Sustainable Production and Consumption 47 (2024) 37–46

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Mapping the flows and stocks of permanent magnets rare earth elements for powering a circular economy in the UK

Wan-Ting Hsu [a,*], Evi Petavratzi [a], Markus Zils [b], Stefán Einarsson [b], Esmaeil Khedmati Morasae [b], Oliver Lysaght [b], Peter Hopkinson [b]

[a] British Geological Survey, Nicker Hill, Keyworth, Nottinghamshire NG12 5GG, UK

[b] The University of Exeter Business School, Faculty of Environment, Science and Economy, The University of Exeter, Streatham Court, Rennes Drive, Exeter EX4 4PU, UK

ARTICLE INFO

Editor: Prof. Konstantinos Tsagarakis

Keywords:
Material flow analysis
Neodymium
Dysprosium
Praseodymium
Terbium

ABSTRACT

A transition towards renewable energy and transport electrification requires a high demand for rare earth elements (REE). China's dominance in REE makes the supply chains vulnerable for REE-consuming countries. The UK is one of the only three major refining plants outside of China, and it has, therefore, an active role in the global REE supply chain. In addition, the UK recycling capacity of REE permanent magnets is in development. Understanding REE flows and stocks is required both for scaling up upstream refining capacity and for the recycling projects that are currently in commercial development. This study developed a material flow model of REE in NdFeB magnets used in electric vehicles and wind turbines, taking the UK (2017–2021) as a case. Results show that the UK is a net importer (1238 t of REE in REE compounds, 7787 t of REE in NdFeB magnets) and has a highly fragmented value chain. A significant amount of the REE remains in stocks, whilst most end-of-life REE-containing components were not recovered. Substantial data challenges cause a lack of traceability across the global REE supply chain. This needs to be addressed in order to enhance knowledge of how these REE are utilised. The proposed model and policy interventions can be applied to other countries to improve traceability and circularity.

1. Introduction

Rare earth elements (REE) are essential materials for a range of applications and significant materials enabler for the clean energy transition (Adamas Intelligence, 2022; Deetman et al., 2018; Gielen and Lyons, 2022). Global REE upstream supplies are highly exposed to disruptions due to a concentrated dependency on China for mining and processing, with limited production and processing capacity elsewhere (Adamas Intelligence, 2022; Gauß et al., 2021; Gielen and Lyons, 2022). Thus, there is a global race for securing access to REE, where projected demand is expected to outstrip supplies with anticipated upward pressure on pricing (Adamas Intelligence, 2022; IEA, 2023).

According to the UK criticality assessment, REE are at the top of the list in the global supply risk assessment (Lusty et al., 2021). Currently, the UK is 100 % dependent on imports for REE as there is no mining or large-scale commercialised post-consumer REE recycling operations. However, the Pensana project is developing mining (overseas) and refining capacity (UK) and is planning to produce 5 % of global magnet rare earth oxide (4500–5000 tonnes (t)) in the UK by 2025 (Pensana PLC, 2022, 2023). Moreover, the UK produces REE alloys and is therefore reliant on rare earth oxide feedstock. The UK Government's Net Zero commitments, which include reaching 50 GW (gigawatt) of installed offshore wind capacity by 2030 (UK Government, 2023a) and banning the sale of new petrol and diesel cars by 2035 (UK Government, 2023b), will accelerate domestic demand for REE (Walton et al., 2021).

Partly in response to the risk to supply security associated with REE, the UK government announced the UK Critical Minerals Strategy in 2022 (UK Government, 2022). In this, accelerating to a circular economy with improved end-of-life treatment has been put forward as a key strategy (UK Government, 2022). CE for REE can provide important environmental benefits, as mining and processing of primary REE is linked to significant environmental impacts and ecological degradation in mining areas (Bai et al., 2022; Zaimes et al., 2015; Zapp et al., 2022). Recycling REPM has lower environmental impacts than REPM manufactured by virgin REE (Jin et al., 2018; Wang et al., 2022b). The first key stage of developing a future circular economy for REPM requires a detailed

* Corresponding author.
E-mail address: wthsu@bgs.ac.uk (W.-T. Hsu).

https://doi.org/10.1016/j.spc.2024.03.027
Received 15 January 2024; Received in revised form 23 March 2024; Accepted 24 March 2024
Available online 28 March 2024

understanding of baseline REPM flows and stocks at global and the UK national scales to identify and quantify value chain CE opportunities (Bandara et al., 2014; Busch et al., 2014; Geng et al., 2023).

