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Scotland's critical raw materials supply chain for the net zero energy sector: opportunities and risks

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1 Executive Summary

1.1 Background

Critical raw materials (CRMs) are essential for many technologies needed to reach net zero, including wind and solar power, hydrogen, batteries, and the electricity grid. By 2030, the energy transition alone is expected to have increased global demand of CRMs by 3.5 times.

CRM supply chains face risks from limited availability, concentrated supply, global competition, and environmental and social impacts. This can lead to supply disruptions, price volatility, trade dependencies, and wider strategic risks for governments and industry.

However, the transition to net zero also presents significant opportunities, including through circular economy approaches that can reduce supply chain risks. There is a pressing need for robust, coherent and evidence-based policy on CRMs to support Scotland's net zero transition.

The study combined evidence review, stakeholder engagement and modelling to assess Scotland's future CRM needs, supply chain risks and opportunities for action. We also explore opportunities for action, particularly to support Scotland's circular economy.

1.2 Key findings

1.2.1 Projected CRM needs for net zero technologies in Scotland

The expansion of net zero technologies is expected to drive rapidly increasing demand for the CRMs they require in the coming years. Scotland has ambitious policy targets across multiple net zero technology sectors. These include: an additional 10 Gigawatts (GW) of onshore wind by 2030; total 8-11 GW of offshore wind by 2030 and 40 GW by 2040; and total 4-6 GW of solar deployment by 2030. Electric vehicle (EV) sales are projected to reach 579,000 by 2030 and 3.4 million by 2050. Hydrogen production is expected to reach 5 GW by 2030 and 25 GW by 2045. The associated demand for seven of the CRMs in Scotland is shown in Table 1, based on our data modelling.

Table 1: Summary of projected Scottish demand for critical raw materials in net zero technologies

Selected CRM	Net zero technology	Projected demand in Scotland in NZTs		
		Required in 2030	Required in 2040	Cumulative 2026-2040
Cobalt	Batteries (EV and storage)	690 t	655 t	9,330 t
Copper	Wind, solar, batteries, grid	37,630 t	26,905 t	442,080 t
Lithium	Batteries	1,210 t	1,295 t	16,710 t
Manganese	Wind, batteries	3,430 t	1,805 t	34,475 t
Nickel	Wind, solar, hydrogen, batteries	5,220 t	5,215 t	68,925 t
Rare earth elements (REEs)	Wind, hydrogen	330 t	465 t	5,390 t
Silicon	Batteries, solar	2,785 t	940 t	27,520 t

Aluminium, iron and niobium were not included in our modelling exercise, due to the scope and timeline constraints of our study, and the complexity and granularity of available data. Instead, we note here headline figures drawn from literature. For aluminium, total projected Scottish demand from 2023 to 2050 is 1,100 kt (Zero Waste Scotland, 2023b). For iron, total projected Scottish demand for the same period is 3 million tonnes (Zero Waste Scotland, 2023b). For niobium, only a snapshot global figure was found, of 103 kt in 2031 (Mordor Intelligence, 2026).

1.2.2 Key CRM supply chain risks

Scotland is vulnerable to disruptions in global CRM supply chains. The biggest risks include:

- **Geographical concentration of supply:** For each of the CRMs examined, the top three countries account for over 50% of global extraction. Processing and refining are also geographically concentrated, with China particularly dominant.
- **Demand outpacing supply:** Global CRM demand is projected to increase faster than extraction. This could affect Scotland's rollout of net zero technologies, particularly where copper, lithium, nickel and rare earth elements (REEs) are required.
- **Geopolitical and economic tensions:** Conflict, cartels and trade restrictions could disrupt the supply of several CRMs, including cobalt, manganese, nickel, REEs and lithium. These risks are heightened by geographically concentrated supply.
- **Price volatility:** Unpredictable prices can discourage investment in new CRM projects and are compounded by complex supply chains.
- **Risks relating to recycling and recovered materials:** Recovering CRMs from existing products can be difficult. While recycling rates are relatively high for some CRMs, such as nickel, aluminium, iron and copper, recycling alone is unlikely to meet near-term demand.

- **Environmental, Social and Governance (ESG) concerns:** Many CRM reserves are located in areas with prominent ESG concerns related to water use, energy consumption, human and labour rights. This creates challenges for responsible and sustainable sourcing.

The most significant medium-term risks are concentrated supply chains, particularly China's role in processing, and global demand growth for copper, lithium, nickel and REEs.

1.2.3 Scotland's strengths, weaknesses, opportunities and threats

Figure 1 summarises the key strengths, weaknesses, opportunities and threats we identified for CRM supply and circular economy approaches in Scotland. Circular economy approaches could help mitigate some of the risks identified in Section 1.2.2.

Strengths	Weaknesses
• **Skills:** Expertise in minerals, mining, manufacturing, and offshore wind • **Research and Development (R&D) capacity:** Business, academia and research (access to investment and advanced technology) • **Existing net zero technology capacity:** potential for CRM recovery from wind turbine decommissioning • **Extraction:** Nickel/cobalt exploration potential • **Recognised high ESG standards**	• **Lack of strong international partnerships** • **Low domestic extraction potential** for most CRMs • **Low recycling rates** due to material volumes, lack of infrastructure (e.g. magnet REEs), markets and incentives • Significant proportions of **key materials are exported** (copper, aluminium, waste electrical and electronic equipment) • **Industry:** some offshoring in industrial and manufacturing base • **Skills/labour:** Capacity lacking for manufacturing and recycling
Opportunities	**Threats**
• **Reduce exports and increase CRM recycling** (aluminium, lithium, neodymium, etc.) • **Material recovery** via decommissioning, industrial wastes and reprocessing (e.g. aluminium, lithium, neodymium) • **Alternative uses** such as end-of-life EV battery use for storage/backup • **Develop industry** for green steel, wind turbine technology/component remanufacture • **Ports:** Possible centres for recovery/reuse from decommissioning of renewables infrastructure	• **CE challenges:** recycling rates, recycling technology/infrastructure capacity • **Secondary CRMs:** unpredictable supply, economies of scale, material purity • **Price volatility of CRMs:** investment uncertainty • **Social licence to operate (SLO):** can pose a risk to CRM-related activities

Figure 1 Summary of SWOT analysis for circular economy approaches in Scotland related to CRMs

1.3 Potential actions

Scotland is in a strong position to use circular economy approaches to address CRM supply chain risks for the net zero transition. We have identified potential actions to address the risks, weaknesses and threats identified in Figure 1. These are summarised in Table 2.

Risk, weakness or threat	Examples of opportunities for Scottish action
Increasing global-level demand for CRMs	• Explore extension of life of net zero technologies • Explore material substitution opportunities
Geographical concentration of CRM supply, and link to geopolitical tensions	• Seek to influence United Kingdom (UK) membership of strategic global CRM partnerships • Seek to influence UK trade-related policies
Lack of Scottish strategy on CRMs and regulatory uncertainty	• Identify niches of excellence for Scotland to contribute to implementation of UK Critical Minerals Strategy • Address Scottish regulatory barriers, e.g. waste regulation, permitting and licensing
Limited activity and lack of data on exploration for CRM deposits in Scotland	• Further explore extraction potential for CRMs in Scotland. • Draw on existing Scottish expertise and skills in mining, oil and gas, and R&D
SLO and ESG concerns	• Continue adherence to high ESG standards to increase acceptance for future CRM actions
Low/variable CRM recovery and recycling rates	• Explore development of Scottish recycling for CRMs, including aluminium, lithium, and neodymium
Limited recovery, recycling, reprocessing and remanufacturing infrastructure	• Leverage existing Scottish port infrastructure to establish hubs or clusters for efficient use, reuse, and recovery of CRMs for reprocessing • Consider prioritising actions related to midstream material (re)processing
Limited supply of secondary CRMs for recycling/processing	• Map presence of existing CRMs in Scotland • Explore Scottish stockpiling of components containing CRMS • Develop Scottish processing of end-of-life products
Lack of data on presence, traceability and quality of CRMs	• Push for ambitious international standards and support rollout of product passports
Technical skills gaps in CRM supply chain	• Build on, deploy or upskill existing Scottish skills capacity from engineering and geology, materials R&D and Science, Technology, Engineering and Maths (STEM) universities
Price volatility and low resale value for some secondary materials	• Explore options to develop Scottish markets via voluntary industry commitments or use of commercial procurement criteria
Lack of domestic investment in CRM circularity solutions	• Promote investment in Scottish R&D activities, recycling reprocessing and remanufacturing infrastructure • Leverage existing UK funds

Table 2: Summary of opportunities for Scottish action

Three priority themes emerged: developing recycling and reprocessing capability, improving data and traceability of materials, and strengthening Scotland's contribution to UK and international CRM policy.

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2 Abbreviations table

AEL	Alkaline electrolysers
BESS	Battery Energy Storage Systems
BGS	British Geological Survey
CBAM	Carbon Border Adjustment Mechanism
CE	Circular economy
CMIC	Critical Minerals Intelligence Centre
CRM(s)	Critical raw material(s)
c-Si	Crystalline silicon
DRC	Democratic Republic of the Congo
EoL	End of life
EU	European Union
ESG	Environmental, Social and Governance
EV(s)	Electric vehicle(s)
FES	Future Energy Scenarios
GW	Gigawatt
GWh	Gigawatt hour
kg	kilogrammes
kt	Kilotonnes
kW	Kilowatts
WE	Lithium-iron-phosphate
Li-Co	Lithium-cobalt
Mt	Million tonnes
MW	Megawatt
MWh	Megawatt hours
NESO	National Energy Systems Operator

NZTs	Net Zero Technologies
PEM	Proton exchange membrane electrolysers
PEMFC	PEM fuel cells
PiVs	Plug-in Vehicles
PV	Photovoltaic
R&D	Research and development
REEs	Rare earth element(s)
SHJ	Silicon heterojunction solar cells
SLO	Social Licence to Operate
SOEC	Solid oxide electrolyser cell
STEM	Science, Technology, Engineering and Maths
SWOT	Strengths, weaknesses, opportunities and threats
t	tonnes
UK	United Kingdom
USA	United States of America
WEEE	Waste electrical and electronic equipment

3 Introduction

3.1 Background and context

Critical raw materials (CRMs) are essential for technologies linked to the transition to low-carbon economies, including wind and solar power, hydrogen and batteries. Global demand for CRMs required for the energy transition alone is expected to increase by 3.5 times by 2030 (Green Alliance, 2024a) and supply chains face numerous challenges.

There is limited material availability, which is concentrated in few locations, alongside global competition for resources. CRM production has climate, environmental and social impacts. Implementation of circular approaches for recovering and reprocessing CRMs are lacking. All of this leads to supply vulnerabilities, price volatility, trade dependencies, and associated strategic risks for governments and industry.

Nevertheless, net zero offers significant opportunities for economic growth and job creation, including through circular economy (CE) approaches. For the purposes of this report, circular economy approaches include reuse, repair, remanufacturing, recycling, recovery and reprocessing of materials and components. Recovered and recycled materials are referred to collectively in some sections as 'secondary supply' or 'secondary materials'. In this report, these terms refer to materials obtained from products, infrastructure or waste streams rather than from primary extraction. There is therefore a pressing need for robust, coherent and evidence-based policy on CRMs in Scotland, including through CE policies.

Several pieces of legislation, policies and strategies provide the Scottish context for this research. These are summarised in Table 10-2 in Appendix A. Key elements related to CRMs and CE approaches include:

- The **United Kingdom (UK) Critical Minerals Strategy**, which sets a vision and some targets) for the UK to secure critical minerals for economic growth and the clean energy transition. It recognises the role of CE, UK strengths in research and development and innovation, midstream processing and recycling, and the need for skills development, access to finance and investment. It also specifically notes Aberdeen and Fort William as promising regional clusters.
- The **Scottish Green Industrial Strategy**, which aims to build supply chain resilience, including through CE approaches to secure CRMs for the energy transition. It notes recycling/remanufacturing of wind economy facilities as a particular opportunity.
- The **Scottish Draft Energy Strategy and Just Transition Plan**, which notes a commitment to adopting CE approaches to sourcing materials, including recycling and refurbishment of wind turbines and electric vehicle battery recycling.
- The **Scottish National Adaptation Plan 2024-2029**, which notes the need to explore how recycling and remanufacturing can build supply chain resilience regarding CRMs for the energy transition.
- The **Circular Economy Strategy for Scotland**, which aims to make the Scottish economy more resilient to disruptions in global supply of materials, including CRMs. It includes a priority to maximise the role of CE for CRMs in Scotland, and notes energy infrastructure and transport as priority sectors of relevance. It also points to key policy levers available to take action, including: business support, behaviour and systems change, place-based

approaches, procurement, due diligence, skills and education, data improvements, and greater policy alignment.

Several UK and Scottish strategies recognise the importance of critical raw materials and circular economy approaches for the net zero transition. However, while a number of relevant strategies exist, Scotland does not yet have a dedicated strategic approach to critical raw materials. This creates challenges for policy coordination, prioritisation and long-term planning across the CRM supply chain.

3.2 Report aims and structure

The aim of this research is to increase understanding of CRM supply chain needs and risks in Scotland for renewable and net zero technologies (NZTs), and to explore the role of CE in mitigating these needs and risks. We address the following questions:

1. What is the current and projected CRM demand associated with Scotland's renewable and NZTs?
2. What are the most significant risks to these CRM supply chains over the medium-term time horizon (2025-2040) relevant to Scotland's renewables and net zero sectors? At what stages of renewable deployment do these risks lie?
3. What are the key economic strengths, weaknesses, opportunities and threats associated with CRMs, especially in the context of a CE for Scotland?
4. How can the Scottish Government and public sector bodies support CE activity and other measures that strengthen the resilience of CRM supply chain?

4 Methodology

This research adopted a mixed methods approach, including evidence review, stakeholder engagement and modelling. More detail is provided in Appendix B, and Appendix C with regards to our modelling.

4.1 Selection of focus CRMs

We selected the CRMs to focus on for this project from the United Kingdom (UK) 2024 Criticality Assessment's list of 34 CRMs (Mudd et al, 2024), plus copper. Key considerations included:

- The relevance of each CRM to a list of NZTs provided by the Steering Group (See Appendix B)
- The comparative importance of NZTs in Scotland, cross-checked with the National Energy Systems Operator Future Energy Scenarios. These led to a priority list of NZTs: on/offshore wind, hydrogen/fuel cells, batteries, the grid and solar/Photovoltaics
- The UK criticality score for each CRM
- The presence of the CRMs on other countries' criticality lists (the European Union, United States of America, Canada and Australia)

Based on this, we selected ten focus CRMs: aluminium, cobalt, lithium, copper, iron, manganese, nickel, niobium, rare earth elements (REEs) and silicon. This list captures some of the most critical battery metals (cobalt, nickel, lithium), crucial materials for motors and wind turbines (REEs) and for solar, grid infrastructure, and emerging hydrogen technologies (silicon, aluminium, iron, manganese, niobium), and copper, which will be vital for wider electrification.

Ten CRMs were selected for review, with quantitative modelling undertaken for seven where sufficient data were available. The modelled CRMs were cobalt, copper, lithium, manganese, nickel, REEs and silicon.

4.2 Review of literature and stakeholder engagement

We identified eight key pieces of Scottish and UK legislation and policy, together with around 70 pieces of potentially useful academic and grey literature from over 30 different organisations and authors.

The stakeholder engagement phase comprised an online survey and a series of semi-structured online interviews. The survey contained sections related to specific CRMs, technologies and supply chain risks. We focused on addressing knowledge gaps from the literature review. We received 17 responses from a mix of private sector companies, public and private research institutions, industry associations, civil society organisations, and academia. An explanation of how we cite the survey responses throughout the report can be found in Appendix B.

We also carried out nine semi-structured online interviews. Interviewees were chosen to achieve a balance between Scottish, UK and international expertise, different backgrounds (academia, business/industry, public sector and non-governmental organisations) and areas of knowledge.

4.3 Modelling of CRM supply and demand

We modelled future predicted supply and demand of seven CRMs in NZTs at three geographical levels: in Scotland, the rest of the UK, and the rest of the world. The aim was to gain insights into future supply and demand threats and opportunities. The CRMs included in our modelling are cobalt, copper, lithium, manganese, nickel, REEs and silicon. Datasets used at all three geographical levels are the annual uptake rates for NZTs, quantities of CRMs used in NZTs, and average lifetime of NZTs.

We compiled and analysed available global level data on annual primary and secondary production of CRMs, and demand for CRMs in non-NZT applications. Our findings include projections for annual CRM demand per NZT at the three geographical levels, annual net CRM availability for NZTs only for Scotland and more broadly, and annual NZT end-of-life quantities for Scotland and the rest of the UK. The full methodology, data sources and set of assumptions for our modelling are provided in Appendix C.

4.4 Limitations

Our research faced some limitations. These are noted briefly here, and discussed in more detail in Appendix B and Appendix C.

We focused on only 10 CRMs (seven for our modelling exercise), and a subset of NZTs. The report should therefore not be seen as providing a full picture regarding all 34 UK CRMs plus copper, nor being across all NZTs.

The modelling also assumes that Scottish and UK policy ambitions for deployment of net zero technologies are achieved. Actual deployment rates may differ due to changing policy priorities, market conditions, investment decisions or implementation constraints. Results should therefore be interpreted as indicative scenarios rather than forecasts of what will necessarily occur.

We also found limited Scotland-specific data sets, meaning that in some cases we rely on very limited Scottish data sets, or UK-wide or global data. This is specified where appropriate in the report.

Given the relatively low response rate to our survey, and limited set of interviews, the full range and nuance of stakeholder opinion may not be reflected.

Our modelling exercise also faced some key uncertainties. These include difficulties in identifying the future speed and volume of NZT uptake, the quantity of CRMs in NZTs and how this may change over time (e.g. with new technological developments), and the availability of primary CRMs. See Appendix C for a full discussion of modelling limitations.

5 Current and projected CRM needs for Scotland

The expansion of renewable and net zero energy technologies will result in rapidly increasing demand for the associated CRMs (Jolly, 2024). This chapter sets out the predicted future roll-out of NZTs in Scotland, and the associated CRM requirements. Additional detail, where appropriate, is included in Appendix D.

5.1 Net zero technology projections

5.1.1 Onshore wind

An additional 10 Gigawatts (GW)[1] of Scottish onshore wind capacity will be installed by 2030 (Scottish Government, 2023), with a further 20 GW by 2050 (Zero Waste Scotland, 2023b). A steep growth in annual onshore wind installed capacity is necessary for Scotland to meet its 2030 ambitions (see Figure 2). In Q2 2025, onshore wind represented 59% of Scotland's cumulative installed renewable electricity generation capacity, at 10.4 GW (Department for Energy Security and Net Zero, 2025a).

5.1.2 Offshore wind

Operational offshore wind capacity is set to increase from 1.9 GW in June 2022 to between 8 and 11 GW of installed capacity by 2030 (Scottish Government, 2023). A Scottish Government consultation that closed in August 2025 includes proposals to increase capacity to 40 GW by 2040 (Scottish Government, 2025b). In Q2 2025, offshore wind – both seabed and floating – accounted for 24% of Scottish cumulative installed renewable electricity generation capacity, at 4.3 GW (Department for Energy Security and Net Zero, 2025a).

[1] These figures have been updated from those stated in the referenced reports to account for capacity increases since their publication.

5.1.3 Solar photovoltaic (PV)

The Scottish Government announced in 2023 an ambition for solar deployment of 4-6 GW by 2030 (Martin, 2023). As of Q2 2025, Solar PV represented 4% of Scotland's cumulative installed renewable electricity generation capacity, at 764 Megawatts (MW) (Department for Energy Security and Net Zero, 2025a).

In Q2 2025, Scotland's total electricity capacity from wind and solar was 15.5 GW. The additional wind and solar capacity would increase this to around 35 GW in 2030, and 85 GW in 2050. Figure 2 shows projected new annual capacity installations, for on-shore and off-shore wind, solar, and the associated battery energy storage systems (BESS).

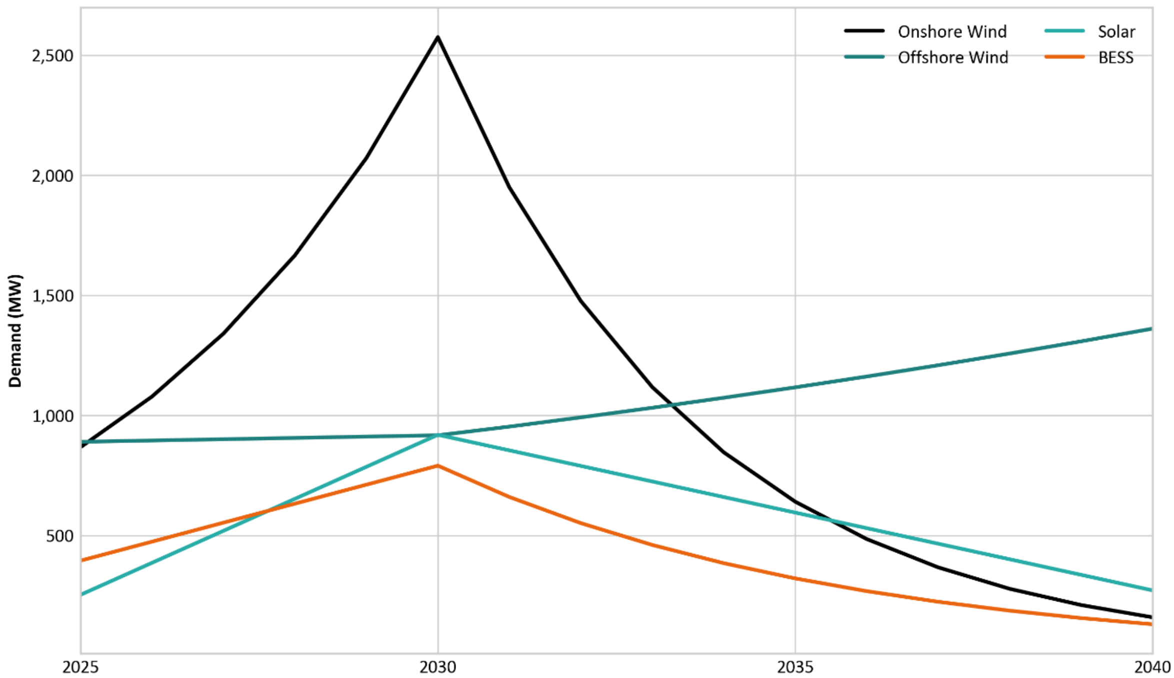

Figure 2 Projected wind, solar and battery storage capacity additions in Scotland, 2025-2040. Source: Modelled data

5.1.4 Electricity Grid

A significant increase to grid transmission and distribution infrastructure will be required to enable distribution of the increased electricity supply (Jackson et al., 2024). Scotland's more remote regions are becoming increasingly important for energy production as wind power capacity grows, necessitating upgrades to grid infrastructure in these regions. Additionally, the Scottish grid may need to be upgraded to cope with additional connections of electric vehicles (EVs), heat pumps and low-carbon energy generation.

To meet the grid requirements for the roll-out of renewable energy and other planned upgrades, the United Kingdom (UK) Critical Materials Intelligence Centre estimates the UK will need up to 1.6 million tonnes (Mt) of copper, and 300 kilotonnes (kt) of aluminium between 2023 and 2050 (Jackson et al., 2024). As over 90% of new onshore and 75% of new offshore wind installations in the UK from 2025-2030 are forecast to be in Scotland, this adds considerably to Scotland's total forecasted copper and aluminium needs (see Section 5.2 for details).

5.1.5 Electric vehicle batteries

Under the UK's Zero Emissions Vehicle Mandate, which applies to Scotland, the sale of new petrol and diesel cars will be phased out by 2030, and hybrid cars and vans with internal combustion engines by 2035 (Department for Transport et al., 2025). Additionally, the Scottish Government's Climate Change Plan contains a target to phase out all petrol and diesel vehicles – including heavy-goods vehicles – by 2050 (Scottish Government, 2025a).

In Q2 2025, there were 141,967 EVs in Scotland. According to Zero Waste Scotland, the net zero transition will require the number of EVs in Scotland to reach 579,000 by 2030 and 3.4 million by 2050 (Zero Waste Scotland, 2023b). Figure 3 shows projected annual EV sales required to meet the 2030 and 2050 net-zero requirements.

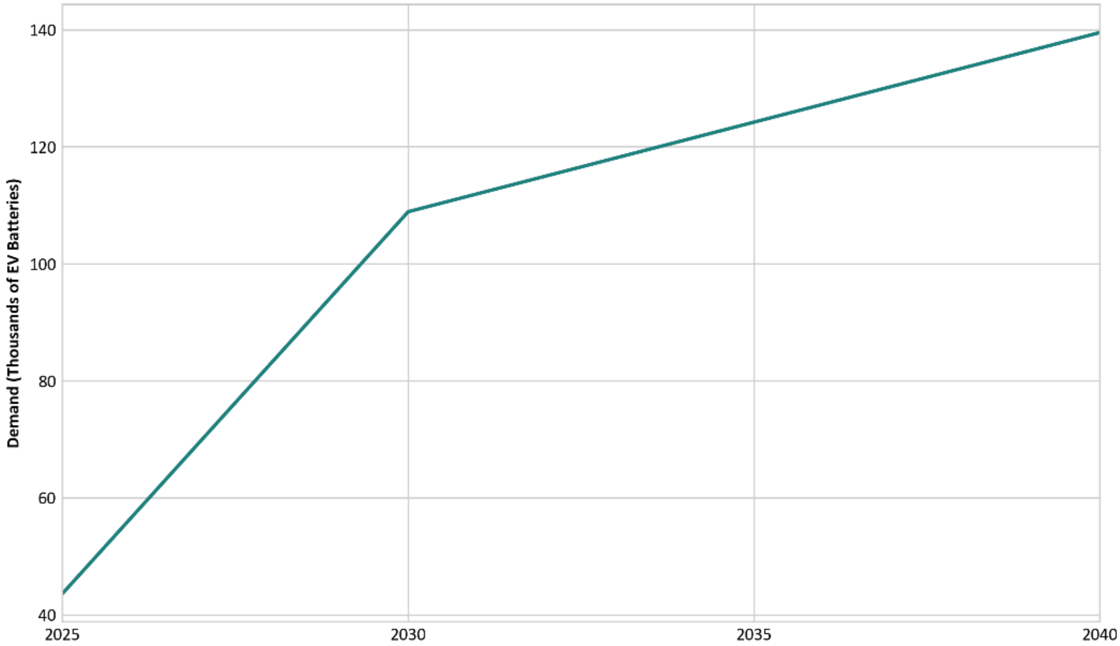

Figure 3 Projected electric vehicles sales in Scotland, 2025-2040. Source: Modelled data

Given the limited EV battery manufacturing that takes place in Scotland, the majority of demand for CRMs for EVs is in the form of finished products, rather than for domestic manufacturing.

5.1.6 Hydrogen and fuel cells

The Draft Energy Strategy and Just Transition Plan outlines the Scottish Government's plan to scale up low-carbon hydrogen production to 5 GW by 2030, and 25 GW by 2045 (Scottish Government, 2023). 57% of the UK's currently proposed green hydrogen capacity is in Northern Scotland (National Energy System Operator, 2025). Figure 4 shows projected annual hydrogen installations required to meet the 2030 and 2045 targets.

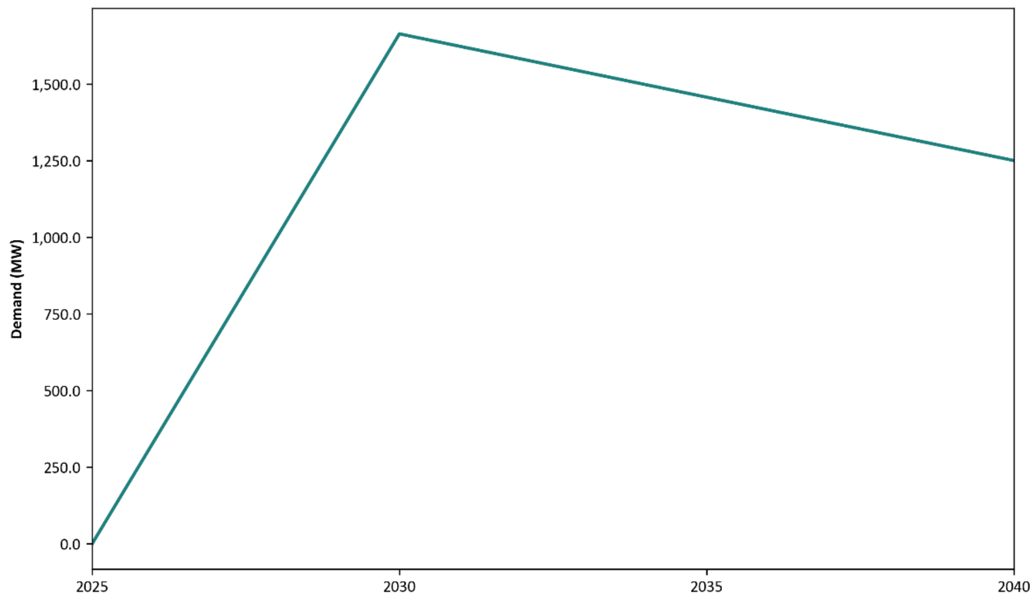

Figure 4: Projected hydrogen production in Scotland, 2025-2040. Source: Modelled data

Similarly to EV batteries, hydrogen fuel cell production in Scotland is limited, and thus reliance on CRMs for their increased usage will also be predominantly in the form of finished products rather than raw materials.

5.2 CRM demand in net zero technologies

Information on projected demand for each CRM is detailed below. Appendix D details the CRMs used in each of the NZTs included in this research. We note that one Zero Waste Scotland report mapping material demand for energy infrastructure (2023b) provides much of the data, since it contained the most complete Scottish data in our reviewed literature. Graphs are included for the CRMs included in our modelling exercise.

5.2.1 Aluminium

Aluminium is widely used in renewable and NZTs, including wind, hydrogen, solar, batteries and the grid. Given the necessary growth of these technologies in the pursuit of net zero, an increase in aluminium supply will be required to meet demand from the renewable energy sector through to 2050.

