China's role in the UK energy *transition*: from mine to technology

PUBLISHED

DEPARTMENT OF ENGINEERING,
UNIVERSITY OF CAMBRIDGE,
CAMBRIDGE, UNITED KINGDOM

15 AUGUST 2025

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PLEASE CITE AS: SERRENHO A, CULLEN JM. (2025). CHINA'S ROLE IN THE UK ENERGY TRANSITION: FROM MINE TO TECHNOLOGY.

DOI: 10.17863/CAM.123213

GET IN TOUCH: CCML@ENG.CAM.AC.UK

AVAILABLE FOR DOWNLOAD AT: WWW.REFFICIENCY.ORG

RESEARCH IN THIS REPORT IS FUNDED BY CCG, CLIMATE COMPATIBLE GROWTH: HTTPS://CLIMATECOMPATIBLEGROWTH.COM/ABOUT-US/

1.

EXECUTIVE SUMMARY

The dominant position of China in the global supply chain of clean technology has been raised by a number of governments and researchers with ambitious decarbonisation and clean energy deployment targets. China is responsible for processing over 50% of the lithium, copper, and graphite that go into electric vehicles, and controls even greater shares of the production of EV battery cells and cell components. Given this, countries undergoing an energy transition are looking to understand the extent of their own dependence on China and the mitigation strategies and opportunities to reduce this dependency.

The location of mines is fixed by the geography of where critical minerals are found and are feasibly extractable, whereas processing plants have fewer constraints on their geography. However, secondary sources such as recycling of end-of-life products offer a potential means to supplement primary extraction, though current volumes remain limited for many critical minerals. Given the fixed availability of these minerals, understanding where they come from and where they are likely to end up is of primary importance. In this report, we take a holistic view of the critical mineral value chain, linking together all steps to understand critical minerals, from mine to final technology use.

Figure 1 shows the overarching structure of this report. The main body of the report (sections 2-4) covers the full range of the value chain before discussing future cross-cutting work. From this, we draw out several key insights for the UK dependency on China for critical minerals. These are set out below:

→ UK decarbonisation is dependent on key critical minerals. Analysis in Section 2 finds that 99% of the critical mineral demand in 2050 is from six critical minerals (cobalt, gallium, graphite, lithium, silicon, and tellurium) needed to decarbonise the energy and transport sector. To date, China has established strong competitive advantages in the production and refining of these minerals (it has majority positions in the processing of all six minerals listed in cluster 1).

→ Strategic planning by the Chinese Government has been successful in identifying critical minerals and renewable energy technologies that will be important in the future and establishing a dominant position in these industries. While the UK criticality assessment (UK Government, 2023) accounts for expected future demand growth, our analysis finds that the demand for key critical minerals is expected to decline in future decades (in energy and transport sectors) due to the phase out of specific technologies like catalytic converters. The UK assessment of critical minerals needs to better account for these changing overall demand profiles and prioritise the future supply of minerals that are known to be in future demand.

→ Supply chains have become increasingly globalised. As such, the minerals extracted in mines controlled by UK companies are not correlated with the minerals in UK products. Analysis of the location and ownership of critical mineral mine reserves revealed that ownership does not impact where minerals are used (geographically). Instead, it is the location of mines that determines how minerals are used, and who has final control over exports. This holds true even when looking at the ownership of projects under development, showing the importance of taking a global perspective to understand critical mineral supply chains evolution over time.

→ Overall, we find that the UK has a relatively strong position when it comes to mine ownership. Chinese dominance in critical mineral supply chains is primarily centred around the refining and processing stages for these minerals, alongside the end-use technologies. The UK is thus vulnerable to China on these latter stages of the value chain. The focus for future work should be on how the UK can reduce its dependence on China, specifically for the production of intermediate and final clean energy products.

Based on these insights, a number of policy-relevant recommendations are made, with a more extensive discussion of the policy insight in Chapter 7:

→ Revise and Update the UK Critical Mineral Strategy

- Align the strategy with evolving mineral demand trends, prioritising the six minerals crucial for decarbonisation (cobalt, gallium, graphite, lithium, silicon, and tellurium) and reevaluating the four minerals tied to nuclear power and carbon capture deployment (indium, niobium, tungsten, and vanadium).
- Incentivise the development and deployment of decarbonisation technologies that are less reliant on critical minerals such as sodium-ion batteries.
- Accelerate recycling initiatives to capture end-of-life minerals and build domestic supply, to reduce future dependency.

→ Secure UK Mineral Supply Beyond Mine Ownership

- Build strong strategic relationships with countries with growing production to mitigate supply disruptions and potential export bans.
- Leverage the UK's strong global mine ownership position to counterbalance China's dominance in the processing and refining stages.
- Recognise that the balanced ownership of mineral assets (UK and Chinese companies serving each other's markets) offers strategic opportunities. However, such ownership structures may be more complex than they appear, as Chinese financial institutions and state-backed investors also hold significant equity stakes in some nominally UK-based companies.

→ Diversify Supply and Processing Capacities

- Take early action to secure non-Chinese critical mineral production as global competition for alternative supplies intensifies.
- Foster international investment in extraction and refining capacities in allied and partner countries.
- Develop domestic or allied refining and intermediate processing capabilities to reduce reliance on Chinese processing.

So what?

People are increasingly concerned about the dominant position China has in the supply chain for critical minerals. Given the amount of refining and processing completed in China, this concern is clearly justified. However, informed and evidence-based responses remain limited. Current policy and industrial strategy responses have focused on supporting domestic processing and manufacturing capacity, with less emphasis on where international feedstocks for such facilities come from, and who controls them.

The location of the deposits of critical minerals cannot be changed or moved (although new deposits are still being discovered). The good news is that there is sufficient mining capacity outside of China to meet the UK demand for critical minerals, although this non-China supply is likely to be constrained through competition. Given that China also has insufficient domestic mining to meet its own internal demand, the UK retains some leverage over China given its strong position in global mine ownership.

Finally, it is undeniable that over the short to medium term, the UK will be dependent on a number of critical minerals, primarily processed in China, for its clean energy technologies. However, key decisions over technology choices and energy and resource efficiency remain can help reduce the UK's overall dependency. Specific minerals see a wide degree of uncertainty over their future demand depending on the deployment of nuclear and carbon capture and storage in the UK. Reducing the use of these technologies, which is shown to be possible in many scenarios, could reduce the number of minerals where the UK is dependent on China and reduce dependence in the future. Finally, potential decarbonisation pathways make a range of assumptions about the final demand for all technologies, up to 2050. Comparing demand across different scenarios shows that reducing the final demand for clean goods such as solar and wind power and batteries can lower overall mineral needs. Energy efficiency measures and optimisation for travel and electricity use can further reduce the total amount of mineral dependance

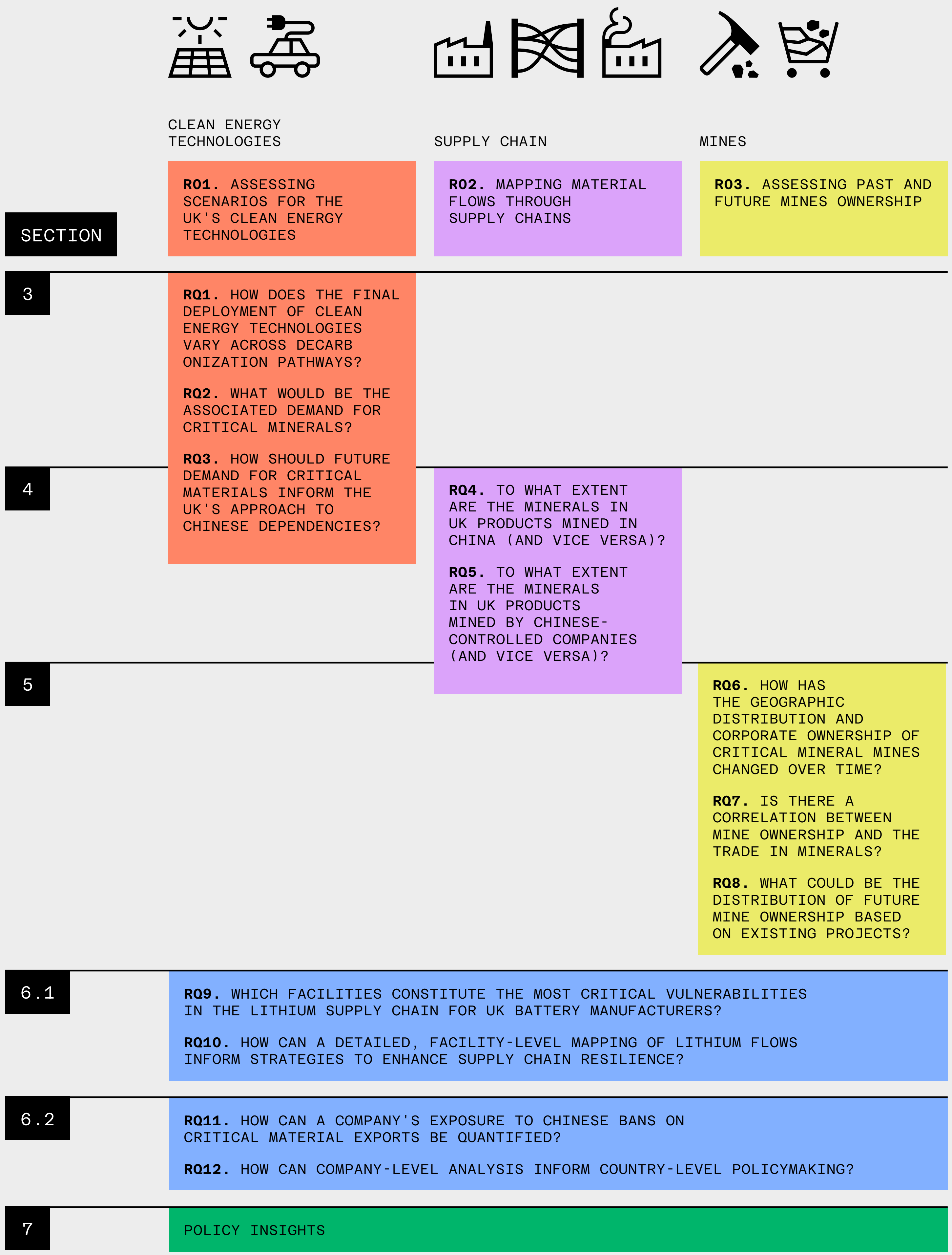

FIGURE 1: REPORT SUMMARY.

2. Critical Minerals and the low-carbon transition

The mining, refining, and processing of critical minerals is crucial to the successful transition to a low-carbon economy. These minerals are used in the technologies that will underpin the clean energy transition such as solar panels, batteries and wind turbines. As such, ensuring a continuous supply of these materials and managing risks to supply chains are critical to the long-term success of the transition. The supply chains behind clean energy technologies are complex, spanning across multiple countries and companies. China currently dominates several stages of clean energy technology supply chains, from mineral refining to component manufacturing. The UK has ambitions to reach Net Zero emissions 2050. Achieving such goals requires a secure supply of components and technologies related to the transition.

Concerns over the supply of these materials has grown in recent years as the demand for materials is recognised and the geo-political and strategic implications of this increased demand comes into focus. Foremost among the geo-political concerns surrounding the supply of critical materials is the current dependency on China. According to the International Energy Agency (IEA) the supply chain risks are greatest for electric vehicles (EVs) and Solar Photovoltaics (Solar PV) as the processing for these materials is heavily concentrated in and dominated by China. However, this is true for all technologies necessary for the clean energy transition. China is the largest single processor of copper, cobalt, lithium and graphite in the world, and the second largest refiner of nickel (International Energy Agency, 2024). In the case of graphite, China currently processes over 90% of the battery grade graphite globally, and is expected to maintain this dominance until 2040 (at a minimum).

In addition to processing the raw materials, China also maintains a strategic lead in the production of clean energy technologies. Based on information compiled by the International Energy Agency, China accounted for 76% of global battery manufacturing, 79% of solar PV manufacturing, and 65% of wind turbine manufacturing capacity in 2022 (IEA, 2025). Moreover, while other countries, particularly those in Europe and North America, are attempting to reduce their dependency on Chinese manufacturing capacity and grow their own domestic manufacturing, the same IEA 2025 analysis shows that the current pipeline of new manufacturing capacity will not change China's leading position in these three technologies.

Policy initiatives to reduce China's dominant position in this space have been formulated to increase manufacturing capacity elsewhere, particularly in Europe (with the European Net Zero Industry Act) and in the United States of America (despite the uncertain future of the Inflation Reduction Act). Nevertheless, China's hegemonic position still leaves Western countries and the UK at significant risk.

Currently, approximately 59% of the critical materials used in new clean energy technologies are processed in China (based on 5 materials critical to the transition: copper, cobalt, lithium, nickel and graphite). If the UK meets it decarbonisation targets and reduces its emissions in line with UK decarbonsiation pathways, this dependency is expected to increase to between 62 and 64% in 2040.

2.1. Previous report delivered in 2024

This report builds on our preliminary report (produced in 2024) which showed that the UK has direct and indirect trade dependencies on China related to critical mineral supply chains which are used in EV batteries, solar PV and wind power. The direct dependencies lie in the imports of components that UK businesses use for assembling final technologies, such as solar cells. Indirect dependencies are due to UK trade with Germany of EVs, or wind turbine magnet components which are mainly processed in China and then used by companies which supply the UK.

The UK has ambitions to reach Net Zero emissions by 2050. Achieving such goals requires a secure supply of components and technologies related to the transition. The UK has exposure to supply chain risks related to critical minerals, prompting the need for a coordinated policy response to mitigate supply chain risks and secure continued access to critical minerals, components and/or technologies which underpin the clean energy transition. This is made more challenging by the projected growth in demand for clean energy technologies, driven by the UK's net zero carbon policy aims, and competition with other countries and corporations to secure access to critical materials going forward. Key to the UK's response is the development of quantitative analyses that allow the risks, opportunities, and trade-offs related to the supply of critical materials to be explored and to guide strategic decision making towards a lower risk and more resilient transition to a low carbon future.

In last year's report, we started investigating the UK's dependency on China in terms of mine ownership. Results show that, historically, mine ownership of critical minerals related to EV batteries, wind, and solar PV technologies has involved a degree of UK ownership. For copper, UK mine ownership has been decreasing in the last 20 years (2000-2022). Currently, the UK owns 10% of the world's copper mines. In turn, China's mine ownership has surged from 2% to 13%, which is faster than China's production rate, which increased from 2% to 7%, over the same period. For cobalt, though most of the production takes place in Africa, almost none of the mines are owned by African companies. The UK once owned some production (in the period considered) but by 2022, the UK no longer owned any cobalt mines. This is compared with China, who own more than 20% of cobalt mines. For nickel, the share of mines owned by UK and Chinese companies increased, reaching 7% and 15% of global production, respectively. Other minerals require further exploration including investigating the accuracy of the data used.

2.2. Research Objectives and report structure

Building on the results of last year's report, the current report addresses three research objectives.

The three research objectives (ROs) addressed in this current report are:

1. Assessing scenarios to identify the risks, opportunities and trade-offs related to the UK's future access and manufacturing of clean energy technologies. Integrating detailed data on mining facilities to examine the UK's risks in accessing critical materials for manufacturing and clean energy technologies, via supply chains that are dominated by China.
2. Mapping material flows from mining to final manufacturing of products and identifying vulnerabilities related to ownership – This objective aims to chart the complete processing journey from mining to final products, for solar, wind, and EV battery technologies. It will evaluate if the nationality of mine ownership has any impact on the export of minerals to other regions and whether there is evidence of any influence of ownership on trade flows in downstream processing steps in the supply chain.
3. Assessing past and future mines ownership – This objective involves identifying the nationality of the critical mineral mine owners and assessing the proportion of UK and Chinese ownership. Using the nationality ownership data, we will assess future projects under development and identify vulnerabilities and risks which might impact the UK.

This report then sets out future work on this topic that will be able to provide additional detail, clarity and insight on these important topics.

→ Section 3 begins to answer RO1 by quantifying the UK's future demand for critical minerals for decarbonisation utilising data from a variety of UK decarbonisation pathways. Future demand is projected for the 16 critical minerals as identified by the UK critical mineral strategy. Section 4 answers RO2 by mapping material flows through the supply chain for UK critical minerals and showing the dependency on China for these minerals. Specifically this section shows the relationship between production and consumption and ownership and consumption for key critical minerals in the UK and China. Section 5 explores the relationship between mine ownership and production in more detail in order to answer RO3. Moreover, the section projects how global mine ownership is expected to evolve over time. Utilising data on expected mine development shows mine ownership and production geography out to 2040.

- Section 6 introduces the additional and ongoing work being done on this topic. Specifically two work products are introduced. [1] A global value chain model which maps the movement of key critical minerals (in the first instance lithium) from extraction to end use and will facilitate a more detailed understanding of how the UK is dependent on China for critical minerals at all stages of the value chain. [2] A stock flow model is being developed that can be used to explore disruption to UK clean energy manufacturing in the event of a China-UK export ban and potential mitigation strategies. Both models are currently under developement promising to deliver interesting and unique insights into the current UK-China dependency for decarbonisation of possible mitigation strategies.
- Section 7 provides conclusions based on the insights from the work conducted over the year and subsequent policy recommendations.

2.3. Minerals and metals scope for each section

Ideally, we would aim to cover all minerals identified as critical to the UK's decarbonisation strategy across all sections of this report. However, the scope of each section is constrained by both data availability and methodological feasibility. These limitations are primarily due to the need to combine high-resolution datasets—most notably the GLORIA Multi-Regional Input-Output (MRIO) database and the SP Capital IQ Pro corporate ownership dataset—which do not comprehensively cover all critical minerals. Specifically:

- Section 3 focuses on identifying the minerals most critical to the UK's energy transition, based on forward-looking demand projections and sectoral decarbonisation pathways. This section sets the context for the report.
- Section 4 maps international supply chains using GLORIA MRIO and SP ownership data. Due to the structure and sectoral coverage of these databases, this analysis is currently limited to eleven metals: bauxite, copper, gold, iron, lead, manganese, nickel, silver, tin, uranium, and zinc.
- Section 5 examines global mine ownership patterns using SP data. To ensure analytical robustness, we include only materials for which at least 50% of 2022 global production (as reported by the British Geological Survey) is covered in the database. This yields a broader but still limited set: coal, cobalt, copper, gold, iron ore, lead, lithium, manganese, nickel, silver, uranium, and zinc.
- Section 6 presents preliminary work on facility-level supply chain modelling, which is highly data-intensive and, for now, focused on lithium due to the availability of high-quality facility-level data.

As a result, there is partial but not complete alignment across sections in terms of which minerals are included. We acknowledge that this limits full comparability between sections. Despite these constraints, the analyses presented in this report collectively offer complementary perspectives, across supply chains, ownership, and trade, on the UK's dependencies on China for critical minerals.

2.4. Limitations

The main limitations for each section are as follows:

- Section 3. This analysis faces three main limitations. First, it assumes constant material intensities over time, even though technologies are improving and shifting toward substitutes with lower critical mineral use. Due to uncertainty around future trends, a constant intensity based on current technology was preferred over arbitrary projections, likely leading to overestimated demand. Second, material intensities come from an open-source database Cervantes Barron and Cullen (2024); while care was taken to ensure quality, the results depend on this data's accuracy. Third, future demand projections rely on three organisations' scenarios, which lack uncertainty ranges and likelihoods, so no scenario weighting was applied.
- Section 4. This study has five main limitations. First, ownership data is incomplete. Second, using equity shares as a proxy for national control oversimplifies real-world influence, which varies across countries and companies. Third, the analysis excludes key critical materials like rare earths and focuses only on 2000–2022. Fourth, input-output models cannot capture company-level trade agreements or internal transfers, possibly missing indirect effects of control. Finally, GLORIA's sector aggregation and Sankey scaling limits reduce precision in tracing flows.
- Section 5. This study has several limitations. Mine ownership data may miss ultimate parent companies due to complex corporate structures. Remote sensing fills data gaps but cannot detect underground activity or inactive sites. Ownership types (e.g. SOEs vs. private firms) are treated equally, ignoring strategic differences. Trade analysis is limited to ores and concentrates, excluding refining and downstream stages. Projections assume ownership structures remain fixed and all planned projects proceed on time, which is unlikely. Finally, key external factors like regulatory changes, political instability, and environmental risks are not included.
- Section 6. The facility-level lithium chain model is a proof of concept built around a single, data- rich commodity (lithium). The system-dynamics stock-and-flow prototype is built around a single focal UK battery manufacturer. Both models' generalisability to other minerals, technologies and corporate structures still needs validation. Key parameters (e.g. facility utilisation rates, supplier- allocation rules under force majeure, strategic stockpile sizes) are calibrated from public sources and expert judgment rather than proprietary operating data, which may bias disruption-impact estimates. Integration between the two strands (high-resolution physical mapping and macro-level policy scenarios) is not yet automated, so policy simulations cannot be updated in real time as new plant-level information emerges.