To date, the flows and stocks of REE and REPM in the UK economy are poorly understood. This paper represents the first UK model based on material flow analysis (MFA), cross-linking diverse publicly available data sets to improve quantification and traceability and enhance our current state of knowledge on how these REE are utilised. This study aims to address the following research questions:

(1) What are the flows and stocks of REE in the electric vehicles and wind turbines in the UK, which may enable the development of a circular economy?
(2) What are the data qualities and gaps across the UK supply chain?

2. Literature review on REE MFA

REE material flow analysis has been undertaken at various geographical scopes, including global (Du and Graedel, 2011; Eheliyagoda et al., 2023; Liu et al., 2022; Nansai et al., 2014; Peiró et al., 2013), Europe (Ciacci et al., 2019; Guyonnet et al., 2015; Rollat et al., 2016), Denmark (Habib et al., 2014), Republic of Korea (Lee and Kim, 2014; Swain et al., 2015) and the USA (Alonso et al., 2023; Chen et al., 2023). Wang et al. (2024) estimated global REE MFA and analysed its regional interdependence between 2021 and 2050. Most of the REE MFA studies focus on the role of China, as it dominates the upstream REE value chain. The Chinese REE flows of neodymium (Chen et al., 2018; Geng et al., 2021; Yao et al., 2021), dysprosium (Wang et al., 2022a; Xiao et al., 2022), praseodymium (Xiao et al., 2000), and terbium (Gao et al., 2022) have been reported. These studies reveal that monitoring REE material flows is challenging due to the lack of consistent datasets and transparency on the activities in the REE supply chain.

The majority of the REE MFA studies focused on neodymium, as it represents an essential constituent of the REPM. Alonso et al. (2012); Rademaker et al. (2013); Reimer et al. (2018); Restrepo et al. (2017); van Nielen et al. (2023) have examined the concentration of REE in electric vehicles (EV) and wind turbine (WT) components, concluding that electric vehicle motors and wind-power generators have the potential as sources of long-term future secondary neodymium and dysprosium supply from the waste flows. Less attention has been given by research on the quantification of the flows of praseodymium and terbium because these elements tend to substitute neodymium and dysprosium in REPM, causing higher uncertainty about their fraction in the REPM composition.

Existing MFA studies focus on REE permanent magnets used in clean energy technologies, such as EV and wind turbines, but they focus on the permanent magnets (first-use) to the final product, excluding the intermediate component level of the electric traction motors and generators. However, it is vital to understand the UK REE flows at the electric traction motor component stage, as the UK demand for electric traction motors is expected to increase from 0.3 million components in 2022 to 2.1 million in 2030 (Advanced Propulsion Centre, 2023). As the UK represents a significant manufacturer and exporter of automotives (Morris et al., 2020), supply constraints run the risk of negatively impacting industry output. In a nutshell, high-import reliance of REE along the full supply chain in the UK, coupled with significant issues on data traceability across the whole value chain and increasing demand from the UK manufacturing sector, is driving interest in exploring the potential secondary supply of REE through circular economy value chains. This study adds to the existing knowledge and contributes towards new robust data, information, and tracking of the REE flows and stocks, using UK as a case study. Specifically, this paper has four core areas of novelty: 1) The first material flow analysis model to track the rare earth elements used in permanent magnets in electric vehicles and wind turbines in the UK; 2) New data that track all four key permanent magnet rare earths (neodymium (Nd), dysprosium (Dy), praseodymium (Pr), and terbium (Tb)) covering the whole value chain; 3) Detailed investigation and analysis of the data availability, including uncertainty analysis and the motor/generator components stage (not investigated by any previous studies), contributes towards new information and knowledge; 4) Detailed recommendations that contribute towards the development of a circular economy in the UK, and the likely contribution of the circular economy to the security of supply and policy interventions required.

3. Methods

This section introduces how the material flow analysis was conducted in this study including system boundary definition, data collection, sources, and estimations, and the uncertainty analysis.