Zero Waste Scotland estimated that up to 1,100 kt of aluminium will be required for installation and life extension of renewable energy technologies between 2023 and 2050 (Zero Waste Scotland, 2023b). However, this estimate is caveated by a lack of confidence in related capacity forecasts, including those for hydropower and hydrogen. 300 kt of aluminium will be needed for grid upgrades across the UK from 2023-2050 (Jackson et al., 2024), with at least half of this required by 2030.

Zero Waste Scotland analysis has concluded that only a small increase in the volume of total UK aluminium imports would be required to meet demand for NZTs (Zero Waste Scotland, 2023b).

5.2.2 Cobalt

Cobalt and related oxides are predominantly used in the production of batteries. Given projected EV sales and battery storage installations, our modelling shows that annual cobalt requirements for these two technologies in Scotland is projected to approach 700 tonnes (t) in 2030, even as cobalt content in EV batteries is projected to decline.

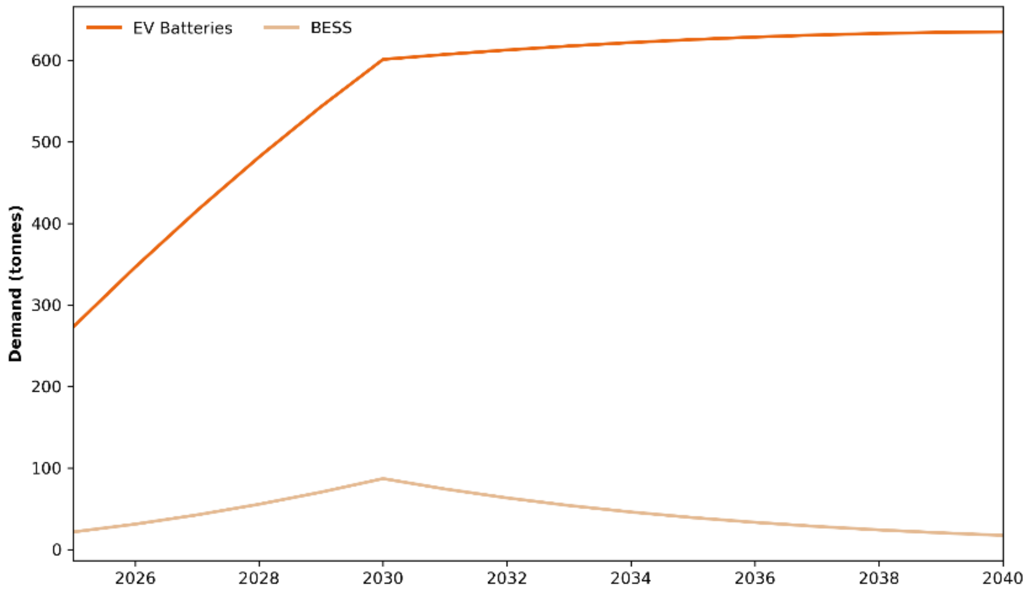

Figure 5: Projected Cobalt Demand from NZTs in Scotland, 2025-2040. Source: Modelled data

Projected UK demand for cobalt varies widely based on future battery chemistry scenarios but could reach 11.2 kt by 2030 (Task & Finish Group, 2023). Another study places the cobalt demand for batteries across the UK at 11 kt by 2030 (Lusty et al., 2022).

5.2.3 Copper

Copper is used widely in renewable technologies, including wind power, solar power, batteries and in the grid. It is also widely used in heat pumps (Zero Waste Scotland, 2023b).

Our modelling shows that copper demand in NZTs is projected to approach 38 kt in 2030, driven primarily by grid and wind power needs. One MW of offshore wind requires nearly 3 times the copper of onshore wind, meaning copper needs in Scotland for the two technologies are nearly identical in 2030, despite new onshore wind capacity in 2030 being over double that of offshore (2,575 MW vs 917 MW, respectively).

Zero Waste Scotland research estimates that cumulatively 1,300 kt of copper will be needed in Scotland to meet demand for installation and life extension of renewable technologies through to 2050. This means that by 2050 Scotland would annually require double the copper that was imported into the UK in 2023 (Zero Waste Scotland, 2023b).

Cumulative UK-wide demand for copper to 2050 is set to reach 2.4 million tonnes (Mt), equal to 30-fold growth from 2024 levels (Petavratzi et al., 2024c). This is driven by demand in growth for heat pumps (1.34 Mt), traction motors for EVs (626 kt) and wind turbines (402 kt) (Lusty et al., 2022).

In the short term, substitution of copper with other materials will be difficult, meaning increased demand cannot be alleviated through alternative material selection (Energy Transitions Commission, 2023e).

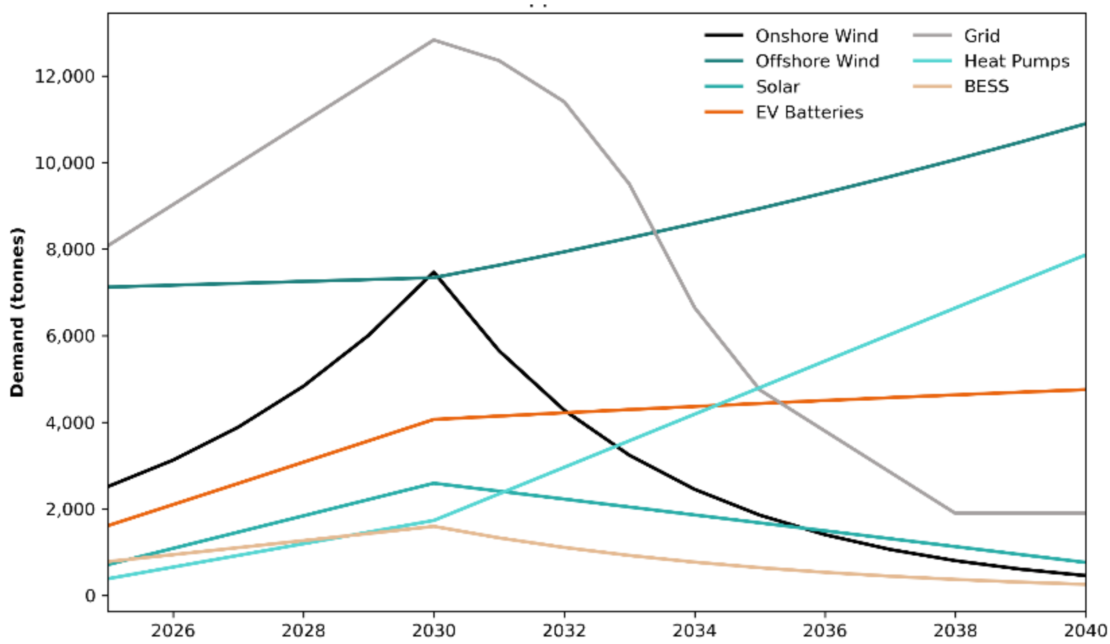

Figure 6 Projected Copper Demand from NZTs in Scotland, 2025-2040. Source: Modelled data

5.2.4 Iron

Iron and its alloy steel are also used across wind power, solar power, hydrogen, batteries and grid infrastructure. Research estimates that 3 Mt of iron will be required in Scotland to meet renewable energy technology demand through to 2050 (Zero Waste Scotland, 2023b). An 11% increase of iron and steel is set to be required by Scotland by 2050, based on UK import figures from 2023 (Zero Waste Scotland, 2023b).

5.2.5 Lithium

Lithium is predominantly used in EV batteries and battery storage systems. Average lithium content in EV batteries is projected to increase over time, so more will be needed to achieve Scottish EV targets and the battery storage required for solar and wind electricity. Our modelling shows that in 2030, Scotland is projected to require 1,200 t of lithium in the form of new EV batteries and battery storage.

By 2030 Scotland may require as much as 150% more lithium-cobalt (Li-Co) – the oxide used in EV batteries – than was imported into the UK as a whole in 2020, owing to growth in EV usage (Zero Waste Scotland, 2023b).

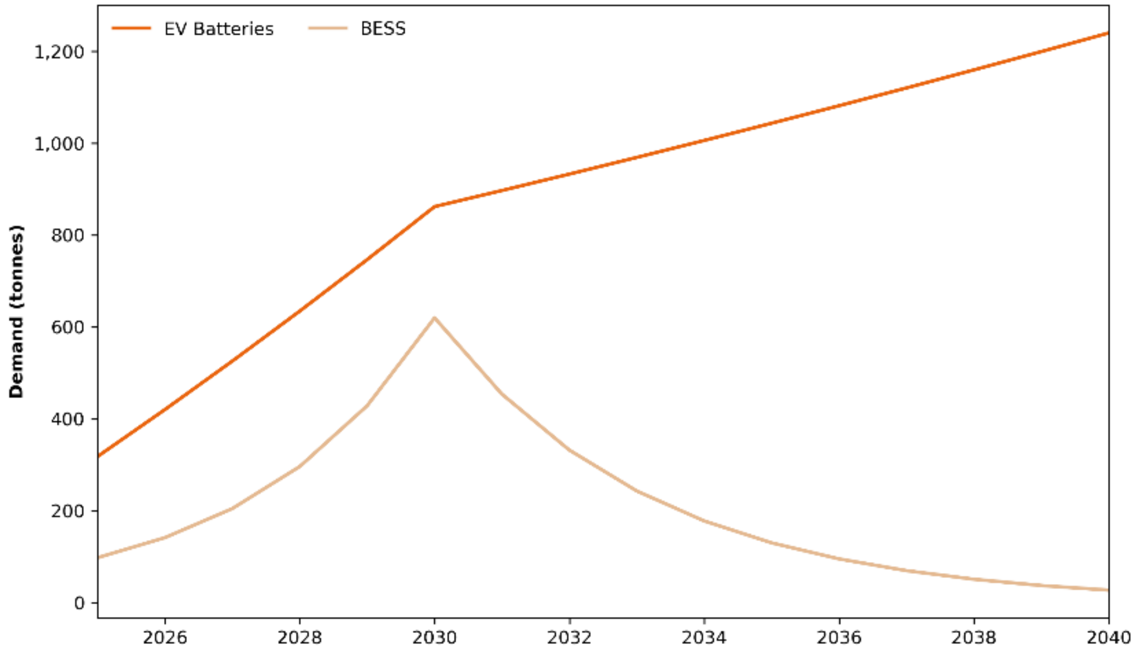

Figure 7 Projected Lithium Demand from NZTs in Scotland, 2025-2040. Source: Modelled data

5.2.6 Manganese

Modelling shows that Scotland is projected to require over 3,400 t of manganese in 2030 to meet its NZT ambitions, with manganese being required in the production of wind turbines and associated battery storage. It is also required in the production of battery cathodes in EVs.

Annual UK demand for manganese from batteries is forecast to reach 10 kt by 2030 (Lusty et al., 2022). Projected cumulative demand for manganese from EVs in the UK between 2018 and 2040 has been estimated at 493,632 t (Jolly, 2024).

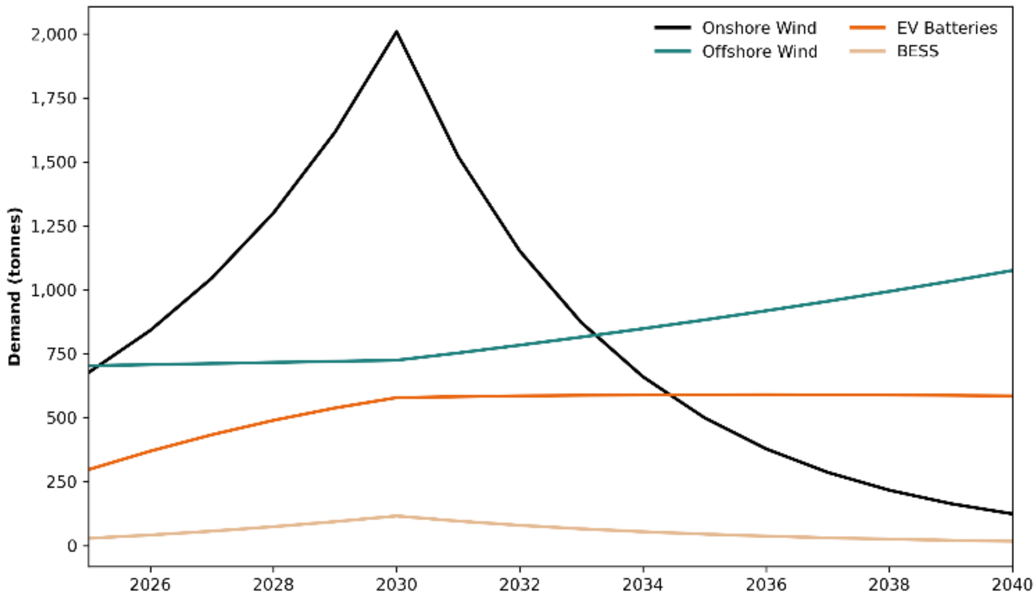

Figure 8 Projected Manganese Demand from NZTs in Scotland, 2025-2040. Source: Modelled data

5.2.7 Nickel

Nickel is used across wind power, solar power, hydrogen and batteries. Nonetheless, its demand is predominantly driven by EV sales, given its use in battery cathodes (Petavratzi et al., 2024c).

Modelling shows that in Scotland, the demand for nickel in NZTs in 2030 is projected to be over 5,000 t, of which 70% is due to EV sales. The UK's annual demand for nickel for batteries production is forecast to reach 90 kt by 2030 (Lusty et al., 2022).

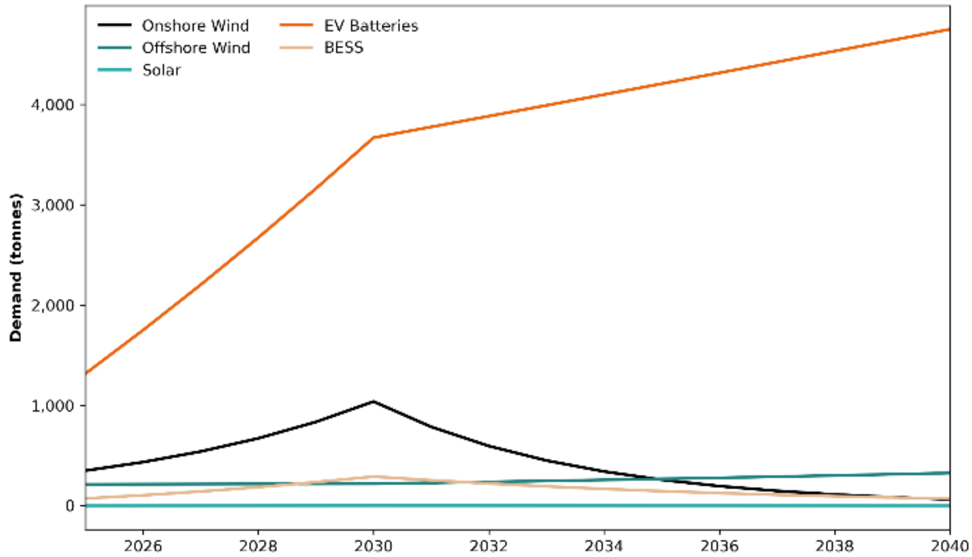

Figure 9 Projected Nickel Demand from NZTs in Scotland, 2025-2040. Source: Modelled data

5.2.8 Niobium

Niobium is widely used within renewable energy technologies, for example within high grade steel, which is used within wind turbines, towers and pipelines (Oakdene Hollins, 2014). Niobium also has the potential for increasing usage in battery anode materials to improve battery stability and fast charging (Kim, et al., 2021).

The reviewed literature did not contain any concrete figures on current Scottish or UK niobium demand, supply or projections relevant to NZTs. One industry source forecasts that global niobium demand will rise from 79.68 kt in 2025 to 103.18 kt by 2031, driven in part by hydrogen pipeline expansion and niobium-doped Li-ion batteries (Mordor Intelligence, 2026).

5.2.9 Rare Earth Elements (REEs)

REEs such as neodymium and dysprosium are used to produce permanent magnets and generators for use in wind turbines, as well as in electric motors (Task & Finish Group, 2023). They are also used within fuel cell catalysts for the generation of hydrogen power. REE demand worldwide is expected to increase three- to seven-fold by 2040 (Arup, 2024).

Cumulative UK demand by 2050 for REEs has been estimated at 57,300 t, the majority of which is set to be driven by growth in the number of wind turbines (Petavratzi et al., 2024c). Installing 75 GW of offshore wind energy in the UK would require 93 kt of permanent magnets – since these magnets are typically 28.5% neodymium and 4.4% dysprosium, it is clear that growth of the UK wind sector is heavily dependent on these materials (Task & Finish Group, 2023).

In Scotland, REE demand in NZTs is driven primarily by use in magnets in offshore wind turbines. Two-thirds of the 300 t of REEs projected to be required in 2030 for NZTs are driven by new offshore wind installations. Over 300% more neodymium per year is forecast to be required for Scotland to meet its targets for onshore and offshore wind by 2050 (Zero Waste Scotland, 2023b).

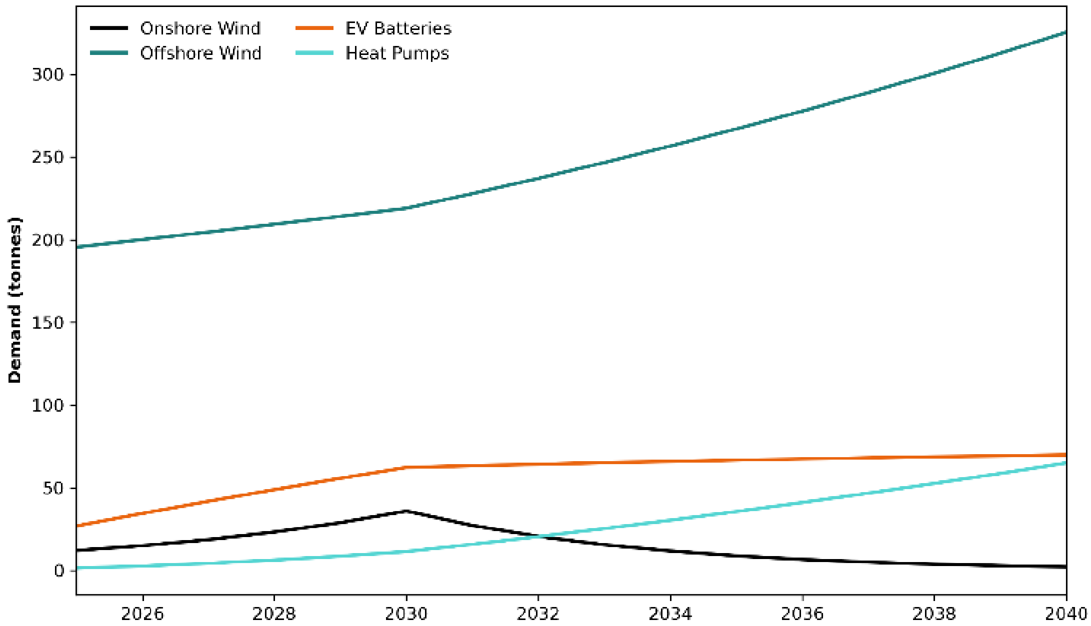

Figure 10 Projected REE Demand from NZTs in Scotland, 2025-2040. Source: Modelled data

5.2.10 Silicon

Silicon has a variety of uses in renewable energy technologies, including battery anode doping, in semiconductors, and in solar cells (Task & Finish Group, 2023).

Modelling shows over 2,500 t of silicon are projected to be required in 2030 for Scotland to meet its net zero ambitions. This is driven predominantly by use in solar electricity generation.

Cumulative demand for silicon in the UK from NZTs is forecast to reach 283.6 kt by 2050, fuelled by growth in PV cells (Petavratzi et al., 2024c). UK demand for silicon from solar PV alone is estimated at 190 kt by 2050 (Petavratzi et al, 2024b).

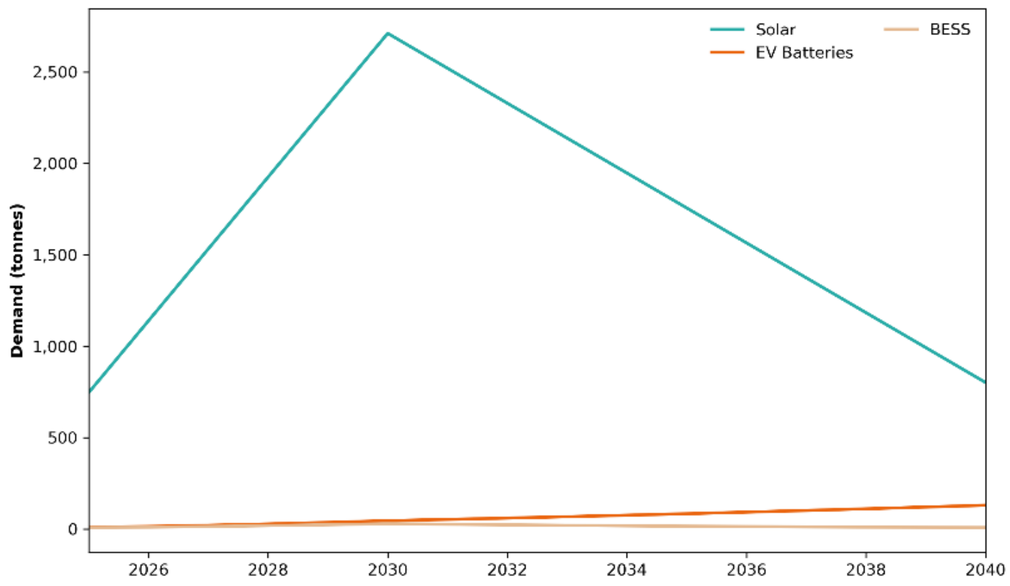

Figure 11: Projected Silicon Demand from NZTs in Scotland, 2025-2040. Source: Modelled data

6. Global CRM supply for Scotland’s net zero technologies

The modelling in this section draws on the global supply chain analyses detailed in Appendix E. See Appendix C for modelling methods, data and assumptions.

For the purposes of this analysis, availability reflects modelled estimates of future global supply relative to projected demand under the assumptions described in Appendices C and E. Availability should therefore be interpreted as an indicator of potential supply pressure rather than a prediction of future shortages.

Scotland’s ambitious 2030 target for onshore wind means that near-term availability of CRMs is of critical importance. As shown in Figure 6-9, net global copper availability may be a risk to Scotland achieving this target. In the longer term, net copper availability is predicted to decline from 2029 onwards. REE availability is also constrained from 2030, putting longer-term onshore wind projects at risk.

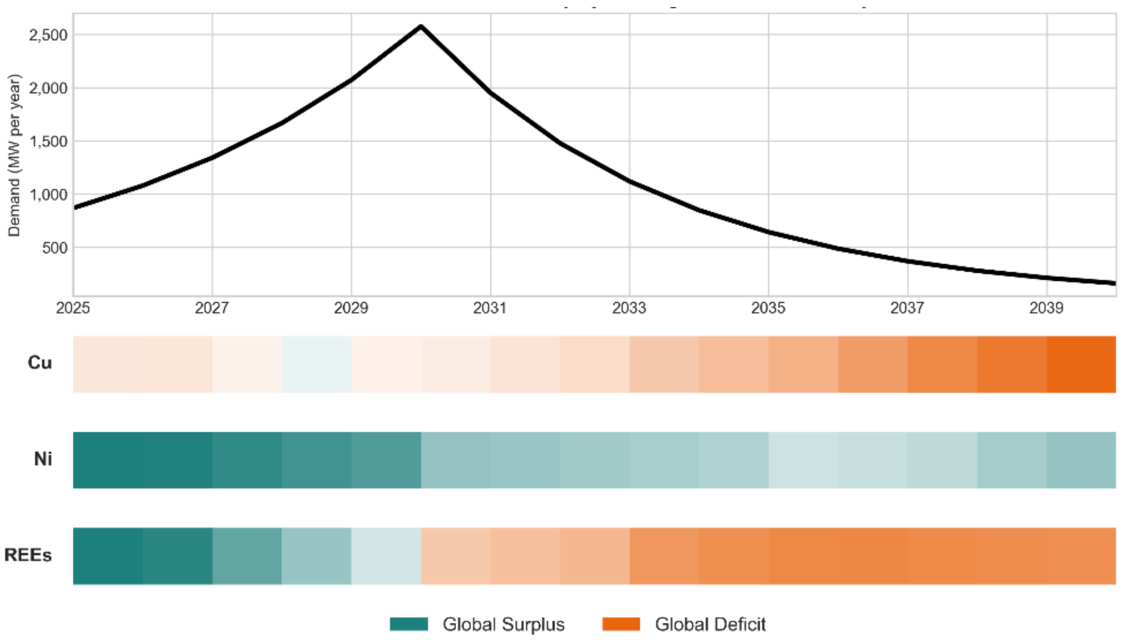

Figure 12: Scotland onshore wind projected annual installations and global availability of copper, nickel and REEs. Source: Modelled data

Scotland has large long-term **offshore wind** ambitions, making the long-term availability CRMs of key concern for offshore wind. In particular, the long-term global supply constraints of copper, nickel and REEs could threaten Scotland's 2040 offshore wind ambitions.

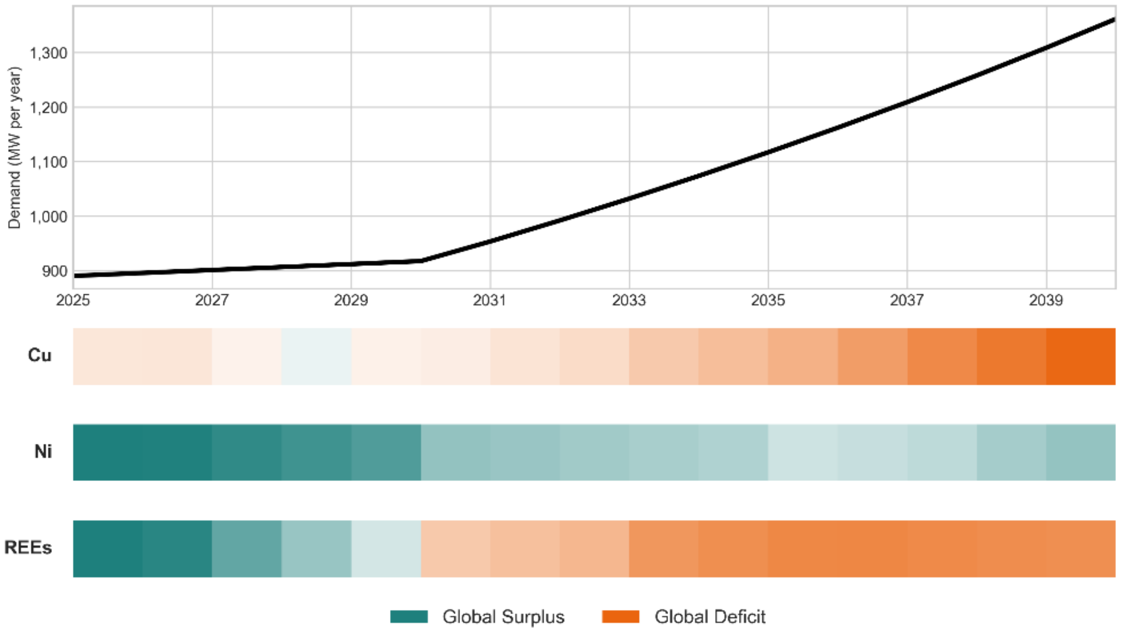

Figure 13: Scotland offshore wind projected annual installations and global availability of copper, nickel and REEs. Source: Modelled data

The near-term global availability of copper is a concern for Scotland to achieve its **solar** target of 4-6 Gigawatts (GW) installed capacity by 2030, as shown in Figure 6-11.

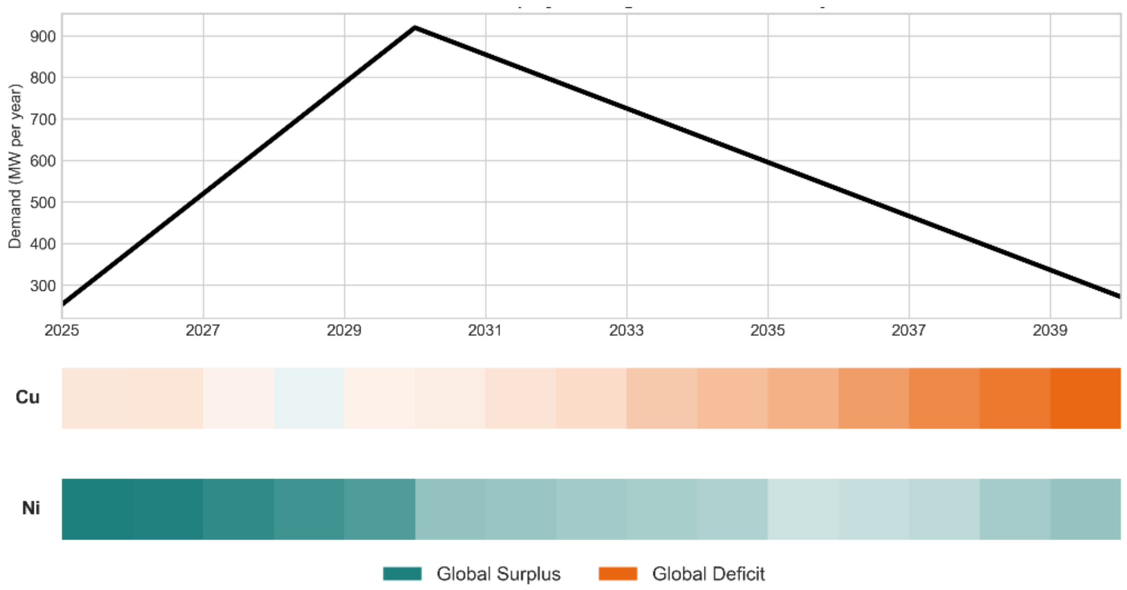

Figure 14 Scotland solar projected annual installations and global availability of copper and nickel. Source: Modelled data

Scotland's **battery storage** ambitions are potentially constrained by the short-term supply constraints of copper and lithium, and longer-term constraints on copper, lithium and nickel. As battery storage is required to optimise the functioning of wind and solar farms, constraints in battery storage CRMs pose a risk to Scotland achieving its renewable energy targets.