3. Understanding demand for critical materials in the UK's energy and transport sectors

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This section assesses the projected UK demand for critical minerals in the energy and transport sectors over the next 25 years, assuming that decarbonisation targets are met. The analysis in this section uses our material demand projection modelling and considers how different demand profiles are affected by Chinese control of different critical mineral supply chains.

3.1. Context

The supply of critical materials is essential to the longterm ability of the UK the meet its decarbonisation targets and ultimately to reach net zero by 2050 (Vakulchuk et al., 2020). Currently, the UK decarbonisation pathway is governed by 'carbon budgets'. These budgets, produced by the Climate Change Committee and approved by Parliament, set out the amount of emissions that can be produced over a five-year period and get progressively tighter towards the goal of net zero in 2050 (Climate Change Committee, 2019).

However, while the production of carbon budgets provides some outline of the pathway to net zero, the final pathway, the final demand for decarbonisation products, and by extension, the demand for critical materials, remain unknown (the uncertainty and risks in current net zero pathways can be seen in Stephenson and Allwood (2023)). To understand the demand range for critical materials up to 2050 we have analysed the technology assumptions (for energy and transport systems) across a range of different decarbonisation pathways for the UK. This enables subsequent analysis of how much critical material may be required for decarbonisation, and which materials it may be beneficial to reduce our demand for, in seeking to reduce our future dependence on China. A more holistic comparative analysis of the critical mineral requirements for different net zero pathways has been prepared for academic publication and shared with the FCDO alongside this report. The research questions for this section are:

→ How does the final deployment of clean energy technologies vary across decarbonisation pathways?

→ What would be the associated demand for critical minerals?

→ How should future demand for critical minerals inform the UK's approach to Chinese dependency?

3.2. Analysis of future critical material demand in the UK

Analysis of the future demand for critical materials is based on net zero pathways produced by three organisations: the National Energy System Operator (National Energy System Operator, 2024), the Climate Change Committee (Climate Change Committee, 2019) and the Centre for Research into Energy Demand Solutions (Barrett et al., 2022, 2021). Between these three organisations, ten scenarios have been considered, which span the full range of proposed pathways from technology and innovation-led pathways to low energy demand solutions.

THE NATIONAL ENERGY SYSTEM OPERATOR	THE CLIMATE CHANGE COMMITTEE	THE CENTRE FOR RESEARCH INTO ENERGY DEMAND SOLUTIONS
Electric Engagement	Balanced Pathway	Shift
Hydrogen Evolution	Headwinds	Transform
Holistic Transition	Widespread Engagement	
	Widespread Innovation	
	Tailwinds	

TABLE 1: NET ZERO SCENARIOS ANALYSED FOR MATERIAL DEMAND PROJECTIONS

Figure 2 shows the assumed deployment of the five key clean energy technologies in 2050: Solar PV, Wind, Batteries, Hydrogen and Electric Vehicles, which is used to understand the differing assumptions and final results of the pathways analysed. Where multiple types of technology are available, for example, onshore and offshore wind, these are both included. Electric vehicles includes all types of vehicles: cars, vans, HGVs and buses. The bars in Figure 2 show the average deployment across the ten scenarios in 2050, with the deployment assumed in each scenario shown by an individual point, the shape of each point indicating the organisation that produced the scenario.

FIG. 2

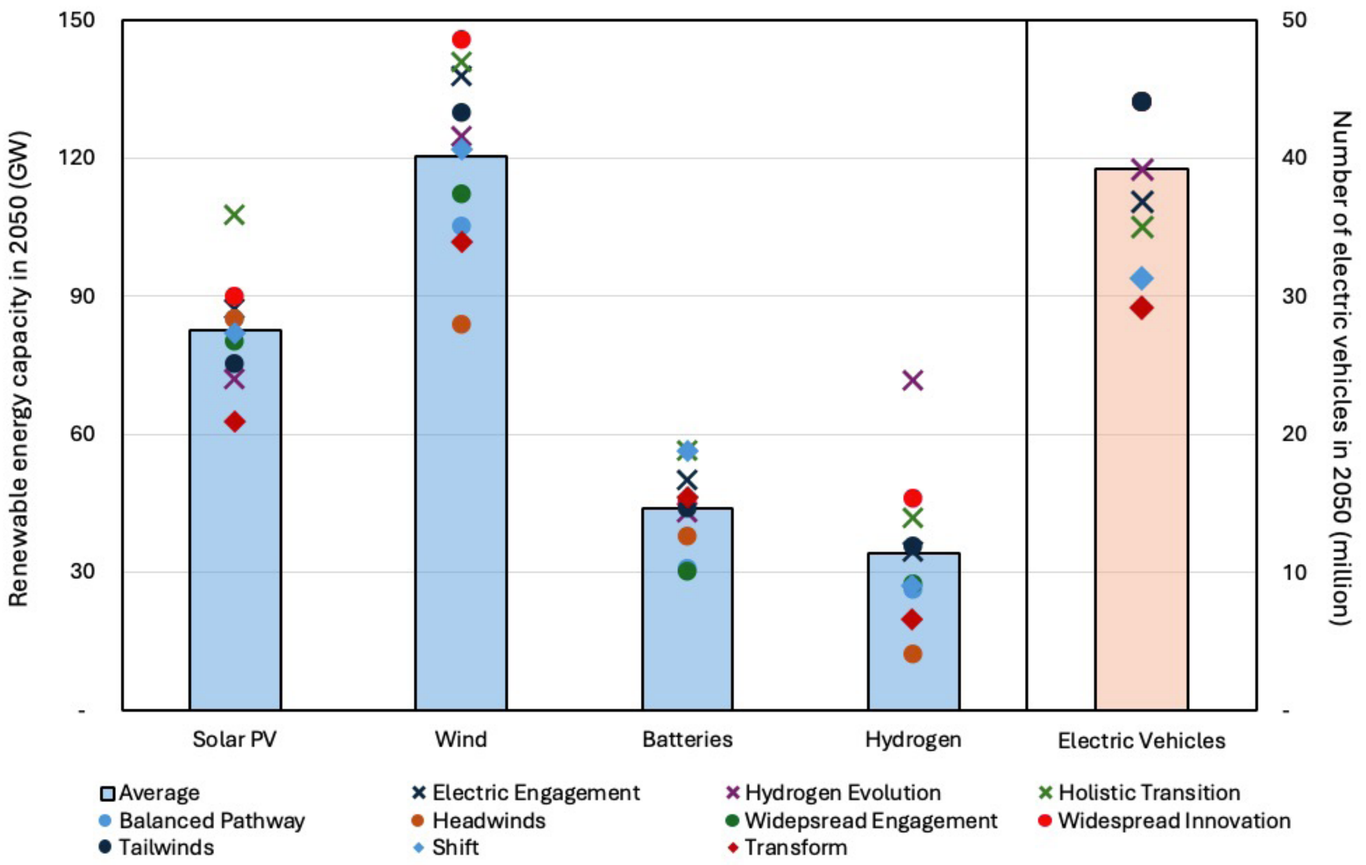

FIGURE 2: ASSUMED CLEAR ENERGY TECHNOLOGY DEPLOYMENT IN 2050 BY TECHNOLOGY AND SCENARIO.

Our analysis uses a material demand projection model to anticipate demand based on the required low carbon technologies in the energy and transport sectors until 2050. This model is based on the current material composition and intensities for energy and transport technologies and does not account for how future technology changes might affect material compositions and final demand.

The material intensity database, which underpins the models, provides intensity data for 101 minerals and materials, the vast majority of which are not considered to be 'critical'. In the UK, a mineral is considered critical if it has "high economic vulnerability and high global supply risk" (UK Government, 2023). In 2021 the UK Critical Mineral Strategy identified 18 minerals as 'critical' to the UK economy (UK Government, 2023). The strategy also set up a new Critical Mineral Intelligence Centre (CMIC), led by the British Geological Survey to provide an ongoing assessment of criticality in the UK. Since then, the CMIC has produced further reports. Mudd et al. (2024) define 11 critical materials as critical minerals and remove Palladium from the list. However, this has not yet been reflected in the government's critical mineral strategy, which is currently under revision. To reflect and recognise this distinction, this report primarily focuses on the 18 minerals currently defined as critical in the UK's existing strategy, while separately reporting on the additional 11 materials also in the 2024 CMIC report which we believe will play a role in the forthcoming strategy.

A full list of materials covered in this section is provided in Table 2.

Of the 18 critical minerals included in the UK government's official strategy, two minerals, Antimony and Bismuth, are excluded from the analysis due to insufficient data about their material intensity in energy and transport technologies. In addition, 6 of the 11 additional materials from the 2024 CMIC report are excluded from the analysis for the same reason. An analysis of the literature found no reference to these elements as major components of the technologies considered in this section. The exception to this is Rhodium, primarily used in catalytic converters and in nuclear reactors. Finally, the demand for phosphorus was excluded from the final analysis as it is not contained in any of the technologies considered in this section.

MATERIALS DEEMED CRITICAL IN THE GOVERNMENT'S 2021 CRITICAL MINERAL STRATEGY		
1. Antimony *	7. Lithium	13. Silicon
2. Bismuth *	8. Magnesium	14. Tin
3. Cobalt	9. Niobium	15. Tantalum
4. Gallium	10. Palladium	16. Tellurium
5. Graphite	11. Platinum	17. Tungsten
6. Indium	12. Rare Earth Elements	18. Vanadium
ADDITIONAL MATERIALS DEEMED CRITICAL IN THE 2024 BGS CRITICALITY ASSESSMENT		
1. Aluminium	6. Iridium	12. Rhenium *
2. Borates *	7. Iron	13. Rhodium *
3. Germanium	8. Magnesite *	14. Sodium *
4. Hafnium	9. Manganese	15. Titanium
5. Helium *	10. Nickel	16. Zinc
	11. Phosphorus **	

* not included in analysis as materials are not included in reference database of material intensities
** not included in as not present in any technologies considered

TABLE 2: LIST OF CRITICAL MINERALS INCLUDED IN THE UK CRITICAL MINERAL STRATEGY AND ADDITIONAL MATERIALS INCLUDED IN THE 2024 BGS UK CRITICALITY ASSESSMENT

Table 3 shows the embodied consumption of 25 critical minerals in energy and transport technologies, and the relative growth of each, between 2025 and 2050. The table shows the estimated average consumption in 2025 and 2050 based on the 10 scenarios considered, the full range of potential final embodied consumption for these minerals is shown in Figure 3, and the relative change in embodied consumption of each mineral over the time period analysed.

CRITICAL MINERAL	2025 EMBODIED CONSUMPTION (kt)	2050 EMBODIED CONSUMPTION (kt)	RELATIVE CHANGE (TIMES)
Aluminium	7168	11566	1.6
Cobalt	35.75	511.12	13.3
Gallium	0.02	0.07	2.95
Germanium	0	0.01	4.8
Graphite	180	2593	13.4
Hafnium	0.003	0.005	1.5
Indium	0.05	0.08	0.65
Iron	1.02	6.09	6
Lithium	24.12	342	13.2
Magnesium	59.8	0.03	-1
Manganese	198	1147	5.8
Nickel	175	1562	8.9
Niobium	2.57	1.59	-0.4
Palladium	0.04	0	-1
Platinum	0.19	0	-1
Rare Earth Elements	10.83	15.12	1.4
Ruthenium	0.000006	0.000022	3.77
Silicon	65.08	314	3.83
Tin	30.97	0.04	-1
Tantalum	1.33	0	-1
Tellurium	0.02	0.11	3.83
Titanium	0.17	14.9	85
Tungsten	0.03	0.05	0.5
Vanadium	0.01	1.57	178
Zinc	296	671	2.27

TABLE 3: ESTIMATED EMBODIED CONSUMPTION OF UK CRITICAL MINERALS IN 2025, 2050 AND THE RELATIVE CHANGE.

Of the 25 materials considered, the demand for five minerals is found to increase over ten-fold by 2050; cobalt, graphite, lithium, titanium and vanadium. Of these, demand for cobalt, graphite and lithium are expected to exceed 100kt (by an order of magnitude in the case of graphite). The demand for both aluminium and silicon is also expected to exceed 100kt, however the relative change is significantly less. While aluminium is the most consumed critical mineral by weight (by an order of magnitude) total increased demand is comparatively small — 60% in 2050. Finally, the relative change in demand for vanadium is significant, but the final embodied consumption remains relatively small (<2kt). Within the clean energy transition (for energy and transport) vanadium is found predominantly in carbon capture and storage technology, however the vast majority of the material (around 90%) is used in a steel alloy (ferro vanadium), and to produce aluminium vanadium master alloys for the aerospace sector.

Moreover, our analysis shows that for six of the minerals on in the UK critical mineral list (magnesium, niobium, palladium, platinum, tin and tantalum) demand (from energy and transport technologies) will decrease over the next 25 years, in the case of all but niobium to near zero. This is because current demand is driven through their use in fossil fuel technologies, for example the primary use of palladium and platinum in these sectors is in catalytic converters in petrol/diesel vehicles.

Further analysis of future demand is shown in Figures 3 and 4. They show how demand for critical minerals could vary between 2025 and 2050 (based on the scenarios' assumptions). These results show the uncertainty in the final demand in 2050. Critically, they show that the final demand for critical minerals, particularly those that are expected to grow significantly over the next 25 years, can vary significantly and depend on the policy and technology choices made during the transition. Considering cobalt, graphite and lithium, choices over technology deployment could reduce demand for these minerals by up to 45%.

RARE EARTH ELEMENTS IN THE GREEN TRANSITION

Rare Earth Elements (REE; or Rare Earth Metals) are a group of 17 heavy metals that have similar properties and a wide variety of uses. For this reason they are normally grouped together. Among them; Neodymium, Dysprosium, Praseodymium and Terbium are all components of wind turbines, the largest single source of clean energy in the UK in 2050 under a net zero transition. Grouping REEs together obfuscates a number of details that are worth clarifying here. Table 3 shows that the embodied consumption of REE is expected to increase by a modest 50% between 2025 and 2050. This is partially due to the current use of REE in internal combustion engines. Growing demand for REEs in wind turbines is offset against a declining demand for REEs in internal combustion engine. One petrol/diesel car will typically include about 200g of REE, but 11 different REEs. In contrast, producing 1MW of offshore wind capacity requires between 62-148kg of REE distributed across 4 REEs. Considering REEs in aggregate hides the changing demand for different elements, and also obscures the limitations of recycling current 'dirty' technologies to produce the minerals for future clean technology. This section considers the demand for REEs in the aggregate inline with the approach taken by the critical minerals strategy. However more work is needed to understand the future demand for different rare earth elements.

OTHER MINERALS NECESSARY FOR THE CLEAN ENERGY TRANSITION

The UK critical mineral strategy does not include a number of other important minerals whose demand will increase significantly, but are not considered critical. This includes the demand for copper which is critical component of the energy grid. It is our view that copper should be considered a critical mineral for the UK.

DEMAND FOR CRITICAL MINERALS BEYOND THE ENERGY AND TRANSPORT SECTOR.

This section explores the demand for critical minerals in the energy and transport sectors in line with different net zero pathways. The consideration of these two sectors is based on data availability and existing work in this space (Cervantes Barron and Cullen, 2022, 2024) and does not consider the demand for critical minerals in other sectors, where they also play an important role in the UK economy, such as the defence and manufacturing sectors. Moreover, the analysis presented in this chapter explores how decarbonisation in line with the government's legislative targets could be impacted by China's dominance over the clean energy supply chain. As such, it does not take into account other sectors or the demand stimulated by other government priorities (for example increased defence spending). The findings for future critical mineral demand in the energy and transport sectors should be read alongside other reports that consider the demand in other sectors. Finally, the demand profiles presented here all assume that the UK meets its decarbonisation targets, which they are currently not on track to do (Climate Change Committee, 2025), as such, real future demand may look different if the UK's fails to decarbonise at the rate required.

3.3 Three types of demand projections and their implications for Chinese dependency

By analysing the patterns in the growth profiles of critical minerals, three distinct clusters are identified: steady growth in demand, declining demand over time, and fluctuating demand/uncertain trends. Each cluster represents different technological influences that shape the future demand for these minerals.

CLUSTER 1: STEADY GROWTH IN DEMAND

The first cluster includes minerals that show a consistent rise in demand over the projected period. These minerals are the primary components in key emerging clean energy technologies such as battery storage (including for EVs) and solar energy. Note: these assessments do not account for changes in material composition or technology innovation. While there is significant research in this area, there remains too much uncertainty over which innovations will be commercialised to include it in the final analysis.

FIG. 3

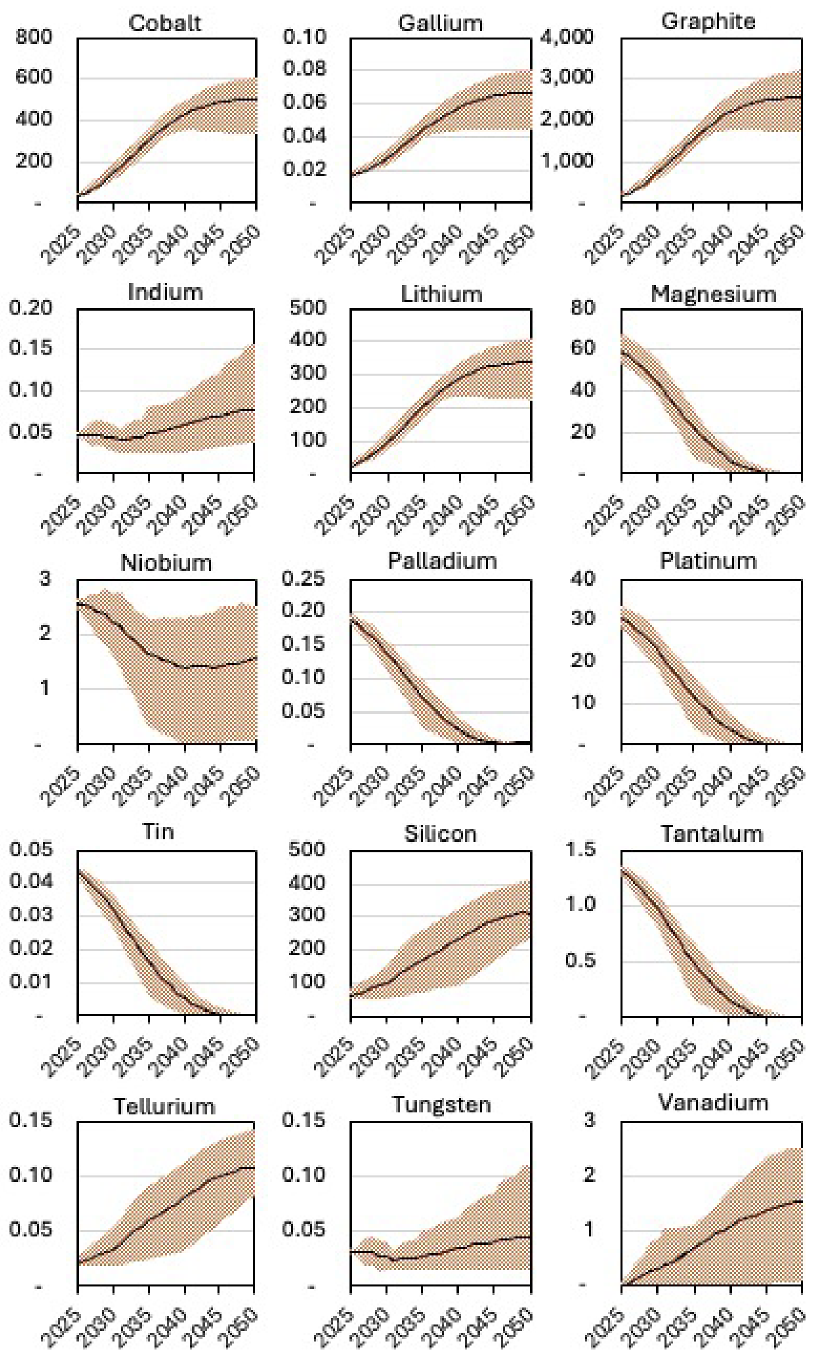

FIGURE 3: EMBODIED DEMAND FOR CRITICAL MINERALS IN THE UK 2025-2050 (IN KILOTONNES)