3.1. System boundary definition

Material flow analysis, a methodology using the mass conservation principle to quantify flows and stocks of materials in a pre-defined spatial and temporal system boundary (Brunner and Rechberger, 2016), is applied to track the UK REE flows. Fig. 1 illustrates the system boundary of the REE flows and stocks, which are taken into consideration. The MFA model focuses on four targeted REE (Nd, Dy, Pr, Tb) essential in NdFeB magnets for EV and wind turbines in the UK between 2017 and 2021. The system definition given in Fig. 1 is based on the literature review and stakeholder consultations. In Fig. 1, markets are separated from the manufacturing stages as the markets are where the materials and products are exchanged. The UK-based manufacturing and trade markets operate from the REE compounds phase to the recycling phase. The potential circular flows are also depicted in Fig. 1, including product reuse, dismantling of end-use products into components of electric traction motors and REPM, as well as recycling of the REE compounds and metals/alloys, which can feed the secondary compounds/metals/alloys back to the upstream UK markets. A detailed list of the flows/stocks/markets is represented in supporting information Table S1.

3.2. Data collection, sources, and estimations

This study applied the conventional MFA approach linking public data and industry data to develop a model that deciphers the UK REE material flows. No single UK public data source provides the required information to build a material flow model; hence, multiple data sets and various assumptions and estimations are required, to enable the quantification of REE flows. Data challenges are outlined in greater detail in the uncertainty analysis and discussion section.

Table 1 summarises the main data sources used and assumptions made. The trade, production and in-use stock data were collated from the UKtradeinfo, PRODCOM, Driver and Vehicle Licensing Agency (DVLA), Energy Trends UK renewables and Renewable Energy Planning Database. In certain cases, modifications to the data were made when there were gaps or erroneous data by using interpolation or average numbers from other years. Detailed datasets regarding EV were derived from The Society of Motor Manufacturers and Traders (SMMT). Where consumption data is not available from existing public data or consultations, then the apparent consumption was calculated to be the sum of imports plus production minus exports. Data on REE content, material intensity, market share, mass per unit, losses were collated from extensive peer-review papers, grey literature and stakeholder engagement. A detailed list of flows/stocks, eight-digit HS (Harmonised System) and/or CN (Combined Nomenclature) codes, which are systems used internationally and by the European Union for the classification of traded goods, are in Table S1.

The estimations of the REE flows equal the amount of the trade, production, consumption, in-use stocks, and waste (kilogram, number of items) multiplied by the Nd, Dy, Pr, and Tb content (%) or material

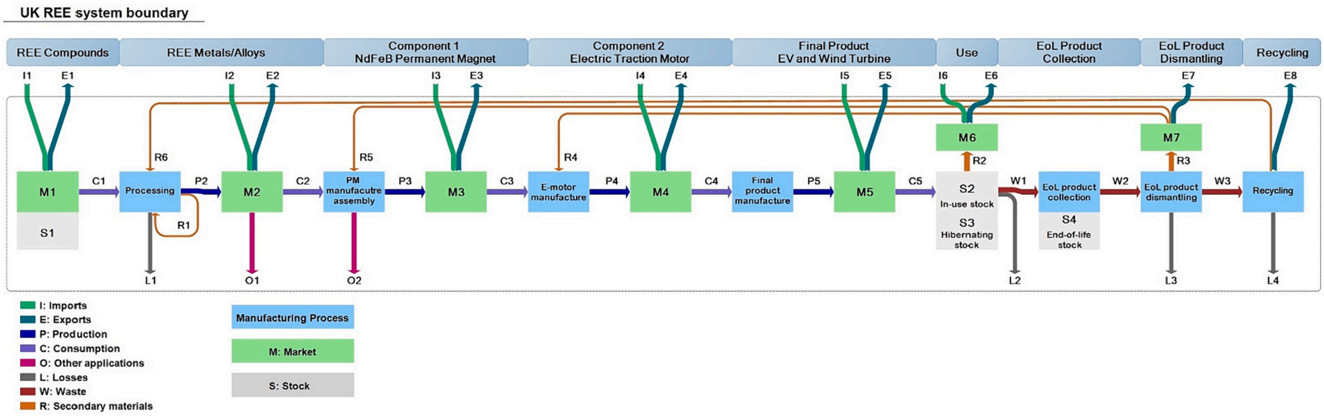


Fig. 1. System boundary of the UK REE.