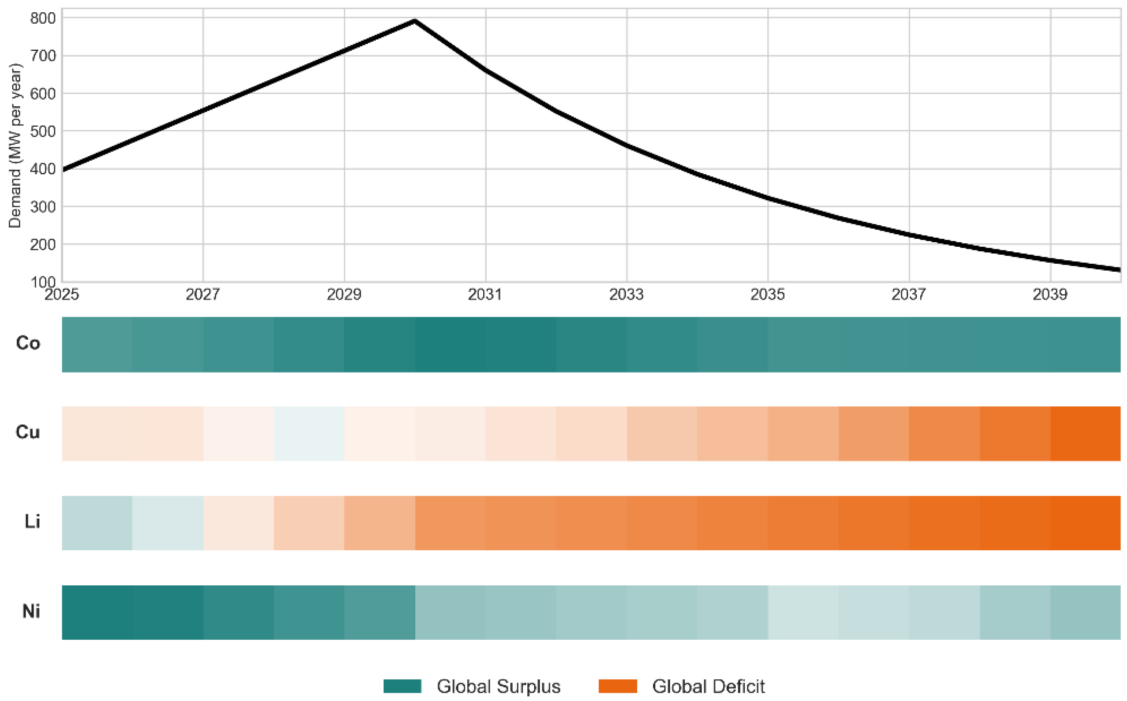

Figure 15 Scotland battery storage projected annual installations and global availability of cobalt, copper, lithium and nickel. Source: Modelled data

Achieving Scotland's **EV** ambitions involves a continuous annual increase in EV sales out to 2040. Copper and lithium supply constraints in the near term, and copper, lithium, nickel and REE constraints in the long term, pose risks to the achievement of EV rollout at the required speed and scale.

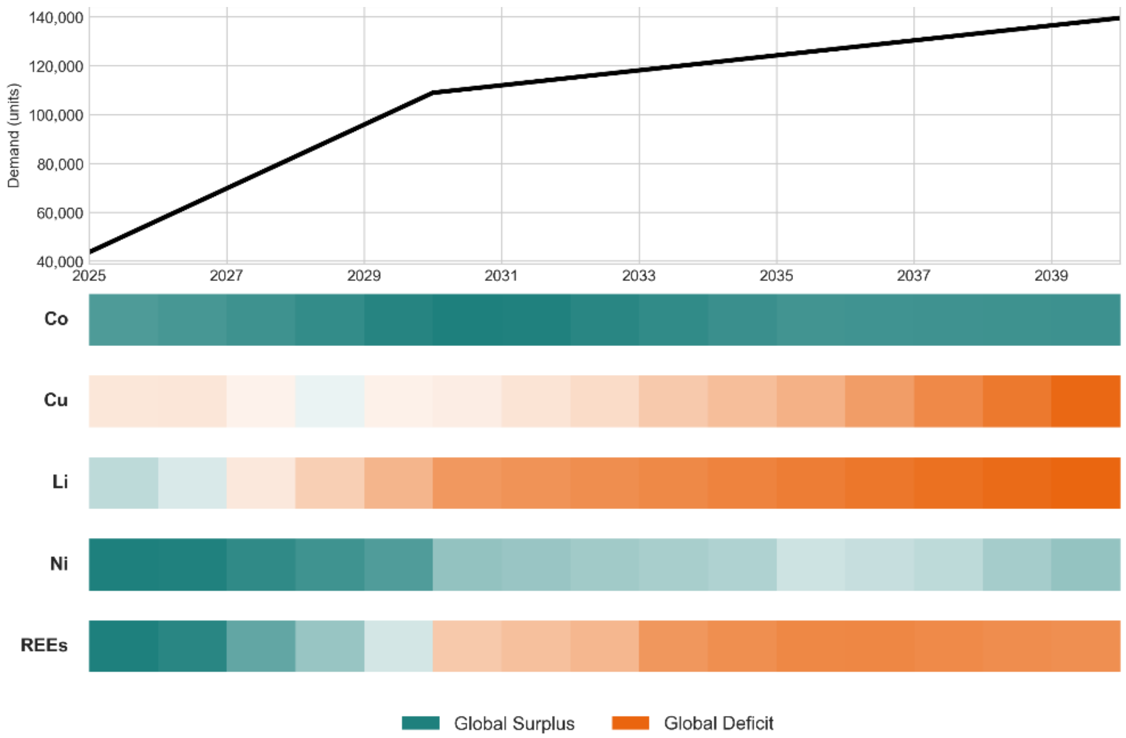

Figure 16 Scotland electric vehicles projected annual sales and global availability of cobalt, copper, lithium, nickel and REEs. Source: Modelled data

The rollout of **hydrogen** production is dependent on the global availability of nickel, and is increasingly at risk into the medium- and long-term as net nickel availability is predicted to decline.

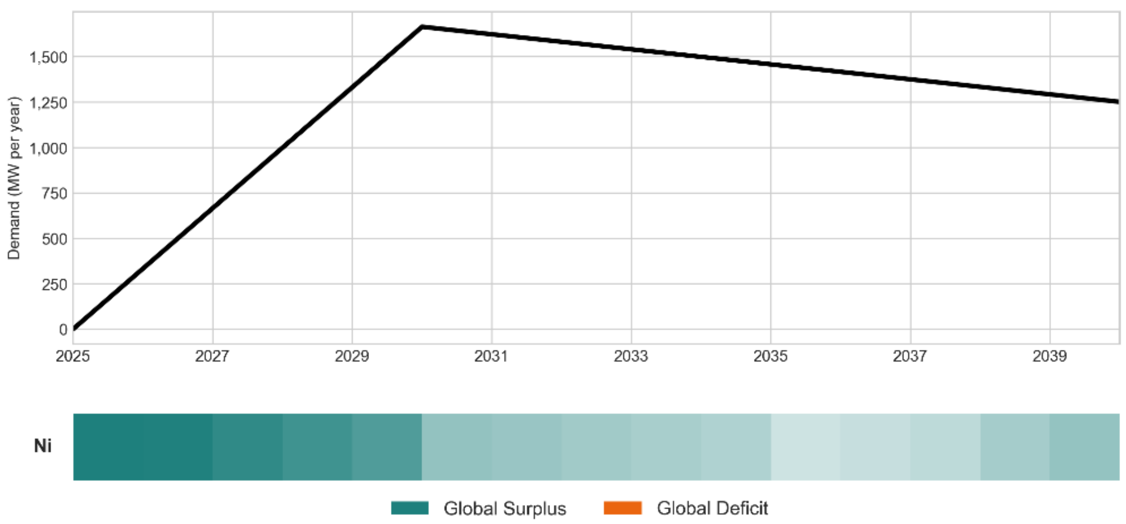

Figure 17 Scotland Hydrogen production projected annual installations and global availability of nickel. Source: Modelled data (see Appendix C)

Scotland’s long-term **heat pump** ambitions are at risk from the predicted lack of long-term availability of copper and REEs. The heat pump deployment assumptions used in this analysis are set out in Appendix C.

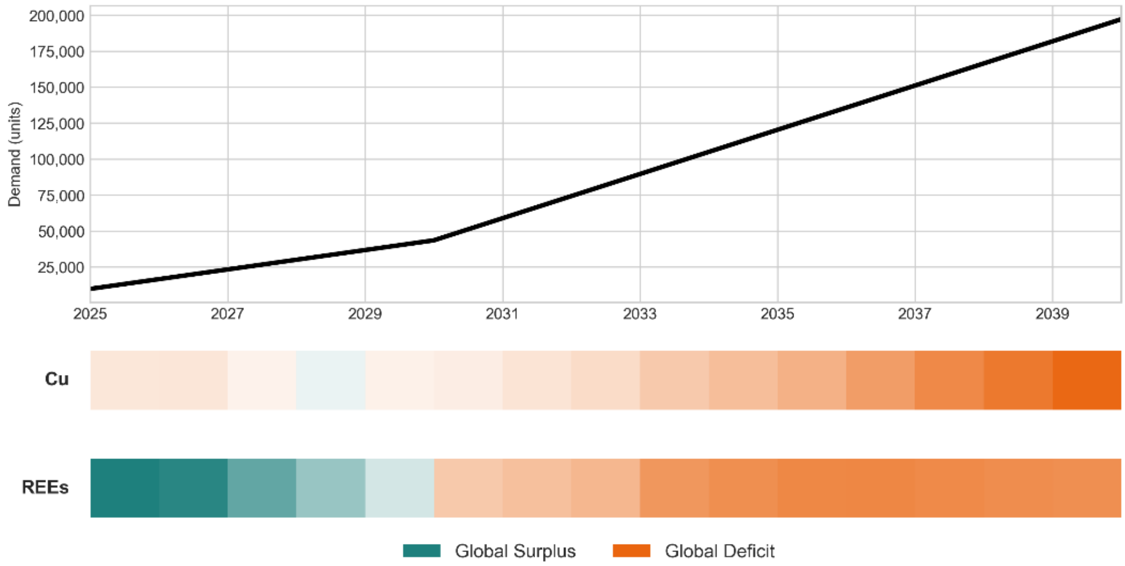

Figure 18 Scotland heat pump projected annual installed units and global availability of copper and REEs. Source: Modelled data

Overall, the modelling suggests that Scottish net zero deployment ambitions may be exposed to constraints in several global CRM supply chains. Potential vulnerabilities are evident for copper, lithium, nickel and rare earth elements, although the significance varies by technology and time period. Copper is of particular relevance, as potential supply constraints are identified across multiple technologies including wind, solar, battery storage, electric vehicles and heat pumps. These findings highlight the importance of understanding wider CRM supply chain risks, which are explored in the following chapter.

7 Significant CRM supply chain risks

As part of an island nation with limited resource deposits (Task & Finish Group, 2023), Scotland is highly vulnerable to any disruptions in the global CRM supply chain (Lusty et al., 2022). We have identified several key threats to CRM supply in the short- to- medium-term, which are discussed below. Throughout the chapter, we acknowledge where these threats are interconnected and may exacerbate the risk of another. We also note how they relate to deployment of NZTs. Where relevant, we discuss when issues are a significant concern only for particular CRMs.

7.1 Geographical concentration of supply

Supply of CRMs is geographically concentrated across multiple stages of the supply chain, which are addressed separately below. ‘Extraction’ refers to the mining and extraction of raw CRMs from deposits. ‘Processing and refining’ refers to any post-mining activity whereby value is added or materials are upgraded from their virgin state (Frazer-Nash

Consultancy, 2025). Finally, trade refers to the import and export of both raw and refined CRMs.

7.1.1 Extraction

As Figure 19 shows, extraction of CRMs is highly concentrated in a few countries globally, on which the United Kingdom (UK) and Scotland are dependent for imports (Petavratzi et al, 2024a; Zils et al, 2024a; Ross & Wright, 2025). The top three countries for each of our focus CRMs constitute over 50% of global extraction (Petavratzi et al, 2024a), exacerbating the risk of other threats such as geopolitical and economic tensions. Figure 20 shows the share of global CRM extraction by country.

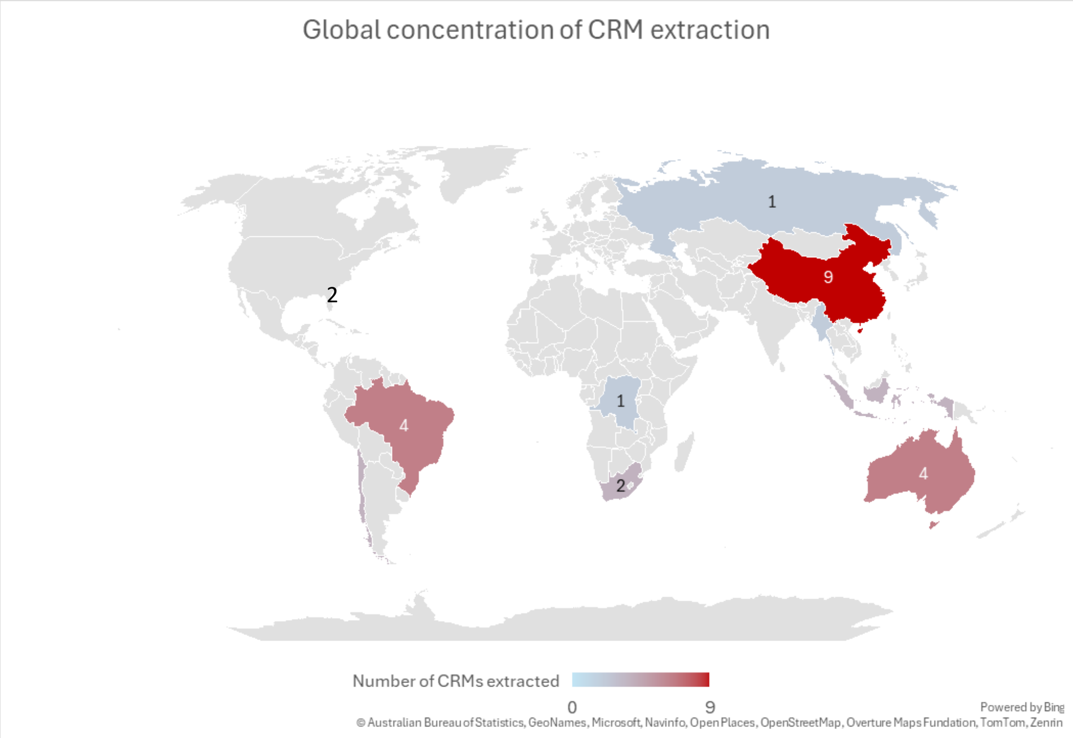

Figure 19 Map showing the global concentration of CRM extraction, including any country which is part of the dominant extractors for each CRM. Note this map does not show all CRM production by any one country, nor all producers for each CRM.

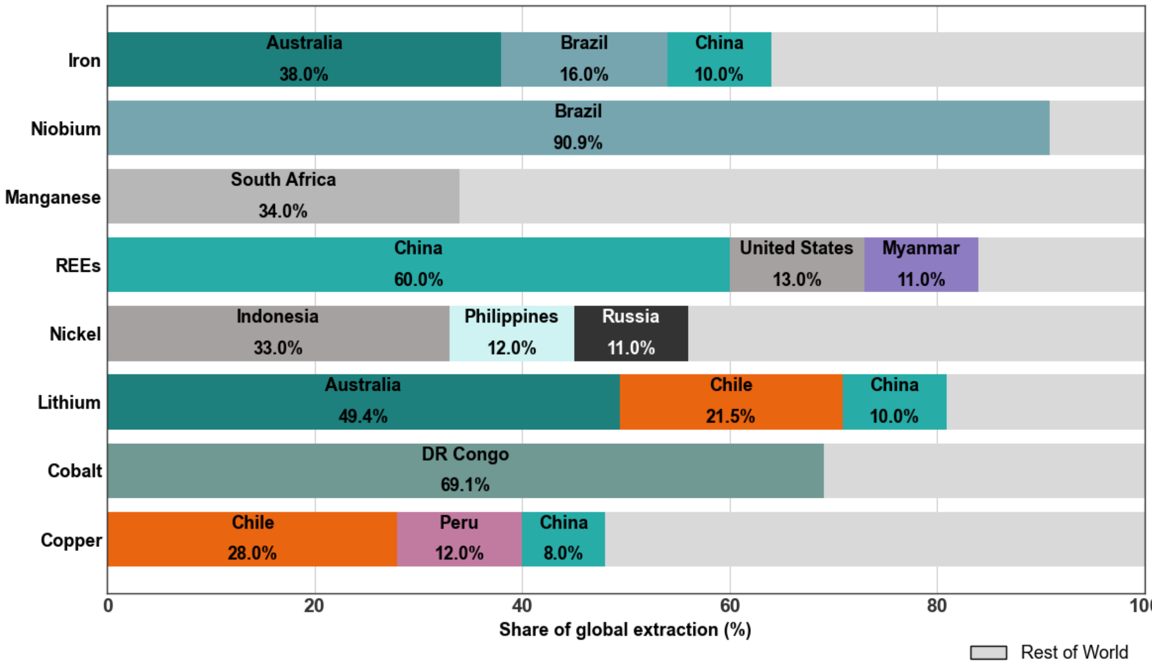

Figure 20 Share of global CRM extraction by country

Copper extraction is dominated by Chile (Arup, 2024) and other south American countries including Brazil (Bielowicz, 2025).

Although **cobalt** extraction remains highly concentrated, production is expanding in other countries, reducing reliance on a single dominant source. At the same time, China’s growing role within the cobalt supply chain is expected to reinforce its broader influence across global CRM markets (Energy Transitions Commission, 2023a; Ross & Wright, 2025).

Lithium extraction is similarly concentrated among a small number of countries, with extraction shares shifting over time between leading exporters, reflecting evolving supply dynamics within global markets (Petavratzi et al, 2024a).

Whilst **nickel** extraction is dominated by Indonesia (Arup, 2024) following rapid and large expansion in recent years (Energy Transitions Commission, 2023b), Russia and South Africa were also key exporters of nickel in 2025 (Bielowicz, 2025).

Extraction of aluminium and iron is dominated by a limited number of countries. Scotland relies significantly on imported steel, particularly from China, South Korea and several European countries (EUROFER, 2024).

Rare Earth Element (REE) extraction is particularly concentrated globally, with 90% of supply coming from three countries: China, Myanmar and Australia. An academic stakeholder highlighted that China’s dominance in REEs in particular leaves Scotland’s net zero transition vulnerable to potential geopolitical disruptions, due to a lack of strong alternative supply chains. This concern was also raised by other stakeholders, despite emerging REE projects in other countries including Norway, Finland, Greenland, Angola, and the US.

The geographical concentration of CRMs was a concern raised by interviewees across all stakeholder groups. China’s current dominance across extraction of all CRMs (Petavratzi et al, 2024a), and across full CRM supply chains, was specifically noted as a concern by five interviewees. China's approach to CRM supply is unpredictable. For example, its foreign trade policy for CRMs is still under review (Beijing Newsroom, 2026), and the example of the Chinese ban on plastic waste imports in 2017 highlights the significant global impact its policies can have (Sommer, 2024). China also banned exports of certain CRMs to the United States of America (USA) in response to trade tensions (Lv & Munroe, 2024), further illustrating potential risks for the UK and Scotland related to global uncertainty alongside supply chain concentration.

Research sector interviewees agreed that reliance on imports linked to supply chain vulnerabilities including geographical concentration, geopolitical tensions and environmental, social and governance (ESG) concerns is a particular risk for Scotland. A lack of current potential domestic mining opportunities was noted by research sector and academic stakeholders in interviews. However, it was still felt the UK Critical Minerals Strategy (UK Government, 2025) aim of 10% domestic production for selected minerals is achievable. Potential for domestic extraction is discussed further in 8.1.1.

7.1.2 Processing and refining

CRM processing and refining is also geographically concentrated (Mudd et al, 2024; Petavratzi et al, 2024a; Frazer-Nash Consultancy, 2025). For example, Figure 21 highlights China's dominance in mid-stream CRM processing. An academic interviewee noted that China dominates production and processing of both light and heavy REEs. Other important processing and refining countries for each CRM in the scope of this study are also shown in Figure 21.

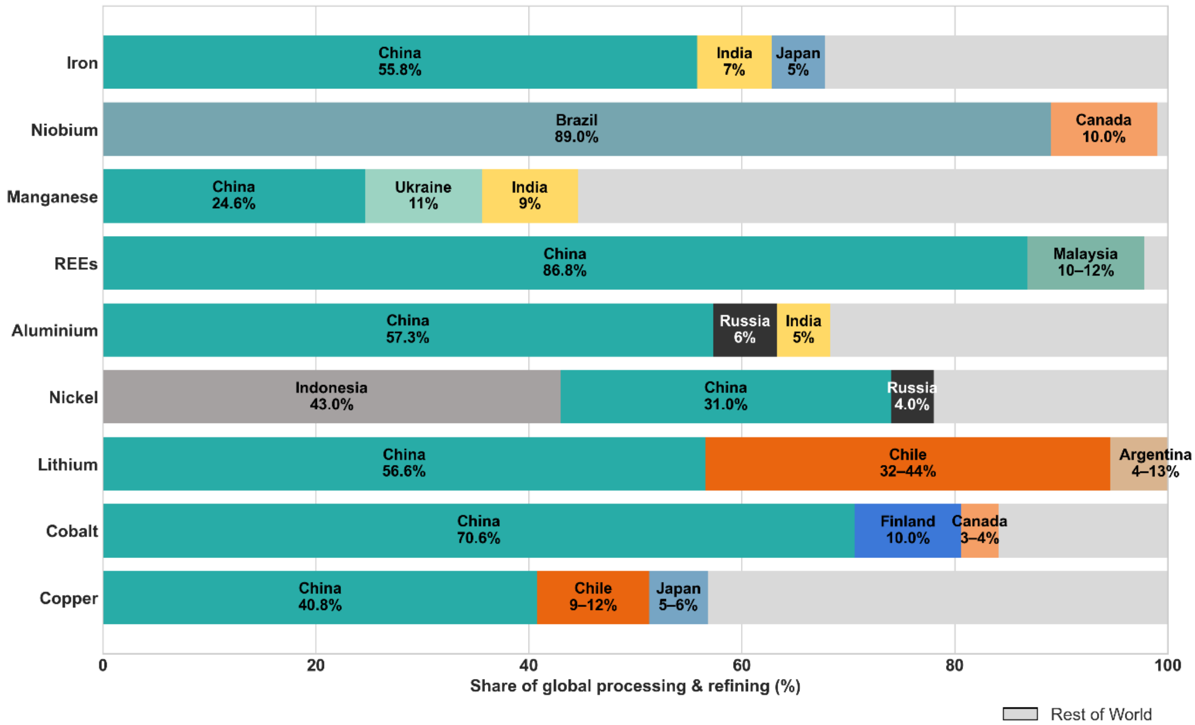

Figure 21 Share of global CRM processing and refining by country

Processing and refining were perceived to be more of a bottleneck than extraction by interviewees in the research sector. Two interviewees from academia and technical institutes noted that the UK has limited processing and refining operations and is therefore dependent on the global supply chain. However, a 2025 research report conducted for the Department for Business and Trade indicates otherwise. It states that the UK has a strong reputation for refining REEs, aluminium and nickel, and also has activity in refining copper, iron, and silicon (Frazer-Nash Consultancy, 2025). These activities do still rely on imports for their materials, and the report notes that capacity is not strong enough to influence global markets. Excluding secondary CRM recycling and recovery, the report lists five active UK refineries relevant to the CRMs covered by this report, and a further two relevant processing plants (Frazer-Nash Consultancy, 2025).

7.1.3 Trade

Trade in imports and exports of CRMs is also geographically concentrated, affecting supply security (Zils et al, 2024a). Table 3 details the main importing and exporting countries for selected CRMs, and the share of the market they hold in each case, illustrating the concentration in trade systems.

Table 3: Dominant importing and exporting countries for selected CRMs, globally

CRM	Main importing countries (trading / supply)	Import market share	Main exporting countries	Export market share	References
Cobalt [a]	China, Zambia and Morocco	> 95%	DRC, Thailand and Malaysia	> 95% (DRC accounting for 91%)	(Petavratzi et al, 2024a; Petavratzi et al., 2024c)
Nickel [a]	China, South Korea and Japan	> 90%	Philippines, Indonesia and Zimbabwe	> 90%	(Petavratzi et al, 2024a; Petavratzi et al., 2024c; Zils et al, 2024a)
Iron	*No information*	-	Australia, Brazil and South Africa	> 80%	(European Commission, n.d.)
Manganese [a]	China	> 75%	South Africa, Gabon	> 80%	(Petavratzi et al, 2024a)
Copper [a]	China, Japan, South Korea	> 70%	Peru, Chile, Australia	> 40%	(Petavratzi et al, 2024b)
Silicon [a] (refined, 99.99%)	China, Japan, Other Asia	> 60%	Germany, USA, South Korea	> 60%	(Petavratzi et al, 2024b)

[a] China made up over 50% in these cases (Petavratzi et al, 2024a; Petavratzi et al, 2024b).

In terms of suppliers, five companies are responsible for 75% of global lithium chemical production (Task & Finish Group, 2023). It is unclear whether the market is similarly dominated by few companies for other CRMs.

It should be noted that, typically, component and product manufacturing involving CRMs, such as wind turbine components and electrolysers, is less geographically concentrated (Zils et al, 2024a). Further exploration on this is an important area for further research.

7.2 Increase in demand outpacing supply

7.2.1 Supply and demand

Another risk to CRM supply chains is the increase in demand outpacing supply rates, as shown in our modelling detailed in Appendix E. We find varied urgency between CRMs, which is supported by other analyses (Zero Waste Scotland, 2023a; Ghorbani et al., 2024). Demand outpacing supply is partly due to net zero transitions requiring significant amounts of CRMs (Frazer-Nash Consultancy, 2025), which a large majority of survey respondents agreed was a factor affecting global demand. CRM demand in NZTs is discussed in Section 5.2.

Projected increases in demand over the next 10 to 15 years are not being met by an equivalent increase in extraction projects (Arup, 2024). This is reflected by relatively low production rates for many CRMs (Simas et al, 2022).

It should be noted that supply shortfalls do not necessarily equate to a lack of resources or reserves (see section 6.2.2). Current annual extraction rates can be maintained for 37 years for **copper**, 30 years for cobalt, 85 years for **lithium**, 31 years for **nickel**, and 413 years for REEs (Arup, 2024). However, increased extraction rates are needed to meet growing demand. Current projections of CRM supply would only meet 30-40% of global demand by 2050 (Energy Transitions Commission, 2023a). This is a particular threat for **copper**, **lithium** and **REEs** which face the risk of supply gaps. These are also the materials that emerge most consistently in the modelling analysis presented in Chapter 6.

Details of supply and demand for each material are set out in Appendix D.

7.2.2 Risks to new CRM extraction

Bringing new CRM supply on-stream is a risk due to long lead times for mining projects (Ghorbani et al., 2024; Jackson et al., 2024; Ross & Wright, 2025). Typically, only 0.1% of mineral exploration projects become mines (Task & Finish Group, 2023). A majority of survey respondents saw this as a factor affecting global CRM demand. For example, new lithium mines have a shorter lead time than other CRMs, but can still take between four and seven years to become operational (Energy Transitions Commission, 2023d). Lead times can be 15-20 years for copper mines (Simas et al, 2022; Energy Transitions Commission, 2023e), 13-19 years for nickel and 10-20 years for REEs (Simas et al, 2022). Plans to increase exploration and expand reserves (Energy Transitions Commission, 2023a) are further inhibited by geographical or political inaccessibility of reserves, such as those within protected areas, dense forest, or indigenous land (Arup, 2024), or mineral supply and investment plans that fall short of net zero energy needs (International Energy Agency, 2022; Energy Transitions Commission, 2023e).

One survey respondent from business/industry emphasised that new projects can be inhibited by artificially depressed market prices. When dominant supply countries like China purposefully flood the market with cheap CRMs, new extraction becomes economically unviable, allowing the country to retain dominance. One research sector interviewee noted the same applies for production of certain key components, such as EV batteries.

Declining quality of mineral reserves (International Energy Agency, 2022; Ross & Wright, 2025) also poses increasing risk, especially for the supply of low volume, high specification materials (Oakdene Hollins, 2014). Around one-third of survey respondents felt this affects global CRM demand, with one respondent noting this was mainly a concern for copper, which is nearing peak production due to declining ore quality and reserve exhaustion (Energy Transitions Commission, 2023e; Arup, 2024). There are also challenges in supply of the high-purity class 1 nickel and refined nickel sulphate used in batteries (Energy Transitions Commission, 2023b).

ESG concerns are also relevant, with expanded mining activities bringing a risk of local issues relating to mining conditions, human rights, and child labour concerns (Energy Transitions Commission, 2023a; Bielowicz, 2025; Energy Transitions Commission, 2023c). This was seen as a factor affecting global demand for CRMs by around half of survey respondents (see Section 6.6).

7.3 Geopolitical and economic tensions

The threat of conflict impacting the supply of CRMs is a risk for many countries, particularly in the upstream and mid-stream stages of the supply chain (SFA Oxford, 2023; Mudd et al, 2024), a concern reiterated by several stakeholders. For example, there is a threat of mineral cartels and conflict in the Democratic Republic of the Congo (DRC), a dominant cobalt producer (Ross & Wright, 2025; Energy Transitions Commission, 2023a; Arup, 2024). Around one-third of survey respondents identified cartelisation in key supplier countries as a threat to CRM supply chain resilience. Geopolitical issues are also likely to lead to supply and price volatility (Ross & Wright, 2025). A large majority of survey respondents agreed this is a threat, and a majority felt local or regional conflicts would also impact CRM supply chain resilience in the next 5-10 years. Stakeholder views are backed by historical examples, such as a recent coup d'etat in Gabon disrupting manganese supply, and civil war in Zambia affecting cobalt as noted by one research sector stakeholder. It is also important to note that any country with significant CRM reserves has the potential to capitalise on the net-zero transition to become more geopolitically influential, even if they are not currently exploiting this (Ghorbani et al., 2024).