FIG. 4

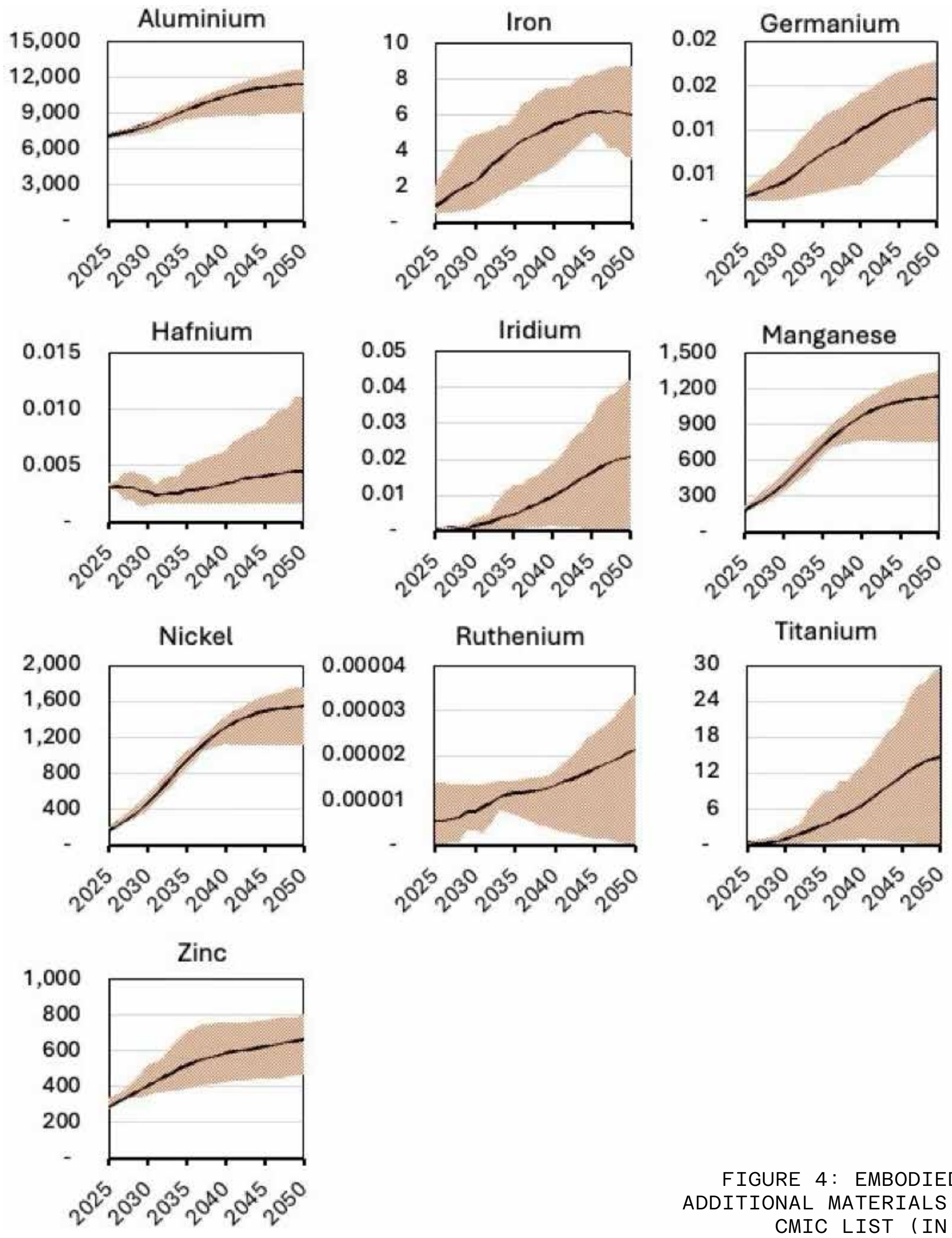

FIGURE 4: EMBODIED DEMAND FOR ADDITIONAL MATERIALS IN THE 2024 CMIC LIST (IN KILOTONNES)

Minerals in this cluster:

- Cobalt: A key component in lithium-ion batteries including for electric vehicles, in all scenarios cobalt demand grows significantly, however the final embodied consumption will depend on policy choices around transport, the size of vehicles and the use of demand-side measures to impact electricity consumption.
- Gallium: There is increased use of gallium in electric vehicles and it is also used in the production of solar PV. Gallium is currently used in the production of internal combustion engines which could provide some domestic supply through recycling.
- Graphite: An essential material in battery anodes, demand grows significantly. By 2050, around 70% of all critical minerals in the energy and transport sectors will be graphite (around 2600kt out of a total 3760kt required, of the 16 critical mineral considered here).
- Lithium: Demand for lithium grows significantly under all scenarios up to 2050, reflecting its critical role in battery technologies for EVs and energy storage.
- Silicon: As the primary component of solar PV panel, demand for silicon reflects projected increased demand for solar power.

- Tellurium: Also used in solar panels (within energy and transport decarbonisation) and as such following a similar growth pattern to the demand for silicon.

Additional minerals identified as critical by the 2024 BGS Criticality Assessment

- Aluminium: Widely used across all energy and transport sectors in both clean and fossil fuel technologies. However, on average, newer, clean technologies have a higher aluminium content than fossil powered technologies leading to a growth in demand over the next 25 years
- Germanium: used in the production of high-efficiency solar cells, as such demand for germanium directly correlated with that of silicon and the demand for solar panels.
- Iron: The primary use for iron (as a final product) in the technologies considered is as an oxygen carrier in the steam methane reforming (SMR) production of hydrogen, therefore demand for iron depends on the demand for, and viability of CCS supported SMR produced hydrogen.
- Manganese: widely used in the production of clean energy technologies, particularly Nickel, Manganese, Cobalt (NMC) batteries for use in storage and electric vehicles. Managanese is also used in a number of other clean energy technologies including CCS and wind turbines, as a result demand is expected to increase significantly over the next 25 years. Note: this does not account for any potential change in batteries technologies, for example, in China, there is growing use of Lithium Iron Phosphate batteries (LFP). While this has not been seen in Europe as widely to date, final demand for Manganese remains uncertain.
- Nickel: Like Manganese, Nickel is used in a rane of clean energy technologies, notably batteries but also wind turbines and carbon capture technology. The same caveats regarding changes in future battery technology impacting final manganese demand also apply to nickel.
- Zinc: currently used in both vehicles using internal combustion engines and electric motors. Increased demand in the future stems from new uses in clean energy technologies, including wind turbines and carbon capture technology.

DEPENDENCE ON CHINA

The first cluster reflects the critical minerals central to the development of future clean technologies, particularly for the production of new solar PV and batteries (both for grid storage and electric vehicles). Over dependence on China for the extraction and processing of these materials therefore creates significant supply chain risk that would jeopardise the UK's ability to reach net zero.

10 of the 12 minerals discussed here are dependent on China for either the extraction or processing (all except Manganese and Nickel). In extreme cases China refines and processes over 75% and 80% of the global production of Cobalt and Gallium, respectively. It is also the largest miner of (natural) graphite, extracting over 82% of all natural graphite and refining over 90% of all battery-grade graphite. Global lithium supply is slightly less dependent on China, however it remains its second largest miner (18% of all lithium is mined in China and 65% of lithium processing occurs in China). Furthermore, China produces around 70% of the world's metallurgical-grade Silicon and 77% of the world's Polysilicon which is required to manufacture solar panels. China produces around 50% of the global supply of Tellurium and is the only country that directly targets the mining of Tellurium, rather than as a by-product.

Finally, in addition to its dominance over the critical mineral supply chain, China is also dominant in the manufacturing of clean energy technology. Based on information compiled by the International Energy Agency, (2025), in 2022 China manufactured 76% of global battery manufacturing, 79% of solar PV manufacturing and 65% of wind turbine manufacturing capacity.

For the additional minerals identified in the 2024 BGS Criticality Assessment, China is the largest producer of aluminium (producing over ten times as much as the second country India) and produces over 65% of the world's supply of germanium. China is also the largest producer of both iron ore and pig iron and finally is the largest global producer of zinc. For the two exceptions to this, South Africa produces the largest share of the world's manganese (China is 5th) and Indonesia is the largest producer of Nickel. However while China is not a producer of nickel, it is the second largest refiner of nickel behind Indonesia.

In conclusion, we can see from this breakdown how China holds a strategic position in the majority of critical minerals that are crucial to the clean energy transition (i.e., their demand will increase as we shift towards clean energy and transport technologies). This shows just how dependent the UK is on China for the critical minerals it needs to drive the clean energy transition and the risks posed by that level of exposure to China.

CLUSTER 2: DECLINING DEMAND OVER TIME

The second cluster comprises minerals whose demand is projected to decline. This trend suggests shifting industrial preferences, substitution with alternative materials, or decreasing reliance on specific technologies.

Minerals in this cluster:

- Magnesium: Currently used in lightweight alloys found in internal combustion engine vehicles, demand for magnesium falls to near zero as electric vehicles replace petrol and diesel cars.
- Palladium: A key element in catalytic converters, palladium demand is decreasing as EV adoption reduces the need for internal combustion engine components.
- Platinum: Another major component in catalytic converters, platinum follows a similar downward trajectory due to the shift toward cleaner technologies. However, there remains some demand for platinum for future use of fuels cells in vehicles and the production of hydrogen through electrolysis. This new demand can be met through recycling.
- Tin: Primarily used in the production of internal combustion engine vehicles (and nuclear power to a lesser extent), the demand for tin is set to decline to near 0 by 2050.
- Tantalum: A material with primary uses in the energy sector and for internal combustion engines in the transport sector. Demand for tantalum is set to decline over the next 25 years.

DEPENDENCE ON CHINA

The overall decline in demand for these five minerals means the UK already has a sufficient stock of minerals embodied in the it's existing transport and energy assets. Successful utilisation of existing stock will require the UK to invest in domestic recycling capacity (particularly for cars reaching their end of life) and manage the manufacturing of new technologies that require these minerals (for example hydrogen electrolysers in the case of platinum) to be aligned with the availability of recycled material. Moreover, these resources on the whole are less dependent on China for their extraction/production. The exception to this is Magnesium as China mines around two-thirds of global Magnesium supply. The largest producer of Platinum and Palladium is South Africa. China is the largest singe producer of Tin, however, it does not control a majority of the market; China mines very little of global Tantalum supply.

CLUSTER 3: FLUCTUATING DEMAND/UNCERTAIN TRENDS

The third cluster includes minerals with non-linear trends, indicating fluctuations or uncertainties in future demand due to technology choices and assumptions made in difference decarbonisation pathways.

Minerals in this cluster:

- Indium: averaged across all scenarios, demand for indium is expected to stay flat as the decline in internal combustion engines, where it is currently found, is offset against increased deployment for solar PV.
- Niobium: There is significant uncertainty over the future demand for Niobium, with current demand primarily from use in internal combustion engines. However, in the future, new demand stems from increased deployment of carbon capture and storage. The uncertainty in future demand for CCS results in significant uncertainty over the future demand for niobium in the energy and transport sector.
- Rare Earth Elements: As discussed previously, the future demand for rare earth elements presents a mixed picture given the variety of minerals included within the REE cluster. Analysis of future clean energy deployment shown in Figure 2 shows that the largest provider of clean energy in 2050 will be wind power. Given this, the demand for REEs used in the production of wind turbines will increase. However the demand for REEs for use in combustion engines will decline. While this offsets the total demand for REE, a number of REEs currently used in vehicles aren't found in wind turbines, offering limited opportunity for recycling. A more detailed analysis of the demand for individual rare earth elements (and the potential for future substitution) is required.
- Tungsten: On average demand for tungsten is expected to stay constant. Its future uses are in solar PV (although minimal) and plug-in hybrid vehicles. While future demand could increase from deployment of plug-in hybrid vehicles, the overall increase in demand would be small. Additional demand could be created outside of energy and land transport, as Tungsten retains a number of industrial applications, including aerospace and high-strength alloys.
- Vanadium: shows significant uncertainty given its primary use in carbon capture technology. This is directly linked to the significant variance in future demand for carbon capture in the different net zero pathways.

Additional minerals identified as critical by the 2024 BGS Criticality Assessment

- Hafnium: the only use of hafnium in the clean energy and transport sectors is in nuclear power. Given this the final demand for Hafnium over time is determined by the amount of new nuclear constructed. There is significant variance in the demand for nuclear among the different pathways resulting in the uncertain future demand for this material.
- Iridium: Similar to hafnium, demand for iridium is based on technologies with uncertain future demand: fuel cell electric vehicles and electrolysis-produced hydrogen. The future demand for these technologies ranges significantly across the different pathways so future demand is uncertain.
- Ruthenium: in the energy and transport sectors, ruthenium is used as a hydrogenation catalyst in the burning of biomass, (both with and without a CCS component). Future demand for ruthenium (in these sectors) is therefore tied to the demand for biomass as an energy source. Overall demand is expected to grow over the next 25 years, although the final demand is uncertain given the uncertain role as biomass as a long term fuel source and the viability of CCS technology.
- Titanium: has similar uses to iridium, as an input for fuel cells and electrolysis. As such, while on average the demand for titanium is expected to grow significantly in these sectors, there remains a high degree of uncertainty over how much hydrogen or fuel cells have been deployed in 2050.

DEPENDENCE ON CHINA

Cluster 3 shows how policy and technology choices affect overall future demand, and by extension, the dependency of China for key critical minerals, particularly Tungsten and Vanadium. 85% of Tungsten is produced in China. Its primary use across the technologies considered is in nuclear power generation. On average, demand for tungsten is shown to stay constant over the next 25 years. However, there remains significant uncertainty given the different projections of nuclear power through to 2050, under the different scenarios. The maximum demand for tungsten shown in Figure 3 is over 250% greater than the average demand for Tungsten. Increased demand for nuclear power in net zero strategies would therefore place a greater dependency on China for the critical minerals to support this increased deployment. The future demand for indium is also highly uncertain. Currently 58% of indium is produced in China and like Tungsten, its primary use in a clean energy system is in nuclear power. However the dependency on China for indium, if the UK does pursue significant nuclear deployment, could be mitigated by recycling the indium current used in internal combustion engines.

Niobium is the mineral in cluster 3 the least dependent on China, as the majority of niobium is mined in Brazil and China is only responsible for around 30% of global production. Moreover, niobium is currently used in internal combustion engines, and therefore, like Indium, future demand could be met domestically through successfully deploying recycling measures.

However, the primary use of niobium in a clean energy system is in carbon capture and storage technologies (CCS). The other mineral required for future CCS deployment is vanadium which also shows significant variation in future demand. Currently China mines 70% of global vanadium supply. Reducing the use of carbon capture technology (which is shown to be a viable pathway in the scenarios considered) would therefore reduce the UK's demand for a critical mineral that it is dependent on China for in order to successfully deploy.

The demand for specific rare earth elements needed for wind turbines is expected to increase significantly, however the exact increase is obfuscated by the declining demand for other REEs found in internal combustion engines. Nevertheless REEs are some of the critical minerals most dependent on China. Based on IEA analysis, in 2024 China extracted over 60% of the global supply of rare earth elements and was responsible for processing over 80% of current supply. China's control over the REE supply chain has meant that Chinese government has in the past placed export controls on REEs either as a way to control a strategic industry or as a tool in international trade disputes.

The four materials in this cluster identified as critical in the BGS Criticality Assessment have not been found to be particularly dependent on China (although China is the largest single producer of both titanium and hafnium). China produced 33% of the world's titanium and is the largest single producer. Australia, the second largest producer, has 13% of global production. Hafnium is produced from zirconium, which is found in mineral sand ore deposits of titanium. Alternative sources of heavy mineral sands which can lead to Hafnium are found in Malawi and Brazil. The other materials are not exposed to or dependent on China for their extraction or processing (this does not capture any dependence on China for the final technologies they are used in). The largest three sources of iridium are South Africa, Zimbabwe and Canada. Finally, ruthenium is obtained as a byproduct of processing nickel, copper and other platinum metal ores making future supply not dependent on China.

CONCLUSION

In conclusion, Figures 3 and 4 show the uncertainty in the future demand for critical minerals in the energy and transport sectors based on multiple UK decarbonisation scenarios. We conclude it is possible to significantly reduce our demand for certain minerals, like Vanadium, where the majority of supply currently comes from China. However, overall, the decarbonisation pathways lead to significant increases in UK's demand for critical minerals. Between 2025 and 2050, the total embodied consumption of critical minerals in cluster 1 is expected to increase by at least nine times (on average), with a possible range of 2.5 to 19 times (depending on the critical mineral). Given this, and the dominant position that China holds in the production of many of these minerals, the UK should consider carefully where and how they will source the required critical minerals for a future low-carbon transition. The next section discusses the UK demand in relation to Chinese processing capacity more directly, to inform future decision-making about clean energy technologies.

3.4 Method

Future embodied resource demand is calculated using the CM demand model and previously collected data on the material requirements for energy and transport technologies (Cervantes Barron and Cullen, 2022, 2024). Future demand for end-use technologies in the ten scenarios listed in Table 1 is provided exogenously from other energy and transport scenarios. The material intensity data is provided by the open-source information from previous work. The CM model then applies the material intensity data to the future projections to produce the results shown in Figure 3.

The shaded area in each plot, in Figure 3, shows the maximum and minimum estimated embodied consumption in each year based on the max/min figures produced across all ten scenarios. The clustering performed in Section 2.3 is based on a quantitative assessment of the demand profiles shown for the 16 minerals within each scenario. Clusters 1 and 2 show the same overall demand profile for every scenario [i.e., all scenarios increase or decrease, just to different extents]. Cluster 3 is characterised by non-uniform demand curves across all scenarios. For example, the maximum and minimum values for Vanadium show different growth profiles over time; the minimum values stay flat while the maximum value grows significantly. The production in these clusters is used in the discussion about the key characteristics of these different minerals and the potential implications on Chinese dependency.

3.5 Limitations

While the results presented here lead to a number of policy relevant insights, there are also three key constraints on this analysis that need to be taken into account. First, the material intensity data included in the mode assumes constant material intensities over time, despite ongoing work to reduce the consumption of critical minerals across all the technologies considered. This includes both efforts to improve the efficiency of current technology and find technology substitutes that utilise different materials. Given the high degree of uncertainty over precisely how material intensities are likely to change, the decision to include a (somewhat arbitrary) linear reduction of time was rejected in favour of a constant material intensity based on current technology. The results therefore likely overestimate the final material demand. Second, material intensity data was based on an open source material intensity database produced by Cervantes Barron and Cullen Cervantes Barron and Cullen (2024). While efforts have been taken to ensure the best quality data is utilised in the analysis, the final results are dependent on the quality of the material intensity data. Third, the future projections for material demand are based on information provided by the three organisations listed in Table 1. No uncertainty is provided on the final technology deployment for each scenario, so it could not be included here. Moreover, no indication is given to the likelihood of different scenarios, and therefore there is no weighting given to each scenario in the averages in Figure 3.

4. Mapping material flows through the supply chain

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This section presents an aggregated, country-level mapping of metals value chains from extraction to final consumption.

4.1. Context

Mapping global supply chains for critical materials is inherently complex. These supply chains span multiple stages, including mining, refining, manufacturing, and the final distribution of products. Each stage involves numerous companies and spans many countries Sun and Hasi (2024). Consequently, there is an inherent trade-off between the granularity of the analysis (tracing specific companies, products, and nations) and achieving a comprehensive overview that covers all countries and uses of a given mineral Li et al. (2023b).

In this report, we try to balance these objectives. While Section 3 focuses on detailed UK-specific demand patterns and Section 5 zooms in on the mining stage (including corporate ownership), this section provides an aggregated view of the full value chain. Additionally, later sections will explore a company-level analysis of specific value chains (e.g., lithium) to address further nuances.

The research questions of this section are the following:

→ To what extent are the minerals in UK products mined in China (and vice versa)?

→ To what extent are the minerals in UK products mined by Chinese-controlled companies (and vice versa)?

To capture these complex interactions, we employ a Global Multi-Regional Input-Output (GMRIO) framework (see methods section and the preprint "Mapping regional metal flows from mine ownership to final consumption" for more details). Three definitions are important to understand the findings:

→ **Production-Based Accounting (PBA):** This approach assigns material extraction to the region where the extraction occurs, thus capturing the "supply side" of the chain. We further disaggregate the production-based account by company and company-owner nationality.

→ **Consumption-Based Accounting (CBA):** In contrast, this method attributes material flows to the region where final consumption takes place, thereby accounting for indirect or embodied material flows in traded goods and services.

→ **Mine control:** In the mining industry direct ownership, whether through a majority stake or significant partial holdings via joint ventures, is the most common mechanism for exercising control over a mine and its production (Ericsson et al., 2020). Here, we rely on the variable "control share" as computed by S&P, which corresponds to the equity percentage held. If a company has a control share of 50% or more, we consider that it actually controls 100% as it has the majority of votes. Else, we consider an entity to exercise control only if it holds more than 10% equity (Ericsson et al., 2020). The total 100% of control is then disaggregated proportionally among the companies that meet this threshold.

Visualizing these complex flows is facilitated by the use of Sankey diagrams. These diagrams represent flows as arrows whose widths are proportional to the magnitude of the movement. In our application, Sankey diagrams are extended by incorporating mine ownership data—revealing not only the geographic routes of materials but also the influence of corporate control on these flows. All flows correspond to tonnes of ores.

4.2. Findings

From the extraction perspective, the patterns for Chinese and UK final consumption diverge significantly. For China, a notable share of many materials is mined domestically, with particularly high proportions for Gold (71%), Tin (78%), Zinc (86%), and Lead (93%) (table 4). Even for materials like Iron (41%) and Nickel (47%), domestic mining remains substantial, reflecting China's policy emphasis on safeguarding upstream resource supply. By contrast, UK final consumption is almost entirely supplied by mines located elsewhere: for instance, copper consumed in the UK is extracted 94% in the rest of the world and 6% in China, and no production is sourced domestically. This asymmetry is not solely a result of policy but also stems from the UK's limited geological reserves, smaller territory, and higher population density, which constrain the feasibility of large-scale mining. This heavy reliance on third-country supply chains leaves the UK far more exposed to external shocks and dependencies.