intensities (kilogram/per unit, kilogram/MW). The calculations are categorised into four groups depending on the unit of data. In Eqs. (1), (2), (3) and (4), the amount of the product type i in production, trade and in-use stock in year T is termed $P_i(T)$. When the unit of $P_i(T)$ is kilograms (kg), the amount of Nd, Dy, Pr, Tb is estimated based on Eq. (1). F_i represents the fraction of Nd, Dy, Pr, Tb (%). M_i represents the market share of the REE-embedded components. The market share data is used for the REE-containing permanent magnets, in electric traction motors and wind-power generators. This is taken into consideration to ensure that the flows of embedded REE components are differentiated from competing technologies that do not contain rare earths and to ensure that the REE flows are not overestimated. In all other cases, the M_i is assumed to be 100 %. When the unit of $P_i(T)$ is the 'number of items', the amount of Nd, Dy, Pr, Tb is estimated based on Eq. (2). I_i in Eq. (2) represents the material intensity (kg per unit). Several flows are required to convert the unit of 'kg' into the 'number of items.' They are then estimated using Eq. (2).

The amount of Nd, Dy, Pr, and Tb embedded in wind turbines is estimated based on Eq. (3). $W_i(T)$ represents the megawatt (MW) installation, while I_i in Eq. (3) represents the material intensity (kg/MW). Eq. (4) is applied to estimating imports and exports of generating sets. $AG_i(T)$ represents the average mass of a generator (kg), $R_i(T)$ denotes the average power rating (MW), and $AP_i(T)$ represents the average mass of PM in a wind turbine (kg/MW).

$$REE\ (Nd, Dy, Pr, Tb)_i(T) = P_i(T)[Mass](kg) * F_i[REE\ fraction](\%) * M_i[Market\ share](\%) \quad (1)$$

$$REE\ (Nd, Dy, Pr, Tb)_i(T) = P_i(T)[Unit](number\ of\ items) * I_i[Material\ intensity]\left(\frac{kg}{unit}\right) * M_i[Market\ share](\%) \quad (2)$$

$$REE\ (Nd, Dy, Pr, Tb)_i(T) = W_i(T)[Installation](MW) * I_i[Material\ intensity]\left(\frac{kg}{MW}\right) \quad (3)$$

$$REE\ (Nd, Dy, Pr, Tb)_i(T) = P_i(T)[Mass\ of\ generating\ sets](kg) / AG_i(T) Average\ mass\ of\ generator\ (kg) * R_i(T)[Average\ power\ rating](MW) * AP_i(T)[\text{Average mass of PM in wind turbine}](\text{kg/MW}) * F_i[REE\ fraction](\%) \quad (4)$$

The assumptions and results of this study were subsequently validated through stakeholder consultations by emails and interviews as documented in Table S10.

3.3. Uncertainty Analysis

Uncertainty analysis was undertaken following the approach proposed by Laner et al. (2015), which allows for a comprehensive data quality assessment. This approach characterises the quality of input data to quantitative scores from 1 (good data quality) to 4 (poor data quality) based on five indicators: (1) source reliability; (2) completeness; (3) temporal correlation; (4) geographical correlation; (5) other correlations. The STAN software was used for data reconciliation to balance out the model. Further details are in supplementary information S2.

4. Results

This section explains the results of REE flows and stocks in the UK at each lifecycle stage and the results of the uncertainty analysis showing the uncertainty level of each flow.

4.1. Results of REE flows and stocks in the UK

Fig. 2 summarises REE (Nd, Dy, Pr, Tb) flows and stocks used in the PM for EV and WT in the UK between 2017 and 2021. Missing stages in the UK supply chain, where there are no flows of REE, meaning no domestic production, are presented with a red dashed line. The trade and production data on the upstream are highly aggregated, and disaggregating would introduce high levels of uncertainty and the potential for flawed assumptions. Therefore, the REE flows are aggregated as total REEs in orange for the compounds and metal/alloy manufacturing stages. The horizontal flows represent the consumption and production of the compounds, metals/alloys, components, and final products. The upper vertical flows represent the imports and exports, while the lower vertical flows represent other applications and losses. The results of upstream total REE, Nd, Dy, Pr, and Tb flows are shown in the supporting information S3, respectively.