Similarly, geographically concentrated supply, both for extraction and refining, is vulnerable to the threats of trade restrictions such as export bans and protectionism (SFA Oxford, 2023; Task & Finish Group, 2023; Ross & Wright, 2025). For example, nickel ore export from the Philippines is subject to a licensing agreement and fiscal tax, while nickel ore and concentrate export from Indonesia has been banned by their government since 2020. Similarly, cobalt ores and concentrates from the DRC are subject to various licensing agreements and export taxes (Petavratzi et al., 2024c). Producers of REEs have also historically restricted output to attempt to draw refineries into the country and exercise more control over the value chain, triggering price spikes and stockpiling (Zero Waste Scotland, 2023b; Metabolic et al., n.d.). This is currently a particular concern regarding China's dominance in REE and lithium production (Fletcher & Olaniyi, 2024), a view corroborated by a research sector interviewee. Protectionism and trade and investment barriers are also increasingly seen from the USA and the European Union (Ross & Wright, 2025), with almost all survey respondents agreeing this poses a risk to CRM supply chain resilience in the next 5-10 years. Around half of the respondents felt this impact would be significant, with both academic and business interviewees identifying it as a threat.

7.4 Price volatility

CRM price volatility can act as a significant barrier to investment in new projects, and threaten a stable and secure supply of CRMs (Oakdene Hollins, 2014; Arup, 2024; Bide et al., 2022). Around half of the survey respondents felt this issue would have significant impact. CRM prices are highly dependent on demand as well as the other risks set out in this section. For example, as EV demand increased between 2020-2022, so did battery metal prices, though this will also be influenced by other contextual factors and does not necessarily indicate a causal relationship. The price of battery-grade lithium increased by 500%+, and cobalt by 95%. Equally, as demand subsided with a worsening economic outlook in 2023, so did market prices. The price of lithium was down 75%, cobalt down 50% as of November 2023 (Task & Finish Group, 2023).

This threat is exacerbated by the complex, dynamic, opaque and fragmented nature of global supply chains (Task & Finish Group, 2023; Ghorbani et al., 2024; Mudd et al, 2024). These global factors make it hard to predict changes in these small, equally opaque markets (Bide et al., 2022). For example, CRMs are often not traded on futures markets such as the London Metals Exchange, so there is little transparent information on market-wide demand, supply and prices (Energy Transitions Commission, 2023a).

7.5 Risks relating to secondary supply

One option for reducing supply chain risk is to extract and recycle CRMs from waste, 'secondary supply'. However, there are difficulties in obtaining valuable materials from waste resulting in poor recovery and recycling rates (Oakdene Hollins, 2014; Bide et al., 2022; Task & Finish Group, 2023). Current global recycling rates are below 1% for lithium and REEs (Simas et al, 2022; Currie & Elliott, 2024), although stakeholders noted they are higher for some other CRMs such as nickel, aluminium, iron, and copper. Poor CRM recovery was also specifically noted as an issue by one survey respondent.

Limited consideration is given to reuse of materials in design of NZTs and their components, which also impacts on the secondary CRM supply chain. Interviewees from business/industry and academia noted that design complexity, Intellectual Property restrictions and the lack of documentation of which CRMs are in products inhibit potential CRM recovery from NZTs. This lack of sufficient data inhibits traceability for CRMs (Bide, Horn, & Gunn, 2021). This was corroborated by two stakeholders, though opinion here was less unanimous than with other risks. Similarly, an academic interviewee emphasised the importance of digital traceability of products and components across the entire global value-chain.

An academic interviewee emphasised that, even with sufficient capacity and support, recycling alone would not meet near-term CRM demand, as many CRMs are only now entering the economy in products with long lifespans (e.g. EVs, offshore wind magnets). This is detailed in section 7.3.1. Therefore, the dependence on extraction in a vulnerable supply chain remains, according to one academic and one technical institute interviewee.

Interview insights from academia, the research sector and business/industry highlight the lack of UK REE processing or manufacturing, and the export of ores to other countries such as China, France and Taiwan, as a significant vulnerability. However, a facility for separating and recycling REE magnets was opened in England in January 2026, increasing UK capacity for secondary CRM processing (University of Birmingham, 2026).

7.6 Environmental, social and governance concerns

As discussed in section 6.2, further exploration and expansion of mining and extraction operations is needed globally. However, many resources and reserves are in areas with prominent ESG concerns (Fletcher & Olaniyi, 2024; Ghorbani et al., 2024; Ross & Wright, 2025). Concerns include:

- water supply issues related to mineral extraction (Energy Transitions Commission, 2023a; Arup, 2024)
- energy and emissions intensiveness of production (Energy Transitions Commission, 2023a; Ghorbani et al., 2024; Jackson et al., 2024)
- water stress and drought (Energy Transitions Commission, 2023a; Jolly, 2024)
- flooding, extreme heat, environmental disasters, and extreme storms.

Many of these issues are also related to climate change (International Energy Agency, 2022; Mudd et al, 2024; Ross & Wright, 2025). Exposure of the CRM supply chain to climate risk was raised by one NGO survey respondent as a major threat to supply chain resilience, illustrated for example by storms in South Africa damaging CRM infrastructure. Additional concerns include chemical pollution, biodiversity loss, and land-use change (Jolly, 2024).

ESG issues contribute to concerns surrounding the capacity to increase global copper mines (Mudd et al, 2024). REE production concentration in China and Myanmar is associated with poor ESG performance (Zils et al, 2024a), with China often releasing toxic waste from extraction into the environment (Bielowicz, 2025). One business/industry interviewee noted greater understanding is also needed regarding ESG concerns, with an academic interviewee also noting these impacts are difficult to track. This issue is likely to be at least partially addressed with the introduction of product passports, for example those for batteries, in the future. Increasing traceability of materials will enable companies to be more aware of how materials and components are sourced.

These threats also relate to the current geographical concentration of supply. Certain issues may dissuade the UK from sourcing CRMs from some countries due to growing scrutiny of environmental and social performance (International Energy Agency, 2022). Compounding this issue, several stakeholders noted stringent or differing ESG requirements could impact CRM supply. This could particularly relate to opportunities for domestic extraction, where Scottish planning and permitting procedures are more complex than elsewhere, potentially making domestic supply less efficient or cost-effective.

Trade is a reserved matter, with decisions being made by the UK Government but Scotland may be able to influence decision-making towards responsible sourcing of CRMs (Scottish Government, 2025e). For example, in its Trade Strategy the UK Government recognises the strong growth in Scotland’s net zero economy, and notes that the new Supply Chain Centre in the Department for Business and Trade will work with businesses across the UK on critical supply chains (2025b). This offers an avenue for Scotland to leverage its recognised expertise at the UK level in support of responsible trade in CRMs.

7.7 Implications of significant supply chain risks for Scotland

The geographical concentration of CRM supply throughout the value chain creates a significant vulnerability for Scotland's net zero transition, as part of an island nation with limited domestic resource deposits. Dependence on imports from a limited number of countries, particularly China, exposes the UK and Scotland to the impacts of geopolitical and economic tensions, including trade restrictions and price volatility. This can lead to supply disruptions and increased costs for the CRMs necessary for Scotland’s NZT targets, as set out in Section 5.1.

The inability of current supply to meet rapidly increasing demand, especially for copper, nickel, lithium, and REEs, further exacerbates this risk. This applies to all NZTs (wind, solar, EVs, battery storage, hydrogen production and heat pumps), as they all contain CRMs where demand is likely to outstrip supply. Long lead times for new mining projects and declining ore quality are hindering efforts to scale up production globally. Potential domestic mining opportunities are also currently limited, although some opportunities do exist in Scotland (see section 7.2.1). These supply-demand imbalances, coupled with price volatility, pose a direct threat to Scotland's ability to reliably and affordably source the necessary CRMs for its NZT deployment. Across the risks considered, copper appears particularly exposed due to its importance across multiple net zero technologies and projected supply-demand imbalances. Unlike some other CRMs, copper is a key input across electricity networks, wind power, solar generation, battery storage, electric vehicles and heat pumps. A detailed review of modelled net copper availability is set out in Appendix E.

Limited secondary supply due to low recycling rates, complex product and component design, and limited UK processing infrastructure means Scotland cannot currently mitigate these primary supply risks through circular economy approaches. This leaves the country reliant on external markets.

Finally, ESG concerns surrounding CRM extraction and processing can also impact supply and increase costs, potentially creating a dilemma for Scotland (as part of the UK) in balancing ethical, sustainable sourcing commitments with net zero goals.

8 Economic strengths, weaknesses, opportunities & threats for Scotland

This chapter outlines our findings on economic strengths, weaknesses, opportunities and threats (SWOT) for CRM supply in Scotland. We focus on circular economy (CE), to highlight potential for future adoption of CE practices. It is important to note that many issues are not exclusive to a particular section of this SWOT discussion and as a result, common themes recur.

8.1 Strengths

We identified strengths in three key areas - capacity in the value chain, net zero technologies, and research and development.

8.1.1 Existing capacity across the value chain

Certain strengths have been identified within the value chain in both the United Kingdom (UK) and in Scotland specifically). Specific strengths have been recognised in relation to skills around mineral and mining expertise, high environmental, social and governance (ESG) standards and globally significant investors (National Energy System Operator, 2025).

Scottish Enterprise has identified that some of Scotland's capabilities match well with significant projected market opportunities, including on/offshore wind, heat pumps and heat networks (Scottish Enterprise, 2024).

Regarding mineral resources, Scotland has areas of high potential for nickel exploration, including cobalt as a possible by-product (Gunn & Deady, 2022). Around half of the survey respondents agreed this is a strength. One business/industry interviewee highlighted Scotland has existing strengths in the identification, collection and aggregation of materials and expertise in recovery and collection of copper, aluminium and iron. Strong expertise in oil and gas extraction could be translated to mining more generally (Reeves, 2023). Capability within the British Geological Survey and UK university geoscience departments could be deployed, particularly in CRM extraction research (Reeves, 2023). This was also corroborated by around half of survey respondents and one business/industry interviewee.

There are indications that Scotland has some workforce capacity to deliver many CRM-related needs (mining, geological expertise, end-of-life materials management) for the net zero transition. For example, Scotland and the wider UK have manufacturing, technical and capacity related strengths in offshore wind components (Skills Development Scotland, 2025). Skills Development Scotland predicts that the offshore wind sector workforce will grow from around 9,000 to over 40,000 between 2024 and 2029. There will likely be overlap between existing skills and those needed to develop the offshore wind supply chain, with "significant work" already undertaken to ensure skills needed for the energy transition are being honed (Scottish Government, 2025b). This existing strength was also recognised by a majority of survey respondents.

Furthermore, a Circular Energy Hub at Conexus West aims to provide a South of Scotland facility for the CE value chain generally, with an investment of just under £18 million creating around 100 jobs (Zero Waste Scotland, 2024). Whilst some city deal funding applications have been unsuccessful, this site is part of the Hagshaw Energy Cluster Framework which includes CE activity potential, for example through eventual reuse and recycling of renewable energy infrastructure, such as wind turbines (Land Use Consultants, 2023). The project claims to be an early example of applying a Development Framework to a renewable energy cluster, which has been adopted by Planning Authorities as non-statutory guidance to promote positive change within planning applications. Part of this Development Framework includes a CE strategy, promoting local skills and materials.

Despite these points, our analysis and findings also highlight existing key skills and labour-related gaps across other parts of the value chain, as detailed in section 7.2.3. It is clear however, that Scotland has a strong basis on which to build skills needed to harness CE within the NZT sector.

8.1.2 Existing net zero technology capacity

A range of interviewees agreed that Scotland’s strong natural resources position it well for various NZT development, including on/offshore wind and green hydrogen. Wind turbine decommissioning offers a potential new market (Zero Waste Scotland, 2023a), with Scottish wind power (particularly offshore) currently one of the largest renewable energy markets in the world (Zero Waste Scotland, 2023a). A majority of survey respondents agree that wind turbine decommissioning is a significant potential new market for Scotland. Some Scottish windfarms are already at the decommissioning phase, such as Repower Phase 2 of the Hagshaw extension. There has been research into a business case for a blade recycling centre (Zero Waste Scotland, 2024), and private sector research in the UK to develop alternatives to Rare Earth Elements (REEs) in wind turbines (Task & Finish Group, 2023).

One survey respondent also noted a clear Scottish Government commitment to supporting raw materials industries to invest in production and recycling facilities via Section 23 of the Circular Economy (Scotland) Act 2024. Section 23 required preparation of a report on waste reprocessing infrastructure, which was published in August 2025. The report notes particular opportunities and priorities for Scotland in relation to reprocessing both wind infrastructure, when first-generation turbine decommissioning begins at scale, and batteries (Scottish Government, 2025c).

8.1.3 Existing research and development capacity

In the UK, £1.45bn has been deployed for research and development (R&D) innovation projects since 2017, mostly through UKRI challenge programmes (£0.9bn). These are largely business- and academic-led investments (~£0.4bn). Specific projects investigating CE and supply chain resilience were described as relatively underfunded, receiving a total of £59.8m (4% of the investment) (Reeves, 2023). This includes several multi-year projects at the UK level, with none specific only to Scotland. Key funds and programmes identified related to this R&D area are:

- Strategic Priorities Fund – National Interdisciplinary Circular Economy Research Programme (£30 million, 2021-2025);
- Security of Supply of Mineral Resources (£15 million, 2015-2019); and
- Resource Recovery from Waste (£7.2 million, 2014-2019).

The report does not disaggregate this figure to the Scottish level, but does note key institutes and funding bodies active in the Scottish context, including the National Manufacturing Institute Scotland (NMIS) and Zero Waste Scotland**.**
Since the publication of this R&D mapping study, further studies led by NMIS, Zero Waste Scotland and others continue to be published, many of which form part of this project's literature review. Around half of survey respondents considered significant investment in R&D innovation projects and a history of undertaking high quality research as a strength for Scotland.

8.2 Weaknesses

We identified weaknesses in three key areas – limited capacity for domestic extraction, low recycling rates, and a skills and labour gap.

8.2.1 Capacity for extraction within Scotland and the UK

Current exploration activity for CRMs in Great Britain is low (Bide et al., 2022), with one research sector interviewee noting that Scotland is "chronically under-explored". Geological prospectivity has not been undertaken for a large proportion of Scotland's land area, particularly areas designated as sites of special scientific interest, national parks and National Scenic Areas (Deady et al, 2023). Whilst some literature suggests that significant further research and exploration is needed for materials with identified geological potential (Green Alliance, 2024a), very few survey respondents highlighted low CRM exploration research activity as a weakness. In almost all cases more research is necessary to invest in exploration (Bide et al., 2022).

The lack of a centralised system for reporting exploration data can result in the loss of data needed to inform future exploration (Bide et al., 2022). A minority of survey respondents highlighted this as a weakness. However, aligned and transparent reporting could be a confidentiality or competitiveness risk for the mining industry (Bide et al., 2022).

Table 7-1 presents an overview of the potential extraction capacity of CRMs as identified by the literature and stakeholders. It makes a qualitative assessment of Scotland's capacity to explore and extract each CRM. A 'low' rating indicates either no consensus on potential sites, identified economic cases to extract or whether there is existing mine production. 'Potential' indicates an identified small but growing capacity.

Table 4 Potential extraction capacity related to key CRMs

CRM	Capacity	Notes
REE	Low	• No mine production to date of REE-bearing minerals in the UK (Currie & Elliott, 2024). Potential sites identified by Hebridean New Metals[A]. • Northwest Scotland identified as a UK hot spot for REEs (Currie & Elliott, 2024) with the only viable opportunity for UK REE extraction at Scottish sites (Deady et al, 2023).
Manganese	Low	• Limited historical production in Scotland until rendered uneconomic. • Several sites throughout Scotland but many do not justify exploration or extraction (Josso & Lusty, 2023; Deady et al, 2023). • Potential sites identified by Hebridean New Metals[A].
Lithium	Low	• Currently no commercial scale mine production of lithium in the UK (Shaw, 2022). • Lithium presence at several Scottish sites, generally in minor amounts (Shaw, 2022). Potential sites identified by Hebridean New Metals[A].
Nickel	Potential	• Aberdeenshire identified as key UK nickel source (Gunn & Deady, 2022). Identified in Scotland by Aberdeen Minerals[B]. • Potential for exploration of Cupronickel (Ni-Cu) in North-East Scotland (Petavratzi et al., 2024c) (research sector interviewee). • Untapped resource of nickel and cobalt by-products in Aberdeenshire due to outdated geological mapping (technical institute interviewee).
Cobalt	Low	• No mine production in the UK and no exploration recorded (BGS and Minerals UK, 2020). • Several areas in Scotland prospective for cobalt (Deady et al, 2023). Identified in Scotland by Aberdeen Minerals[B]. • Ores historically mined in Perthshire, Scotland (BGS and Minerals UK, 2020). • Potential for exploration in North-East Scotland noted (Petavratzi et al., 2024c).
Copper	Low	• Identified in Scotland by Aberdeen Minerals[B].
Silicon	Low	• Small but high-quality deposit at Lochaline silica sand mine, suitable for semiconductors and photovoltaics (PVs) (research sector interviewee).

[A] Although information is not yet published (Hebridean New Metals Ltd, n.d.), insight was provided by the Project Steering Group for inclusion in this report.

[B] This organisation focuses on exploration of bedrock deposits of nickel, copper and cobalt in the Northeast of Scotland (Aberdeen Minerals, 2024). Insight was provided by the Project Steering Group for inclusion in this report.

Limitations and capacity constraints in areas beyond extraction were noted as a weakness by around half of survey respondents. However, our reviewed literature makes limited statements regarding capacity, and these are related to specific technologies:

- **Electrolysers:** No mining or refining activities identified in Scotland relating to key materials used for electrolysers, but some UK activity in the component and assembly stages of the supply chain (Zils et al, 2024a).
- **Photovoltaics:** Limited Scottish involvement in the PV supply chain (Petavratzi et al, 2024b).
- **Semiconductors:** Limited Scottish involvement has been noted (Petavratzi et al, 2024b).

8.2.2 Low recycling rates

Low recycling rates for CRMs (Mudd et al, 2024) and subsequent limitations around material circularity (Frazer-Nash Consultancy, 2025) may present a missed economic opportunity for Scotland. This can hamper the transition towards closed-loop supply chains in the energy sector (Task & Finish Group, 2023) and maintain reliance on imports of materials for net zero energy infrastructure expansion. A large majority of survey respondents agreed that low recycling rates for key raw materials was an economic weakness in the context of building a CE in Scotland for CRMs.

There are several underlying causes for low recycling rates. These include technology readiness levels (TRL): costs (including energy costs), infrastructure, investment, regulation and market incentives. The high cost of material reprocessing may mean secondary materials are unable to compete with low-cost virgin alternatives (Scottish Government, 2025c). Typical barriers to infrastructure development, particularly for materials from renewable energy installations, include high material reprocessing costs, low value of secondary materials, transportation and logistics costs, and a small market size (Scottish Government, 2025c). As an example, Scotland currently exports around 78% of battery waste for reprocessing, and the reprocessing sector faces challenges including high energy costs, fires at waste battery storage facilities, high insurance costs, and complex and costly reprocessing processes (Scottish Government, 2025c).

Furthermore, the UK Critical Minerals Strategy (UK Government, 2025) set targets for 2035 for 10% of annual demand to be met through domestic production, and a further 20% to be met from recycled materials. However, the strategy does not specify that these should be domestically recycled materials (i.e. the 20% could be met using recycled, but imported, materials). This therefore reduces market certainty related to the development of domestic recycling facilities. There is also a lack of infrastructure in the UK for permanent magnet recycling, which is important for REE recovery (Task & Finish Group, 2023). Neodymium (a REE) magnets from wind turbines have high market value (National Engineering Policy Centre, 2024). This is currently uncaptured, as the recycling supply chain is immature. Only around 17% of nickel is recycled globally, hindered by its frequent use in alloys which makes recovery difficult (Zero Waste Scotland, 2023b).

UK recycling rates vary significantly for key raw materials (Mudd et al, 2024). For instance, there is no secondary copper smelter-refinery in the UK, although there are private sector initiatives to create a circular economy for green copper production.[2] This means that all copper scrap is currently exported, and products made incorporating the scrap are imported

[2] https://www.evolvemetals.uk/. The company is working to create the "world's first hydrogen-based, non-toxic, low emissions copper refinery".

(Mudd et al, 2024). Similarly, a majority of aluminium scrap is currently exported, as noted by the Scottish Government (2025c) and interviewees. Whilst high collection rates are achieved for waste electrical and electronic equipment (WEEE), most materials are exported for processing (Zero Waste Scotland, 2023b). There is therefore scope in the UK for much greater recycling of key metals from WEEE, such as copper and aluminium (Zero Waste Scotland, 2023b).

One business/industry interviewee highlighted insufficient volumes for economically viable recycling for some CRMs, for example in relation to battery recycling. This interviewee also noted a lack of economic incentives for recovery of certain CRMs (manganese, silicon and niobium) with no established UK market, and a lack of industry knowledge of the economic value in separating manganese from steel. Two technical institute interviewees noted a funding gap between small seed grants (e.g. Innovate UK) and large-scale investments worth >£25 million, as well as a lack of a European Union (EU)-style "strategic project" designation to ease permitting and financing[3]. The following were also all noted by business/industry and technical institute interviewees as major barriers to investment:

- Lengthy and complex planning processes
- Permit delays
- Lack of dedicated expertise and skills from the public sector to execute projects
- A need for coordination between UK and Scottish governments on the role of CRMs.

8.2.3 Skills and labour related gaps

As highlighted in section 7.1, technical skills in certain parts of the value chain are well established in the UK and Scotland specifically. However, some stages in the value chain have been identified in the literature as having gaps that need to be addressed to achieve CE goals in the UK and in Scotland. In particular these relate to industrial capacity, manufacturing and recycling. This section highlights some of these identified gaps in greater detail.

Lack of investment and a "weak industrial base" may have impacted the potential for increased economic opportunities associated with Scotland's net zero transition (Mazzucato & MacFarlane, 2024). In recent decades, the Scottish (and UK) economies have seen structural change with manufacturing contributing less, and financial and business services contributing more. In the context of NZT, highlighting the example of the Scottish offshore wind market specifically, labour skills have dropped significantly based on turnover, indicating the growth of Scotland's wind sector has not been matched by new job creation. Mazzucato & MacFarlane (2024) suggest the greatest potential for job creation in renewables is in manufacturing and construction, due to the capital intensity of renewable energy and the limited operating costs. However, Scotland does not yet have the domestic supply chains needed to meet the demand (Mazzucato & MacFarlane, 2024). The Aldersgate

[3] The EU Critical Raw Materials Act designates strategic projects to increase EU capacity to extract, process and recycle strategic raw materials, and diversify EU supplies from third countries. Project acceptance under this designation allows for streamlined permitting processes. Under the Act, permitting for extraction is capped at 27 months, and 15 months for processing/recycling projects.

Group estimated a potential missed UK economic opportunity of some £30bn between 2008 and 2022 linked to a lack of development of manufacturing capability related to wind power supply chain manufacturing (Aldersgate Group, 2025). A large majority of survey respondents agreed Scotland’s “weak industrial base” is a key weakness, as well as two business/industry interviewees.

Another factor identified in the reviewed literature is a skills gap related to mining engineering, mineral processing and metallurgic skills, with a need to modernise perceptions of work in the sector to provide the skills needed by industry, academia and regulators (Stonehouse, 2023). One survey respondent also suggested a lack of chem-tech processing expertise, with one technical institute interviewee also highlighting that support for chemical engineering is a key need for industrial policy. However, existing skills are present across relevant industries, including strengths in chemical manufacturing at Grangemouth that can be utilised, as recognised in the 2045 Vision for Grangemouth (Leigh & Creamer, 2025). Such skills gaps were seen as a weakness by around half of survey respondents. Furthermore, one academic interviewee noted underinvestment in school and university geology qualifications. A research sector interviewee noted that the UK-mining-specific workforce largely works overseas, for example in Australia and Canada.

Whilst there are some gaps, it is clear that overall Scotland has existing skills capacity that puts it in a strong position to progress CE approaches in the net zero transition, and to become a front-runner in related services in certain parts of the value chain.

8.3 Opportunities

We identified five key opportunities - the wider circular economy, job creation, materials substitution, infrastructure and expertise in ESG standards.

8.3.1 Using the circular economy to alleviate supply pressures

Circular economy approaches include reuse, repair, remanufacturing, recycling, recovery and reprocessing of materials and components. There is potential to increase CRM provision, in both the Scottish and general contexts, through innovative recycling and other circularity-related principles such as materials efficiency (Energy Transitions Commission, 2023a). Recovered and recycled materials are referred to collectively as 'secondary supply' or 'secondary materials'. These terms refer to materials obtained from products, infrastructure or waste streams rather than from primary extraction.

Recycling is likely to make a significant contribution to total supply of CRMs from 2040 (Lusty et al., 2022). For instance, in the context of battery manufacturing, scrap from UK gigafactories is expected to be an important source of cathode active materials as early as 2030 (Lusty et al., 2022). Low-carbon emitting refineries using recycled scrap metal have been developed in the UK, reducing scrap material export (e.g. Alvance, Evolve Metals) (Jackson et al., 2024). Jackson et al. (2024) argue that both government and the private sector have been seeking to mitigate supply risk to date by increasing recycled inputs to component manufacture, “considering” direct financing deals between manufacturers and mining companies, and substituting aluminium for copper. Furthermore, until 2021 the UK had no domestic EV battery recycling capacity – this changed with the development of RSBruce’s in-house LIB battery recycling facility (Lusty et al., 2022). In January 2022, Veolia announced its first EV battery recycling facility in the West Midlands, which by 2024 was processing 20% of the UK's EV batteries (Lusty et al., 2022). One survey respondent highlighted the opportunity for Scottish industry to establish its own recycling systems to ensure future material availability. This is elaborated further below.

Zero Waste Scotland (2023b) highlight the potential for Scotland to domestically recycle a proportion of the currently-exported **aluminium**, **lithium** and **neodymium**, to increase and diversify domestic supply of CRMs (Mudd et al, 2024). Deady et al. (2023) also suggest potential for CRM recovery from waste from historical mining sites, where CRM co- or by-products were not previously extracted with the primary products. There is also potential to generate revenue from key CRMs at the technology end of life stage (EoL) and associated secondary material markets (Lusty et al., 2022; SFA Oxford, 2023). This was recognised as a key opportunity for Scotland by a large majority of survey respondents and one interviewed business group representative. One academic interviewee highlighted that there are companies keen to increase domestic neodymium capacity.

Figure 19 and related figures below show modelled total annual CRM demand for NZTs in Scotland, against the availability of CRMs from NZTs reaching end-of-life. This CRM availability represents a theoretical maximum, and would require 100% recycling rates across all NZTs, with 100% recovery rates of each CRM. The figures provide an indication of Scotland's key CRM capacity if domestic recycling reached full capacity. The quantity of CRMs available at end-of-life can inform decision making on potential sourcing options for future CRM needs.

While **nickel** recycled from end-of-life NZTs could theoretically only supply 1% of Scotland's NZT nickel needs in 2030, this rises sharply to 7% in 2035, and 35% in 2040.

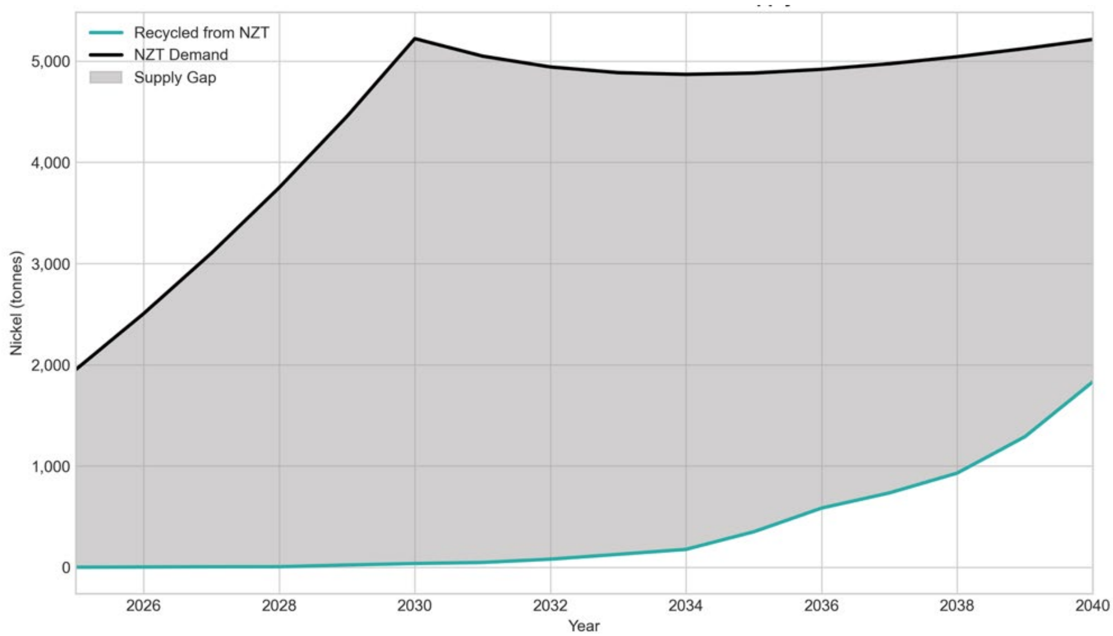

Figure 22 Scotland's NZT-related nickel demand vs potential domestic sourcing capacity from NZTs at end-of-life, 2025-40

Lithium recycled from NZTs could supply 21% of Scotland's NZT lithium needs by 2035, and over half (52%) by 2040.