Ownership data reveals the extent to which Chinese- and UK-owned companies shape metal supply chains regardless of the actual mining location (table 5). For metals ultimately consumed in China, significant portions are extracted by Chinese-controlled companies, such as 50% of Nickel and 54% of zinc. Smaller, but still noteworthy fractions, including around 7% of copper or 12% of iron, are produced by UK-owned firms. For metals consumed in the UK, the largest portion is generally under the control of companies in "the rest of the world" (the top two controlling countries being Canada (11%) and Australia (9%) for more detailed data, see "table1 data.xlsx" in the supplementary information of this article: https://www.nature.com/articles/s43247-025-02321-1)), with only modest contributions from Chinese and UK owners. Yet the interesting parallel is that the fraction of extraction controlled by UK- based companies feeding China's final demand is about the same as the share of Chinese-owned mines feeding the UK. For example, around 12% of iron consumed in China is produced by UK-controlled firms, and a similarly sized 10% of Iron consumed in the UK is produced by Chinese-controlled firms. This has been the case over the whole period studied (2000-2022) and could stay the same in the future (see next section for a discussion on future ownership).

These comparable ownership shares are notable given the stark difference in economic scale between the two countries. They reflect a longstanding influence of UK-based multinationals in the global mining sector, even though modern extraction within the UK itself has dwindled to nearly zero. Although the UK does not mine these metals domestically, its historical legacy and substantial global reach in corporate ownership ensure that UK-controlled firms still play a role in supplying Chinese demand. The symmetrical situation—where UK companies own mines that meet China's needs and Chinese companies own mines that serve the UK—underlines the interconnected nature of international mining networks.

In many cases, a large share of production remains under "unknown" ownership (table 5), reflecting the opacity of mining data. This uncertainty underscores the importance of deeper investigation into corporate structures and more transparent reporting requirements.

The interplay of domestic extraction, foreign sourcing, and corporate ownership suggests that the UK's primary vulnerabilities lie not in upstream access to raw materials, where UK-based firms maintain a significant global presence, but rather in the midstream and downstream stages of the supply chain. In contrast, China's strength lies in maintaining both substantial domestic extraction and dominant control over refining, processing, and manufacturing of clean energy technologies.

	Metals embodied in the UK final consumption have been mined in:			Metals embodied in Chinese final consumption have been mined in:		
METAL	CHINA	UNITED KINGDOM	REST OF WORLD	CHINA	UNITED KINGDOM	REST OF WORLD
Bauxite	0.14	0	0.86	0.41	0	0.59
Copper	0.06	0	0.94	0.43	0	0.57
Gold	0	0	1	0.71	0	0.29
Iron	0.13	0	0.87	0.41	0	0.59
Lead	0.05	0	0.95	0.93	0	0.07
Manganese	0.09	0	0.91	0.21	0	0.79
Nickel	0	0	1	0.47	0	0.53
Silver	0.01	0	0.99	0.55	0	0.45
Tin	0.16	0	0.84	0.78	0	0.22
Uranium	0	0	1	0.13	0	0.87
Zinc	0.03	0	0.97	0.86	0	0.14

TABLE 4. REGION OF EXTRACTION, SHARE IN DECIMALS.

	Metals embodied in the UK final consumption have been extracted by companies controlled by:				Metals embodied in Chinese final consumption have been extracted by companies controlled by:			
METAL	CHINA	UNITED KINGDOM	REST OF WORLD	UNKNOWN	CHINA	UNITED KINGDOM	REST OF WORLD	UNKNOWN
Bauxite	0.07	0.14	0.3	0.49	0.12	0.08	0.16	0.64
Copper	0.08	0.1	0.7	0.12	0.32	0.07	0.43	0.17
Gold	0	0.02	0.75	0.23	0.23	0.02	0.21	0.55
Iron	0.1	0.09	0.63	0.18	0.3	0.12	0.41	0.17
Lead	0.05	0	0.59	0.36	0.44	0	0.07	0.49
Manganese	0.05	0.05	0.69	0.2	0.09	0.03	0.58	0.31
Nickel	0.02	0.03	0.59	0.36	0.5	0.02	0.21	0.27
Silver	0.01	0.03	0.72	0.25	0.09	0.02	0.36	0.53
Tin	0.06	0	0.35	0.58	0	0	0.06	0.94
Uranium	0.1	0	0.82	0.08	0.16	0	0.76	0.08
Zinc	0.05	0.01	0.72	0.22	0.54	0.01	0.12	0.33

TABLE 5. REGION OF CONTROL, SHARE IN DECIMALS.

Figure 5 displays a Sankey diagram that visualizes the proportional flows of copper ores and concentrates through three key stages: corporate control, extraction and consumption. The diagram is based on data where all flows not directly related to the UK or China have been set to zero, and the values represent tonnes of copper ores and concentrates. The UK has control over much more production than what is actually needed for its final consumption. However, the green colour on the UK final consumption node shows that the copper embodied in the UK's final consumption is controlled by other countries, due to the globalised nature of the economy. The Sankey diagrams for all other metals are available in the supplementary information.

Figure 5: Simplified Sankey diagram of copper ores embodied in the final consumption of the UK and China. Any flow represented here is either (i) mined by a company controlled by UK or Chinese owners, (ii) mined in the UK or in China, or (iii) embodied in the UK or China's final consumption. The colour code corresponds to the region of the mine owner (first step). For example, the share of "unknown ownership" that appears in the "rest of world" final consumption node (in grey) corresponds to copper ores mined in China by mine owners of unknown nationality.

Sankey diagrams are effective tools for visualizing complex supply chains and identifying the largest flows.

In one of the publications associated with this report, we mapped more thoroughly the supply chain of ten metals—copper, nickel, lead, zinc, tin, iron, aluminium, uranium, gold, and silver—, and built over 100,000 Sankey diagrams to visualize metal flows across 159 countries and four world regions Andrieu et al. (2025).

For example, Figure fig. 6a compares the global metal production-based account with the global metal consumption-based account. Moving from left to right, the first slice (Nationality of mine owners) of the diagram shows the commodity type, while the second slice (Production-based account) represents the geographic disaggregation of the production-based account (i.e. in what region is the metal extracted). The transition from slice 2 to 3 uses Leontief's inverse (see Methods) to translate from production-based to consumption-based accounting, revealing, for example, that North America consumes 70% more metal ores than it produces. The right-hand side of the diagram (slices 3 to 5) represents the consumption- based account, disaggregated by region of consumption (slice 3), by consumer type (slice 4) or by final consumption sector (slice 5). The final consumption sector is disaggregated between ten types of goods or services that are bought by final consumers or for capital creation. For example, at the global level, 1.4 Gt of metal ores have been used in 2022 (along the whole supply chain) to produce transport equipment. It is important to note that the 'raw materials' node represents the metal ores embodied in the final consumption of products that are directly purchased by end users. Although consumers do not buy raw metal ores, they do purchase items such as cement, glass, and clay building materials, which incorporate these metal ores in their production processes.

We also built diagrams that zoom into specific countries or regions. For instance, Fig. 6b maps the copper ores flows related to China in 2022. Each flow represents either ores controlled by Chines mine owners (slice 1), produced in China (slice 2) or embodied in China's final consumption (slice 3 to 5). The diagram reveals that China's consumption-based account is 75% higher than its production- based account. Fig 6c confirms that the UK controls much more copper mines (equivalent of 275 Mt of ores production) than what is embodied in its final consumption (28Mt of ores). However, the copper embodied in the UK's final consumption has been extracted by companies controlled by other regions (the node "United Kingdom (277,769 kt of ores)" on the third slice of Fig 6c has very little blue).

For the 15 commodities in GLORIA, the period 2000 to 2022, and the 163 GLORIA regions, these Sankey diagrams are available on the web application associated with this paper: https://application- Sankey-rm.onrender.com/.

FIGURE 5

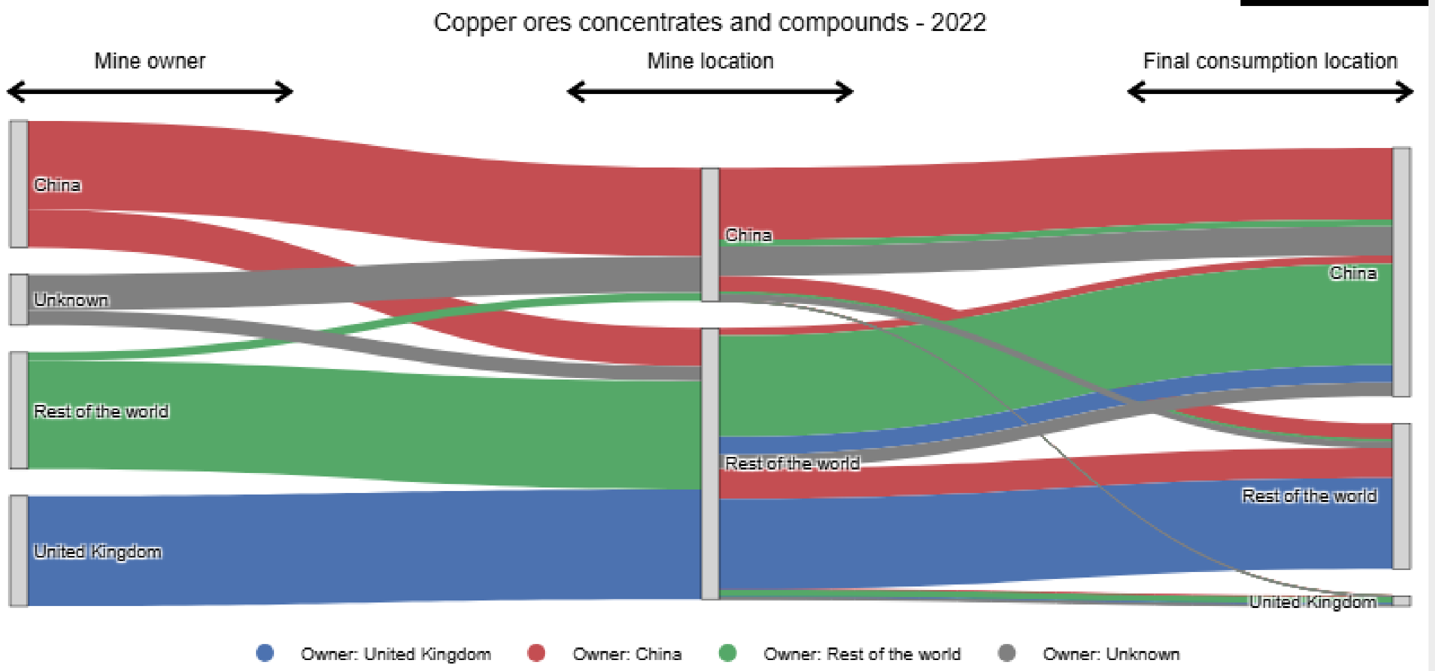

FIGURE 5. SIMPLIFIED SANKEY DIAGRAM OF COPPER ORES EMBODIED IN THE FINAL CONSUMPTION OF THE UK AND CHINA. ANY FLOW REPRESENTED HERE IS EITHER (I) MINED BY A COMPANY CONTROLLED BY UK OR CHINESE OWNERS, (II) MINED IN THE UK OR IN CHINA, OR (III) EMBODIED IN THE UK OR CHINA'S FINAL CONSUMPTION. THE COLOUR CODE CORRESPONDS TO THE REGION OF THE MINE OWNER (FIRST STEP). FOR EXAMPLE, THE SHARE OF "UNKNOWN OWNERSHIP" THAT APPEARS IN THE "REST OF WORLD" FINAL CONSUMPTION NODE (IN GREY) CORRESPONDS TO COPPER ORES MINED IN CHINA BY MINE OWNERS OF UNKNOWN NATIONALITY.

FIGURE 6

A. WORLD

B. CHINA

C. UK

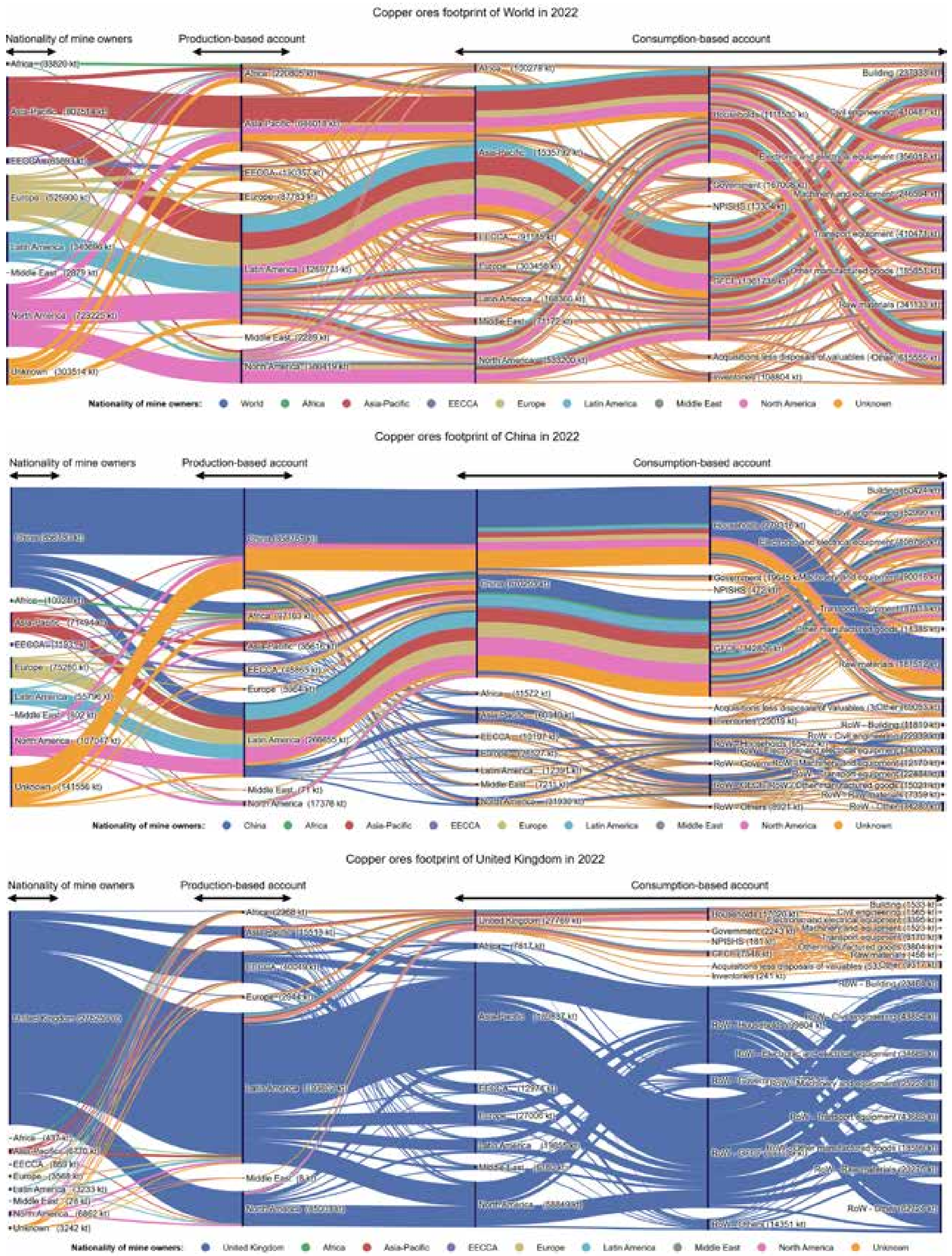

FIGURE 6. METAL ORES FOOTPRINT IN 2022. ANY FLOW REPRESENTED IN B. IS EITHER MINED IN CHINA, OR EMBODIED IN CHINA'S FINAL CONSUMPTION. ANY FLOW REPRESENTED IN C. IS EITHER COPPER ORES MINED BY UK-CONTROLLED COMPANIES OR COPPER ORES EMBODIED IN THE UK'S FINAL CONSUMPTION, AS NO COPPER IS EXTRACTED IN THE UK. THE COLOURS CORRESPOND TO THE FIRST STEP OF THE DIAGRAM. THESE DIAGRAMS WERE BUILT USING AN ALGORITHM TO ISOLATE EACH COUNTRY AND AGGREGATE ALL OTHERS TO BUILD SANKEYS GENERICALLY (FOR HTTPS://SANKEY-26DASHBOARD.REFFICIENCY.ORG/). AS A RESULT, THE UK AND CHINA NEVER APPEAR IN THE SAME DIAGRAM. TO SEE BOTH ON THE SAME DIAGRAM, PLEASE REFER TO FIGURE 5.

4.3. Method

Our methodology integrates two main datasets:

The GLORIA Multi-Regional Input-Output (GMRIO) Database (Lenzen et al., 2017, 2022): This database provides detailed data on metal extraction, trade, and final consumption across multiple countries. It allows us to trace the flow of metals through various sectors, from initial extraction (PBA) to consumption (CBA). All flows are expressed in tonnes of ores.

Ownership Data from S&P Capital IQ Pro: This dataset offers mine ownership percentages by the nationality of controlling companies. By linking these data to the GLORIA flows, we can disaggregate metal production by the nationality of the controlling entity.

To ensure the clarity and interpretability of our visualizations, the raw data are aggregated by broad economic sectors and regions. This aggregation is essential; without it, the resulting Sankey diagrams would become too cluttered to be informative. The technical details—including equations and aggregation steps—are fully described in our accompanying scientific paper (Andrieu et al., 2025).

The overall procedure is as follows:

1. Data Aggregation: Extract production, trade, and consumption data from the GMRIO framework, then aggregate these flows to maintain visual clarity.
2. Integration of Ownership: Disaggregate production figures using mine ownership data so that flows can be attributed to the nationality of the controlling companies.
3. Flow Mapping: Visualize the aggregated flows using Sankey diagrams that transition from PBA to CBA, with an added layer for corporate control.
4. Analysis of Trade Impacts: Compare the physical flows with trade data to evaluate whether current foreign mine ownership translates into observable trade effects. While statistical analysis does not yet reveal a significant correlation between ownership and direct trade flows, the potential for strategic disruption remains a critical insight.

5. Assessing past and future mines ownership

→

This section presents the insights gained from the study of mine ownership. The analysis focuses on 12 metals and mineral ores that, in 2022, achieved at least 50% coverage in S&P relative to BGS totals. These include Uranium (91% coverage), lithium (90%), copper (86%), cobalt (85%), iron ore (82%), manganese (80%), Zinc (75%), nickel (71%), silver (66%), gold (65%), lead (60%), and bauxite (50%). Of these, only cobalt and lithium were identified as critical in section 3. Results for others are nonetheless presented as they allow for comparisons.

5.1. Context

Over the past 150 years, mining production shifted from European dominance in the mid-1800s to North American, then the Soviet Union, and more recently to emerging economies in Latin America, Asia, Africa and Oceania (Ericsson, 2022). Although mine production has shifted from industrialized regions to emerging economies, the control over that production—that is, where the controlling companies' headquarters are located—remains largely in the traditional economic centres (Ericsson et al., 2024). As the decisions on production levels, investments, and pricing are made by companies based in these established centers, incorporating an analysis of corporate control in raw material criticality analyses would provide a more complete picture of supply vulnerabilities (Ericsson et al., 2024).

As a result of majority mine ownership being in the hands of industrialized countries, foreign direct investment (FDI)—an investment made by a company or individual from one country into business interests located in another country—often drives strategic decisions that influence the pace and intensity of extraction (Long et al., 2017). FDI can "lock up" resource supplies by concentrating control in the hands of foreign investors, thereby amplifying national security risks (Moran, 2014). Conversely, under robust regulatory frameworks, FDI may promote diversification and enhance accountability through market scrutiny (Kotschwar et al., 2012). These dual roles of FDI raise a crucial question: to what extent do trade flows reflect, or diverge from, the underlying patterns of corporate control? For instance, (Sun et al., 2024) examined overseas investments and domestic demand for lithium, nickel, cobalt, and platinum in 2019, finding an overlap between investment partners and trade flows. Without statistical analysis, however, it remained unclear whether this overlap was coincidental or indicative of a systematic pattern in which foreign-owned mines preferentially export metals to their owners' home countries.

Furthermore, given that mining projects have long lead times, and ownership structures are often established well in advance of production, it is theoretically possible to project future ownership and production scenarios. Doing so could provide early warnings of potential supply chain vulnerabilities. Despite this possibility, no study has focused on forecasting how both production and ownership might evolve together.

Here, we address these gaps by answering the three research questions that follow:

→ How has the geographic distribution and corporate ownership of critical mineral mines changed over time?

→ Is there a correlation between mine ownership and the trade in minerals?

→ What could be the distribution of future mine ownership based on existing projects?