4.1.1. REE flows in the upstream value chain

The results reveal that the UK has a highly fragmented REE value chain. The UK does not produce any rare earth oxides. Instead, REE compounds (rare earth oxides) are imported from international markets (primarily China). In these five years, the UK imported 2205 t of total rare earth compounds and 450 t of rare earth metals/alloys. Approximately 0.5 % of the imports were secondary REE compounds, and 220 t of REE compounds remained as stock. Around 1018 t of REE compounds were consumed to produce 916 t of REE metals/alloys. Approximately 10 % of REE were lost at this upstream manufacturing stage, namely, 102 t of total REE compounds. Some post-industrial waste was used as feedstock for the processing stage of REE metals/alloys. Those REE metals/alloys were either used for other applications within the UK (273 t) or exported to other countries (1093 t) for manufacturing REPM.

Table 1
Summary of data sources and assumptions.

Data	Flow/Stock	Source/Assumption
Trade	REE Compounds imports and exports (kg)	UK tradeinfo
	REE Metals/Alloys imports (kg)	UK tradeinfo
	REE Metals/Alloys exports (kg)	80 % of inputs (imports and production) based on stakeholder consultation
	PM imports and exports (kg)	UK tradeinfo
	E-motor imports (kg)	UK tradeinfo
	E-motor exports (number of items)	Engine data from The Society of Motor Manufacturers and Traders (SMMT) as a proxy
	HEV/PHEV/BEV imports and exports (number of items)	UK tradeinfo
	Generating sets imports and exports (kg)	UK tradeinfo
Production/ Assembly	Metals/Alloys (kg)	Law of conservation of mass
	PM (kg)	UK PRODCOM
	E-motor (number of items)	Engine data from SMMT as a proxy
	HEV/PHEV/BEV (number of items)	SMMT
Consumption	All (kg)	Law of conservation of mass
	Compounds	100 %
	Metals/Alloys	100 %
Market share (%)	PM	Cui et al. (2022)
	E-motor	IDTechEx report (Edmondson et al., 2022) and stakeholder consultation
	HEV/PHEV/BEV	SMMT
	Generator types	Carrara et al. (2020)
Nd, Dy, Pr, Tb content (%) and/or material intensity (kg/ items)	PM (%)	Multiple peer-review papers, see Table S3
	E-motor (kg/items)	Ballinger et al. (2019)
	HEV/PHEV/BEV (kg/items)	Multiple peer-review papers, see Table S5
	Generator types (kg/items)	Carrara et al. (2020)
	PM in wind turbine (%)	Multiple peer-review papers, see Supporting Information – the Excel spreadsheet named 'REE contents in REPM'
Mass per unit	Generating sets (kg)	The nacelle mass of turbine as proxy of each generating set
	Average mass of PM in wind turbine (kg/ MW)	Multiple peer-review papers, see Table S6
Average power rating	Average power rating (MW)	Wind Europe - Wind energy in Europe annual statistics and the outlook
Loss, Transfer coefficient / Yield (%)	Losses at processing	Geng et al. (2021)
	Losses at ELV dismantling	Law of conservation of mass
EV stocks	EV in-use stock (number of items) Hibernating EV stock (number of items)	Department for Transport (DfT) and Driver and Vehicle Licensing Agency (DVLA) Vehicle licensing statistics
ELV (End-of-Life Vehicles)	ELV collection (number of items) ELV dismantling (number of items)	DfT and DVLA Vehicle licensing statistics
Wind turbines installation	New installation (MW)	Renewable Energy Planning Database (REPD), July 2023; Global Wind Energy Council report for missing 2016 offshore data in REPD
	Cumulative installation (MW)	National statistics Energy Trends: UK renewables

Albeit the UK adds value to REE compounds imported, the majority of the REE alloys produced to serve the permanent magnet global market are exported to international destinations. There is no REPM manufacturer in the UK, and the domestic supply chain at this stage is fragmented.

4.1.2. REE flows in components – permanent magnets

At the component stages, a considerable amount of REE contained in magnets was imported into the UK. In total, the UK imported 10,682 t and exported 2895 t of REE embedded in the PM. This shows that the UK is a net importer. Approximately 568 t of REE were embedded in the PM used in component assembly. Approximately 771 t and 279 t of REE within the PM were consumed to manufacture electric traction motors and other EV applications respectively, whereas 7305 t of REE contained in the PM were used in other applications (see Fig. 2). Among these other REPM applications, consumer electronics were the end-use applications with the highest share of REE, which could be the source of the potential secondary REE supply for the short to mid-term. It is worth noting that no PM were supplied to manufacture wind-power generators in the UK.