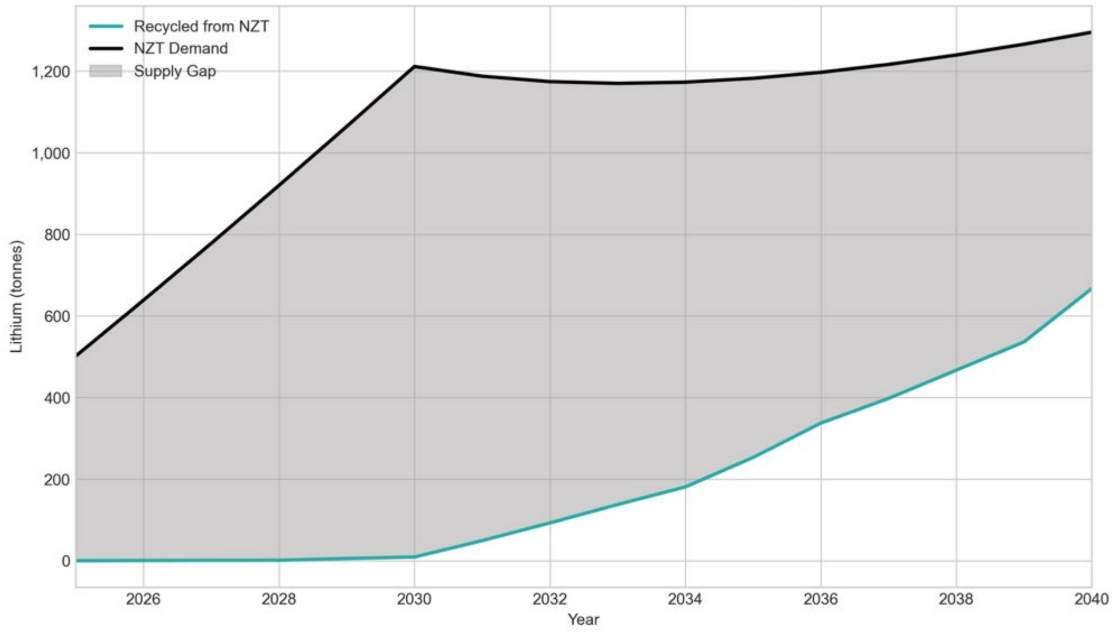

Figure 23: Scotland’s NZT-related lithium demand vs potential domestic sourcing capacity from NZTs at end-of-life, 2025-2040. Source: Modelled data (see Appendix C)

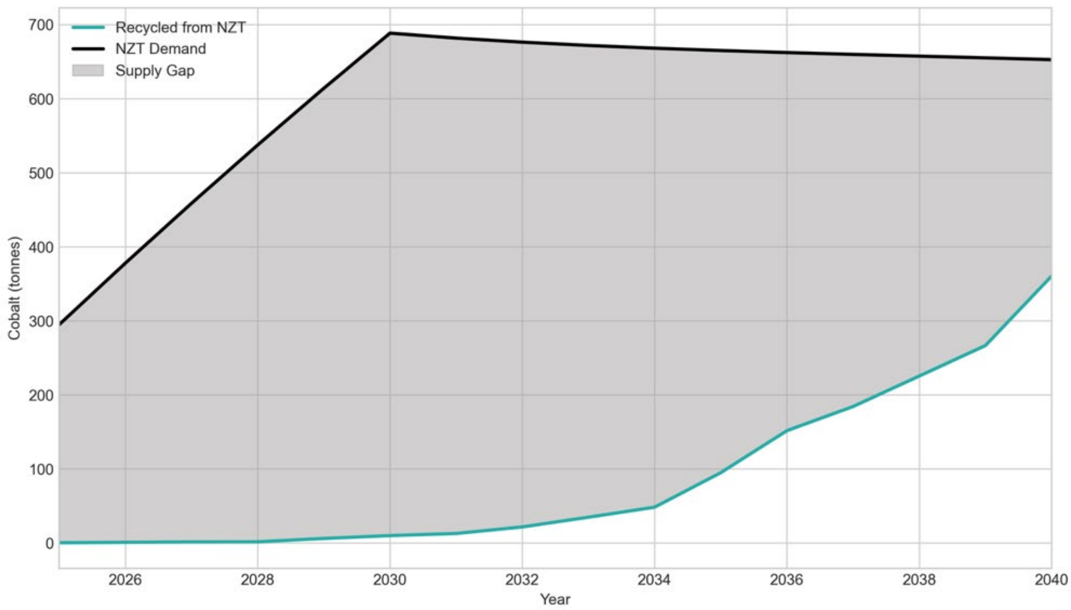

Figure 24 Scotland’s NZT-related cobalt demand vs potential domestic sourcing capacity from NZTs at end-of-life, 2025-2040. Source: Modelled data (see Appendix C)

At UK level, up to the equivalent of 24% of 2020 UK imports of **Li-Co** could be obtained from domestic battery recovery by 2030, rising to over three times the quantity imported in 2020 by 2050. This is because Li-Co can be generated domestically through recovery of materials during decommissioning of assets (Zero Waste Scotland, 2023b). Achieving UK domestic recycling targets could mean domestically recycled **nickel**, **lithium** and **cobalt** could supply over 50%, 43% and 150% respectively of the UK’s EV battery manufacturing requirements by 2040 (Green Alliance, 2024a), with respective economic values of £536 million, £146 million and £63 million. One business/industry interviewee highlighted emerging second tier markets in the UK for key CRMs (**nickel**, **lithium** and **cobalt**), driven by EV battery demand and automotive original equipment manufacturers.

Zero Waste Scotland estimates that 784 kilotonnes (kt) of **aluminium** could be recovered through decommissioning and life extension by 2050 (Zero Waste Scotland, 2023b). Scotland is expanding its capacity to reprocess aluminium via the Alvance-run billet and recycling facility at their Lochaber smelter, estimated to be opened in 2026 or 2027 (Alvance British Aluminium, 2026). This offers an opportunity to redirect the high volume of UK exports of aluminium waste domestically, and to take advantage of significant aluminium stocks in existing infrastructure, not just NZTs (Zero Waste Scotland, 2023b). Interviewees from academia and the research sector also highlighted the opportunity related to the Lochaber aluminium smelter refinery. The plant is investing in circular practices and is considered one of the most sustainable aluminium smelters in the world. This may comprise a potential future business for reprocessing aluminium in Scotland.

Despite the expense and technological complexity of separation processes and secondary production of **REEs**, recycling is becoming increasingly competitive in the face of price volatility and political instability in primary producing countries (Bielowicz, 2025). A majority of survey respondents agreed that CE approaches offer a key opportunity to alleviate supply pressures and exposure to price volatility of CRMs generally. One survey respondent suggested that there may be untapped REE resources in industrial wastes, such as coal fly ash storage sites. One business/industry interviewee highlighted a potential longer-term opportunity for Scotland to develop a reputation in the area of REE identification and recovery.

Increasing domestic recycling/reprocessing capacity would help Scotland to continue to meet local demand for **REEs** (Zero Waste Scotland, 2023b), although one business/industry stakeholder highlighted that the recovery cost is extremely high and not currently reflected in the market price for secondary REE. Two stakeholders also questioned the usefulness of REE recovery in Scotland without an accompanying manufacturing supply chain to produce the products that rely on them. It was also noted that it may not be economically viable to do so, considering existing global competition, for example given China’s dominance in permanent magnets.

The added value of Scotland-specific capacity for REE was not noted in our reviewed literature or by interviewees. One technical institute interviewee highlighted a specific opportunity via the offshore wind sector, with large volumes of reclaimable steel and REE magnets in end-of-life turbines. Although there are no active REE recycling sites in Scotland, UK capacity has recently developed with the opening of the HyProMag recycling and manufacturing plant in Birmingham in January 2026. This has capacity to produce over 300 tonnes (t) of recycled REE alloy per year (Mkango Resources, 2026). Investment in Scottish infrastructure is not currently considered economically viable due to the relatively low amounts of REE source material available in Scotland. However, we believe this could be reconsidered in the future as the decommissioning of offshore wind installations increases (see Figure 25).

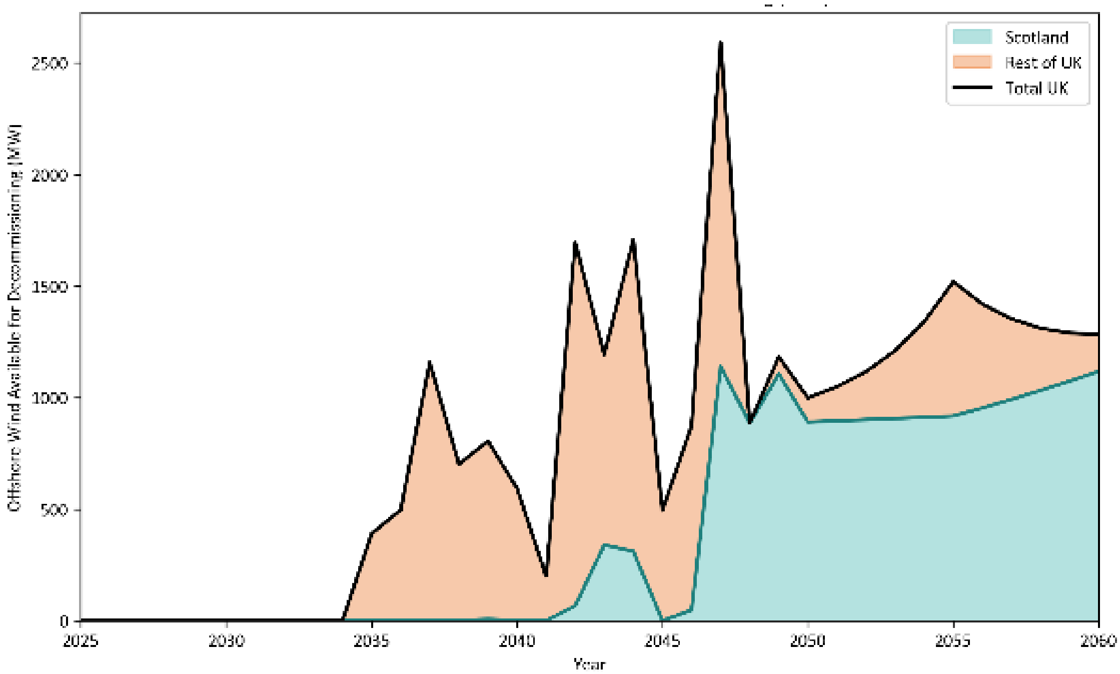

Figure 25 Annual Megawatts (MW) of installed capacity reaching end-of-life for offshore wind, in Scotland and the rest of the UK. Source: Modelled data (see Appendix C)

As offshore wind in Scotland is only expected to reach end of life in large quantities post-2040, REEs availability through recycling up to 2040 remains relatively low at a Scottish level. In 2040, our modelling shows that recycling REEs from end-of-life NZTs in Scotland could only supply less than 10% of Scotland's NZT REE requirements. However, this will increase significantly in the longer-term, and is projected to jump to around 50% by 2050, due to increased annual decommissioning volumes.

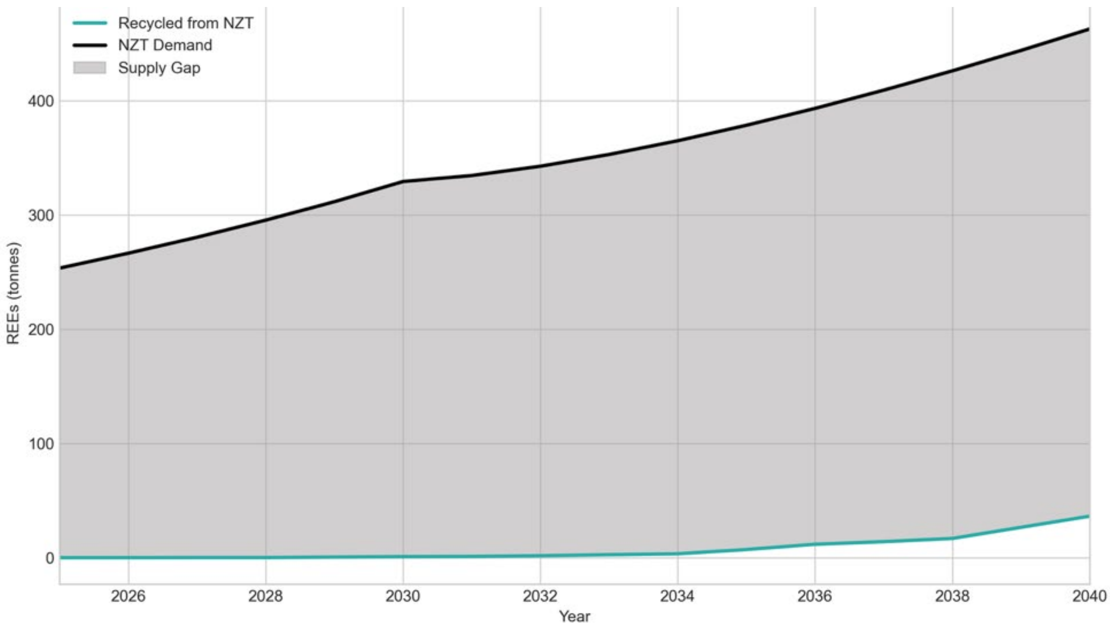

Figure 26 Scotland's NZT-related REE demand vs potential domestic sourcing capacity from NZTs at end-of-life, 2025-2040. Source: Modelled data (see Appendix C)

The quantities reaching end of life for both offshore and onshore wind (see Figures 25 and 27) are of particular importance to understand the potential availability of **copper** from NZT recycling.

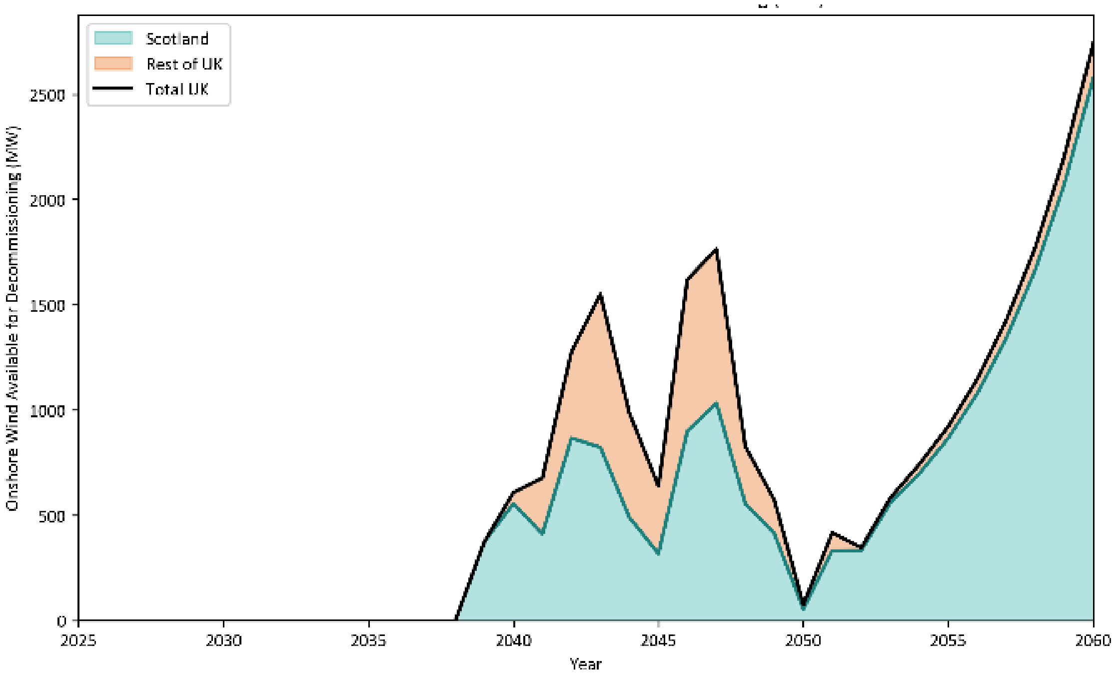

Figure 27 Annual MW of installed capacity reaching end-of-life for onshore wind, in Scotland and the rest of the UK. Source: Modelled data (see Appendix C)

Approximately half of the predicted 2050 **copper** deficit could be filled by materials recovered during decommissioning of various (unspecified) NZTs (Zero Waste Scotland, 2023b). Our modelling supports this finding, showing a strong increase in secondary supply from NZT decommissioning from less than 1% in 2030, through to 19% in 2040, and 51% in 2050 (Figure 28). One technical institute interviewee noted there is also potential in Scotland to increase copper recovery from scrap and post-consumer waste electrical and electronic equipment (WEEE) (Oakdene Hollins, 2014), with the UK the second largest producer of WEEE per capita globally as of 2018 (Forti, Baldé, & Kuehr, 2018).

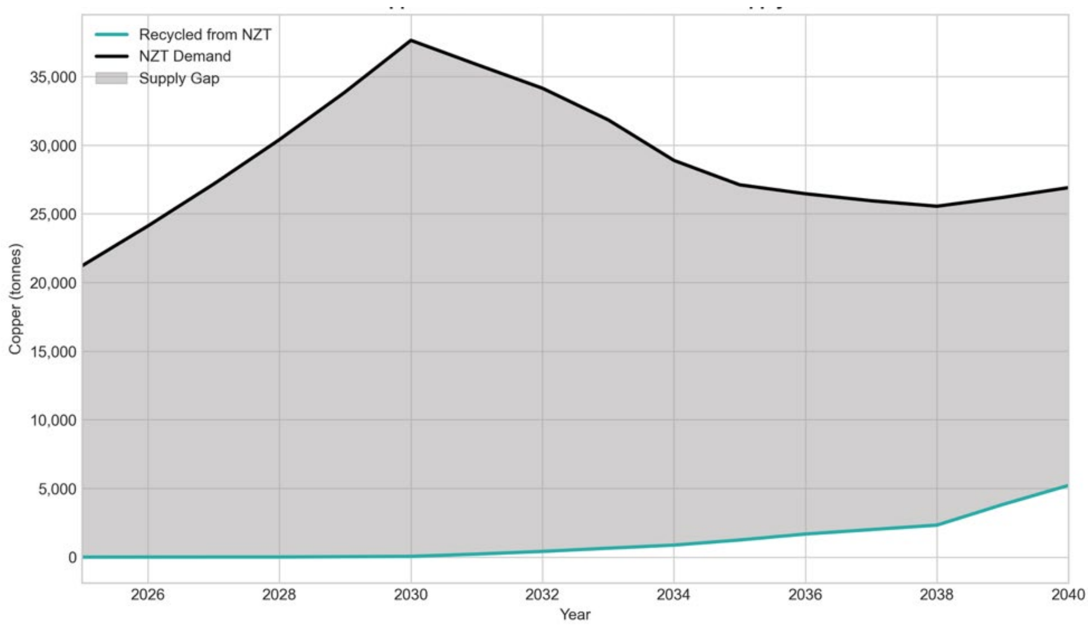

Figure 28 Scotland's NZT-related copper demand vs potential domestic sourcing capacity from NZTs at end-of-life, 2025-2040. Source: Modelled data (see Appendix C)

Approximately 85% of the silicon contained in solar PV units can be reused (Scottish Government, 2025c). UK solar PV waste, around 5% of which is typically silicon by weight, is forecast to cumulatively reach 30 kt by 2030 and 1 million tonnes (Mt) by 2050 (Scottish Government, 2025c). This will increase the potential to meet a portion of domestic demand through reprocessing. Some facilities exist in the UK to reprocess silicon from general WEEE and solar PV WEEE, for example the SRS facility near London. This facility states it can achieve 100% recycling with full transparency and auditable recycling routes for all materials, and has capacity to recycle over 300,000 solar panels per year (Solar Recycling Solutions, 2024).

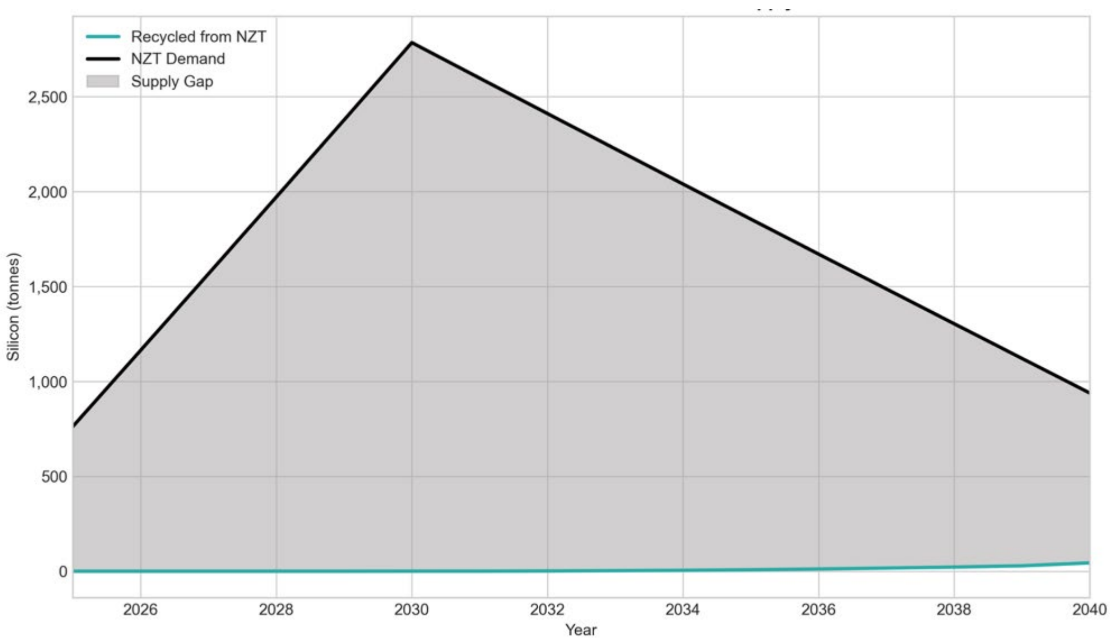

Figure 29 Scotland's NZT-related silicon demand vs potential domestic sourcing capacity from NZTs at end-of-life, 2025-2040. Source: Modelled data (see Appendix C)

Until 2040, secondary **silicon** can make only a limited contribution to supply in Scotland, due to the limited decommissioning of solar farms expected over that period, as shown in Figure 29 and Figure 30.

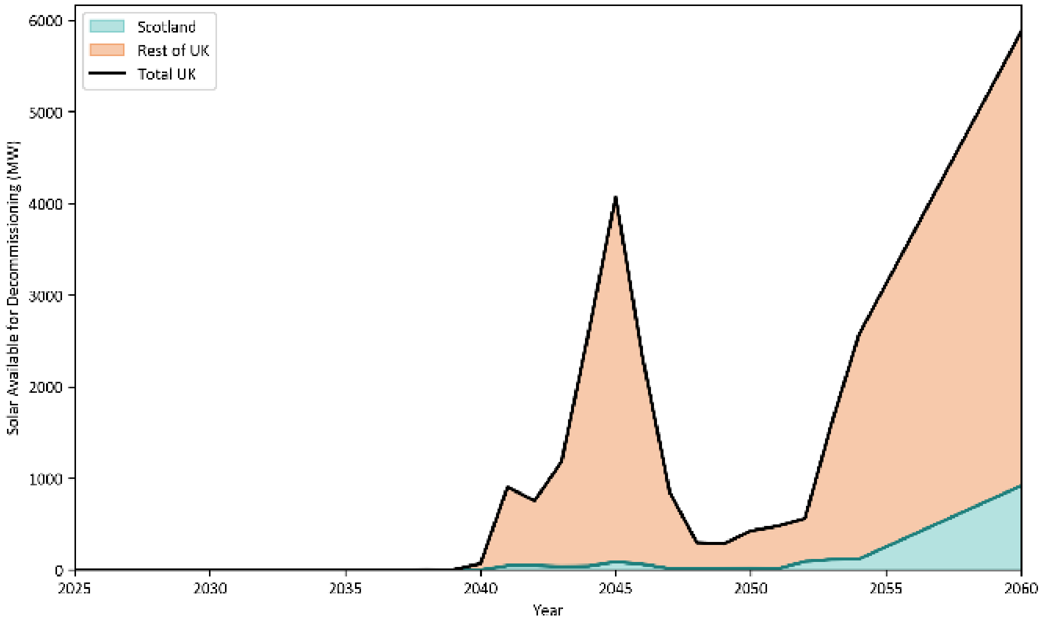

Figure 30: Annual MW of installed capacity reaching end-of-life for solar, in Scotland and the rest of the UK. Source: Modelled data (see Appendix C)

1.5 Mt of **iron** can be recovered through decommissioning and life extension, and there is UK capacity to reprocess iron even though most is currently exported for reprocessing (Zero Waste Scotland, 2023b). An academic stakeholder also noted the potential for investment in renewable energy-powered electric arc furnaces for recycling iron in Scotland.

The potential for Scotland to meet its NZT **manganese** needs from recycling of NZTs increases in the mid- to long-term, from near-zero contribution until 2030, increasing to 6% in 2035, then to almost half (47%) in 2040 (Figure 31).

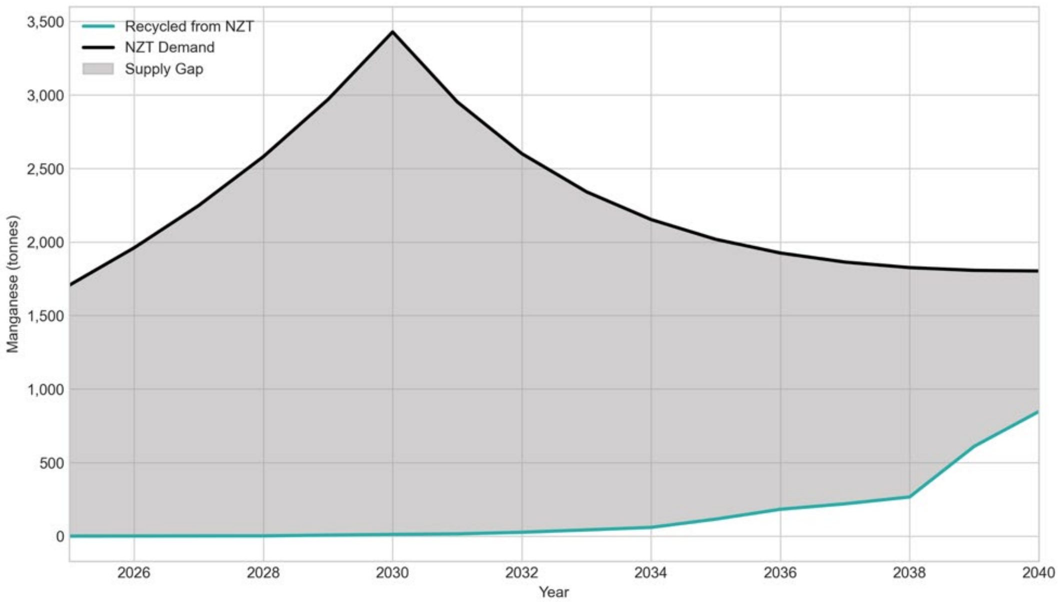

Figure 31 Scotland's NZT-related manganese demand vs potential domestic sourcing capacity from NZTs at end-of-life, 2025-2040. Source: Modelled data

Across all CRMs, there is currently low potential secondary availability from NZTs at end-of-life. This is simply due to few historic installations of these technologies, and therefore low quantities reaching end-of-life today. Secondary availability will increase in the future, increasing more quickly for the CRMs used in technologies with shorter life spans. This is particularly the case for those used in EVs.

This highlights an important limitation of CE approaches in the short term. Whilst recycling, recovery and reprocessing could make a significant contribution to future CRM supply, they are unlikely to address near-term supply pressures because many net zero technologies have not yet reached end-of-life in sufficient volumes.

8.3.1.1 Extending End of Life (EoL)

The National Engineering Policy Centre (National Engineering Policy Centre, 2024) state that the useful life of lithium batteries should be extended as far as possible, given the lack of recycling capacity for the predicted volume of EoL lithium-ion batteries in the coming years. EoL EV batteries can retain up to 75% of their capacity after 10 to 15 years of use, and could therefore be repurposed for stationary or back up power solutions, subject to the establishment of standards and protocols (National Engineering Policy Centre, 2024). Lusty et al. (2022) predict that this could create up to 20 kt of reusable cathode active materials for the UK market, enough to produce 7 Gigawatt hours (GWh) of power for alternative applications, assuming UK battery production capacity reaches 90 GWh by 2030. A majority of survey respondents and a research sector interviewee agreed that such EV battery reuse presents an opportunity.

8.3.2 Job creation and economic benefits

If Scotland meets its 2045 net zero emissions target, employment in low-carbon technologies is projected to exceed current oil and gas industry employment by the late 2030s (Scottish Enterprise, 2024). Around half of survey respondents see an opportunity for increased employment in the net zero transition, related to NZT development and deployment. Academic and research sector interviewees highlighted that Scotland has established energy engineering expertise from the oil and gas sector that could be redeployed into NZTs.

Around half of survey respondents agreed there is an opportunity for a green steel industry in the UK. This could be supported by scaling up electrically powered recycling to support offshore wind development, decommissioning of oil and gas to source recycled steel for new wind turbines (Zero Waste Scotland, 2023a). NGOs have highlighted a potential £9.6 billion UK market for remanufacturing ten key components for wind turbines over the next 10 years (Green Alliance, 2024b). Around half of survey respondents agreed there is a potential UK market for this. Mazzucato & Macfarlane (2024) suggest that an additional 20,000 jobs could be created in the UK by 2030 related to creating a circular economy for the floating offshore wind industry, concentrated in Scotland.

There is an opportunity for the UK to become a frontrunner in sustainable wind turbine technology, and a leading player in international standards development (National Engineering Policy Centre, 2024). Standards for wind turbines provide a basis for design, operation and maintenance and the UK is the greatest contributor of technical experts for wind energy standardisation at the International Electrotechnical Commission (IEC), a key global standards body. Great Britain is also currently chair of the IEC Technical Committee (2024-2029), providing the opportunity to increase the ambition of sustainable wind turbine technologies, and pursue proactive international standards development (National Engineering Policy Centre, 2024). One business/industry stakeholder noted the opportunity for Scotland to invest in digital product passports and design-for-disassembly standards, although such work should align with international action in this area.

