towards more compact designs can reduce copper demand by 50%, significantly mitigating supply shortages. Conversely, aluminum demand increases with compact propane heat pumps. This indicates potential short-term supply constraints, requiring additional mitigation strategies and resource management. Adopting compact propane heat pumps reduces nickel demand by 85%, further eliminating supply risks.

4. Discussion

While projecting exact material demand for heat pumps is challenging due to varying assumptions and uncertainties, this study provides an overview of the potential material requirements for German heat pump deployment through 2045. By comparing projected demand with Germany's allocated share of global supply, the analysis highlights potential short- and long-term supply constraints.

In the long term, copper and nickel present notable availability risks, with cumulative demand exceeding reserve budgets by 108% and 119%, respectively, under the *Reference* scenario. These risks are mitigated under the *Sufficiency* scenario, bringing cumulative demand down to 88% for copper and 97% for nickel, relative to reserve budget. However, it is important to recognize that cumulative demand is assessed over a 25-year period, whereas reserves reflect long-term extractable quantities. Therefore, falling below the reserve budget does not imply that supply risks are entirely resolved. In the short term, this study indicates availability risks across all assessed materials due to the rapid increase in heat pump deployment. These risks are projected to peak around 2030, when material demand reaches its highest level according to the REMod scenarios [15]. Among the materials analyzed, copper poses the greatest challenge, with primary demand exceeding the production budget by 280%, underscoring the need for timely and effective mitigation strategies. While the *Sufficiency* scenario helps to alleviate overall demand pressures, it remains insufficient to fully eliminate material availability risks.

These material shortages could have profound implications for the German heat pump market. If demand continues to outstrip supply, manufacturers may face price volatility, delayed production, and disrupted deployment timelines. The increased cost of raw materials could translate into higher consumer prices, potentially slowing down the market uptake of heat pumps. To mitigate these impacts, companies should prioritize supply chain diversification, establish long-term contracts with suppliers, and invest in material-efficient product designs. Innovations in design can significantly reduce material demand—by 50% for copper and 85% for nickel—highlighting the potential of engineering solutions in addressing resource bottlenecks.

While this study focuses on Germany's heat pump deployment, the key materials assessed—copper, nickel, aluminum, and rare earth elements—are also indispensable for other clean energy technologies such as electric vehicles, wind turbines, and photovoltaic systems. In scenarios aligned with the Paris Agreement, clean technologies are projected to account for over 40% of global copper and rare earth demand and up to 70% of nickel demand by 2040 [7]. This means that the shortages identified here for heat pumps cannot be viewed in isolation: Germany's building-sector transition will unfold in direct competition with parallel demand from mobility, power generation, and storage. Rather than easing pressure, the simultaneous growth across multiple sectors suggests persistent competition for these critical materials, reinforcing the urgency of mitigation strategies such as design innovation, recycling, and diversification of supply.

As Germany scales up heat pump deployment to meet climate neutrality goals, it must also consider long-term material security. Policymakers need to integrate resource planning into energy transition strategies—by monitoring material flows, supporting domestic and EU-level resource development, and reducing import dependency through recycling and substitution initiatives. Particularly for rare earth elements, where refining and magnet production is concentrated in China, overreliance on a single region exposes the supply chain to geopolitical disruptions [20]. The COVID-19 pandemic and the war in Ukraine have demonstrated how sudden global events can severely impact material access, underlining the need for diversified and resilient supply chains.

To ensure material security for large-scale heat pump deployment, policy frameworks should prioritize three areas: (1) support for material-efficient heat pump designs, including funding for R&D and incentives for manufacturers to adopt low-material-intensity technologies; (2) strengthening secondary material use through improved recycling infrastructure, product design standards that enhance recyclability, and monitoring of material flows to increase recovery rates; and (3) strategic resource planning, which includes diversifying import sources, supporting domestic refining capacity within the EU, and integrating material availability assessments into national energy planning.

Circular economy strategies are particularly vital for managing long-term material availability. Unlike linear systems that rely on continuous extraction of raw materials, a circular approach aims to keep resources in use for as long as possible through reuse, remanufacturing, and recycling. For the heat pump sector, this means designing systems that are modular, repairable, and recyclable enabling easier disassembly and recovery of valuable materials. Therefore, improving recycling infrastructure, material tracking systems, and collection schemes will be essential to scale up secondary supply. Embedding circular economy principles into heat pump design and end-of-life management not only reduces pressure on virgin material supply but also increases resilience against geopolitical and environmental risks.

However, realizing the full potential of circularity depends on the recyclability of specific materials. REEs for magnets remain vital for heat pump performance and are over 80% import-dependent, with 94% of global magnet production concentrated in China [7]. This highlights the strategic importance of improving domestic REE recycling. The EU has set ambitious targets to increase recycling, aiming to meet 15% of annual magnet consumption from secondary sources by 2030, with projections suggesting that up to 48% of REE demand could be covered by recycled material by 2050 [21, 22]. Achieving these goals is crucial, not only for material circularity but also for strengthening supply chain resilience amid growing geopolitical uncertainties.

5. Conclusion and Outlook

This study provides a forward-looking assessment of material availability for heat pump deployment in Germany, a cornerstone of the country's decarbonization strategy. By analyzing projected material demand under different energy pathways and comparing it with estimated supply, the study reveals substantial short- and long-term constraints—particularly for copper, aluminum, rare earth elements used in magnets, and nickel.

Despite these insights, the study has several limitations. First, the analysis relies on a single 40kW and 30kW air-source heat pump as a proxy, which may over- or underestimate material demand for other sizes and technologies. Second, global mining production and reserves were allocated to the German heat pump market based on 2023 demand shares, an assumption that introduces uncertainty as markets evolve. Third, supply is dynamic rather than static quantities, meaning their use as a long-term benchmark should be interpreted cautiously.

Future research should address these gaps by incorporating a wider range of heat pump models and lifespans, testing alternative deployment pathways, and applying more nuanced criticality assessments that integrate geopolitical, social, and environmental dimensions. Beyond academia, the findings carry implications for industry and policymakers: advancing low-material-intensity designs, strengthening recycling infrastructure, and integrating resource availability into energy transition strategies will be essential to secure the material base for large-scale heat pump deployment. As the first systematic assessment of material availability for heat pumps in Germany through 2045, this study provides a foundation for future work linking material security with broader decarbonization efforts worldwide. Future research should aim to enhance the robustness of material availability assessments by addressing several dimensions. First, expanding data diversity through the inclusion of a broader range of heat pump models, capacities, and design configurations will enable more representative and granular demand projections. Second, evaluating multiple production scenarios that account for potential policy changes, market dynamics, and technological advancements would provide a more comprehensive outlook on future supply conditions.

Moreover, future studies should conduct comprehensive assessments of supply risk by considering a wider set of influencing factors. This includes not only quantitative metrics such as reserves and production, but also qualitative dimensions like geopolitical dependencies, trade policy uncertainty, environmental and social impacts of extraction, and regulatory developments. Additionally, research should assess the combined effects of different mitigation strategies—such as design optimization, material substitution, and increased recycling—to identify the most effective pathways for reducing material pressure. Finally, expanding the scope of analysis to include additional materials such as chromium and components within electronic control units (ECUs) could provide a fuller understanding of the resource demands associated with large-scale heat pump deployment.

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