4.1.3. REE flows in components – motors

For the electric traction motors, nearly 84 t of REE embedded in electric traction motors were imported, while 383 t were exported. Approximately 771 t of Nd, Dy, Pr and Tb were used to manufacture electric traction motors, while 472 t of Nd, Dy, Pr and Tb were consumed in electric traction motors in the UK. It is interesting that the whole value chain involves many assembling stages. For instance, imported PM are assembled into rotors, which are then sold to OEM (original equipment manufacturer) to further assemble electric traction motors. We assumed there were no losses nor stocks at the manufacturing stage; however, manufacturing processes and/or markets across the whole value chain are likely to have losses and stocks in warehouses. This data is not readily available and is often confidential.

4.1.4. REE flows in final products – electric vehicles and wind turbines

At the final product stage, REE embedded in EVs and wind turbines both showed a net import reliance. Regarding the EV-related flows, 931 t and 750 t of Nd, Dy, Pr and Tb embedded in the EVs were imported and exported, respectively. Approximately 751 t of REE were used to manufacture EVs (472 t for e-traction motors and 279 t for other EV applications), and 932 t of REE contained in the EVs were consumed in the UK.

Regarding the flows related to wind turbines, the UK does not manufacture wind turbines or any of the REE-embedded components. Instead, the UK imported the generating sets to assemble and install new wind turbines. Approximately 1128 t of REE were embedded in the new wind turbine installation between 2017 and 2021. These were supplied by the 554 t of REE within the imported generating sets and 593 t of REE contained in the generating sets imported before 2017. The delay between imports of generating sets before 2017 and wind turbine installation from 2017 to 2021 was likely due to delays with the planning and commissioning process. Only 19 t of REE embedded in the generating

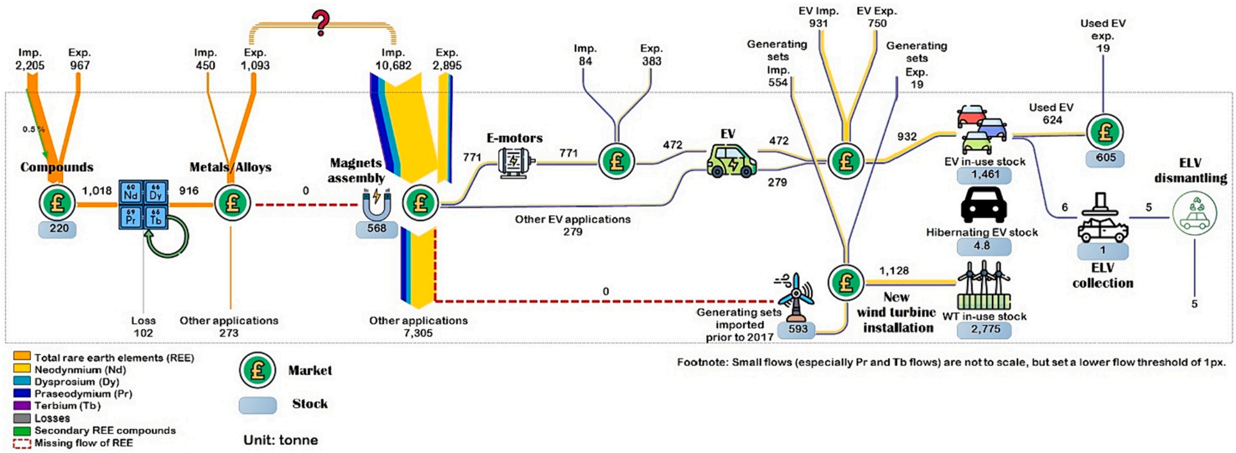


Fig. 2. REE flows and stocks in the UK between 2017 and 2021. The flows represent the sum of the past 5-years. The unit is tonnes of metal contained. A detailed explanation of the representation of the markets and manufacturing stages is given in the supporting information.

sets were exported from the UK.