It has been estimated that wind turbine component reuse, refurbishment and remanufacturing could benefit the UK economy by up to £1.6 billion in total gross value added between 2025 and 2035, not including the potential opportunity generated by turbine decommissioning (BVG Associates, 2023). This process, in Scotland specifically, could have generated up to 1.4 Mt of materials to date (Zero Waste Scotland, 2024). Three interviewed stakeholders from technical institutes highlighted existing expertise in academia (Aberdeen, Edinburgh, Heriot-Watt Universities), university 'spin-outs' such as Birmingham University's HyProMag, and the private sector (companies like Pure Alchemy and ReBlade) that can deliver these activities, particularly around wind turbine decommissioning.

Manufacturing of electrolysers and components could be worth up to £5 billion in the UK by 2030 (Zils et al, 2024a), and the Scottish Government has already commissioned work supporting deployment of an electrolyser supply chain in Scotland (Zils et al, 2024a).

Regarding upskilling, one academic interviewee pointed to Swedish Government support for the development of a master's programme specifically for industrial applications of CE, to upskill engineers on circular materials. It was noted that Scotland could do the same, with a small enough population and established educational.

8.3.3 Material substitution and less critical alternatives

The Renewable Parts Ltd specialist refurbishment centre has been identified as a key Scottish player in the transition to CE principles, particularly in the wind energy industry (Green Alliance, 2024a). Opportunities being explored include material substitution and innovation in alternative synthetics. Such technical development is important to reduce the quantity of primary-supply materials or to find less critical alternatives (Price, 2023). There may be an opportunity for the UK to substitute some copper components with aluminium in high-voltage subsea and underground cables and low-voltage distribution transformers. This could increase copper availability for use in other technologies subject to alignment with regulatory standards (Jackson et al., 2024). Ushie et al. (2025) reviewed global data to explore how to mitigate the volatility of critical copper and aluminium mineral demand for electricity network production in the net zero transition. They found that substitution scenarios reduced both global aluminium and copper demand by 2035. The scenario suggests that the properties and availability of aluminium make it less prone to supply and demand volatility than copper. However, as highlighted in section 5.2, short-term substitution of copper with other materials will be difficult, meaning increased demand cannot immediately be alleviated through alternative material selection (Energy Transitions Commission, 2023e).

8.3.4 Infrastructure

There is an opportunity for Scottish ports to become centres for the use and reuse of CRMs in offshore and onshore renewables manufacture, and disassembly of assets for recovery and reuse (Zero Waste Scotland, 2022). A majority of survey respondents and interviewees from business/industry and the research sector identified this as an opportunity. The Scottish Draft Energy Strategy and Just Transition Plan announced investment in an ultra-deep port in Shetland to increase the competitiveness of Scotland's decommissioning sector. It also notes that decommissioning at Scottish ports should follow CE principles, promoting material reuse over recycling and disposal (Scottish Government, 2023).

Whilst recognising the importance of access to finance, two other technical institute interviewees agreed that Scotland could emulate successful clusters in Teesside (ports), the Southwest (mining heritage) and West Midlands (recycling) by leveraging existing infrastructure and energy assets. Whilst the Scottish Clean Energy Cluster operates across the whole of Scotland, clustering efforts could be focused on areas such as the ultra-deep port in Shetland. This benefits from proximity to the North Sea and related trade routes, as well as relevant skills and labour. Offshore Wind Scotland also highlights the capacities of several other Scottish ports and harbours related to the offshore wind industry (Offshore Wind Scotland, 2026). These are located closer to key logistical centres such as the National Manufacturing Institute of Scotland and Conexus West.

8.3.5 Environmental, Social and Governance opportunity

One business/industry interviewee highlighted an opportunity for Scotland to develop coordination and cooperation with mining countries to reduce environmental impacts by ensuring alignment of ESG standards. The UK is already looking at ways to promote responsible mining and processing of CRMs, with an ambition for London to become a global hub for sustainable mining finance. An academic stakeholder noted that Scottish networks such as the National Manufacturing Institute Scotland (NMIS) offer scope for Scotland to be involved in the establishment of a network of leading R&D facilities for material recovery innovation.

8.4 Threats

We identified four key threats - circular economy viability, economies of scale in supply, price volatility, and the social license to operate.

8.4.1 Viability of circular economy approaches

Whilst embedding CE approaches as business as usual is a key opportunity (see section 7.3), there are inherent viability risks for some of these processes. For instance, global EoL recycling rates vary depending on the material, with processes well established for some (e.g. steel) and others in early stages of uptake (e.g. lithium or REEs) (Energy Transitions Commission, 2023a). The Energy Transitions Commission (2023a) identified key challenges related to efficiency and recycling improvements including:

- Complex and fragmented value chains that dilute market signals for investment in recycling (corroborated by a majority of survey respondents)
- Complexity of recycling processes due to variability in NZT design (verified by around half of survey respondents)

- Lack of cost-effectiveness in some cases (due to lack of volume and long lifespan of technologies) However, cost-effectiveness may increase over time due to economies of scale.

A lack of working capital may also pose a barrier to scaling the CE in CRMs for the energy transition – highlighted in section 7.2.3 and corroborated by the Task & Finish Group (2023).

Whilst secondary supply can be used to alleviate CRM supply chain risks in Scotland, there are also risks associated with secondary supply chains. These are similarly complex and fragmented (Energy Transitions Commission, 2023a) and also rely on imported materials, for example from China. Secondary supply of CRMs is less predictable than primary supply, for example due to the decommissioning cycles of existing infrastructure such as oil rigs or wind turbines. Around half of survey respondents reported the lack of predictability in secondary CRM supply as a risk. Quantities can also be affected by the uptake of circular approaches (such as repair or remanufacturing) that extend the lifetime of technologies and the materials they contain. For example, this can reduce the demand for new steel (Zero Waste Scotland, 2023a). However, Scotland has existing potential in this area (See Section 7.1.1).

Limitations related to capacity in recycling technologies have been identified (Simas et al, 2022). One technical institute stakeholder noted this can lead to disproportionate recovery costs. Industry and academic interviewees noted that Scotland has few recycling and midstream facilities compared to England, for example emerging REE and magnet recycling. This may be due to a lack of economies of scale, reducing the cost-effectiveness of Scottish investment, and lack of a regulatory framework and guidance to respond to inward investment propositions. Technical institute, academic and business interviewees noted that Scottish secondary smelting and refining infrastructure is limited to just one smelter, the Alvance-run billet and recycling facility and aluminium smelter in Lochaber (see section 7.3.1). Two technical institute stakeholders highlighted that high energy costs are a major deterrent for smelting and refining, with UK costs significantly higher than global competitors (see section 7.2.2). The Green Industrial Strategy (Scottish Government, 2024a) aims to maximise economic benefits to Scotland from the global net zero transition. Material reprocessing is noted as central to this goal, but domestic costs are likely to remain a challenge in the short term (Scottish Government, 2024c). We have not identified specific current or planned efforts to reduce these costs.

Current recycling technologies may also not be able to provide the levels of purity required for particular uses of some CRMs (e.g. aluminium), prohibiting the use of secondary supply (Jackson et al., 2024). These factors, along with the lack of a developed market for recovery of several CRMs, mean most scrap material is exported (according to business/industry and technical institute interviewees).

One source suggests Scotland may need to increase technical, skill-based, and infrastructural capacity to boost the domestic supply of secondary CRMs (SFA Oxford, 2023). These factors were reiterated by survey responses and interviewees. One survey respondent suggested a coherent longer-term plan and additional government support for skills relating to secondary CRM supply and CE more broadly, could help to safeguard critical metal supply and critical energy infrastructure.

8.4.2 CRM supply economies of scale

As discussed throughout chapter 6, there are multiple risks to CRM supply chains which can separately and collectively be classified as threats to Scotland's NZT ambitions. Around half of survey respondents agreed that lack of economies of scale for the development of CRM supply chains was a risk. One specific example is the opportunity to develop a battery-grade nickel supply chain in the UK, which must consider that EU demand for EV batteries will likely be realised much faster than that of the UK (SFA Oxford, 2023). Therefore, a nickel supply chain in the UK is only likely to be viable at scale if it can also serve the EU market in the shorter term. Combined with high UK energy costs compared with much of the rest of Europe, once an EU supply chain is established, UK industry might be unable to achieve comparable economies of scale (SFA Oxford, 2023).

8.4.3 Price volatility

As discussed in section 6.4, CRM prices can be highly volatile and affect private investment for further exploration in recycling or reuse (Frazer Nash Consultancy, 2025), corroborated by one business/industry interviewee.

Furthermore, Ross & Wright (2025) argue that Scotland could be "excluded" from certain markets depending on demand for local materials and processing within these markets which can be impacted by global policies and other green subsidy schemes. Around half of survey respondents saw this as a threat. Another consideration is Scottish export activities influenced by EU Acts relating to net zero and CRMs (Ross & Wright, 2025) and by unpredictable US trade protection measures. One survey respondent suggested Scotland could mitigate price volatility by securing long-term contracts for materials producers to provide speciality materials. Well-established strategies include maintaining a working inventory of materials through service-based contracts in which companies retain ownership over products and materials (Oakdene Hollins, 2014).

8.4.4 Social Licence to Operate of CRM-related projects

A Social Licence to Operate (SLO) is the ongoing approval from local communities and the public for an organisation or business to undertake a project. SLO concerns, particularly surrounding conducting exploratory or new CRM projects, have been identified as a significant barrier (Bide et al., 2022). Interviewees from research and academic fields stated that SLO concerns at any stage in the supply chain could also present a barrier to increasing supply in Scotland. Traditionally an energy-resource producer in oil and gas, Scotland is transitioning to be an energy-resource consumer. This structural shift could present a 'cultural shock' to certain communities that inhibits CRM activity (according to one academic interviewee), as community acceptance is critical (as noted by two research sector interviewees).

The landscape for sustainable mining is also complex, creating confusion for companies, consumers and investors (Bide et al., 2022). Risks associated with the acceptability and ESG concerns of CRM-related activities were seen as a threat by around one-third of respondents. One survey respondent highlighted that due diligence related to ESG should not be seen as a threat, but rather as a minimum requirement.

8.5 Implications of SWOT findings for Scotland

Scotland has a strong foundation to embrace a CE for CRMs in the net zero transition. This is underpinned by existing strengths related to established expertise in the mining, oil and gas industry, adherence to high ESG standards, and a robust R&D landscape.

Hebridean New Metals has identified potential sites for REEs, manganese, and lithium. Aberdeen Minerals has identified nickel, cobalt, and copper in Scotland and this review has identified the highest potential for extraction of nickel in Scotland. Whilst historical estimates of nickel (and copper) make up are not known in modern reporting standards, exploration of the Arthrath Intrusion for nickel-copper-cobalt mineralisation was ongoing by Aberdeen Minerals Ltd as of 2022 (Gunn & Deady, 2022). Of course, mining in itself is not circular, so domestic mining potential must be contextualised alongside production and manufacturing potential. Weaknesses in other parts of the value chain, such as manufacturing and recycling infrastructure, have also been identified.

Nevertheless, significant opportunities exist for Scotland to pursue CE approaches in relation to the CRMs needed for NZTs. For instance, boosting domestic recycling efforts could be feasible for CRMs including aluminium, lithium, and neodymium. Our review has also identified the potential to boost the secondary supply of CRMs, for example through recovery of CRMs from historical mining sites. Scotland also has potential to efficiently process end-of-life products, including EV lithium-ion batteries, wind turbines and solar PV panels. Such initiatives could alleviate supply pressures and create new revenue streams for the Scottish economy.

The net zero transition presents a key opportunity for job creation in sectors reliant on CRMs such as green steel production and the expanding offshore wind industry. It has been identified that Scotland can effectively redeploy and upskill its existing offshore and oil and gas engineering capacities.

Scotland also has an opportunity to become a global leader in sustainable wind turbine technology through shaping international standards. One avenue for this is the UK’s current position as chair of the International Electrotechnical Commission Technical Committee, offering a chance for Scotland to push for proactive international standards development.

Scotland can also leverage its existing port infrastructure to establish centres for renewables projects, creating hubs or clusters for the efficient use, reuse, and recovery of CRMs for reprocessing.

9 Conclusions

We found that Scotland faces significant risks from global CRM supply chains as demand for net zero technologies increase. Circular economy approaches could help reduce some of these risks. Scotland has strengths that could support greater recovery, reuse and recycling of CRMs.

Our research focused on 10 CRMs (aluminium, cobalt, copper, iron, lithium, manganese, nickel, niobium, rare earth elements, silicon) and their use in selected net zero technologies (NZTS). These included onshore and offshore wind, solar power, electricity networks, electric vehicles, hydrogen and fuel cells. CRMs are also used in other NZTs and sectors, including defence, transport, chemicals, electronics and medical technology. These uses will also influence future CRM demand and the actions needed to reduce supply chain risks.

Table 4 summarises the main supply chain risks we identified and their implications for Scotland. It also shows where these risks occur across the CRM supply chain and identifies potential opportunities for Scottish action. Most opportunities relate to circular economy approaches, although mineral exploration and extraction could also help reduce some supply risks.

Overall, the evidence reviewed suggest that Scotland has a strong foundation for developing a more circular approach to CRMs. However, gaps in infrastructure, skills, data, investment and markets could limit progress. Addressing these gaps will require coordinated action across government, industry, research and other stakeholders.

Table 5 Summary of risks, weaknesses and threats, their implications, links to supply chain stage, and opportunities for Scottish action

Risk, weakness or threat	Potential implication for Scotland	Stage(s) in the supply chain	Examples of opportunities for Scottish action
Increasing global-level demand for CRMs	Competition for CRM resources leading to future supply risks for Scotland, in particular for copper, lithium, nickel and Rare Earth Elements (REEs).	• Exploration & extraction • Refining & processing • Manufacturing, design & production • Use & end-of-life	• Explore extension of life of NZTs to decrease Scottish demand, e.g. remanufacturing of wind turbine components, use of retired Electric Vehicle (EV) batteries for energy storage. • Explore material substitution opportunities.
Geographical concentration of CRM supply (extraction, processing and refining), and link to geopolitical tensions, e.g. third country policies and tariffs	High reliance on small number of countries for supply of CRMs for net zero, increased risk to UK (and Scotland) from future shocks.	• Exploration & extraction • Refining & processing	• Seek to influence UK membership of strategic global CRM partnerships, e.g. G7 Critical Minerals Production Alliance. • Seek to influence UK trade-related policies, e.g. in relation to tariffs or taxation.
Lack of overall coherent Scottish strategy on CRMs and regulatory uncertainty	Hampers Scottish investment and creation of domestic markets.	• Exploration & extraction • Refining & processing • Manufacturing, design & production • Use & end-of-life	• Identify niches of excellence for Scotland to contribute to implementation of UK Critical Minerals Strategy, coordinating with UK Government. • Address Scottish regulatory barriers, e.g. waste regulation, permitting and licensing.
Limited activity and lack of data on exploration for CRM deposits in Scotland	Limits opportunities for extraction in Scotland and contribution to UK Critical Minerals Strategy 10% domestic production target. Exacerbates Scottish reliance on imports of CRMs.	• Exploration & extraction	• Further explore (via research and geological surveys) extraction potential for nickel, cobalt, copper, REEs, manganese, lithium and silicon in Scotland. • Draw on existing Scottish expertise and skills in mining, oil and gas, and research and development (R&D).
Social licence to operate (SLO) and environmental, social and governance (ESG) concerns for CRM related activities	Balance needed between ethical and sustainably sourced CRMs, net zero goals and public acceptance for Scottish exploration or other new projects	• Exploration & extraction • Refining & processing • Manufacturing, design & production • Use & end-of-life	• Continue adherence to high ESG standards to increase acceptance for future Scottish CRM actions.

Risk, weakness or threat	Potential implication for Scotland	Stage(s) in the supply chain	Examples of opportunities for Scottish action
Low/variable CRM recovery and recycling rates, due to complexity and economies of scale of CRM recycling	Missed opportunities for recovery, processing and supply of CRMs in Scotland, with associated missed economic opportunities.	• Refining & processing • Use & end-of-life	• Explore development of Scottish recycling for CRMs including aluminium, lithium, and neodymium.
Limited infrastructure to recover, recycle and reprocess CRMs, and remanufacture components	Limits Scottish (and UK) CE opportunities for recovery, processing and supply of CRMs.	• Refining & processing • Manufacturing, design & production • Use & end-of-life	• Leverage existing Scottish port infrastructure to establish hubs or clusters for efficient use, reuse, and recovery of CRMs for reprocessing, e.g. steel and REEs from wind turbine decommissioning. • Consider prioritising actions related to midstream material (re)processing.
Limited supply of secondary CRMs for recycling/processing	Hampers development of Scottish (and UK) markets for - and supply of - secondary CRMs, and potential missed revenue for the Scottish economy.	• Refining & processing • Manufacturing, design & production • Use & end-of-life	• Develop Scottish processing of end-of-life products, e.g. wind turbines, EV batteries and solar photovoltaic (PV) panels. • Map presence of existing CRMs in Scotland (e.g. in Waste electrical and electronic equipment (WEEE), NZT infrastructure, industrial/mining wastes, domestic plumbing). • Explore Scottish stockpiling of components containing CRMS.
Lack of data on presence, traceability and quality of CRMs in products, including NZTs	Hampers recovery of CRMs from products, reducing potential Scottish supply.	• Refining & processing • Use & end-of-life	• Push for ambitious international standards and support rollout of product passports, e.g. through UK's chair of International Electrotechnical Commission Technical Committee.
Technical skills gaps in CRM supply chain	Weakens opportunities for Scotland to take CE actions	• Exploration & extraction • Refining & processing • Manufacturing, design & production • Use & end-of-life	• Build on, deploy or upskill existing Scottish skills capacity from engineering and geology (mining, oil and gas), materials R&D and Science, Technology, Engineering and Maths (STEM) universities, e.g. to support development of green steel production and wind turbine decommissioning.

Risk, weakness or threat	Potential implication for Scotland	Stage(s) in the supply chain	Examples of opportunities for Scottish action
Price volatility and low resale value for some secondary materials	Hampers Scottish investment in development of infrastructure and markets for secondary CRMs.	• Refining & processing • Manufacturing, design & production • Use & end-of-life	• Explore options to develop Scottish markets via voluntary industry commitments or use of commercial procurement criteria.
Lack of domestic investment in CRM circularity solutions	Hampers development of infrastructure and circularity actions in Scotland.	• Refining & processing • Manufacturing, design & production • Use & end-of-life	• Promote investment in Scottish R&D activities, recycling reprocessing and remanufacturing infrastructure. • Leverage existing UK funds, e.g. UK R&D funds, UK Contracts for Difference Clean Industry Bonus

9.1 Discussion of opportunities for Scotland

The discussion below is structured around the policy levers identified in the Circular Economy Strategy for Scotland (Scottish Government, 2026). These are: business support, behaviour and systems change, place-based approaches, procurement, skills and education, data improvements, and greater policy alignment.

Our findings identify several areas where Scotland could reduce CRM supply chain risks. Overall, the evidence reviewed suggests that Scotland's strongest opportunities are likely to lie in recovery, reprocessing, remanufacturing and related circular economy activities, rather than large-scale primary extraction of CRMs. These include investment, place-based approaches, procurement, extending product lifetimes, skills, data and policy alignment. Some actions fall within Scottish responsibilities. Others would require action through UK or international channels.

Several recurring opportunities emerge from this research, particularly around circular economy activity, data and traceability, skills development, and policy coordination. The discussion below considers these opportunities in more detail.

9.1.1 Business support through investment

Developing CRM circularity will require **investment** in research (see sections 8.1.3 and 8.1.5) and infrastructure for CRM recycling, reprocessing and remanufacturing. While economic development is a devolved Scottish power, there are also UK funding options to explore. These include UK R&D funds and the UK Contracts for Difference Clean Industry Bonus, which provides additional revenue support to offshore wind projects that invest in shorter supply chains or more sustainable production methods (as noted by a business/industry interviewee). Great British Energy has also announced a £300 million Supply Chain Fund for Offshore Wind and Networks, providing grants for domestic manufacturing of critical components (Great British Energy, 2025). Using funding opportunities such as these could help develop manufacturing activities and supply chains in Scotland and the wider UK, creating markets for secondary CRMs recovered domestically.

9.1.2 Place-based approaches

Scotland’s extensive and growing wind energy capacity and infrastructure, one key opportunity to develop a **Scottish cluster or hub for CRM circularity in onshore and offshore wind**. Relevant devolved powers include economic development, renewable energy, circular economy, waste management, planning and permitting. Stakeholders suggested Scotland prioritising midstream processing and reprocessing to provide secondary CRMs, for example through chemical engineering and magnet recycling. End-of-life turbines offer large volumes of reclaimable steel and rare earth element (REE) magnets. There is also potential for a UK market worth £9.6 billion from remanufacturing ten key wind turbine components (Mazzucato & MacFarlane, 2024). The Development Framework for the Hagshaw Energy Cluster includes a CE strategy focused on local skills and materials, and identified the reuse and recycling of wind turbines as a future opportunity.
Existing **Scottish infrastructure and energy assets**, particularly ports and clean energy to power processing could support domestic CRM recovery, turbine disassembly, material recycling and component remanufacturing. Several interviewees highlighted the potential for Scottish ports to become centres for CRM recovery and reuse in the renewables sector,

supported by access to logistics, skills and labour. This aligns with investment announced in the Scottish Draft Energy Strategy and Just Transition Plan for an ultra-deep port in Shetland to strengthen the decommissioning sector (Zero Waste Scotland, 2022). In addition, Renewable Parts Ltd's innovation centre in Argyll and Bute specialises in circular innovation for the wind industry, such as remanufacturing of wind turbine components (Renewable Parts Ltd, 2026).

One stakeholder indicated potential for the **aluminium smelter** in Lochaber to process some of the aluminium scrap currently collected and exported from the UK, keeping this valuable material in the domestic supply chain. The smelter's use of hydropower helps offset high energy costs, although opportunities of this type are location-specific and would need to be assessed on a case-by-case basis. The **Lochaline silica sand mine** deposit was noted by another stakeholder as small but of a purity suitable for semiconductors and PVs.

Exploring material substitution and innovation in alternative synthetics could alleviate some primary and secondary supply pressure. Scotland's world leading STEM research base could support innovation in this area. Survey respondents also identified revenue generation from key CRMs at the end-of-life stage and development of new secondary CRMs supply markets in the UK are as key opportunities for Scotland.

Domestic **stockpiling of components containing CRMs** could reduce the current loss of CRMs exported for processing and provide initial stocks for domestic refurbishment or reuse, as well as for future domestic recycling facilities. Strategic prioritisation of specific CRMs, such as REEs in wind turbines or aluminium, may allow Scotland to benefit from economies of scale and support future processing and reprocessing. Scotland could also contribute to actions under the recently-signed UK-US Memorandum of Understanding on critical minerals (Department for Business and Trade, 2026).

9.1.3 Procurement

Voluntary commitments or commercial procurement of NZT infrastructure based on standards and product CRM content could also drive circularity. One business/industry stakeholder noted that the wind sector is particularly sensitive to corporate social responsibility and public perception. This could make commitments to procure wind turbines containing a certain percentage of locally recycled magnets a potential selling point. Although aspects of industrial policy are devolved or reserved UK powers, Scotland may be able to take relevant action through its devolved powers in economic development, energy and permitting.

9.1.4 EV battery use

One example of a systems-based approach noted in the literature and by stakeholders is exploring how to **extend the power output of EV batteries**. For example, by using them to store energy generated by Scottish renewables. This could make better use of available battery capacity while helping to address the current lack of recycling capacity for the expected increase in end-of-life lithium-ion batteries.

9.1.5 Skills and education

Both the reviewed literature and stakeholder discussions indicate existing strengths that could be built on to further **develop Scotland's workforce and academic expertise** in CRM circularity. Possible focus areas include material sciences (including innovation, substitution and purification), geology, NZT and component design, recycling innovations and cost-effectiveness, and high-tech and chemical engineering. Scotland's **STEM universities, engineering industries and R&D hubs** provide a strong foundation, alongside expertise in chemical manufacturing at Grangemouth. Interviewees also suggested that targeted academic programmes on CRM could help retain domestic talent and export knowledge to other countries.

9.1.6 Data improvements

An exercise to **map the presence of CRMs in Scotland** and when they may become available would help plan for future domestic supply. CRMs can be found in existing NZT infrastructure, industrial waste such as coal fly ash storage sites (REEs), and domestic plumbing and WEEE (copper). This could provide greater certainty for planning and investment in domestic CRM circularity and strengthen Scotland's expertise in CRM identification and recovery. This would require cooperation between government, SEPA, planning bodies and private sector supply chain actors to ensure robust, whole-system data. Interviewees suggested building on the End of Life Wind (ELMWind) project. This could be aligned with work by the UK Technology Metals Observatory and Critical Minerals Intelligence Centre on data, stocks and flows of 'technology metals'. It could also build on work by the new Supply Chains unit in DESNZ to identify bottlenecks to delivering clean power for 2030.

The provision of **information to allow CRM identification and recovery** at end-of-life is crucial. Supporting the development of international standards, regulation and digital product passports, and aligning national standards with these, could maximise the potential for secondary CRM recovery in Scotland and internationally. Several interviewees highlighted this opportunity. Scotland could also build a global reputation for knowledge on recyclability/disassembly-by-design, standards and traceability. This could be supported by promoting ambitious international standards and the rollout of product passports, including through the UK's current chair of International Electrotechnical Commission Technical Committee.

Whilst domestic extraction is not a CE opportunity, its potential to reduce supply chain risks is noted in the UK Critical Minerals Strategy. Further research and geological surveys could improve **knowledge on Scottish extraction opportunities,** help assess their commercial viability, and even reduce reliance on imports of some CRMs. However, one academic interviewee noted that barriers such as limited material deposits, environmental regulations and permitting may mean that circularity actions in other areas will likely be more meaningful for Scotland.

9.1.7 Greater policy alignment

There may be existing **regulatory barriers** to waste processing that could be addressed in Scotland to support future CRM recycling. Two technical institute interviewees suggested these may include waste classification and shipment rules, permitting and licensing for waste carriers.

Stakeholders highlighted opportunities for Scotland to influence **UK participation in strategic global CRM solutions and partnerships.** One example is the G7 Critical Minerals

Production Alliance. This was created in June 2025 to promote multilateral partnerships and investment in sustainable CRM projects, helping to reduce market concentration and dependencies (Government of Canada, 2025). An academic interviewee suggested Scotland is an attractive partner for mineral-rich countries, with expertise to share on technology, skills and standards. Stakeholders also suggested potential for Scotland to establish a regional or global data hub on CRM flows, and for Edinburgh’s financial sector to support responsible financing of ethical and modern mining projects globally.

Another key priority is to anticipate, understand and respond to **global policy shifts**. These include the European Union (EU)’s carbon border adjustment mechanism (CBAM), green subsidies and trade tariffs. Tools such as the EU’s CBAM can encourage investment in less carbon-intensive supply chains, compared with markets without the same environmental protections in place (SFA Oxford, 2023). As trade and taxation are reserved UK powers, Scotland could seek to influence UK policy in these areas. Scotland could also identify areas of expertise where it can contribute to implementing the UK Critical Minerals Strategy in coordination with the UK Government.

Given the various barriers, uses, challenges and trade-offs, there is a broader need for a **strategic and coherent vision** for Scottish actions on CRM circularity. Implementation of the forthcoming Circular Economy Strategy for Scotland is a key opportunity to outline thematic actions, investment needs and associated timelines for Scotland to realise its CRM-related potential.

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11 Appendices

Appendix A Relevant legislation, policies and strategies

Table 6 summarises the key legislation, policies and strategies that provide the Scottish context for our research.

Table 6: Legislation, policies and strategies relevant to CRMs and NZTs in Scotland

Document	Relevance
Climate Change (Scotland) Act 2009 (as amended in 2019 and 2024)	• Commits Scotland to a net zero target by 2045.
Draft Climate Change Plan (Scottish Government, 2025a)	• Outlines emissions reductions actions related to energy supply, waste management and transport.
Green Industrial Strategy (Scottish Government, 2024a)	• Aims to maximise economic benefits from global net zero transition opportunities, in particular wind and hydrogen. • Objective to build supply chain resilience through recycling and remanufacturing of components and materials, including Circular Economy (CE) approaches to secure critical materials for the energy transition. • Notes recycling/remanufacturing of wind economy facilities as a specific opportunity. • Notes need to collaborate with UK Government on critical imports and supply chain resilience.
Hydrogen Action Plan (Scottish Government, 2022)	• Aims to provide 5 Gigawatts (GW) of hydrogen production capacity (around 15% of Scotland's current energy needs) by 2030 and 25 GW by 2045.
Draft Energy Strategy and Just Transition Plan (Scottish Government, 2023)	• Notes ambition for over 20 GW of additional renewable electricity by 2030, including increase in solar. • Indicates phase out of new petrol and diesel cars and vans by 2030. • Notes ambition to achieve energy security and export surplus electricity. • Notes commitment to adopt CE approaches to sourcing materials (including recycling/refurbishment of turbines and Electric Vehicle (EV) battery recycling).
Scottish National Adaptation Plan 2024-2029 (Scottish Government, 2024b)	• Objective of "Climate resilient economic development and supply chains". • Scottish Government to explore how recycling and remanufacturing can build supply chain resilience regarding critical raw materials (CRMs) for the energy transition.
Circular Economy (Scotland) Act 2024	• Requires Ministers to prepare and publish a CE strategy.
Scotland's Circular Economy and Waste Route Map to 2030 (Scottish Government, 2024c)	• Sets strategic direction for CE in Scotland.