To calculate ownership, we rely on the variable "control share" as computed by S&P, which corresponds to the equity percentage held. If a company has a control share of 50% or more, we consider that it actually controls 100% as it has the majority of votes. Else, we consider an entity to exercise control only if it holds more than 10% equity (Ericsson et al., 2020). The total 100% of control is then disaggregated proportionally among the companies that meet this threshold.

FIGURE 7

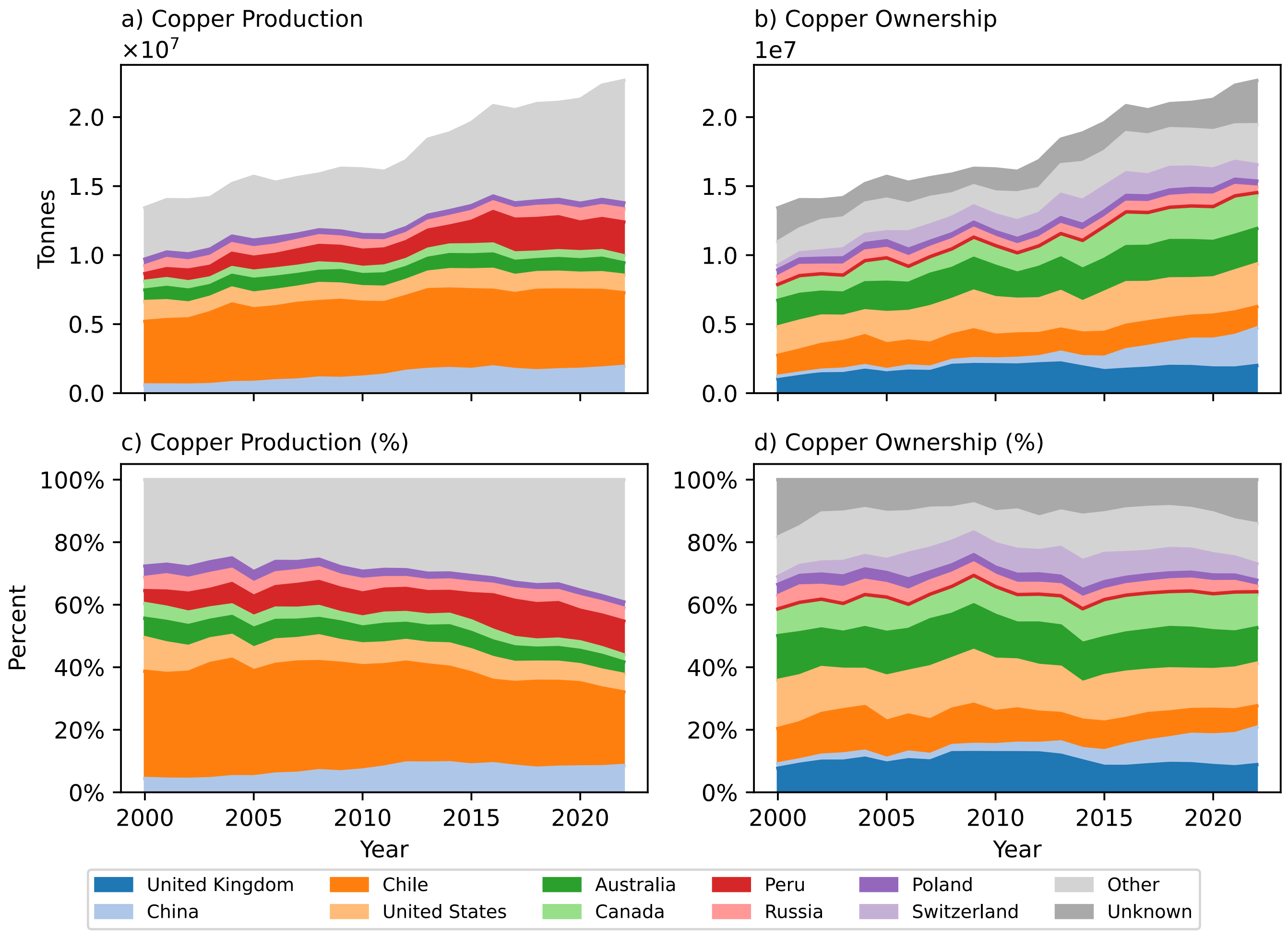

FIGURE 7. COPPER PRODUCTION AND OWNERSHIP BY REGION. THE TOP ROW GIVES ABSOLUTE VALUES WHILE THE BOTTOM ROW GIVES SHARES OF THE TOTAL. PLOTS FOR ALL OTHER MINERALS AND METALS CONSIDERED ARE AVAILABLE IN THE SUPPLEMENTARY INFORMATION.

5.2. Past ownership dynamics

Figure 7 shows the past production (a), and ownership (b), of copper ores disaggregated by region. Similar figures for all cobalt, gold, iron, lead, lithium, manganese, nickel, silver, uranium and zinc are available in the supplementary information. Based on data from these figures, Fig. 8 summarizes all the insights by displaying the share of global production (plain lines) and ownership (dashed lines) from the UK (in blue) and China (in red).

For example, in the cobalt sector, there was no recorded Chinese ownership in 2000, yet by 2022 Chinese control had risen to 17.0%, even though production in China increased only modestly from zero to 2.0%, with the UK remaining completely absent in both ownership and production. This shift in cobalt points to a strategic move by Chinese companies to secure assets in minerals that are becoming increasingly critical in high-tech and clean energy applications.

Copper provides a particularly illustrative example of changing dynamics. In 2000, the UK held a significant ownership share of 11.0% compared to China's 1.0%. By 2022, however, Chinese ownership had surged to 11.0 % while the UK's share had decreased to 9.0%, accompanied by an increase in Chinese production from 4.0% to 9.0% . While the UK once maintained considerable ownership in copper mining, the balance has shifted as Chinese entities have steadily expanded their control and influence over global copper supply. In parallel, the UK does not produce any copper and does not record any reserves to do so.

Other commodities such as Lead, lithium, manganese, nickel, silver, uranium, and zinc follow a consistent narrative of increasing Chinese dominance.

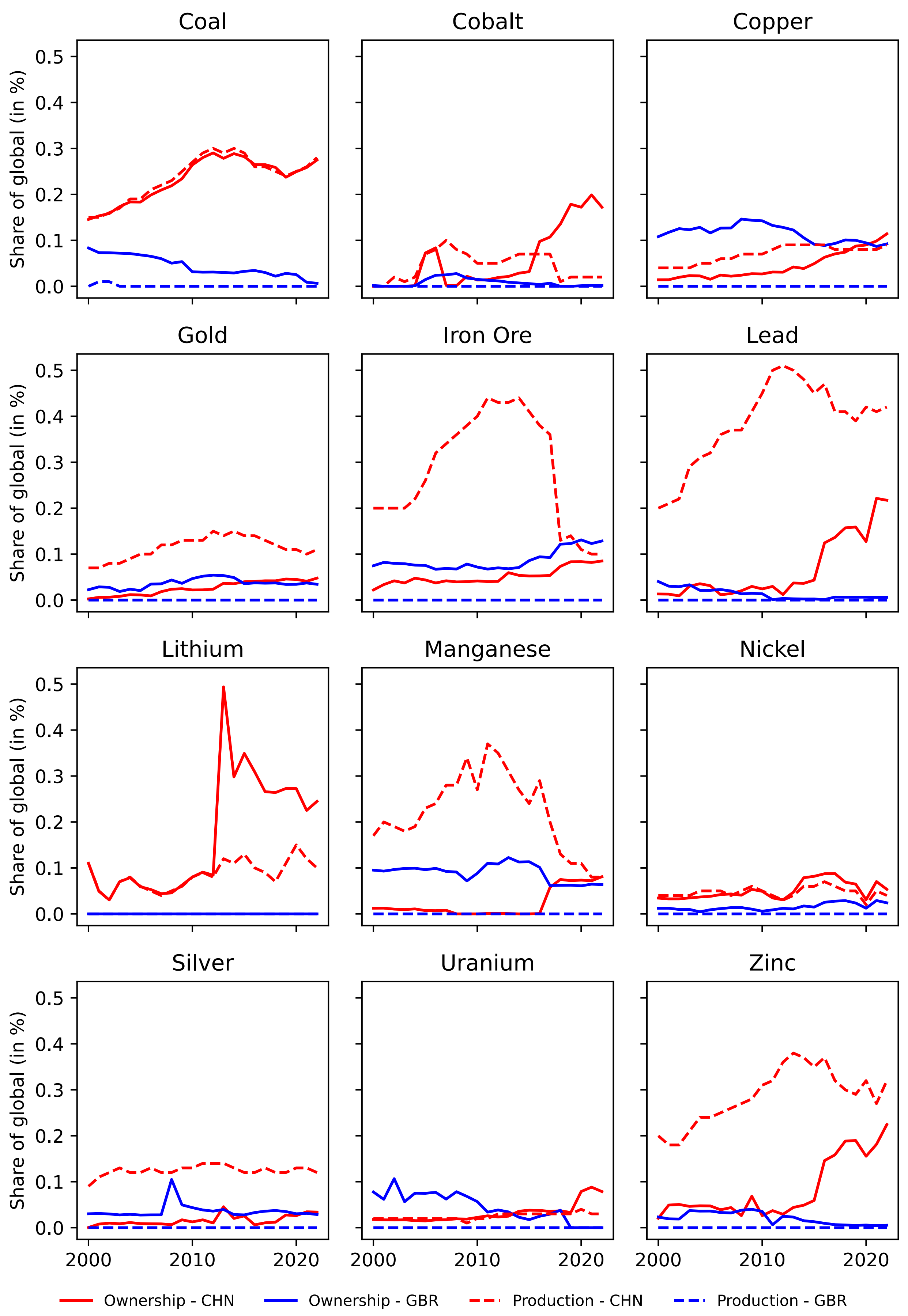

FIGURE 8. PRODUCTION AND OWNERSHIP BY REGION.

For lead, Chinese ownership soared from 1.0% to 22.0%, with a concurrent rise in production from 20.0% to 42.0%, while UK ownership fell from 4.0% to 1.0%. In lithium, Chinese ownership nearly doubled from 11.0% to 24.0%, even as production remained relatively steady. Notably, in uranium the UK's ownership share completely vanished by 2022 as Chinese ownership climbed from 2.0% to 8.0%. These shifts are indicative of a broader strategic consolidation by Chinese firms in sectors that are critical for modern energy and technological applications.

Overall, the insights drawn from Figure 8 reveal that Chinese companies have significantly increased their control over mining assets across a wide array of minerals, while the UK's historical role has diminished. Even when production occurs in regions not directly controlled by the UK, the expanding influence of Chinese corporate ownership reshapes global supply chains. This evolution has major implications for strategic resource security, as it underscores how the global balance of power in mining is shifting toward China—a trend that could amplify supply chain vulnerabilities for countries that have traditionally relied on more diversified or domestically anchored sources of mineral production.

5.3. Impact on trade

We examined the relationship between trade flows—hereafter referred to as "real trade flows"—from country A (where the mines are located) to country B, and the volume of production in country A that is controlled by entities based in country B (termed the "ownership flow," which is a theoretical construct rather than an actual physical flow). We compared the country pairs exhibiting either a trade flow or an ownership relationship. Only a small proportion (between 4% and 10%) of these country pairs exhibit both types of relationships. For country pairs that exhibit both trade and ownership relationships, the squared correlation coefficients (R^2) between the magnitudes of these flows are very low (between 0.00 and 0.13). This pattern is consistent across all product codes analysed, with a maximum overlap of only 16% and a corresponding correlation coefficient of 0.02 (see the preprint "The Impact of Mine Ownership on Trade of Metal Ores" associated with this report for detailed results).

The low overlap between country pairs with both trade flows and ownership ties—and the low correlation coefficients—suggests that countries controlling mining production are not necessarily the same as those engaged in metal ores trade. This decoupling implies that trade is influenced by additional factors. FDI in natural resources typically involves equity stakes, loan-for-offtake agreements, and long-term contracts. Historically, this implied that controlling ownership may aim to diversify supply or expand production rather than secure exclusive output (Kotschwar et al., 2012). However, recent strategies, such as the one employed by the Japan Organization for Metals and Energy Security (JOGMEC), explicitly tie equity financing to offtake rights, mandating that a portion of production be allocated to Japanese firms in proportion to their ownership stake (Baskaran, 2025). Varying investment motivations—such as market-seeking versus export platform strategies—can differently impact trade performance (Franco, 2013) and could contribute to the observed decoupling. Legal regimes and trade policies, including export restrictions and preferential trade agreements, further complicate the link between production and corporate control (Srivastava, 2023). An additional structural factor is the geographic separation between mine ownership and extraction activities: firms based in advanced economies often benefit from favourable legal environments, access to capital, and ease of doing business, making them well-positioned to control assets. By contrast, the physical extraction and trade of raw materials typically occurs in lower-cost jurisdictions, often emerging or developing economies, where operational costs are lower and resource endowments are higher. These spatial and institutional mismatches likely contribute further to the observed decoupling between ownership and trade.

Micro-level studies demonstrate that foreign ownership not only facilitates increased exports to the investor's home country but also enables firms to leverage their foreign status to access broader international markets (Li et al., 2024; Boddin et al., 2017). Thus, the misalignment between trade and ownership flows in our analysis may reflect strategic diversification rather than an absence of influence. Additional insights from bilateral relations literature indicate that factors like political connections (Ding et al., 2018; Sharma et al., 2020), bilateral trust (Guiso et al., 2009), linguistic proximity (Melitz and Toubal, 2014), and both formal and informal institutional ties (Haveman et al., 2017; Araujo et al., 2016; Li et al., 2023a) also significantly enhance trade flows.

5.4. Possible future ownership

The projections in this section rest on the simplifying assumption that the ownership of mines and mining projects observed in 2022 remains unchanged until 2040. For copper, the production distribution remains largely stable, with Chile's share decreasing slightly from 23% in 2022 to 21% in 2040. Ownership shifts are minor: China's share remains steady (14% to 13%), while the share of unknown ownership rises from 1% to 10%. Lithium undergoes greater shifts. Australia's production share drops from 49% to 36%, while the U.S. rises from 2% to 11% and Chile falls from 27% to 12%. Ownership changes include a modest increase for Australia (28% to 33%) and a sharp rise for Canada (1% to 16%); meanwhile, U.S. ownership declines (19% to 7%), and unknown ownership grows from 2% to 15%. Cobalt sees a major redistribution: the DRC's share falls from 66% to 42%, while Australia (6% to 19%) and Canada (3% to 13%) expand. Ownership follows a similar pattern: Australian control rises (6% to 20%), Canada's increases (3% to 15%), and the DRC's drops from 10% to 2%, with unknown ownership growing slightly (7% to 11%) (see Fig. 9).

The hypothesis that the ownership of mines and mining projects observed in 2022 remain unchanged until 2040 is unlikely to hold in practice. For example, current activities may lead to growth in ownership from new high-income countries such as the United Arab Emirates in low-income countries (Bakr, 2024). The evolving geopolitical landscape is expected to significantly influence future investment flows and policy interventions (Humphreys, 2013). For instance, as observed in OECD countries (Sun et al., 2024), while advanced financial systems enable effective exploitation of mineral resources, heavy reliance on external FDI can also heighten vulnerability to commodity price fluctuations and an over-dependence on finite assets. Although our analysis does not incorporate external factors such as changing regulatory frameworks or shifts in FDI, our baseline scenario provides a useful reference point. In the absence of complementary policy measures, the evolving patterns in production and ownership may indirectly amplify long-term supply vulnerabilities.

Supply risk is not limited solely to concerns around market concentration of production and ownership. It arises in combination with other issues such as environmental degradation, social inequities, economic tensions and geopolitical instability. Proactive policy interventions and transparent, multi- stakeholder governance mechanisms will be essential to mitigate these risks (Dou et al., 2023). The projected shifts in production and ownership should thus also be viewed as portents of future complications linked to environmental challenges, thereby informing policies aimed at sustainable resource management (Muhammad et al., 2021).

Future production and ownership scenarios must also be interpreted in the context of potential policy shifts. Changes in governmental policies—such as adjustments to production quotas, local ownership regulations, and other regulatory frameworks—can rapidly reshape both the supply structure and the distribution of ownership (Shen et al., 2020). Strategic policy interventions aimed at resource governance and environmental protection are likely to further influence these dynamics. For example, export tariffs, which serve not only as instruments of trade policy but also as signals of a country's commitment to resource conservation and environmental protection (Chen and Zheng, 2019), can significantly alter market dynamics by affecting price stability and supply security.

Finally, factors such as political stability, legal frameworks and enforcement, and local infrastructure are as crucial as resource endowment in shaping investment decisions (Wang et al., 2021). Together, these considerations underscore the importance of integrating market dynamics with strategic policy measures to enhance both supply chain resilience and sustainable resource management in the future.

FIGURE 9

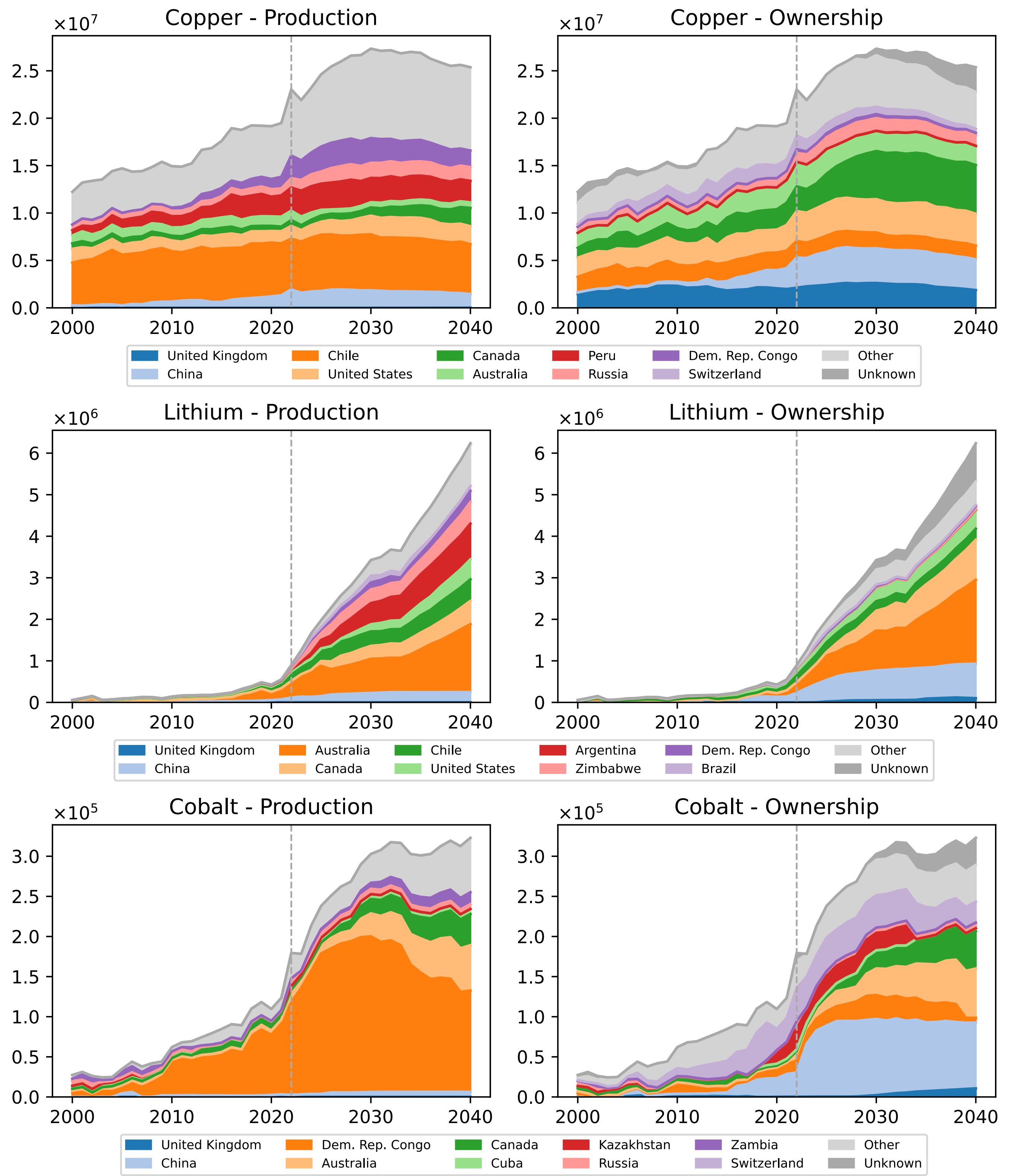

FIGURE 9. FUTURE SCENARIOS OF PRODUCTION AND OWNERSHIP BY REGION. LITHIUM IS IN LITHIUM CARBONATE EQUIVALENT, WHILE COBALT AND COPPER ARE IN METRIC TONNES OF METAL CONTENT.