4.1.5. REE stocks in the use phase

At the use phase, there was a significant quantity of REE embedded in stocks in 2021. Fig. 2 shows that 1461 t of REE were in the EV in-use stock (1,623,213 units of EV), 4.8 t of REE were in the hibernating EV stock (5464 units of EV), which means deregistered but not exported vehicles, and 2775 t of REE were in the wind turbine in-use stock (25,748 MW cumulative installation). The UK in-use stocks of REE in EVs and wind turbines in 2021 are equivalent to 10 % of average global REE (Nd, Dy, Pr, Tb in metal content) mine production between 2017 and 2021, based on our own estimations using the BGS world mineral statistics (British Geological Survey (BGS), 2023).

4.1.6. REE flows in end-of-life products

For the REE embedded in the end-of-life EVs, 624 t of REE were embedded in the used EV flow (711,113 units of used EV) entering the UK used car market. About 19 t of REE embedded in the 22,692 units of used EVs were exported, whilst 6 t of REE embedded in the 6729 units of ELVs (End-of-Life Vehicles) were collected from waste management actors. Our estimation suggests that about 1 t of REE remained in stock at the ELV collection centres, and 5 t of REE embedded in 5514 units of ELV entered the ELV recycling facilities for dismantling. However, at this stage, the REE embedded in ELVs were not recovered, but instead, most likely, they were lost during the shredding process. Most REE embedded in the wind turbines are still in operation, except for limited pilot projects of wind turbine dismantling with a focus on wind blade recycling. Therefore, no REE flows are displayed after the end-of-life stage of wind turbines.

4.2. Results of uncertainty analysis

The uncertainty analysis presented in this study provides a systematic overview of the level of input data uncertainty (see supporting information). Table 2 depicts the heat map of the adjusted uncertainties. Most of the flows have low uncertainty as the data used were from official statistics and peer-reviewed papers. The high uncertainties of the four targeted REE flows relate to NdFeB PM and are due to significant data gaps, which impact the measurement of the individual REE (Nd, Dy, Pr, Tb) flows in this stage.

Even official statistics, for example, trade data from the UKtradeinfo database and production data from the UK PRODCOM dataset on permanent magnets of metals (85051100), have some outlier values. This is not uncommon, and it has been discussed by other researchers too. For example, Chen et al. (2022) point out similar issues with poor quality trade data, which have been encountered in our assessment and impacted tracking the REE flows. The uncertainties caused by outliers in the PM trade (UKtradeinfo) and assembly (PRODCOM) data in this study are not fully reflected in this uncertainty analysis, as the approach established by Laner et al. (2015) and adopted in our assessment considers official statistics as highly reliable. Furthermore, 85,051,100 permanent magnets of metal cannot differentiate between PM of REE and other metals. The uncertainty increases further because, in our estimation, we use the global permanent market share data to determine the share of sintered NdFeB PM, as information on the UK-equivalent market share is missing (see Table S7). Additional uncertainties emerge from the lack of data on electric traction motor manufacturing in the UK. To estimate this, we used the number of UK-manufactured car engines and the UK EV market share as a proxy in our calculation.

In the case of the wind turbines, we used the nacelle mass of a 5 MW turbine as a proxy for each generating set. To account for the market change taking place for wind turbine generators (Serrano-González and Lacal-Arántegui, 2016), we used data on market shares attributed to different technologies that have been provided for the European market. The geographical context in this case is not focused on the UK, which again contributed towards higher uncertainty figures. In general, similar degrees of uncertainties exist for the individual REE (Nd, Dy, Pr, Tb) flows as data on specific REE elements are very rare and in our assessment the quantification is based on the use of similar data sources. Detailed information on the data quality assessment and uncertainty can be found in the supporting information.

5. Discussion

Based on the results, this section discusses data challenges and limitations, UK challenges with the REE supply chain, recommendations on how to capture value from REE stocks in the UK, and proposed policy on a circular economy for critical raw materials (CRM).

5.1. Data challenges and limitations

Data gaps have been persistent throughout the modelling process. The key issues faced are summarised below:

i. Trade data at the material level are highly aggregated. For example, the nomenclature categories (HS/CN codes) for the REE materials traded in the upstream stages of the supply chain do not differentiate the Nd, Dy, Pr, and Tb from the respective 17 REE elements.