Document	Relevance
Draft Circular Economy Strategy (Scottish Government, 2026)	• Calls for Scottish economy based on CE principles, skills and knowledge. Aims to maximise economic value, create supply chain security, innovation and sustainable resource use. • Objective to make Scottish economy more resilient to material supply disruptions, including CRMs. • Includes priority to maximise role of CE for CRMs in Scotland. • Net zero energy infrastructure and transport identified as priority sectors, including relevance to CRMs. • Notes key policy levers: business support, behaviour change, place-based approaches, procurement, skills and education, data improvements, and greater policy alignment.
United Kingdom (UK) Critical Minerals Strategy (UK Government, 2025a)	• Sets vision for UK to have the critical minerals needed for economic growth and clean energy transition. • By 2035, calls for: 10% of annual UK demand from domestic production (extraction, processing and refining), including 50,000 tonnes (t) of lithium/lithium carbonate equivalent; 20% from recycling of products; and no more than 60% of demand from any one country. • Recognises role of CE, but also associated challenges. • Recognises UK strengths in R&D and innovation, midstream processing and recycling, and need for skills development, access to finance and investment. • Specifically notes Aberdeen and Fort William as promising regional clusters.

Appendix B Study methodology

This appendix summarises the study methodology. Key steps were the selection of focus critical raw materials (CRMs) for the research, the selection and review of relevant literature, and the stakeholder engagement survey and interviews carried out to complement the literature review.

Selection of focus CRMs

Before starting the literature review, we defined focus CRMs from within the list of 34 United Kingdom (UK) CRMs plus copper, to keep the research focused and of a reasonable depth.

The key considerations used to select the focus CRMs were:

1. **Relevance of the CRMs to the Steering Group's list of net zero technologies (NZTs):** Using several sources, we checked the relevance of the CRMs to the eight NZTs suggested by the Steering Group: on/offshore wind; fuel cells and hydrogen (grouped in the net zero context); heat pumps; batteries (EV) and energy storage (grouped for similar CRM use); the grid; solar/Photovoltaics (PVs). Ten CRMs were identified as relevant to three or more of the technologies.
2. **Comparative importance of NZTs in Scotland, cross-checked with the National Energy Systems Operator (NESO) Future Energy Scenarios (FES):** We reviewed

the 2023 Draft Energy Strategy and Just Transition Plan for Scotland and cross-checked these with the 2025 NESO FES pathways. This confirmed on/offshore wind, hydrogen/fuel cells, batteries, the grid and solar/PV to be most important.

3. **CRMs with a high UK criticality score:** We reviewed the overall criticality score for each CRM in the 2024 UK Criticality Assessment. Ten CRMs of relevance to NZTs had an overall criticality score of 5 or higher.
4. **Zero Waste Scotland's report on Energy Infrastructure Materials Mapping:** To further consider the Scottish context, we noted the materials this report highlights as vital for future energy infrastructure: aluminium, copper, neodymium (a REE), carbon, iridium, nickel, iron, platinum, lithium-cobalt oxide and titanium (chromium, steel and concrete are not on the UK CRMs list).
5. **Presence on other countries' criticality lists:** To consider global criticality and competition for CRMs, we noted which UK CRMs are also on criticality lists for the European Union (EU), United States of America, Canada and Australia.

The application of the selection criteria is summarised in Table 7, with the CRMs in bold selected for the focus list. This list captures: some of the most critical battery metals (cobalt, nickel, lithium), crucial materials for motors and wind turbines (Rare Earth Elements, REEs) and for solar, grid infrastructure, and emerging hydrogen technologies (silicon, aluminium, iron, manganese, niobium), and copper, which will be vital for wider electrification.

Table 7: Summary of selection criteria for focus CRMs *W = wind, H = hydrogen, S = solar, B = batteries, G = grid ^EU lists these as 'strategic' rather than 'critical', hence the .5 scores

CRM	Relevance to key net zero technologies*	UK overall criticality score	Presence on other criticality lists
Aluminium	W H S B G	4.2	4
Antimony	S	4.5	4
Bismuth	S	4.5	4
Borates	W S	4.5	1
Cobalt	W H B	6.4	4
Copper	W S B G	3.4	1.5^
Gallium	S	5.3	4
Germanium	S	6	4
Graphite (carbon)	H B	4.1	3
Iridium	H	5	4
Iron	W H S B G	4.8	0
Lithium	B	4.7	4
Manganese	W H B	4	4
Nickel	W H S B	4.3	3.5^
Niobium	W B	6.6	4
Phosphorus	B	5.8	1
Platinum	H	4.6	4
REEs	W H B	6.2	4
Ruthenium	H	5.6	4
Silicon	W S B	5.3	2
Titanium	H B	4.7	4
Vanadium	B	5.2	4
Zinc	W S	4	2

Selection and review of literature

Selection of literature

We identified a range of literature including official Scottish (and UK) legislation and policy (to understand the policy context), academic literature (to gather data and peer-reviewed insights), and other literature such as reports by organisations and research consultancies (to gather data and insights from various interests).

The key policies and legislation used to confirm the policy context were:

- The Climate Change (Scotland) Act 2009;

- The Draft Climate Change Plan;
- The Scottish National Adaptation Plan 2024-2029;
- The 2022 Scottish Hydrogen Action Plan;
- The 2024 Scottish Green Industrial Strategy;
- The 2023 Scottish Draft Energy Strategy and Just Transition Plan;
- The 2025 UK Critical Minerals Strategy;
- The Circular Economy (Scotland) Act 2024;
- Scotland's Circular Economy and Waste Route Map to 2030; and
- The 2025 Draft Circular Economy Strategy for Scotland.

We searched the websites of key organisations, including Zero Waste Scotland, the UK Critical Minerals Intelligence Centre (CMIC), the UK Technology Metals Observatory, Scottish Enterprise and the NESO. We focused on documents addressing net zero energy technologies, CRMs and material supply chains. Most of the literature found via this route is grey literature, or technical reports. We received a small number of additional useful suggestions from the project steering group.

In addition, we used Google Scholar and wider Google searches to identify potentially useful literature. This was based on single and combined keyword searches, with terms including "Scotland", "Scottish", "critical raw materials", "net zero", "renewable*", "energy", "energy technolog*", "circular", "risk", "econom*" and "supply chain".

In total, we reviewed ten key pieces of official policy and legislation and around 70 pieces of other (academic, technical and grey) literature, written by over 30 different organisations and authors. Around 20% of the sources selected for review are academic literature, around 40% technical (e.g. British Geological Survey, UK CMIC, Energy Transitions Commission, NESO) and the remaining 40% grey literature. Limited Scotland-specific data sets were found.

Review of literature

Each source was reviewed by one member of the team. Firstly, the executive summary/abstract was screened using keyword searches. Keywords used, in addition to those noted in the previous section, were the ten focus CRMs and the five key NZTs.

For each source found to be of relevance, we searched the remainder of the document for the same keywords. We logged useful information in a literature review sheet in a central shared Excel register, including key document details and information of relevance to the research questions.

Stakeholder engagement

Following the literature review, we undertook a stakeholder engagement phase comprised of:

1. Engagement with stakeholders via an online survey
2. A series of semi-structured online interviews with selected stakeholders.

We obtained informed consent from all stakeholders via a project information form and consent form (either at the start of the survey or prior to interview). Stakeholders were made aware of how their inputs would be used and offered the chance to withdraw consent at any time. All data was handled and held in accordance with GDPR and confidentiality requirements.

Online survey

The survey contained a section on each of the project's main research questions:

- What is the current and projected CRM demand associated with Scotland's renewable and NZTs?
- What are the most significant risks to these CRM supply chains over the medium-term time horizon (2025-2040) relevant to Scotland's renewables and net zero sectors? At what stages of renewable deployment do these risks lie?
- What are the key economic strengths, weaknesses, opportunities and threats associated with CRMs, especially in the context of a circular economy for Scotland?

We developed questions related to specific CRMs, technologies and/or supply chain risks, with a particular focus on knowledge gaps identified via the literature review. Question formats used a range of multiple choice, Likert scale questions, and open-ended questions to allow respondents to provide more detailed answers. The survey was designed to allow different respondents to complete only sections relevant to their background, skills and experience. Our communication to stakeholders clarified which sections and questions related to which topic areas.

Using the Excel-based register compiled during the literature review phase, all documents with named authors were interrogated further to identify email addresses. These were obtained via a basic Internet search. This created a 'long-list' of identifiable stakeholders to send the initial stakeholder survey to. The survey was not initially sent to stakeholders identified as potential interviewees, although it was sent as an alternative to those who declined an interview.

The survey was sent to 90 stakeholders, who were then sent reminders in an attempt to increase the response rate. In total, we received 17 responses. Five responses were received from private sector companies, five from public and private research institutions, three from industry associations, two from civil society organisations, and two from academia.

In the report we have simplified how we cite the number of respondents giving a particular answer, by consistent application of the following bands:

- 0-10% of respondents - very few
- 11-25% of respondents - a minority
- 26-40% of respondents - around one third
- 41-60% of respondents - around half
- 61-75% of respondents - a majority
- 76-90% of respondents - a large majority
- 91-100% of respondents - almost all

Stakeholder interviews

We discussed a longlist of potential interviewees with ClimateXChange. After review, a shortlist of interviewees was identified. We selected participants for interview based on a combination of factors. The first was geography – aiming to achieve a balance between those living and working in Scotland, the wider UK and internationally. Additionally, a variety of institutional backgrounds – academia, business/industry, public sector and non-governmental organisations (NGOs) – were targeted to ensure representation across stakeholder groups. Finally, we aimed to ensure that the expertise of those interviewed together covered topics related to all three key research questions.

We sent personalised invitations for interview to 14 individuals. Nine accepted, with interviews held over a five-week period from December 2025 to January 2026. Three interviewees were from academia (professors of geology, energy materials and sustainable material manufacture), two from the research sector, two from business/industry and two from technical institutes. The organisations are as follows (one anonymised by request):

- Academia: Cranfield University, St. Andrews University and Lincoln University
- Research sector: SINTEF (Norwegian independent research organisation) and British Geological Survey
- Business/industry: Circularity Collective and Business group (anonymised)
- Technical institutes: Institute of Materials, Minerals and Mining, and Critical Minerals Association

Interviews were up to one hour long and used a semi-structured format. We tailored questions to the expertise of each interviewee, taking account of their published work identified in the literature review. Individuals were encouraged to elaborate on the findings of their work in the context of the core research questions. They were also invited to offer policy-related reflections based on their expertise and experience.

We conducted and recorded interviews via Microsoft Teams, with transcription (verbatim) using the built-in Artificial Intelligence function. A written two-page summary was produced from each transcript. We then collated key points related to the project's core research questions into a sheet in the study's Excel register and integrated these into the relevant chapters of this report. Points mentioned by several stakeholders were prioritised for inclusion in the report. Points mentioned by only one interviewee were included if deemed to be of particular importance or contributing something new. Less pertinent points made by only one interviewee were not included. The type(s) of stakeholder making each point is noted in the report, to provide context on where the comments originate from.

Limitations

Our research faced some limitations. We focused on only 10 CRMs, and a subset of NZTs. These choices were made to keep the research manageable and to focus on areas where more data was anticipated to be available. The report should therefore not be seen as providing a full picture regarding all 34 UK CRMs plus copper, across all NZTs.

We also found limited Scotland-specific data sets, meaning that in some cases we rely on UK or global data. We relied in particular on one Zero Waste Scotland source (2023b) for Scotland-specific information on materials for the energy transition.

Regarding the stakeholder engagement phase, we had a somewhat limited response rate to the survey, meaning that responses may not reflect the full range of stakeholder opinion.

The number of interviews held was as anticipated based on the study resources, but again may not be fully representative of all stakeholder views.

For discussion surrounding uncertainties and interpretation related to the modelling data and methodology, please see Appendix C.

Appendix C Modelling data and assumptions

This section presents background details to understand the modelling work. This includes:

- The methodology used to create the model;
- All data sources and assumptions that fed into the model; and
- Discussion on uncertainty and interpretability of the results.

Model methodology

The aim of the modelling exercise was to forecast supply (primary and secondary) and demand for six critical raw materials (CRMs) in Scotland over time. We ultimately looked at seven CRMs due to good data availability, and the presence of multiple different CRMs in so many net-zero technologies (NZTs) in scope.

The modelling was designed to answer the following questions:

- What is the Scottish annual demand for CRMs for applications in NZTs into the future?
- What is the production/availability of secondary CRMs for use in Scotland/the United Kingdom (UK), assuming appropriate domestic recycling facilities are developed?
- What is the global availability of primary CRMs?
- What are the net required imports of CRMs over time in Scotland?
- Should Scotland invest in domestic recycling capacities, and for which CRMs would this be appropriate?

The CRMs included in this analysis are: cobalt, copper, lithium, manganese, nickel, Rare Earth Elements (REEs) and silicon. These were selected because they had the best data availability. In the process of shortlisting the CRMs, attention was paid to the CRM make-up of the NZTs. It is important to note that the data and modelling in this study is restricted to demand from NZTs. It does not consider alternative demand-side pressures in a comprehensive or systematic way, relying predominately on a single source from the International Energy Agency (International Energy Agency, 2022). Care should therefore be taken when interpreting these results.

The modelling analysis predicts future supply and demand of these CRMs at three geographical levels: Scotland, the rest of the UK, and global. A number of datasets were used as inputs to the modelling.

Historic and projected data were used as inputs at each of the three geographical levels regarding:

- The annual uptake rates of each NZT. For example, annual installed Megawatt (MW) capacity of onshore wind.

- The quantity of each CRM required for a ‘unit’ of a NZT. For example, the quantity of copper required in a MW installed capacity of onshore wind, which changes over time due to a changing onshore wind technology mix.
- The average lifetime of each NZT. E.g., the average lifetime of an onshore wind farm.

In addition, at a global level only, the model uses historic and projected data on:

- The annual global primary production of each CRM. For example, the annual production of primary refined copper.
- The annual global secondary production of each CRM. For example, the annual production of secondary refined copper.
- The demand for each CRM in other technologies outside of NZT demand. For example, the annual non-NZT global demand for copper.

Where available, this data was obtained from external sources. Where data gaps existed, the data was produced by the modelling team. The full set of external data sources, as well as the assumptions used by the team to fill data gaps, is set out in 10.6 below.

The model then took these inputs, and created the following projections:

- Annual CRM demand per NZT in Scotland (see Figure 5-11), the rest of the UK, and globally
- Annual net CRM availability (supply minus demand) considering NZTs only (for Scotland, see Figure 12 to Figure 18) and across all uses (Figure 34 - Figure 37 for net global supply in the context of Scottish NZT ambitions)
- Annual NZT end of life quantities (see Figure 22 to Figure 25) for Scotland and the rest of the UK).

Modelling includes timeseries analysis using raw- and generated- data.

Data, data sources and assumptions

The following section records data, sources and assumptions systematically for each datapoint used within these models.

Grid infrastructure

Copper is one of the core CRMs needed for grid infrastructure (Petavratzi et al., 2024c). The following data sources were used to model grid copper requirements;

- At the global level, copper demand for electricity grids between 2020 and 2040 (International Energy Agency, 2021b);
- At the UK level copper demand in grid infrastructure is available for 2030 and 2050 (Jackson et al., 2024);
- Scottish copper requirements for the grid were assumed to be 9.5% of this, as Scotland has 9.5% of UK power meter connections (Department for Energy Security and Net Zero, 2025c).

Net zero technology uptake

The uptake of NZTs in Scotland has been modelled based on Scottish policy projections.

Table 8 Data used to model projected uptake of NZTs in Scotland

NZT	Data Source	Assumptions/how data is used
Onshore and offshore wind	Wind energy in Scotland (Scottish Parliament, 2023)	This provides current deployment and government targets for the UK and Scottish Governments for on and offshore wind up to 2050
Solar Photovoltaic (PV)	Deployment ambition for solar power generation 2030: EIR release (Scottish Government, 2024d)	We take the 2030 deployment target of 4-6 Gigawatts (GW) (assuming 5 GW) and model an annual increase based on actual deployed capacity until 2024, to reach the necessary cumulative total in 2030 for Scotland. We assume a linear progression. Due to a lack of target made in Scotland for solar deployment past 2030, for the figure up to 2040, we set this as a % of the UK target, equal to 2030 ratio.
Battery Energy Storage Systems (BESS)	Good practice principles for grid-scale battery Storage (Gardner, et al., 2020)	Grid scale battery storage predictions for Scotland up to 2045.
	National Energy Systems Operator (NESO)’s Future Energy Scenarios (FES) (National Energy System Operator, 2025)	Future predictions for Battery Storage in Scotland and UK up to 2050.
EV batteries	According to Zero Waste Scotland, the net zero transition will require the number of EVs in Scotland to reach 579,000 by 2030 and 3.4 million by 2050 (Zero Waste Scotland, 2023b)	We model forwards to 2030 and 2050 for Scotland, using existing data, based on these projections.
	Electric Vehicle Sales Forecast for the UK: Integrating Machine Learning, Time Series Models, and Global Trends (Veysi et al, 2025)	This study models data from 2026 to 2035, based on current / historic data in the UK. From 2036, we assume that demand is maintained.
Heat pumps	Modelling heat pump growth in Scotland (Usher, 2022)	We use the model provided in this source in order to calculate the total installation capacity in Scotland in 2030 and 2040.
H_2 Fuel Cells	Hydrogen Production Projects (International Energy Agency, 2025b)	This provides current commissioned projects for Hydrogen Production worldwide, separated by country.
	Draft Energy Strategy and Just Transition Plan (Scottish Government, 2023)	Provides Scottish Government targets for Hydrogen Production deployment (5 GW by 2030 and 25 GW by 2045).

Table 9 Data used to model projected uptake of NZTs in the rest of the UK

NZT	Data Source	Assumptions/how data is used
Onshore and offshore wind	Wind energy in Scotland (Scottish Parliament, 2023)	This provides current deployment and government targets for the UK and Scottish Governments for on and offshore wind up to 2030 and 2050
Solar PV	Solar Roadmap (Department for Energy Security and Net Zero, 2025b)	Provides UK Government targets for solar deployment (46 GW by 2030 and 70 GW by 2035).
EV batteries	Electric Vehicle Sales Forecast for the UK: Integrating Machine Learning, Time Series Models, and Global Trends (Veysi et al, 2025)	This study models data from 2026 to 2035, based on current / historic data in the UK. From 2036, we assume that demand is maintained.
BESS	NESO's Future Energy Scenarios (National Energy System Operator, 2025)	Future predictions for Battery Storage in Scotland and UK up to 2050. Data based on this study's 'holistic scenario'.
Heat pumps	Heat Pump Investment Roadmap: Leading the way to Net Zero (Department for Energy Security and Net Zero, 2023a)	Modelled based on aim to increase the number of heat pump installations from 55,000 a year in 2021 to 600,000 a year by 2028.
H_2 Fuel Cells	Hydrogen Production Projects (International Energy Agency, 2025b)	This provides current commissioned projects for Hydrogen Production worldwide, separated by country.
H_2 Fuel Cells	Hydrogen Production Delivery Roadmap (Department for Energy Security and Net Zero, 2023b)	Provides UK Government targets for Hydrogen Production deployment (10 GW by 2030). From 2030, UK demand is modelled in proportion with Scottish demand, for lack of other targets.

Table 10 Data used to model projected uptake of NZTs in the rest of the world

NZT	Data Source	Assumptions/how data is used
Onshore wind	Renewable Energy Progress Tracker (International Energy Agency, 2025c)	Historical data and forecasts for offshore and onshore wind 2000 – 2030. Model from 2031 onwards is based on projections for copper demand between 2030 and 2040.
Offshore wind	Renewable Energy Progress Tracker (International Energy Agency, 2025c)	Historical data and forecasts for offshore and onshore wind 2000 – 2030. Model from 2031 onwards is based on projections for copper demand between 2030 and 2040.
Solar PV	World Energy Transitions Outlook 2024, (International Renewable Energy Agency , 2024)	We use the data provided in this report for global projections of installed solar PV capacity from 2025-2030.
	Overall mineral demand from solar PV 2020-2040 (International Energy Agency, 2021c)	Provides (amongst others) copper demand in 2020, 2030 and 2040. We applied % increase in copper demand 2030-2040 to increase in MW, to produce predicted MW installed 2030-2040 (assumed linear year-on-year increase).
EV batteries	Annual electric car sales in the Sustainable Development Scenario, 2020-2040 (International Energy Agency, 2021d)	Used to model annual demand between 2020 and 2040. This is a scenario projection, based on a Sustainable Development Scenario. It is optimistic.
BESS	Annual battery storage capacity additions in the Sustainable Development Scenario, 2020-2040 (International Energy Agency, 2021e)	Global predictions for battery storage capacity additions, 2020 – 2040
Heat pumps	Net Zero by 2050: A Roadmap for the Global Energy Sector (International Energy Agency, 2021f)	Modelled based on 2020, 2030 and 2050 number of heat pumps installed.

Existing NZT installations

Existing NZT installations can be recycled at end of life to extract CRMs. The quantity and age of existing NZTs is used in the model to predict future availability of secondary CRMs.

Table 11 Data used to model existing NZT installations in Scotland

NZT	Data Source	Assumptions/how data is used
Onshore wind	Energy Trends: UK renewables (Department for Energy Security and Net Zero, 2026)	This provides total installed capacity of multiple NZTs (including onshore and offshore) across UK as well as at the Scottish level, quarterly from 2011 to Q3 2025.
Offshore wind	Energy Trends: UK renewables (Department for Energy Security and Net Zero, 2026)	This provides total installed capacity of multiple NZTs (including onshore and offshore) across UK as well as at the Scottish level, quarterly from 2011 to Q3 2025.
Solar PV	Energy Trends: UK renewables (Department for Energy Security and Net Zero, 2026)	This provides total installed capacity of multiple NZTs (including solar PV) across UK as well as at the Scottish level, quarterly from 2011 to Q3 2025.
EV batteries	Vehicle licensing statistics data tables (Department for Transport; Driver and Vehicle Licensing Agency, 2026)	This data is based on the # of new vehicles registered each year, not MW of power. Using dataset VEH0181: Plug-in vehicles (PiVs) registered for the first time by body type and fuel type, including breakdown of generic models: Great Britain and UK. This gives annual data from 2010 to 2024. We include all vehicles.
Heat pumps	8 heat pumps across Scotland in 2013 up to 3045 in 2024 (Scottish Government, 2024e)	Only includes heat pumps installed with Scottish Government funding/ support. These numbers are based on totals of air and ground source heat pumps. This is likely a low estimation, as this source does not include any privately funded heat pumps. Slight deviance from numbers presented in Heat Pump Deployment Statistics (UK Department for Energy Security and Net Zero).

Table 12 Data used to model existing NZT installations in the rest of the UK

NZT	Data Source	Assumptions/how data is used
Onshore wind	Energy Trends: UK renewables (Department for Energy Security and Net Zero, 2026)	This provides total installed capacity of multiple NZTs (including onshore and offshore) across UK as well as at the Scottish level, quarterly from 2011 to Q3 2025.
Offshore wind	Energy Trends: UK renewables (Department for Energy Security and Net Zero, 2026)	This provides total installed capacity of multiple NZTs (including onshore and offshore) across UK as well as at the Scottish level, quarterly from 2011 to Q3 2025.
Solar PV	Energy Trends: UK renewables (Department for Energy Security and Net Zero, 2026)	This provides total installed capacity of multiple NZTs (including solar PV) across UK as well as at the Scottish level, from 2011 to Q3 2025.
EV batteries	Vehicle licensing statistics data tables (Department for Transport and DVLA, 2025)	This data is based on the # of new vehicles registered each year, not MW of power. Using dataset VEH0181: Plug-in vehicles (PiVs) registered for the first time by body type and fuel type, including breakdown of generic models: Great Britain and UK. This gives annual data from 2010 to 2024. We include all vehicles.
BESS	Clean Power 2030 Action Plan (UK Government, 2024)	Current installed capacity and DESNZ predictions for Battery Storage in the UK
Heat pumps	Heat Pump Deployment Statistics (Department for Energy Security and Net Zero, 2024)	Provides quarterly and annual deployment statistics between 2018 and Q3 2025 in the UK.

Table 13 Data used to model existing NZT installations in the rest of the world

NZT	Data Source	Assumptions/how data is used
Onshore wind	Renewable Energy Progress Tracker (International Energy Agency, 2025c)	Historical data and forecasts for offshore and onshore wind 2000 – 2030
Offshore wind	Renewable Energy Progress Tracker (International Energy Agency, 2025c)	Historical data and forecasts for offshore and onshore wind 2000 – 2030
Solar PV	Installed solar capacity (2000-2024) (International Nickel Study Group, 2025)	Total solar (on- and off-grid) electricity installed capacity, measured in gigawatts. This includes solar PV and concentrated solar power, and we did not separate these values.
EV batteries	Annual electric car sales in the Sustainable Development Scenario, 2020-2040 (International Energy Agency, 2021d)	Used 2020 figure and modelled backwards, based on production capacity ramping up in 2010.
BESS	Annual battery storage capacity additions in the Sustainable Development Scenario, 2020-2040 (International Energy Agency, 2021e)	Modelled backwards from 2020 figure.
Heat pumps	Net Zero by 2050: A Roadmap for the Global Energy Sector (International Energy Agency, 2021f)	Modelled based on 2020, 2030 and 2050 number of heat pumps installed.

CRMs in NZTs

The tables in this section set out the data used to model the quantity of each CRM required on average within a given NZT.

Table 14 Data used to model cobalt requirements in NZTs

NZT	Data Source(s)	Assumptions/how data is used
Battery Storage	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022; International Energy Agency, 2021e; International Energy Agency, 2021g; International Energy Agency, 2021d)	Sources provide MW of storage and quantity of cobalt. Using data from the "stated policies scenario". From this, t/MW installed calculated for 2020, 2030, 2040.
EV batteries	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022; International Energy Agency, 2021e; International Energy Agency, 2021g; International Energy Agency, 2021d)	Sources provide annual car sales and quantity of cobalt. Using data from the "stated policies scenario". From this, calculated total demand/ annual sales (t/vehicle) for 2020, 2030, 2040. Kilogram (kg)/vehicle prior to 2020 assumed equal to 2020, kg/vehicle post 2040 assumed equal to 2040.

Table 15 Data used to model copper requirements in NZTs

NZT	Data Source	Assumptions/how data is used
Onshore wind	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022) / Demand for Copper and Aluminum for electricity grids (International Energy Agency, 2021b)	2.9 t per MW hours (MWh)
Offshore wind	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022) / Demand for Copper and Aluminum for electricity grids (International Energy Agency, 2021b)	8 t per MWh
Solar PV	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022) / Demand for Copper and Aluminum for electricity grids (International Energy Agency, 2021b)	2.8221 t per MWh
Battery Storage	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022) / Demand for Copper and Aluminum for electricity grids (International Energy Agency, 2021b)	Source provided MW of storage and quantity of copper. Using data from the "stated policies scenario." From this, t/MWh installed calculated for 2020, 2030, 2040 then extrapolated linearly from 2020 onwards. For before 2020, we have assumed the same as 2020.
EV batteries	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022) / Demand for Copper and Aluminum for electricity grids (International Energy Agency, 2021b)	Sources provide annual car sales and quantity of copper needed. Using data from the "stated policies scenario". From this, calculated total demand/ annual sales (t/vehicle) for 2020, 2030, 2040. Kg/vehicle prior to 2020 assumed equal to 2020, kg/vehicle post 2040 assumed equal to 2040.
Grid	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022) / Demand for Copper and Aluminum for electricity grids (International Energy Agency, 2021b)	Data for 2020, 2030, 2040 taken from stated policies scenario for electricity grids.
Heat pumps	A UK foresight study of materials in decarbonisation technologies: the case of heat pumps (Zils, Einarsson, & Hopkinson, 2024b)	CRMs in heat pump data from Table 2 (page 9). Modelled an 'average' copper content assuming ratio of domestic to commercial heat pumps identical to ratio of electricity meters.
	Regional and local authority electricity consumption statistics (Department for Energy Security and Net Zero, 2025c)	Ratio of commercial to domestic heat pumps assumed identical to ratio of commercial to domestic electricity meters.

Table 16 Data used to model lithium requirements in NZTs

NZT	Data Source	Assumptions/how data is used
Battery Storage	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	Source provided MW of storage and quantity of lithium. Using data from the "stated policies scenario." From this, t/MWh installed calculated for 2020, 2030, 2040 then extrapolated linearly from 2020 onwards. For before 2020, we have assumed the same as 2020.
EV batteries	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	Sources provide annual car sales and quantity of lithium needed from stated policies scenario". From this, calculated total demand/ annual sales (t/vehicle) for 2020, 2030, 2040. Kg/vehicle prior to 2020 assumed equal to 2020, kg/vehicle post 2040 assumed equal to 2040.

Table 17 Data used to model manganese requirements in NZTs

NZT	Data Source	Assumptions/how data is used
Onshore wind	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	0.78 t per MWh
Offshore wind	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	0.79 t per MWh
Battery Storage	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	Source provided MW of storage and quantity of manganese. Using data from the "stated policies scenario." From this, t/MWh installed calculated for 2020, 2030, 2040 then extrapolated linearly from 2020 onwards. For before 2020, we have assumed the same as 2020.
EV batteries	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	Sources provide annual car sales and quantity of manganese needed from "stated policies scenario". From this, calculated total demand/ annual sales (t/vehicle) for 2020, 2030, 2040. Kg/vehicle prior to 2020 assumed equal to 2020, kg/vehicle post 2040 assumed equal to 2040.

Table 18 Data used to model manganese requirements in NZTs

NZT	Data Source	Assumptions/how data is used
Onshore wind	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	0.4035 t per MWh
Offshore wind	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	0.24 t per MWh
Solar PV	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	0.0013 t per MWh
Battery Storage	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	Source provided MW of storage and quantity of nickel. Using data from the "stated policies scenario." From this, t/MWh installed calculated for 2020, 2030, 2040 then extrapolated linearly from 2020 onwards. For before 2020, we have assumed the same as 2020.
EV batteries	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	Sources provide annual car sales and quantity of nickel needed from "stated policies scenario". From this, calculated total demand/ annual sales (t/vehicle) for 2020, 2030, 2040. Kg/vehicle prior to 2020 assumed equal to 2020, kg/vehicle post 2040 assumed equal to 2040.