5.5. Methods

Obtaining reliable mining data poses significant challenges. National statistical agencies such as the British Geological Survey (BGS) and the United States Geological Survey (USGS) provide aggregated production figures at the country level, but they lack the granularity needed for detailed global analysis. To address this, researchers often rely on proprietary databases such as S&P and Rystad Energy, although these sources are not without shortcomings, with satellite imagery comparisons indicate that up to 50% of mining sites in some regions may be missing from records. In this study, we build a global time series spanning from 2002 to 2022 by using the S&P database (downloaded in January 2024) and supplementing missing values with data from BGS, where available. The analysis focuses on 12 metals and mineral ores that, in 2022, achieved at least 50% coverage in S&P relative to BGS totals. Data are aggregated at the country level, with missing figures filled in from BGS data when possible.

Ownership of mines is determined by examining direct equity stakes, using the S&P computed variable for control share. An entity is considered to exercise control only if it holds more than 10% equity, thereby minimizing the influence of smaller shareholders. The resulting control figures are then disaggregated proportionally among the companies exceeding this threshold.

Trade flows in the mining sector present further complexities, as metals can be exported in various forms ranging from raw ore and concentrates to processed products. In this analysis, the focus is placed on ores and concentrates because they remain closely linked to mine output. Data are drawn from the BACI trade database, which provides bilateral trade flow information for 200 countries across a wide range of products classified under the Harmonized System. Trade flows from countries without documented mine production are set to zero, with remaining non-zero flows likely attributable to re-exporting or domestic processing activities. The study compares actual trade flows with theoretical ownership flows by examining both the proportion of country pairs that exhibit both trade and investment ties and the correlation between the magnitudes of these flows.

Future production estimates and gap-filling represent further challenges. Although the S&P database offers annual production forecasts up to 2040, many future projects lack complete data. For 2022, missing production values—affecting approximately 15% of global cobalt, 14% of copper, and 10% of lithium production—are estimated by integrating remote sensing data. This involves identifying mining locations and their surface areas, matching these with S&P coordinates, and incorporating remotely sensed particulate emissions as a proxy for production levels. For projecting future production, the methodology accounts for estimated start dates, closure timelines, and production levels. When direct forecasts are unavailable, production is inferred based on established relationships between reserves and production, or by calibrating against the median output of existing mines. The calibration parameter for future production is adjusted for each metal so that global production in 2040 aligns with demand projections from the International Energy Agency's Announced Pledges Scenario. This scenario was chosen as at the time of the report it was the only one from the IEA with metal demand scenarios.

6. Ongoing work on this subject

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This section presents two ongoing research projects, newly developed to map critical minerals at the facility level for the UK-China study. This preliminary, novel work has been developed in the 2024/2025 year, and has been verified and validated to serve as a proof-of-concept for modelling approaches that we intend to develop further in 2025/2026.

6.1. Facility-level mapping of global lithium supply chains to identify opportunities for improving resilience

6.1.1. Context

Lithium is a critical resource underpinning the global transition toward clean energy technologies, primarily because of its essential role in lithium-ion batteries used in electric vehicles and energy storage systems (Zepf, 2020; IEA, 2021). Growing demand—driven largely by the electrification of transportation—has intensified competition for lithium resources worldwide (Cheng et al., 2024). Although extraction is concentrated in countries such as Australia, Chile, and Argentina (Tan and Keiding, 2024; Shao et al., 2022), recent research describes a more intricate supply chain that spans multiple stages, from mining and refining through to cathode production, battery cell manufacturing, and final assembly (Jin et al., 2023; Ouyang et al., 2024a). Control over key stages of this chain is consolidated among a few multinational corporations, with Chinese companies (such as CATL or BYD) playing a prominent role; indeed, in 2023, approximately 84% of lithium-ion battery manufacturing was located in China (Intelligence, 2025). In the context of the UK, where securing critical material supply and reducing dependency on Chinese processing capacity are high priorities, it is essential to understand the vulnerabilities inherent in these complex networks.

This section addresses two research questions:

→ RQ9. Which facilities constitute the most critical vulnerabilities in the lithium supply chain for UK battery manufacturers?

→ RQ10. How can a detailed, facility-level mapping of lithium flows inform strategies to enhance supply chain resilience?

Here, we map the global lithium supply chain at the facility level, explicitly tracing lithium flows from mines to final products. The novel detail of this analysis allows for the identification of previously unrecognised sources of vulnerability and risk within the global lithium supply chain.

6.1.2. Results

This study maps the flows of lithium through the global supply chain at facility-level resolution. We define "focal nodes" as the highest-vulnerability facilities and "focal edges" as the highest-vulnerability flows of lithium, with vulnerability defined from the perspective of downstream UK consumers.

MAPPING VULNERABILITIES AT THE FACILITY-LEVEL.

Facility-level mapping permits an explicit representation of the upstream supply chain for any battery manufacturer. The following tables demonstrate the advantage of understanding differences in upstream dependencies by geography, through the analysis of one manufacturer in the UK. Supply chain disruptions can occur at individual facilities or along the flows between them. Table 6 details the focal nodes for the supply chain of the UK battery manufacturing facility.

Table 6 indicates that only one of the ten most important nodes in the upstream supply chain for the UK manufacturer is located in China, and that facility is responsible for only 9% of the total lithium content. Moreover, seven of the ten nodes are in mining countries, with five located in Chile and two in Australia. With the exception of the immediate supplier of cathodes from Japan, most of the focal nodes are upstream in the supply chain, at either the mining or processing stage. In addition, there is notable concentration at every stage, with two nodes in the top ten for cathode production, four for mining, two for carbonate, and two for hydroxide.

NODE ID	COUNTRY	SUPPLY STAGE	PRODUCT	PRODUCT MASS (T)	% TOTAL PRODUCT	LITHIUM EQV. (T)	% TOTAL LITHIUM
10994	JPN	Cathode	NCM mid nickel	544	70	45	48
369	CHL	Mining	Brine	179	61	34	36
565	CHL	Carbonate	Lithium Carbonate	179	50	34	36
27	AUS	Mining	Spodumene	112	44	21	22
575	CHL	Hydroxide	Lithium Hydroxide	39	14	11	12
639	CHL	Carbonate	Lithium Carbonate	50	14	9	10
115	CHL	Mining	Brine	49	17	9	10
600	CHN	Hydroxide	Lithium Hydroxide	31	11	9	9
403	AUS	Mining	Spodumene	42	16	8	8
10766	KOR	Cathode	NCM mid nickel	84	11	7	7

TABLE 6. TOP 10 FOCAL NODES IN THE UPSTREAM SUPPLY CHAIN OF A UK-BASED BATTERY MANUFACTURING FACILITY, RANKED BY THE SHARE OF THE BATTERY'S LITHIUM THAT FLOWED THROUGH A GIVEN FACILITY. EACH ROW REPRESENTS A FACILITY INVOLVED IN MINING, PROCESSING, OR CATHODE PRODUCTION. FOR EACH FACILITY, WE REPORT: (I) THE PRODUCT TYPE AND TOTAL MASS OF PRODUCT IT SUPPLIED TO THE UK MANUFACTURER'S UPSTREAM CHAIN; (II) THE SHARE OF TOTAL GLOBAL PRODUCTION OF THAT PRODUCT TYPE REPRESENTED BY THIS FACILITY (% TOTAL PRODUCT); AND (III) THE AMOUNT AND SHARE OF TOTAL LITHIUM CONTENT IN THE FINAL BATTERY THAT PASSED THROUGH THIS FACILITY (% TOTAL LITHIUM). FOR EXAMPLE, FACILITY 10994 IN JAPAN SUPPLIES 544 TONNES OF NCM MID- NICKEL CATHODES, REPRESENTING 70% OF GLOBAL PRODUCTION OF THIS CATHODE TYPE, AND 45 TONNES OF LITHIUM EQUIVALENT, WHICH CORRESPONDS TO 48% OF THE TOTAL LITHIUM CONTENT USED IN THE UK BATTERY.

SOURCE ID	SOURCE COUNTRY	TARGET ID	TARGET COUNTRY	PRODUCT	PRODUCT MASS (T)	% TOTAL PRODUCT	LITHIUM EQV. (T)	% TOTAL LITHIUM
10994	JPN	1469	GBR	NCM mid nickel	544	70	45	48
369	CHL	565	CHL	Brine	179	61	34	36
565	CHL	10994	JPN	Lithium Carbonate	73	20	14	14
565	CHL	575	CHL	Lithium Carbonate	60	17	11	12
115	CHL	639	CHL	Brine	45	15	8	9
10766	KOR	1469	GBR	NCM mid nickel	84	11	7	7
639	CHL	10994	JPN	Lithium Carbonate	28	8	5	6
30953	KOR	1469	GBR	NCM high nickel	58	14	4	5
10843	KOR	1469	GBR	NCM mid nickel	49	6	4	4
575	CHL	10994	JPN	Lithium Hydroxide	13	5	4	4

TABLE 7. TOP 10 EDGES WITH THE HIGHEST PERCENTAGE OF TOTAL BATTERY LITHIUM CONTENT EQUIVALENT DEPENDENT ON THEIR PRODUCTION. PERCENTAGE OF TOTAL PRODUCT REFERS TO THE PERCENTAGE OF THAT PRODUCT THAT IS CONCENTRATED IN THAT FLOW BETWEEN FACILITIES, AND PERCENTAGE OF TOTAL LITHIUM REFERS TO THE PROPORTION OF THE TOTAL LITHIUM CONTENT OF THE BATTERY THAT IS DEPENDENT ON THAT FLOW. TOTAL PRODUCT ADDS UP TO 100% FOR EACH PRODUCT, WHEREAS TOTAL LITHIUM ADDS UP TO 100% FOR EACH SUPPLY CHAIN STAGE.

Table 7 details the focal edges for the supply chain of the UK battery manufacturing facility.

It demonstrates that focal edges do not necessarily correspond to the most critical nodes because a focal node may distribute its production among several flows. Three of these edges occur entirely within Chile, and none of the most critical edges for the UK manufacturer involve China. In addition, although four out of ten critical edges involve the UK, the remaining six represent indirect vulnerabilities. As with the focal nodes, the majority of these flows are situated upstream.

At the global level, a small number of nodes and edges, particularly in upstream mining, appear among the top ten most vulnerable points in most manufacturers' supply chains. These vulnerabilities are not concentrated solely in China; the most critical nodes and edges are predominantly located in Chile and Australia, reflecting the concentration of mining activities, with occasional heightened criticality for specific technologies such as the NCM low-nickel cathode facility in Japan. Although geopolitical risks affect entire countries, risks related to production issues, strikes, and natural hazards occur at individual facilities. Disruptions at locations outside China could have more severe consequences than a reduction in output from China.

FIGURE 10

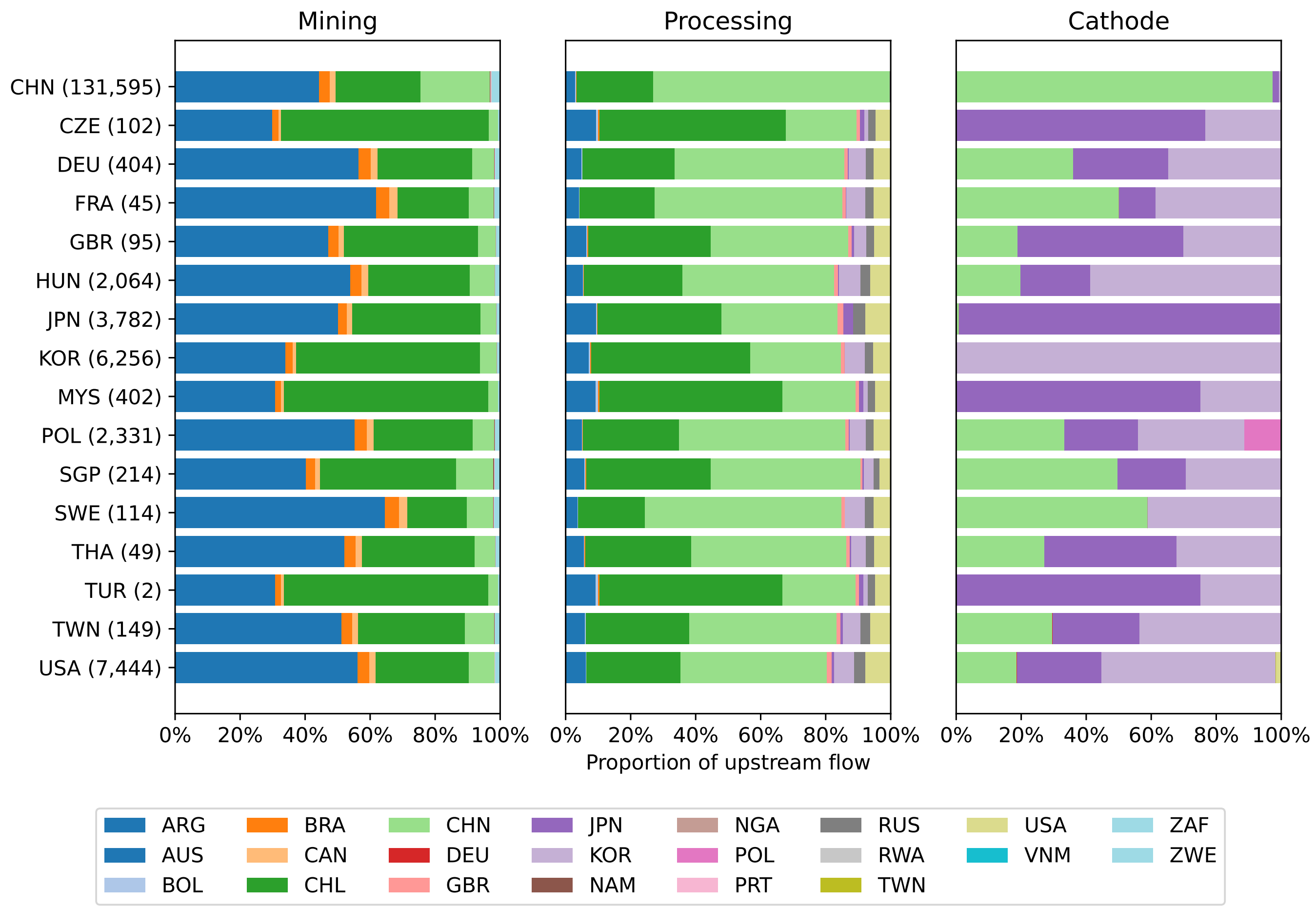

FIGURE 10. PROPORTION OF GLOBAL MATERIAL FLOW THROUGH EACH COUNTRY AT UPSTREAM LI-ION BATTERY SUPPLY CHAIN STAGES.

Figure 10 displays the geographical disaggregation of each supply chain stage for countries that produce batteries, with the mining stage represented in the first column, the processing stage in the second column, and the cathode stage in the final column. This disaggregation is possible due to the company-level mapping. The figure shows that vulnerabilities vary by manufacturing country and that battery manufacturing outside of China depends on Chinese processing by at most 50%, and much less for other stages. Although this analysis is limited to cathodes, it suggests that if battery manufacturing was to be scaled up in other countries to mitigate the geopolitical risk associated with Chinese production, the supply chains could exist independently of China. Moreover, Korea is entirely self-sufficient in cathode manufacturing, while Australia, despite dominating spodumene production, conducts very limited processing locally and does not produce cathodes or batteries. Chile performs both mining and processing domestically but does not engage in cathode or battery production. Only four countries—China, Japan, Korea, and Poland—produce cathodes.

6.1.3. Discussion

This study presents the first comprehensive mapping of the global lithium supply chain at the facility level. Analysis at the country level often misses significant internal country flows and tends to concentrate the issue on overall national concentration. In contrast, facility-level mapping is necessary to properly evaluate supply chain vulnerabilities and mitigate supply risks. Although China dominates battery manufacturing with 84% of production in 2023, it does not control the upstream supply chain for other countries. Scaling up battery manufacturing in other regions is possible without heavy reliance on China, thereby potentially increasing overall resilience. While China is largely self-sufficient beyond the processing stage, it remains heavily dependent on Australia and Chile for raw materials. Many countries may be wary of bottlenecks in China; however, China itself is as vulnerable to upstream bottlenecks in Australia and Chile, as are the United States or Japan. The facility-level analysis reveals opportunities to improve resilience through targeted investments in mining infrastructure or backup transportation systems at the most critical nodes. Such an approach provides downstream companies with insight into specific upstream elements that warrant investment—a detail often obscured by supply chain complexity and country-level aggregation—and suggests that battery manufacturing can be expanded in additional regions without over-reliance on any single country.

The flow allocation method presented in this study establishes a baseline for mapping global supply chains at the facility level, given access to production statistics, and can be replicated for other materials. The method more accurately represents real-world flows when applied to materials with a limited number of supply chain nodes or specific feedstock requirements at each node. For materials with more variability, such as iron, incorporating additional information—such as off-take agreements—may be necessary to capture the full complexity of the global supply chain. The approach can be adapted to situations with greater data availability by initially using off-take agreements and subsequently filling in remaining gaps.

6.1.4. Methods

Here, we modelled the lithium supply network as a directed graph from upstream mines to downstream end-uses. Facility-level industry data is used to populate production at nodes, and a flow allocation method infers the graph edge-weights representing material flows between facilities, ensuring consistency with the requirements of product composition at each supply chain stage.

Facility-level data for mining, mineral processing, cathode manufacturing and lithium-ion battery manufacturing is sourced from Benchmark Mineral Intelligence production statistics. We define nodes as the facilities operational with non-zero output in 2023, although the methodology is replicable for any time-frame. Facility-level mapping is conducted from mine to battery manufacturing to identify resilience, with end-uses aggregated to regional levels and grouped by technology: electric vehicles (EV), energy storage systems (ESS), and portable electronics.

This study only considers processed lithium used in Li-ion batteries and therefore does not account for alternative destinations for processed lithium products. This limitation does not affect the evaluation of resilience for Li-ion battery supply chains, which is essential for the energy transition, but could be considered in future studies, where the scope is extended to the overall mapping of lithium as a commodity.

This study uses a replicable prioritised allocation method to map the material flows between supply chain stages at the facility level, providing a baseline for flow mapping for any facility-level study. A flow between facilities requires the output type of the upstream facility to match the feedstock type necessary for the downstream facility, within the supply chain stages depicted in figure 11a. Beyond this, flows are calculated based on a hierarchy of most likely facility-level relationships, which are prioritised to include source and destination nodes that are in the same country or owned by the same company as illustrated in figure 11b.

6.2. Stock flow model of the value chain for understanding Chinese disruption

6.2.1. Context

Findings throughout this report have elucidated the need for understanding supply chains from start to finish: in the case of critical materials, from mine to final consumer. The specific interest in the power held by a country, China, over the UK supply of critical materials, puts the focus on a gap in existing research and industry tools. This requires a bridging of the company-level analysis, to understand the propagation of stock through the supply chain, and country-level analysis, in order to explore the impact that Chinese policy could have on UK net zero goals.

In addition to the bridging of these two areas - company-level and country-level analysis - the first of which is largely dominated by data-driven industry tools (SAP, Oracle, Altana) and the second by qualitative academic investigations (e.g. (Rabe et al., 2017; Koyamparambath et al., 2022)). The analysis presented here includes the addition of stock and flow dynamics, a complexity of company-level production that is essential for determining exposure to disruption risk. This has the fundamental advantage over previous studies, that the supply chain has been mapped at the facility level, making the analysis widely applicable to decision-makers without the need to upload data.