Table 19 Data used to model REE requirements in NZTs

NZT	Data Source	Assumptions/how data is used
Onshore wind	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	0.04 t per MWh
Offshore wind	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	0.239 t per MWh
EV batteries	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	Sources provide annual car sales and quantity of REEs needed from "stated policies scenario". From this, calculated total demand/ annual sales (t/vehicle) for 2020, 2030, 2040. Kg/vehicle prior to 2020 assumed equal to 2020, kg/vehicle post 2040 assumed equal to 2040.
Heat pumps	(Zils, Einarsson, & Hopkinson, 2024b; Department for Energy Security and Net Zero, 2025c)	CRM in heat pump data multiplied by government statistics. 7.7% of heat pumps assumed commercial. Assumed no heat pumps prior to 2010 had permanent magnets. Increased linearly up to 2025 with 50:50, then by 2040 100% of heat pumps have magnets.

Table 20 Data used to model silicon requirements in NZTs

NZT	Data Source	Assumptions/how data is used
Solar PV	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	2.9483 t per MWh
Battery Storage	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	Source provided MW of storage and quantity of silicon. Using data from the "stated policies scenario." From this, t/MWh installed calculated for 2020, 2030, 2040 then extrapolated linearly from 2020 onwards. For before 2020, we have assumed the same as 2020.
EV batteries	The Role of Critical Minerals in Clean Energy Transitions (International Energy Agency, 2022)	Sources provide annual car sales and quantity of Silicon needed from "stated policies scenario". From this, calculated total demand/ annual sales (t/vehicle) for 2020, 2030, 2040. Kg/vehicle prior to 2020 assumed equal to 2020, kg/vehicle post 2040 assumed equal to 2040.

NZT average lifetime

The availability of secondary CRMs is modelled based on new NZTs reaching the end of their life. For this, it is necessary to know the age at which a NZT reaches its EoL and can be recycled.

Table 21 NZT age at end of life

NZT	Datapoint (years)	Data Source
Onshore wind	30	(Wiser & Bolinger, 2019)
Offshore wind	25	(Shafiee, 2024)
Solar PV	30	(Komoto & Lee, 2020)
EV batteries	15	(International Energy Agency, 2024)
Battery Storage	10	(Smith, et al., 2017)
H2 fuel cells	25	(U.S. Department of Energy, n.d.)
Grid	45	(Ofgem, 2024)
Heat pumps	15	(ASHRAE)

CRM primary production volumes (Scotland, UK, Global)

The tables below provide the data and sources for primary production volumes of each CRM, where data is available.

Table 22 Primary production of CRMs

CRM	Data Source	Assumptions/how data is used
Cobalt	127 kilotonnes (kt) in 2020, 153 kt in 2021, 163 kt in 2022 (International Energy Agency, 2022) 200 kt in 2023, 305 kt in 2024, 411 kt in 2030 (Jenns, 2025)	IEA provides data for 2000 until 2023. We model linearly between 2024 and 2030. Assume that this remains constant from 2030 onwards.
Copper	24,850 kt in 2020, 27,500 kt in 2030 (MineralsUK; Natural Environment Research Council, 2026; International Energy Agency, 2022)	Assume that 1/5 of CRM under construction comes online over 5 years, from 2031. Assume remains constant from 2035 onwards.
Lithium	90 kt in 2020 (MineralsUK; Natural Environment Research Council, 2026) 156 kt in 2024, 203 kt Li_2CO_3 eq. under construction in 2030 (International Energy Agency, 2022)	Assumed 1/5 of what is under construction in 2030 comes online annually over 5 years, then assumed no change after that Converted into kt lithium using molar mass.
Manganese	1,288 tonnes (t) in 2020, 1,409 t in 2021, 1,225 t in 2022, 1,086 t in 2023 (MineralsUK; Natural Environment Research Council, 2026)	Original data is ferromanganese, multiplied by 0.7 to get manganese content.
Nickel	2,562 t in 2020 (MineralsUK; Natural Environment Research Council, 2026) 3,530 t in 2024, 3,735 t in 2025 (International Nickel Study Group, 2025) 4,100 t in 2030 (International Energy Agency, 2023)	Modelled linearly between years with available data.
REEs	263 t in 2020, 390 t in 2024 (U.S. Geological Survey, 2026) 390 t in 2028, 400 t in 2033 (REIA, n.d.).	Modelled linearly between years with available data. Magnet REEs are assumed to equate to 30% of total REEs (REIA, n.d.).
Silicon	3,680 t in 2023 (MineralsUK; Natural Environment Research Council, 2026)	Data available for 2000-2023. No further modelling done.

Non NZT demand

The table below provides figures related to weights, per annum, of CRMs needed for non NZT applications.

Table 23 Projected global demand for CRMs in non-NZT sectors

CRM	Data Source	Assumptions/how data is used
Cobalt	119.2 kt in 2020, 158.8 kt in 2030, 204.5 kt in 2040 (International Energy Agency, 2022)	Assumed linear demand 2020-2030 and 2030-2040.
Copper	18.3 million tonnes (Mt) in 2020, 20.6 Mt in 2030, 21.7 Mt in 2040 (International Energy Agency, 2022)	Assumed linear demand 2020-2030 and 2030-2040.
Lithium	51.8 kt in 2020, 77.7 kt in 2030, 97.4 kt in 2040 (International Energy Agency, 2022)	Assumed linear demand 2020-2030 and 2030-2040.
Manganese	No data	Not applicable.
Nickel	2144.3 kt in 2020, 2490.83 kt in 2030, 2780 kt in 2040 (International Energy Agency, 2022)	Assumed linear demand 2020-2030 and 2030-2040.
REEs	26.2 kt in 2020, 39.2 kt in 2030, 52.9 kt in 2040 (International Energy Agency, 2022)	Assumed linear demand 2020-2030 and 2030-2040. Neodymium is REE used in the largest quantity, so assumed Neodymium is equal to total REE demand, for lack of more granular data.
Silicon	No data	Not applicable.

Average recycling rates of CRMs

The table below provides the global recycling rates of CRMs, where available. This is not specific to NZT applications.

Table 24 Recycling rates by CRM

CRM	Data Source	Assumptions/how data is used
Cobalt	32% (International Energy Agency, 2022)	This is average global recycling rate of cobalt from all uses. More granular data is not available.
Copper	45.5% (International Energy Agency, 2022)	This is average global recycling rate of copper from all uses. More granular data is not available.
Lithium	0.5% (International Energy Agency, 2022)	This is the average global recycling rate of lithium from all uses. More granular data is not available.
Manganese	37% (African Development Bank Group, 2021)	Updated based on data from 2025.
Nickel	60% (International Energy Agency, 2022)	This is the average global recycling rate of nickel from all uses. More granular data is not available.
REEs	0.2% (International Energy Agency, 2022)	This is the average global recycling rate of REE from all uses. More granular data is not available.
Silicon	No data	Not applicable.

Uncertainty and interpretation

Our modelling work was forward-looking, and predicting the future is always an uncertain exercise. In particular, uncertainties that have a large potential impact on the modelling results exist around:

- The speed and volume of uptake of NZTs
- The quantity of CRMs contained within an average 'unit' of NZT, and how this quantity will change over time
- The availability of primary CRMs from mining.

These uncertainties are discussed below.

At a Scottish and UK level, when predicting NZT roll-out, the model assumed all ambitions stated in Scottish and UK policy will be achieved. In reality, changing politics and priorities, as well as practical barriers and delays to implementation, may mean these targets are not achieved. In particular, only 4 years remain to achieve any 2030 targets. An analysis of current pipeline projects may shed further insights into likely new NZT installations between now and 2030.

Globally, future supply and demand are both uncertain.

On the demand side:

- NZT CRM content is changing (see Section 10.8 below for a full analysis):
    - Different battery technologies require different levels of cobalt, lithium, manganese and nickel. An emerging dominance of one technology over another could drastically shift projected CRM needs for electric vehicles (EVs) in particular.
    - Permanent magnets used in wind turbines and heat pumps are becoming more common, increasing REE needs for these technologies. Alternatively, as wind turbines become more powerful, the required REE content per installed MW could decrease.
- New technologies and uses of CRMs are emerging. For example, the impact of data centres on future CRM needs is only beginning to be understood (see, for example, (Yergin et al, 2026)).
- The speed at which the world decarbonises is uncertain, which means both cumulative and annual CRM demand from NZT could be significantly higher or lower than predicted.

On the supply side, primary CRM production levels can change significantly, even over a relatively short period of time. For example, cobalt primary production has doubled from 2021-2024 (Jenns, 2025), which was largely unexpected and unpredicted by forecasts as recent as 2023 (see, for example, (Energy Transitions Commission, 2023c)).

As such, future predictions of net global CRM availability should be interpreted with caution.

Uncertainties that have a smaller impact the modelling results include:

- Future recycling rates and secondary CRM availability at a global level:
    - The impact on the model is small because secondary supply is only a small contributor to total global supply, particularly in the shorter term.

- Average NZT lifetimes:
    - This shifts the exact timeframes when CRMs will be available at end-of-life, but overall trends on end-of-life availability will still be maintained, provided changes in average lifetimes are small relative to those modelled here.

Appendix D CRMs used in net zero technologies

Onshore wind

The REE requirements and market shares of the four dominant onshore wind turbine technologies are set out below (Petavratzi, Josso, Shaw, & Horn, 2024d).

Table 25 Wind turbine technology market share

Wind turbine technology	Permanent-magnet synchronous generator (PMSG)	Electrically excited synchronous generator	Double-fed induction generator
REE Use	Yes	No	No
Current market share	23%	5%	72%
2050 projected market share	70%	5%	25%

Onshore wind turbines use a variety of CRMs, with Arup estimating that 10.3 t of these materials are required per MW, the majority being zinc and copper (Arup, 2024). Iron is a critical component in the gearbox, while copper is used in the generator (Stavridou, Koltsakis, & Baniotopoulos, 2020) and is required for wiring and cables (Arup, 2024). Aluminium is used across all four turbine types, particularly within structural components (Petavratzi, Josso, Shaw, & Horn, 2024d). Zinc, manganese, chromium and nickel are also used in offshore wind technology (Arup, 2024).

Material intensity per MW of energy generated may be reduced through to 2050 by increasing the size of turbines, leading to higher capacity factors (Energy Transitions Commission, 2023a). Demand for materials can also be met through increased recycling, with there being potential globally for 90% of wind turbines to be collected for recycling by 2050 (Energy Transitions Commission, 2023a). In Scotland, city ports could act as circular hubs for the recycling of onshore renewables alongside manufacturing of offshore renewables using these reclaimed CRMs (Zero Waste Scotland, 2022).

Offshore wind

As technologies using REE-containing permanent magnets hold a higher market share of offshore turbines, total CRM material requirements per MW for offshore are estimated to be higher, at 15.5 t (Arup, 2024). According to UK CMIC, permanent magnet technologies (direct-drive permanent-magnet synchronous generators and direct-drive electrically excited synchronous generators) held a combined market share of 94% in offshore wind in 2020, with this figure expected to increase to 100% in 2050 (Petavratzi, Josso, Shaw, & Horn, 2024d). Furthermore, copper requirements for offshore wind are estimated to be approximately 8 t per MW – roughly 2.5 times higher than onshore, since increased electricity infrastructure is required over longer distances (Arup, 2024).

Solar photovoltaic (PV)

Research suggests that on average approximately 6.7 t of CRMs are needed for each MW of solar capacity, of which the majority is silicon and copper (Arup, 2024). Estimates vary for the proportions between the two metals, though the United States Copper Development Association estimates the copper requirement to be 5.5 t per MW (Copper Development Association, undated). Passivated emitter and rear solar cells (PERCs) are the most commonly used solar PV technology, holding a 90% share of the global market in 2020 (Petavratzi et al, 2024b). This technology relies on a silver front contact layer, crystalline silicon (c-Si) substrate and aluminium paste rear contact layer (Petavratzi et al, 2024b). Silicon heterojunction solar cells (SHJ) are the next most common, at 5% of the market, using a silver paste front and back contact layer, with a c-Si substrate (Petavratzi et al, 2024b). Aluminium is also frequently used in the support structure for all cell types. These two c-Si based technologies are forecast to continue to lead the market through to 2050, though SHJ's share is forecast to increase to 40% by 2035 (Petavratzi et al, 2024b).

Grid infrastructure

Material requirements for improving grid infrastructure centre on large quantities of copper and aluminium, which are used across both the transition and distribution networks, and across other distribution technologies such as solar connections, grid storage batteries and EV (Electric Vehicle) charging infrastructure (Petavratzi et al., 2024c).

Electric vehicles and vehicle batteries

Three of the priority CRMs in this study – nickel, cobalt and manganese – are used in the production of the battery cathodes used in EVs. Copper, aluminium and graphite are also used in battery production. Planned UK vehicle battery manufacturing plants, also known as 'gigafactories', are expected to reach an annual production capacity in 2030 of 135 Gigawatt hours (Lusty et al., 2022). Across EVs as a whole, including the battery, Arup estimates that 215 kg of CRMs are used per vehicle (Arup, 2024).

Demand for these CRMs can be partially met through pre- and post-consumer battery scrap, which is expected to represent a key source of recycled cathode materials in the UK by 2030 (Lusty et al., 2022), though this is dependent on regulatory decisions on the processing of waste batteries. Additionally, the number of end-of-life EVs in the UK is expected to increase significantly by 2040 and may by that point also be a key source for recycled critical cathode materials (Lusty et al., 2022). New and emerging technologies – such as sodium-ion batteries, may also decrease demand for CRMs in future (Arup, 2024).

Hydrogen and fuel cells

Electrolysers are devices which use electricity to split water into hydrogen and oxygen, used for the production of green hydrogen. Four main types of electrolyser technology exist: alkaline electrolysers (AEL), proton exchange membrane electrolysers (PEM), solid oxide electrolyser cell (SOEC) and anion exchange membrane electrolysers (AEM) (Zils et al, 2024a). AEL and PEM electrolysers are currently dominant globally, holding roughly a 60% and 30% share of total global capacity respectively (Zils et al, 2024a). By 2030 across the UK, this split is expected to be 70% PEM, 25% AEL and 5% SOEC.

AELs use approximately 0.8 t of nickel per MW, as well as 0.5 t of aluminium, 100 kilograms of zirconium, and small quantities of cobalt and copper (Zils et al, 2024a). PEM technology uses catalysts with a platinum and iridium base, requiring 0.3 kg of platinum and 0.4 kg of iridium per MW (Zils et al, 2024a). The composition of SOEC technology varies, but is understood to require per MW approximately 175 kg of nickel, 40 kg of Zirconium, 20 kg of lanthanum (a REE), and 5 kg of Ytterbium (also a REE) (Zils et al, 2024a). AELs use approximately 0.8 t of nickel per MW, as well as 0.5 t of aluminium, 100 kilograms of zirconium, and small quantities of cobalt and copper (Zils et al, 2024a). PEM technology uses catalysts with a platinum and iridium base, requiring 0.3 kg of platinum and 0.4 kg of iridium per MW (Zils et al, 2024a). The composition of SOEC technology varies, but is understood to require per MW approximately 175 kg of nickel, 40 kg of Zirconium, 20 kg of lanthanum (a REE), and 5 kg of Ytterbium (also a REE) (Zils et al, 2024a).

Fuel cells convert hydrogen into electricity and have a variety of applications including transport (e.g. EVs and aviation) and grid storage. Key fuel cell types include proton exchange membrane fuel cells (PEMFC), solid oxide (SOFC), alkaline (AFC), phosphoric acid (PAFC), and molten carbonate (MCFC). The most commonly-used technology, PEMFC, uses three of the priority CRMs – cobalt, aluminium (approximately 300 grams per 1 kilowatt (kW) fuel cell) and copper (approximately 20g per 1kW fuel cell) (Petavratzi, E. et al., 2024e).

Appendix E Projected global supply and demand of selected CRMs

Figures 32 to 36 show the projected global supply and demand of selected CRMs across all uses (including non-NZT uses). See Appendix C for a discussion on uncertainty within these predictions. Supply includes both primary supply from mining activities, and secondary supply. The supply gap (where demand outpaces supply) is an indication of periods when Scotland may struggle to obtain the CRMs it requires to meet its NZT ambitions, or when CRM costs may be prohibitive.

There is a particular risk regarding **copper** as production is near peak levels, and is expected to plateau in the coming years based on recent production forecasts (Yergin et al, 2026). The current copper mine project pipeline points to a potential 10-15% supply shortfall by 2030 (Ross & Wright, 2025) and 30% by 2035. Reasons include declining ore grades (reiterated by a research sector interviewee), rising capital costs (around one-third of survey respondents felt this was a factor affecting global CRM demand), limited resource discoveries, and long lead times (International Energy Agency, 2025a). Risks of new CRM extraction are discussed in more detail in Section 7.2.2. Globally, copper demand is expected to increase two- to three-fold by 2040 (Arup, 2024).

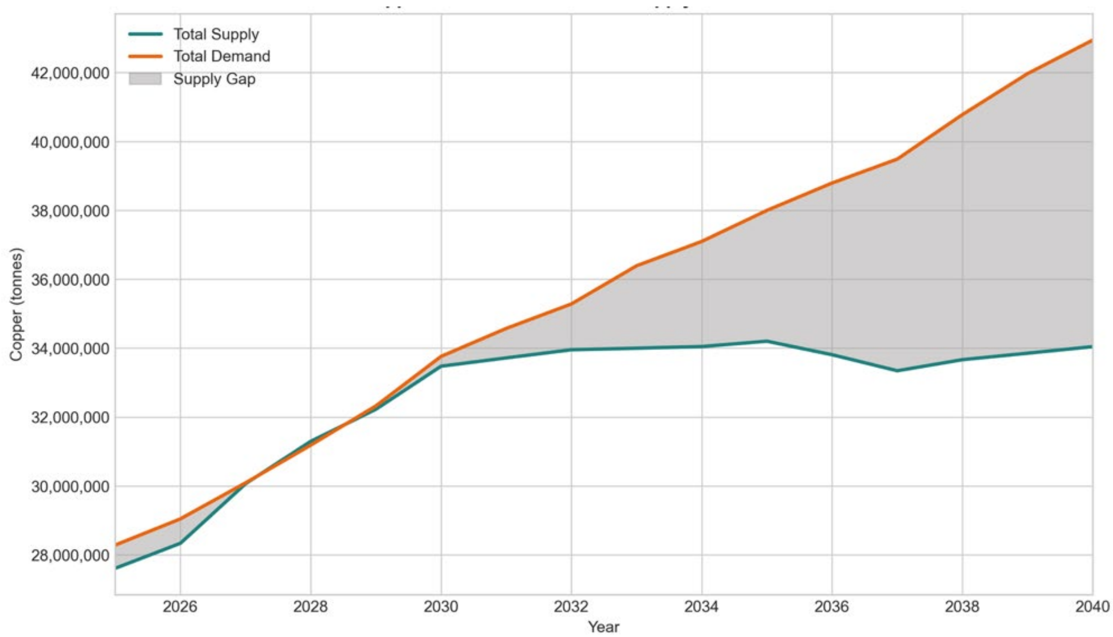

Figure 32 Global supply-demand dynamics for copper, 2025-2040. Source: Modelled data

Nickel supply until recently was expected to exceed demand only until 2026 (SFA Oxford, 2023) and to be in a 10-15% deficit by 2030. However, supply of nickel has increased in recent years (International Nickel Study Group, 2025), driven in particular by growth in Indonesian and Chinese production. This means in the short-term a continued surplus is likely. However, with demand increasing sharply any supply surplus margin remains small, particularly beyond 2035. As both supply and demand forecasts are inherently uncertain, shortfalls in nickel supply should be planned for.

IEA modelling of two different demand scenarios has estimated that nickel demand worldwide is expected to increase by 7 to 19 times by 2040, with the latter being the figure necessary for a demand pathway consistent with meeting the goals of the Paris Agreement (International Energy Agency, 2022).

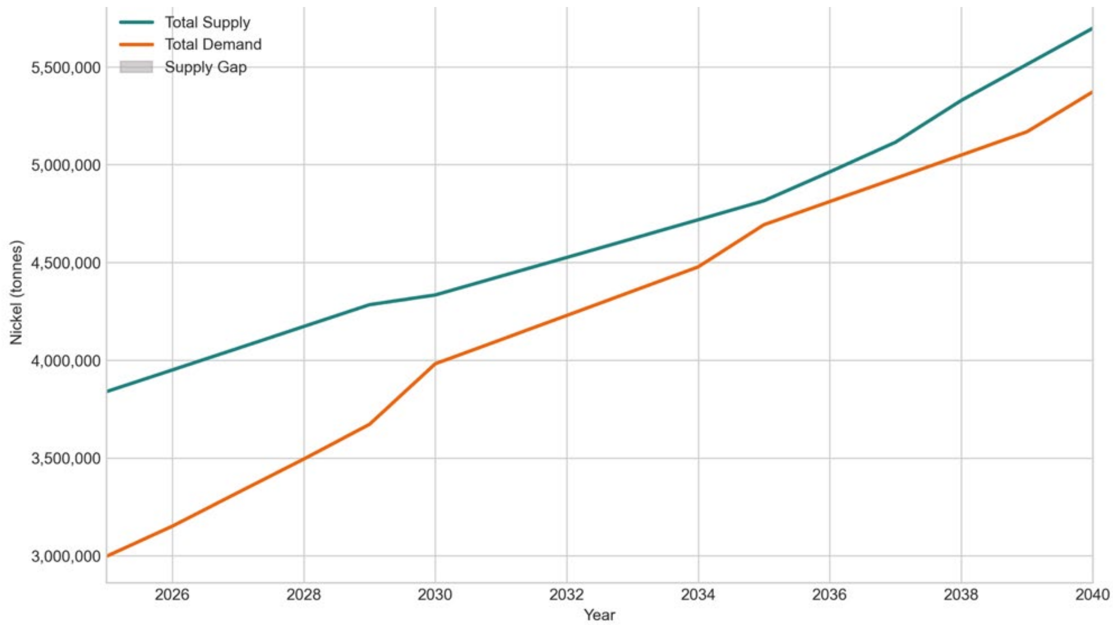

Figure 33 Global supply-demand dynamics for nickel, 2025-2040. Source: Modelled data

For **lithium**, near-term markets appear well-supplied, but rapidly growing demand is expected to push the market into deficit by the 2030s (International Energy Agency, 2025a). Even a lower demand projection with high efficiency and recycling of lithium exceeds reserves (Energy Transitions Commission, 2023d). Global lithium demand is expected to increase by 13 to 42 times by 2040 (Arup, 2024).

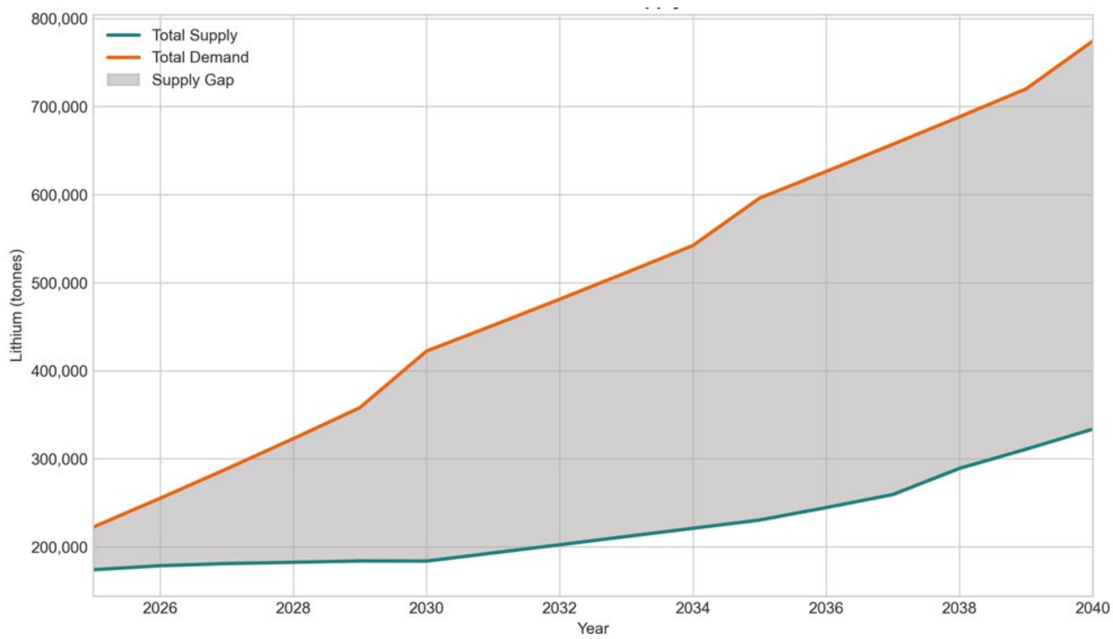

Figure 34 Global supply-demand dynamics for lithium, 2025-2040. Source: Modelled data (see Appendix C)

There are also competing demands for production, particularly for nickel and other base metals, which are in higher demand than other CRMs (Price, 2023).

Global **cobalt** demand is expected to increase by 6 to 21 times by 2040 (Arup, 2024). A recent large increase in cobalt production (Jenns, 2025) means cobalt supply is likely to be sufficient to meet increasing demand to at least 2040.

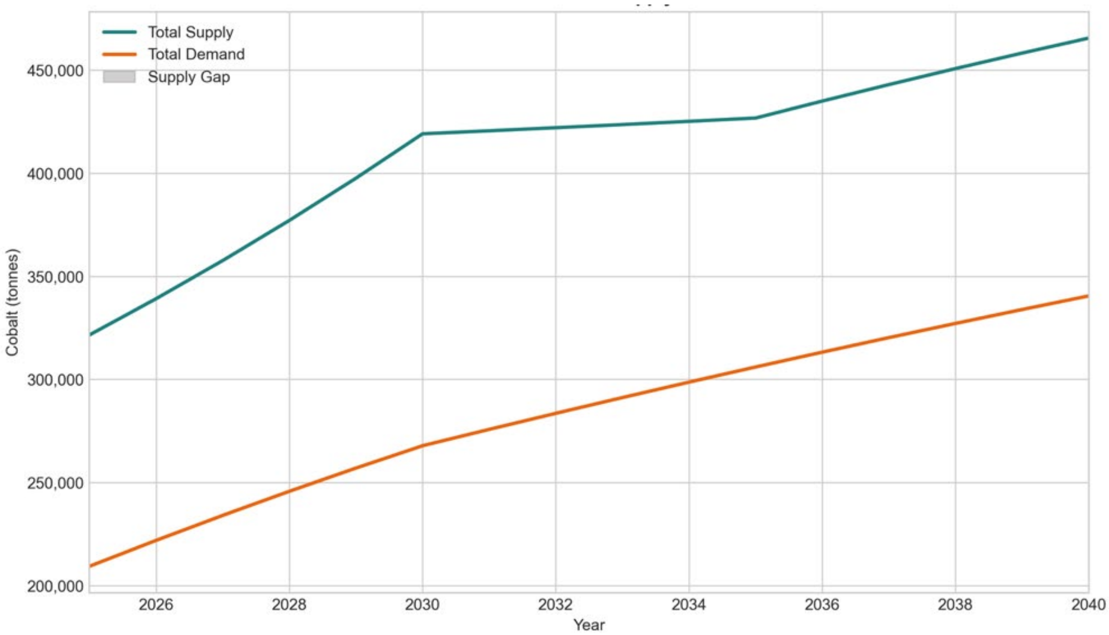

Figure 35 Global supply-demand dynamics for cobalt, 2025-2040. Source: Modelled data

Modelling shows that the global demand for **REEs** used in magnets is expected to exceed supply from 2030, posing a risk to Scotland’s net zero ambitions, for wind, Electric Vehicles (EVs) and heat pumps.

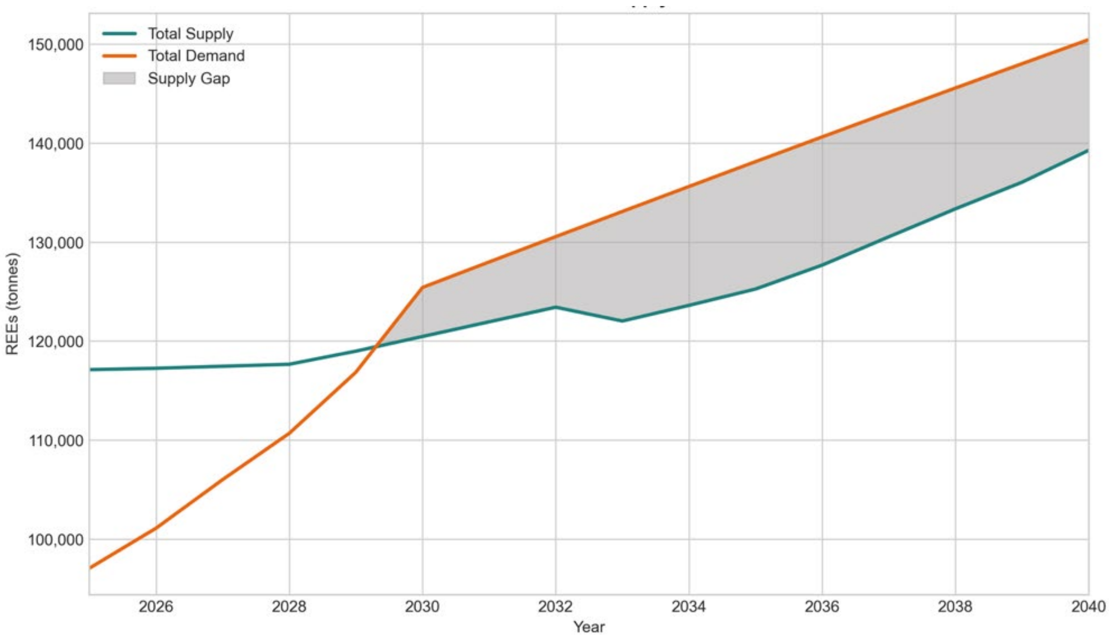

Figure 36 Global supply-demand dynamics for magnet REEs, 2025-2040. Source: Modelled data

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