The preliminary work presented here narrows the focus of the problem to a scenario-based analysis. A system dynamics model simulates a hypothetical scenario: the implementation of a total ban on the direct export of some (or all) critical materials from China to the

FIGURE 11

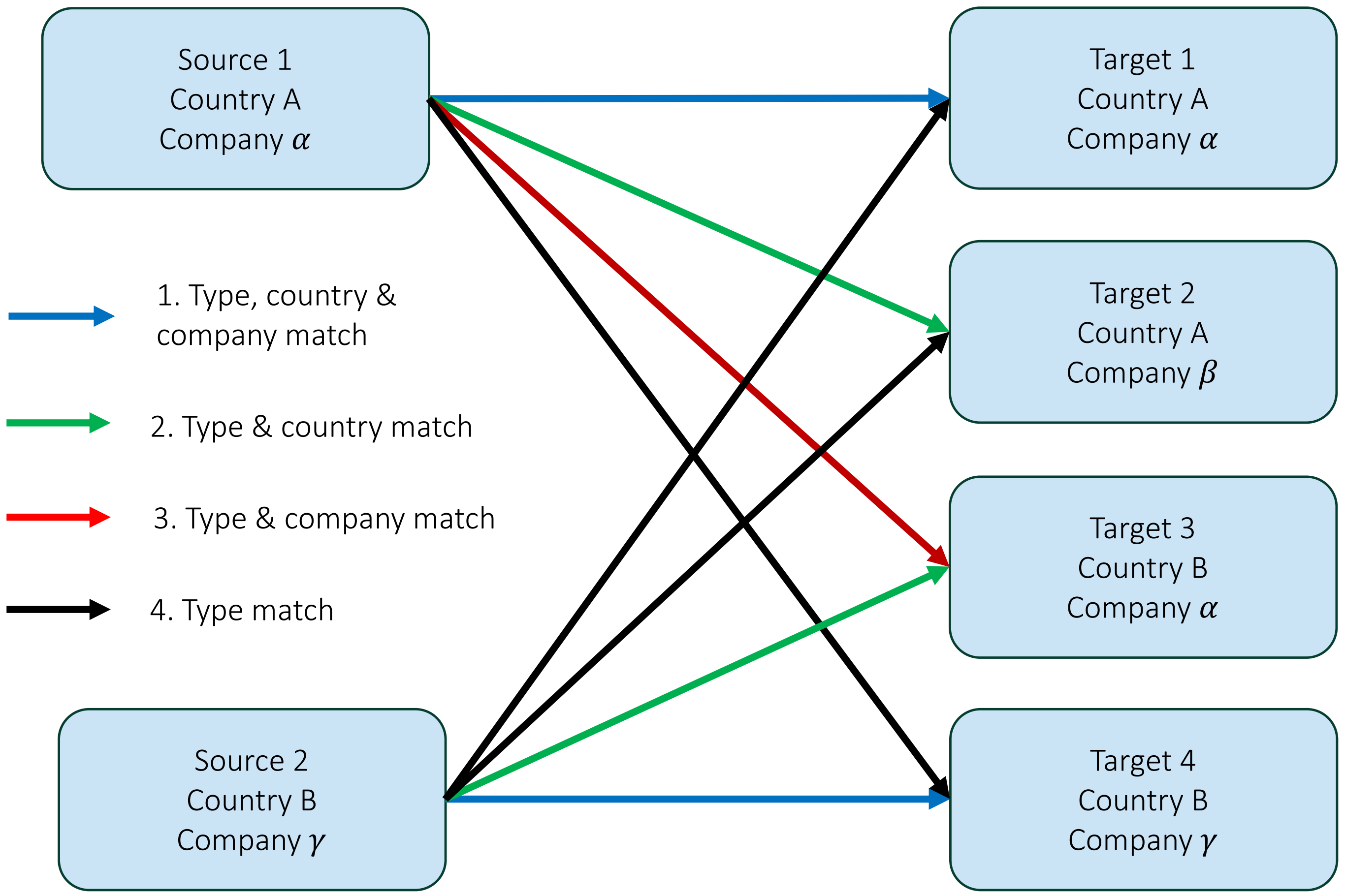

FIGURE 11. FACILITY-LEVEL MATERIAL FLOW CALCULATION METHOD ACCORDING TO A HIERARCHY OF RELATIONSHIPS: A) TYPES OF EDGES BETWEEN SUPPLY CHAIN STAGES. B) ILLUSTRATION OF HIERARCHY WITH PRIORITY OF FLOWS DEPICTED AS 1-4.

United Kingdom. This stress-test approach does not reflect an expected policy outcome, but rather serves to evaluate supply chain behaviour under extreme conditions. The risk exposure is computed for a UK company, from which strategic insights, including at the country level, can be gleaned. With the company-level data having the highest accuracy and resolution for lithium, the electric vehicle battery manufacturing supply chain was selected for a case study in this report.

The model was applied to analyse AESC UK, a lithium-ion car battery gigafactory in Sunderland which has been producing batteries for the Nissan Leaf since 2013 (originally a Nissan, NEC, NEC Tokin joint venture). AESC now partners with BMW, Mercedes-Benz, and Nissan. Its second gigafactory, operational in 2025, follows Envision's 2018 majority stake acquisition. Despite the Chinese stake in its ownership, this report treats AESC as a UK company based on location (a point for future model refinement). AESC UK remains vital, irrespective of the ownership, as the only lithium-ion battery cell manufacturer on UK shores, justifying its selection for this illustrative case study.

The model simulates how the company's risk exposure varies with: (i) a variation of export ban implementation; (ii) a change in the relationship between the company and its largest non-Chinese supplier, from Japan; (iii) the emergence of a non-Chinese alternative supplier.

An outline of the model's methodology is provided in Section 6.2.3, but there are a few pertinent points to be highlighted before any results are presented.

1. The metric used to analyse the effect of the export ban: Mean Risk Exposure.

   A practical approach is to quantify the subject company's exposure in £, so that the conclusions drawn are easily understood and tangible. The use of the term 'exposure', rather than simply 'risk' is deliberate, to illustrate that the likelihood of the ban coming to pass is not included in the analysis (this is a what-if analysis; how much the firm will suffer, in the event that the hazard comes to pass). However, it is not sufficient to consider only losses incurred by the firm while the export ban is active, since firms often take expensive, precautionary measures when they believe that such a threat is plausible, procuring more than they need. The contribution of the export ban to such precautionary costs should therefore also be included. Hence, the working definition for risk exposure is: The difference between a firm's profits in the case where the threat of a China-to-UK lithium export ban is negligible, and its profits in the case where the ban comes to pass.

   Using this definition, it is evident that the risk exposure can be calculated by taking the difference between the firm's profits in the ideal scenario, Case A, (where there is no threat of the ban, and it does not come to pass) and the profits in the export ban scenario, Case B. This difference is computed by simulating each of the two cases Monte-Carlo style, as described in Methodology 2 of Section 6.2.3. As with the rest of the model, this Monte-Carlo simulation includes proper probabilistic treatment of uncertainty, resulting in a distribution of risk exposure values at the end of the realisation time.

   The mean risk exposure is the average of these distributed results.

2. The firms whose export behaviour is governed by China's export controls. Further iterations of this model will account for the nuances of Chinese governmental influence over Chinese-owned firms located abroad. This model uses the simplest interpretation - that all firms located in China, and no others, are governed by the Chinese government's export controls.

3. The timescale on which the model is applicable. In the preliminary work, the model has been limited to timescales on which there is very little supply chain flexibility (meaning firms cannot enter the supply chain, and firms cannot switch their suppliers). Over this time period, the output target of the firm is also considered static. This assumption makes the preliminary model less accurate, if the model is used for simulations further into the future, but is considered to hold for up to twelve months, depending on the typical duration of trade contracts in the industry analysed.

4. The model's ability to simulate stock and flow dynamics, which allows generation of an accurate picture of the company's resilience to disruptions. This complexity is absolutely necessary for a realistic simulation, but is impossible for any research group which has not generated such high resolution facility-level data as seen in Section 6.1.

6.2.2. Company-level Insights

The output of the proof-of-concept model, applied to AESC UK, is presented with a short discussion to illustrate the types of insight that the model facilitates.

Figure 12 plots the mean risk exposure, as a proportion of annual revenue for a firm, versus the number of months that a China-UK export ban is in place. It shows that after 6 months the firm will have lost 20% of their annual revenue. We define mean risk exposure as the expected loss in profit resulting from Chinese dependence, assuming a China-UK export ban is implemented. We then explore how mean risk varies with the trade ban duration for strategically important companies in the UK (i.e. approximately £20 million per month for AESC UK). This allows the value of efforts made to repair trade relations or provide more resilience to be quantified. The results can also be translated from the value of risk exposure into the number of final products (Li-ion battery cells) that the company fails to produce, due to the shortfall in procurement. Here, 10% of annual revenue is equivalent to the production of about 6,000 Li-ion battery packs.

A peculiarity of this result is that the mean risk exposure is at a minimum (near zero) at around one month in duration. This is an artefact, resulting from the firm already having deliberate disruption mitigation measures in place (such as small-scale over-procurement). For this year, the firm would save money if there were an export ban for around one month, but it would exhaust the firm's disruption mitigation measures, increasing its mean risk exposure for the following year.

Figure 13 computes the proportion of procurement that should be sourced from a Chinese-independent supplier, assuming that the procuring firm is profit-maximising. Given the short-term nature of the model, it assumes that this new procurement is in addition to existing contracts. While such an insight is valuable from the purchasing firm's perspective in determining purchasing behaviour, it can also be utilised from the opposite perspective - the perspective of the supplier. For instance, consider a hypothetical government-backed venture which aims to produce cathodes for Li-ion batteries without relying on Chinese mining or processing. In the development of such a project, it would be of interest to determine how price-competitive the venture needs to be compared with Chinese suppliers, to capture market demand. Using figure 13 we can compute the proportion of a company's demand that such a venture is likely to capture. In this scenario-based case, where the procuring company assumes that a China-UK export ban will be active between six and twelve months, the minimum price competitiveness to capture some of AESC's demand, is to be producing within a 44% premium of Chinese suppliers.

When a firm deals with a supplier which is not Chinese but has some upstream Chinese dependencies (Type C), the amount of product received depends on how the supplier chooses to allocate among its customers in the event of reduced capacity. When major disruptions result in suppliers being unable to fulfil their contractual agreements, so-called 'force majeure' clauses in the agreements typically become active, relieving supplier obligations and allowing them to allocate the product they do have in an unprescribed way. This creates significant variation to the amount of product the subject firm can receive.

Figure 14 shows two extremes: either the subject firm, AESC UK, is prioritised, meaning its demands are met before any competitors, or that it is deprioritised, meaning that all other competitors are satisfied first, with the subject firm only being allocated what remains. We also include a neutral scenario, where a reduction in supplier capacity is distributed equally across all its customers. The scenarios are assessed using the mean exposure risk to the firm. At the company level, information of this type can be instructive, allowing a firm to prioritise suppliers based on the strength of the relationship that exists. For AESC, it stands to gain little by differentiating itself from the pack of customers, with prioritisation (which reduces risk exposure by 0.1%) offering little benefit compared with the consequence of being deprioritised (which increases risk exposure by 8.8%) by its largest supplier, the Japanese cathode producer Nichia Chemical. This insight also is informative for the question of how relations with third-party countries might affect the UK in the event of an export ban. Warmer relations between Japan and the UK may result in Japanese companies prioritising (or at the least, not deprioritising) UK companies under the conditions of a Chinese export ban, reducing the risk exposure to UK firms.

FIGURE 12

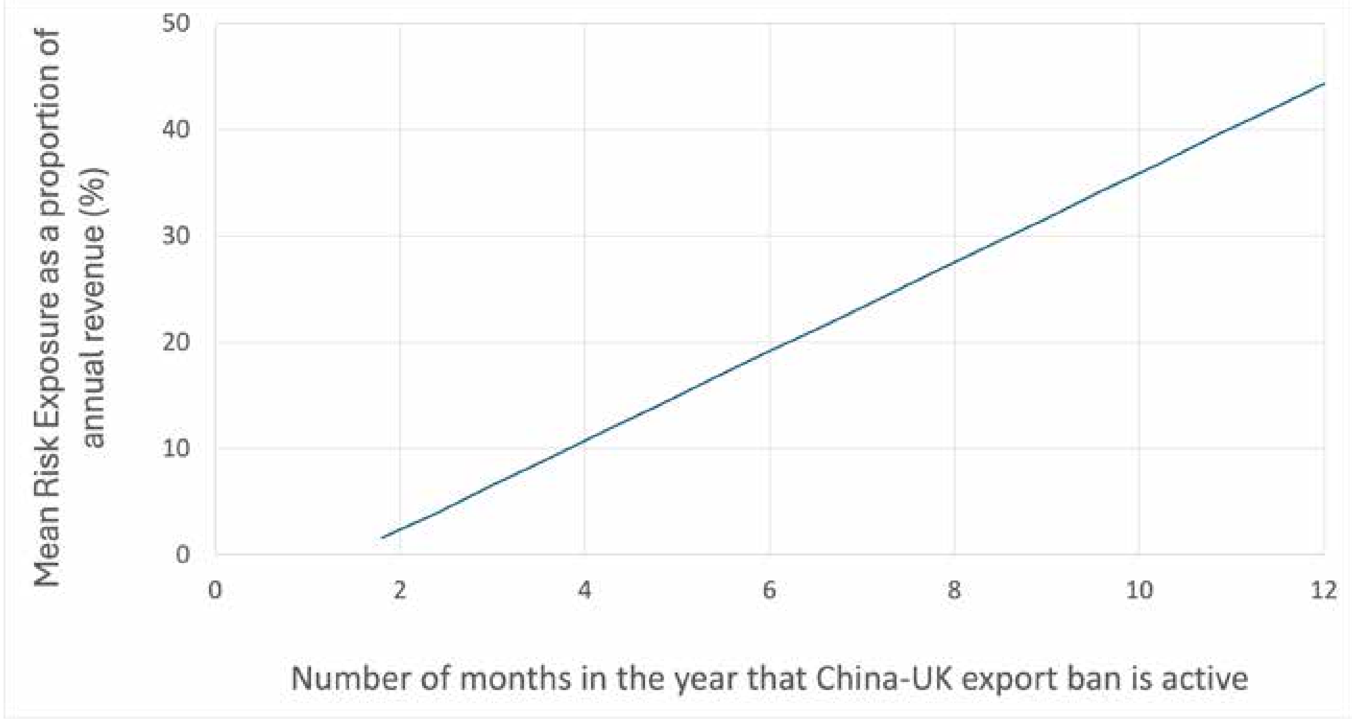

FIGURE 12. THE VARIATION OF THE FIRM'S MEAN RISK EXPOSURE WITH THE DURATION OF THE CHINA-UK EXPORT BAN.

FIGURE 13

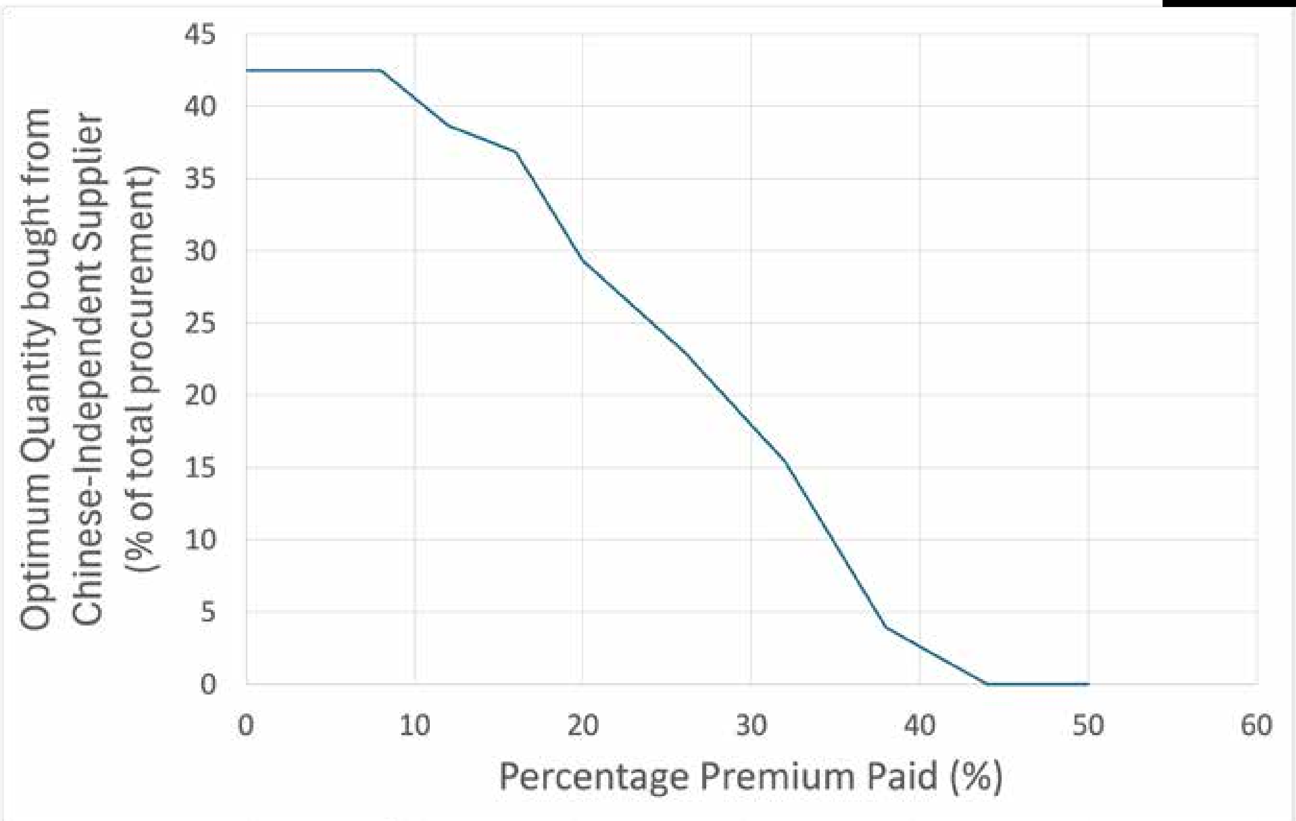

FIGURE 13. THE OPTIMUM PROPORTION THAT THE FIRM SHOULD PROCURE FROM A CHINESE-INDEPENDENT SUPPLIER, IF ONE EXISTS, DEPENDING ON THE PREMIUM CHARGED.

FIGURE 14

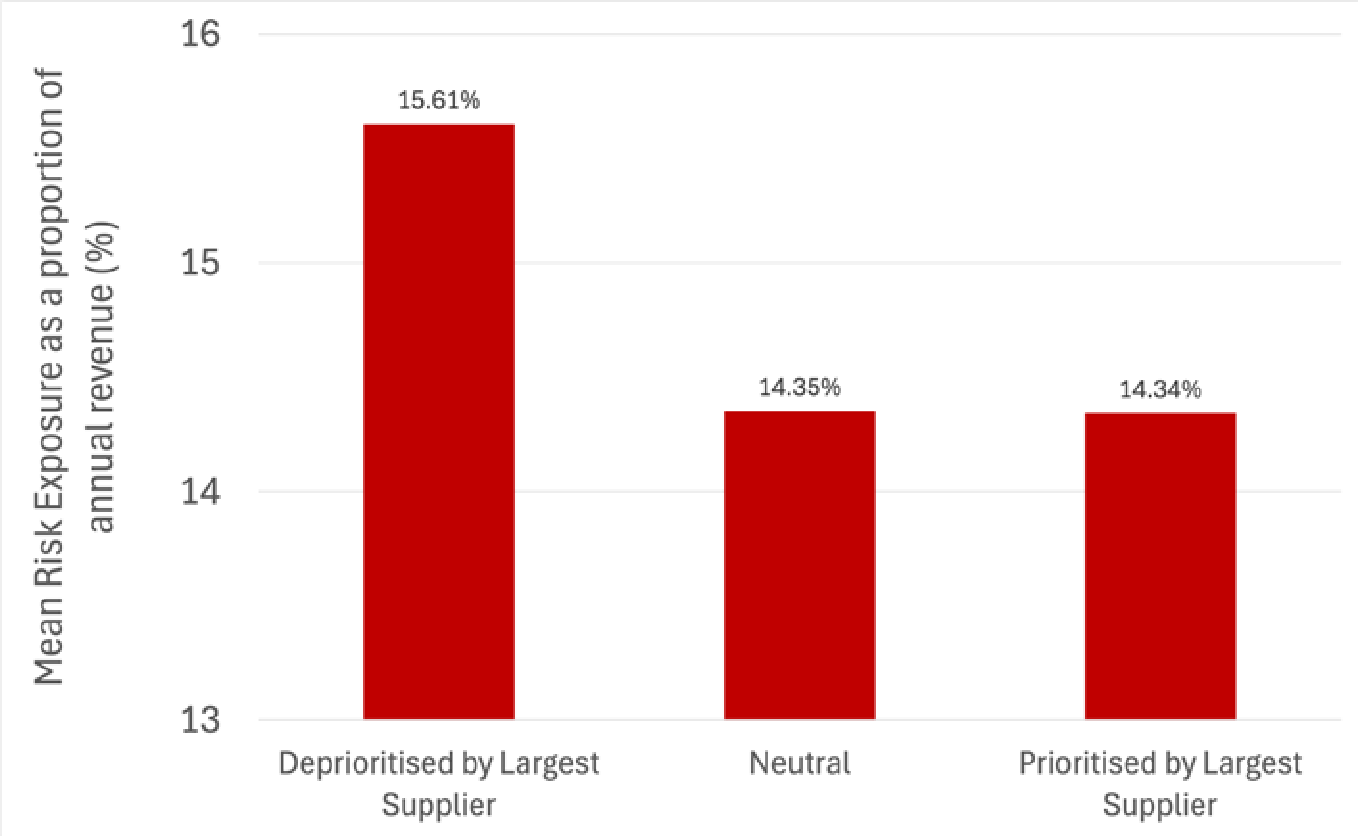

FIGURE 14. THE EFFECT THAT THE FIRM'S STANDING WITH ITS SUPPLIERS HAS ON ITS MEAN RISK EXPOSURE.

FIGURE 15

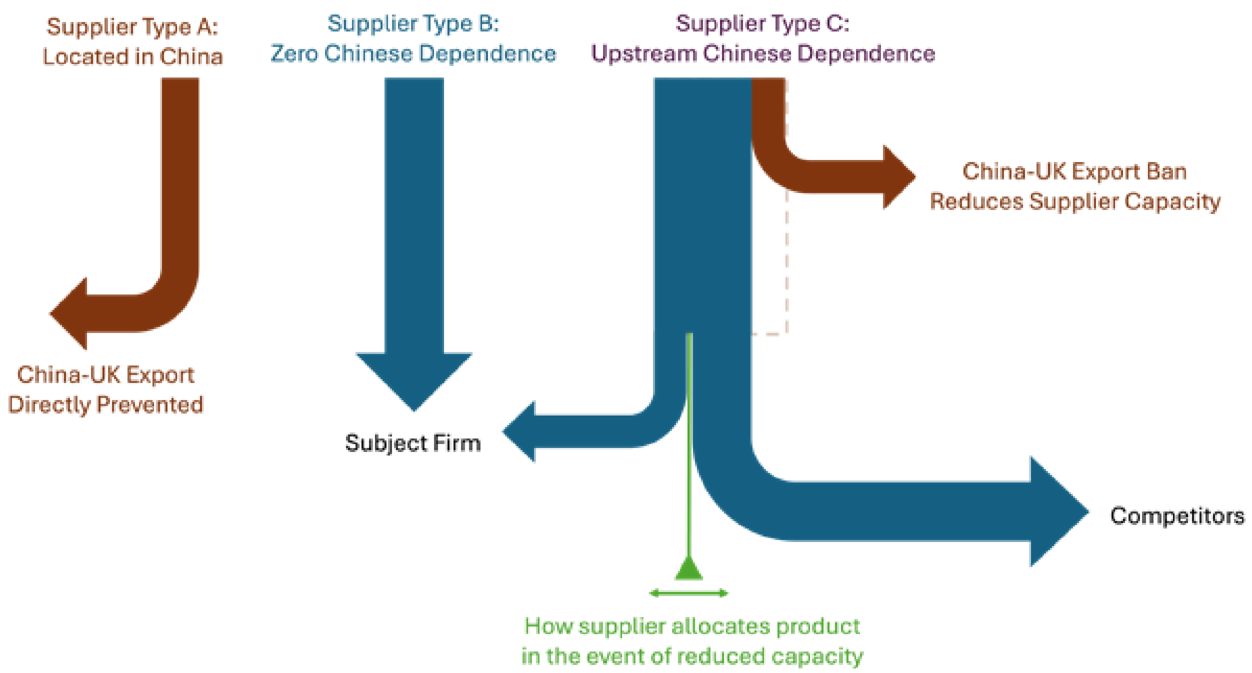

FIGURE 15. SUPPLIERS WITH CHINA-DEPENDENCE SCORES OF 1, 0 AND BETWEEN 1 AND 0 RESPECTIVELY. PROCUREMENT DEPENDS ON THE DEPENDENCE SCORE OF EACH SUPPLIER, AND HOW THEY ALLOCATE PRODUCT IN THE EVENT OF REDUCED CAPACITY.

6.2.3. Methods

Existing approaches to the supply chain disruption problem are hamstrung by broad scopes and little facility-level data, and therefore neglect the dynamic nature of the risk profile. Instead, they assign dependence or risk scores as state variables, essentially neglecting stock and flow effects (Ouyang et al., 2024b; Wang et al., 2022). This model revises the state variable approach to quantifying risk exposure by simulating the company's production through time and allowing for more complex interactions with suppliers.

In this prototype model, the complex analysis is applied to only one company (with upstream companies being analysed in a more typical state variable-like approach), but future iterations will improve realism by applying the same simulation technique to upstream companies as well, thus generating a realistic flow model which tracks the movement of critical materials across the entire value chain. Further development will allow the decision makers' beliefs about likelihoods of various disruption events to be included in the model, dispensing with the limitations of a single scenario. The success of these modelling improvements is contingent on data availability. The model can be used to analyse a company in two ways: either remotely, as has been done for AESC UK in this report, where bespoke research-based estimations of the company's unit costs and output targets are made, or alternatively, in direct partnership, where data is provided by the company itself. The only inputs necessary for analysing upstream production processes are the production times and material conversion factors, meaning that the simulation approach can be scaled without the need for more detailed research on any company but the one being analysed.

METHODOLOGY 1: STATE-VARIABLE ASSIGNMENT OF CHINESE DEPENDENCE SCORES

Taking a state-variable approach, the companies upstream of the subject firm in the supply chain are analysed for their specific dependence on China-to-UK exports. The dependence score, whose definition can be tailored to the scenario of interest, indicates how much of the firm's procurement of critical materials would be disrupted if there were a China-to-UK export ban.

The methodology for determining a company's dependence score is made possible using detailed data from Section 6.1, as presented below.

STAGE ONE: MINING COMPANIES

→ The mining stage represents the origination of the critical material into the supply chain. Procurement of mining companies is not reliant on any imports of the raw material, so these are assigned a dependence score of zero.

STAGE TWO: FIRST PROCESSING STAGE

→ If a company is in the UK, its dependence score equals the fraction of its procurement that came from Chinese suppliers, a measure of the company's risk exposure to the export ban.

→ Otherwise, its dependence score remains zero.

SUBSEQUENT STAGES

→ If the analysed firm is from the UK and the supplier is from China, the dependence score associated with this supplier is set to 1, since the entire flow will be affected by the ban.

→ Supplier dependence scores propagate to the analysed firm, weighted by the proportion of procurement coming from that supplier.

This methodology has assumed proportional propagation of supply shortages through the supply chain, in a similar way to conventional supply disruption models. However, at the company's immediate supplier stage, the sophistication of the model is initiated by allowing the allocation of scarce product to vary according to the supplier's preferences. Then, the effect of reduced procurement is simulated in a process-dependent way, as shown in figure 16. With future development of the model, these sophistications will be incorporated higher and higher up the supply chain, until all of the material flow is simulated with similar realistic complexity.

METHODOLOGY 2: PROCESS-DEPENDENT SIMULATION OF RISK EXPOSURE

The system dynamics model simulates supply chain material flows by stepping through time. Initially, procurement flows follow the business-as-usual data obtained from Section 6.1. After the China export ban, which is by default implemented six months into the twelve-month simulation period unless otherwise specified, flows are adjusted based on supplier dependence scores, with China-to-UK flows set to zero. Simulations explore neutral, prioritised, and deprioritised supplier relationships.

The production model assumes that the firm controls the quantity of material to put into production daily, aiming to match future production to targets, using available inputs material stock, the difference between the procurement inflow and the production outflow, total cost, encompassing procurement, stock holding and production shortfalls, is calculated. Risk exposure, in £, is the difference between the costs to the firm given its Chinese dependence, and the costs it would face under completely desrisked conditions, reflecting both the realized and the anticipated disruption impacts. A Monte Carlo simulation, incorporating input uncertainty, generates the risk exposure score as the product of the likelihood and severity of costs.

EXPOSURE = (LIKELIHOOD × SEVERITY OF COSTS INCURRED) − COSTS INCURRED IF ZERO DEPENDENCE

FIGURE 16

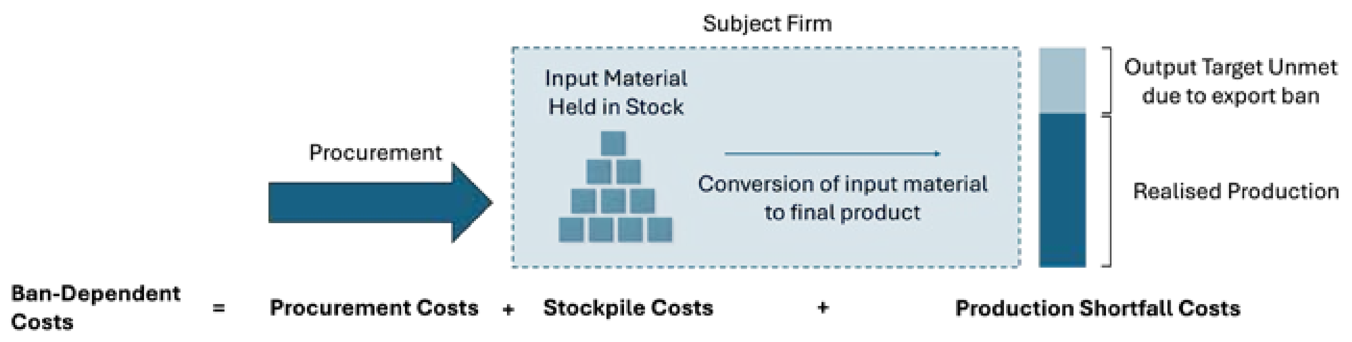

FIGURE 16. COSTS INCURRED BY THE FIRM DEPEND ON THE DYNAMICS OF PRODUCTION.

7. Conclusion

→

This work answers and builds on the initial research objectives set out in the 2024 scoping report. The results and findings presented here draw several policy-relevant conclusions. Based on these findings and subsequent conclusions, a number of specific policy insights are set out. Finally we end by discussing the potential policy insights from ongoing research.

RQ1: HOW DOES THE FINAL DEPLOYMENT OF CLEAN ENERGY TECHNOLOGIES VARY ACROSS DECARBONISATION PATHWAYS?

Figure 1 shows the deployment in 2050 for five key clusters of clean energy technologies, solar PV, wind, batteries, hydrogen and electric vehicles. The spread in final deployment for solar, wind, and batteries is consistent across technologies, where the deployment range is approximately 55% of the average deployment. The projected number of electric vehicles is more certain with a deployment range of 38% of the average deployment. Finally, there is significant uncertainty over the final deployment of clean hydrogen, as the deployment range is 178% of the average deployment.

RQ2: WHAT WOULD BE THE ASSOCIATED DEMAND FOR CRITICAL MINERALS?

Three clusters of critical minerals are identified based on their future demand: Cluster 1 materials see a significant increase in demand over the next 20 years; Custer 2 see a decline in demand over time; Cluster 3 minerals present an uncertain picture of future demand based on policy and technology decisions.

RQ3: HOW SHOULD FUTURE DEMAND FOR CRITICAL MINERALS INFORM THE UK'S APPROACH TO CHINESE DEPENDENCIES?

Cluster 1 materials that show the greatest growth in demand are significantly dependent on China which currently processes a majority of these minerals. Cluster 2 minerals are currently dependent on China; however, this dependency could be reduced through the development of better recycling and circular economy initiatives. Finally, the dependence of Cluster 3 minerals on China varies, with some, such as Tungsten and Vanadium, being very dependent on China for processing. These dependencies could be reduced however through reduced deployment of CCS and nuclear technologies.

RQ4: TO WHAT EXTENT ARE THE METALS IN UK PRODUCTS MINED IN CHINA (AND VICE VERSA)

For metals embodied in UK final consumption, all mining takes place outside the UK—with, for example, only about 7% of the copper consumed in the UK coming from mines in China. In contrast, Chinese final consumption relies substantially on domestic extraction (e.g. approximately 48% of copper is mined in China). This contrast reflects China's mining capacity in contrast with the UK's heavy reliance on imported minerals.

RQ5: TO WHAT EXTENT ARE THE METALS IN UK PRODUCTS MINED BY CHINESE-CONTROLLED COMPANIES (AND VICE VERSA)

Ownership data reveal that only a modest share of metals embodied in UK products originates from Chinese-controlled mines. For example, while Chinese firms have significantly expanded their control over critical mineral assets—such as in the copper or cobalt sectors—the fraction of these metals that enter UK products via Chinese-controlled mining remains relatively low. Similarly, UK-controlled companies contribute only a small proportion of the metals used in products consumed in China. This indicates that, although Chinese dominance is pronounced in downstream processing and refining, the upstream mining stage exhibits a more diversified set of ownership profiles across both regions.

RQ6: HOW HAS THE GEOGRAPHIC DISTRIBUTION AND CORPORATE OWNERSHIP OF CRITICAL MINERAL MINES CHANGED OVER TIME?

Over the last two decades there has been a clear shift in the global landscape: Chinese companies have markedly increased their control over critical mineral mines while the UK's share has declined. For example, in the copper sector, UK mine ownership fell from about 11% in 2000 to 9% in 2022, as Chinese ownership increased from 1% to 11%. Similar trends are seen for other minerals (e.g. cobalt and gold). The amount of production controlled by China is still lower than its final consumption.

RQ7: IS THERE A CORRELATION BETWEEN MINE OWNERSHIP AND TRADE IN MINERALS?

Our analysis finds no meaningful correlation between mine ownership and actual trade flows in minerals. Only about 4–10% of country pairs display both a trade relationship and an ownership tie, and the calculated correlation coefficients are extremely low (ranging from 0.00 to 0.13). This clearly demonstrates that the extent of corporate control over mining operations does not predict the patterns or volumes of mineral trade, which are instead driven by a broader set of economic and contractual factors.

RQ8: WHAT COULD BE THE DISTRIBUTION OF FUTURE MINE OWNERSHIP BASED ON EXISTING PROJECTS?

Projections based on current data suggest limited redistribution in mine ownership by 2040. For example, in the copper sector, Chile's production share is expected to decline slightly while Chinese and "unknown" ownership shares may increase. In the lithium market, there is an anticipated shift away from Australia—with rising shares for the US and Canada—while in cobalt the Democratic Republic of the Congo's share is projected to fall in favor of higher ownership from Australia and Canada. These scenarios assume that current ownership patterns persist, though real-world outcomes may be further affected by evolving geopolitical and market forces.

RQ9: WHICH FACILITIES CONSTITUTE THE MOST CRITICAL VULNERABILITIES IN THE LITHIUM SUPPLY CHAIN FOR UK BATTERY MANUFACTURERS?

Our facility-level mapping reveals that the most critical vulnerabilities are found upstream in the supply chain—primarily within mining and processing facilities located in Chile and Australia. In contrast, only one of the top critical facilities is in China, indicating that UK battery manufacturers face significant risks from upstream facilities outside of China.

R10: HOW CAN A DETAILED, FACILITY-LEVEL MAPPING OF LITHIUM FLOWS INFORM STRATEGIES TO ENHANCE SUPPLY CHAIN RESILIENCE?

By pinpointing the exact facilities and flows that carry the highest concentration of lithium, facility-level mapping enables targeted interventions. This granularity may help stakeholders to focus on reinforcing or diversifying these critical nodes, thereby reducing overall supply chain risk and dependency on any single country or facility.

RQ11: HOW CAN A COMPANY'S EXPOSURE TO CHINESE BANS ON CRITICAL MATERIAL EXPORTS BE QUANTIFIED?

Simulation of procurement and production processes results in analysis that is more realistic than conventional approaches, by accounting for stock-and-flow effects. It also allows for investigation of the exposure's variation with changes in inputs, including the duration of the export ban, the supplier's allocative preferences and how the firm's purchasing decisions depend on both price and Chinese-dependence of suppliers.

RQ12: HOW CAN COMPANY-LEVEL ANALYSIS INFORM COUNTRY-LEVEL POLICYMAKING?

First, insights from strategically important companies could motivate policymakers to address factors which are revealed to be valuable to the company; for instance, by prioritising relations with strategically important third- party supplier countries. Second, by analysing companies' decision-making, policymakers can better understand how to engage with them; for instance, by determining the level of cost-competitiveness needed for a UK-based supply chain to attract demand.

7.1. Policy insights

These overarching conclusions lead to several important policy recommendations to support and enhance the strategic availability of critical minerals to support the UK's decarbonisation objectives going forward.

1. The UK critical mineral strategy does not reflect how demand for different minerals is expected to evolve over time. Only six critical minerals in the UK strategy will be important for UK decarbonisation [cobalt, gallium, graphite, lithium, silicon and tellurium]. A further four materials are dependent on the future use (and successful deployment of) nuclear power and carbon capture and storage [indium, niobium, tungsten, vanadium].
   - 1.1 The UK could reduce its dependency on China by choosing decarbonisation pathways which are less reliant on critical minerals. The large scale deployment of nuclear and CCS will place additional risk on delivering the UK climate targets by increasing the number of critical minerals that we are dependent on China for to decarbonise (specifically Tungsten and Vanadium). Pathways with lower final energy demand (by employing more energy efficiency and demand management measures) reduce the total demand for critical minerals (in kilotonnes) therefore making the UK less dependent on minerals that are primarily processed in China.
   - 1.2. The UK could improve its resiliency and dependency on China through increased energy efficiency and reducing final energy demand. The pathways analysed in Chapter 3 show that final demand for the most important critical minerals (cluster 1) which are all highly dependent on China for their processing could be reduced by up to 40% by choosing pathways with a lower final energy demand.
   - 1.3. Early action should be taken to capture the minerals at the end of life for recycling, to reduce overall demand and thus potential future supply risks. Where overall demand decreases (Cluster 2) domestic demand can likely be met through recycling. Stockpiling and early action may be necessary to build up the necessary resources where current technology has not yet scaled, but are planned. For example, the current stock of platinum in internal combustion engines could be recycled to produce a domestic supply of platinum for use in hydrogen electrolysers.
2. The UK's favourable position for mine ownership does not guarantee its future supply as significant vulnerabilities sit more midstream of the supply chain.
   - 2.1. The UK needs to work to establish strong relationships with countries where production will grow, to reduce the risk of supply shortages and export bans.
   - 2.2. China also does not control sufficient mining capacity to meet its own demand for clean energy technologies. It therefore, has significant risk of supply shortages itself. This presents potential strategic opportunities for the UK to leverage its relatively strong position in mine ownership against Chinese dominance of the intermediate steps of the supply chain.
   - 2.3. While we have seen increased concern over Chinese ownership of critical mineral assets, particularly in the global south, UK ownership of minerals supplying final goods in China is roughly equal to the Chinese ownership of mineral extraction that end up in UK products.
3. There is sufficient non-Chinese owned and produced critical minerals to meet UK demand but early action is needed to secure supply.
   - 3.1. Demand for minerals is expected to grow over time as countries seek to 'friend-shore' production as (western) countries try to move away from China. This will place competition on non-Chinese processed goods. Ongoing work in section 6 shows the extent to which companies can benefit from paying above market prices for a percentage of their supply to make their supply chains more resilient.
   - 3.2. Finally, China remains dominant in the intermediate product stage of the supply chain. In addition to securing supply of raw critical minerals, the UK needs to work to establish non-Chinese supply chains to leverage their strength in mine ownership. This is beyond the scope of what is discussed in this report but is a key area of future work.

7.2. Policy relevance of ongoing work

1. Granular Identification of Supply Chain Vulnerabilities:
   - 1.1. The facility-level mapping pinpoints critical nodes—primarily in upstream mining and processing in countries such as Chile and Australia—that pose significant vulnerabilities for UK battery manufacturers.
   - 1.2. This type of model can help identify the most important supply chain stages to invest in.
2. Diversification Beyond Chinese Processing:
   - 2.1. While China dominates certain processing stages, the analysis reveals that critical vulnerabilities are not exclusively located within Chinese borders.
   - 2.2. Policies can support the development of non-Chinese processing capacities by incentivising regional collaborations or public–private partnerships.
3. Quantification of Disruption Risk and Strategic Mitigation:
   - 3.1. The stock-flow model quantifies the risk exposure of UK companies to potential export bans by simulating stock shortages, production losses, and cost impacts.
   - 3.2. Such quantitative risk assessments can inform the design of strategic reserves, guide procurement diversification strategies, and establish thresholds (e.g. acceptable price premiums) for alternative sourcing.
4. Informing Short- and Medium-Term Policy Interventions:
   - 4.1. By simulating the timing and impact of supply disruptions, the model highlights critical time windows where mitigation measures (such as temporary stockpiling or accelerated contract renegotiations) are most effective.
   - 4.2. These insights may allow the development of develop flexible, time-sensitive responses that minimize production shortfalls during periods of acute disruption.
5. Enhancing Strategic Supplier Relationships:
   - 5.1. The analysis of supplier allocation preferences under supply constraints underscores the value of fostering strong relationships with key non-Chinese suppliers.
   - 5.2. Policy measures that encourage transparency, fair contracting practices, and diversified supplier networks can improve the bargaining positions of UK companies' and ensure more stable supply flows.
   - 5.3. In cases where direct supplier relationships are limited or infeasible, facilitating open trade through mechanisms such as licensed exchanges or transparent trading platforms can provide an alternative route to securing critical materials.

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PLEASE CITE AS: SERRENHO A, CULLEN JM. (2025). CHINA'S ROLE IN THE UK ENERGY TRANSITION: FROM MINE TO TECHNOLOGY.

DOI: 10.17863/CAM.123213

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RESEARCH IN THIS REPORT IS FUNDED BY CCG, CLIMATE COMPATIBLE GROWTH: HTTPS://CLIMATECOMPATIBLEGROWTH.COM/ABOUT-US/

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WHO WE ARE

CAMBRIDGE CRITICAL MATERIALS LAB

We believe the energy transition must be equitable and inclusive. That means mineral-rich countries and their communities should benefit fully from their resources. By co-creating information platforms, producing rigorous research, and building tools for better decision-making, we work to strengthen equity in how critical materials are used to ensure no one is left behind.

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HOW WE WORK

We combine independent, interdisciplinary research with close collaboration across the Global South to ensure mineral governance is technically sound, socially just, and climate-compatible. By integrating engineering, policy, and social sciences, we create actionable insights that empower governments and communities to defend their rights, advance their interests, and navigate the complex environmental, social, and economic challenges of the energy transition.

OUR TEAM

Blending engineering, policy, and social sciences, our team finds innovative solutions to complex challenges.