Table 2
Heat map of the adjusted uncertainties. A very low uncertainty (0 % - 10 %) is shown in dark green, low uncertainty (10 % - 20 %) is shown in light green, medium uncertainty (20 % - 30 %) is shown in amber, high uncertainty (30 % - 40 %) is shown in pink, very high uncertainty (> 40 %) is shown in red.

Code	Flows	Uncertainty level (%)			
I1	Import of total REE compounds	2.3			
E1	Export of total REE compounds	2.3			
C1	Total REE compounds consumption	5.4			
L1	Losses at processing stage	5.4			
I2	Imports of REE metals/alloys	2.3			
E2	Exports of REE metals/alloys	3.7			
P2	REE metals/alloys production	5.4			
C2	Total REE metals/alloys consumption to NdFeB PM	3.7			
		Nd	Dy	Pr	Tb
		(%)			
I3.1	Imports of NdFeB PM	41.6	41.6	41.6	41.6
E3.1	Exports of NdFeB PM	14.5	14.5	14.5	14.5
P3.1	NdFeB PM assembly	15.3	15.3	15.3	15.3
C3.1	NdFeB PM consumption to e-motors	8.9	10.5	11.8	10.8
C3.2	NdFeB PM consumption to other EV applications	7.1	6.7	6.1	6.9
O3.1	NdFeB PM consumption to other applications	60.8	63.9	60.4	60.1
I4.1	Imports of PM electric traction motors	15.1	15.4	15.5	15.4
E4.1	Exports of PM electric traction motors	19.9	16.8	15.6	16.6
P4.1	Total PM electric traction motors production	8.9	10.5	11.8	10.8
C4.1	Total PM electric traction motor consumption	7.0	6.6	6.0	6.8
I5.1	Total EV imports	2.6	2.7	3.1	2.7
E5.1	Total EV exports	3.2	3.1	3.6	2.9
P5.1.0.1	Total EV production – electric traction motors	7.0	6.6	6.0	6.8
P5.1.0.2	Total EV production – other applications	7.7	6.7	6.1	6.9
C5.1	Total EV consumption	5.4	5.2	7.0	5.0
I5.2	Generating sets imported prior to 2017	36.5	38.8	28.6	17.9
I5.1.4	Imports of generating sets	14.7	14.7	14.7	12.2
E5.2	Exports of generating sets	14.7	14.7	14.7	14.7
C5.2	New wind turbine installation	17.5	16.8	17.8	10.4
R2.1	Total used EV to reuse	4.9	4.9	6.0	4.6
E6.0	Exports of total used EV/EOL EV	2.8	2.8	3.3	2.7
W1.0	Total EOL passenger EV to collection	3.2	3.1	3.5	2.9
W2.0	Total EOL passenger EV to dismantling	3.2	3.0	3.4	2.9

0% - 10%	10% - 20%	20% - 30%	30% - 40%	>40%

ii. Trade data at the component level do not differentiate components with REE-embedded materials. The REE permanent magnets are not clearly outlined in the nomenclature. Instead, they are grouped together with other types of permanent magnets of metal. This is problematic, as it is difficult to quantify the proportion of REPM in these flows.
iii. Trade data associated with semi-finished products do not provide sufficient explanatory information to enable mapping them to their final end-use. For example, the categories available for electric motors provide information on the type of motor (e.g., DC or AC) and their output, but those categories in eight-digit HS/CN code do not include any notes on where they may find application (e.g., electric vehicles, other electric devices, pumps etc), neither differentiate whether these product categories use REPM. Equally, for the generators used in wind turbines, the code '28112400 (CN 850231) generating sets, wind-powered' does not provide any clarifications on the characteristics of this product category. It is unclear whether this refers to a component such as the nacelle of the wind turbine or the whole generating set. Different types of generators may be designed using different technology configurations (e.g., direct-drive, with a gearbox) and may have varied outputs. Thus, different generators tend to contain various content of Nd, Dy, Pr and Tb. However, none of this information is explicit in the existing code. Also, the unit employed to track the trade flows of generating sets is set to kilograms. This increases the uncertainty of the estimation of the embedded REE flows because we first need to quantify the number of generating sets out of these traded quantities and then calculate their REE material intensity. Finally, the technological evolution in both the area of EV and wind turbines is fast and very dynamic with significant implications for material and product composition. For example, the same brand and model of an EV may change the design, number, or type of electric traction motors used over time.
iv. Production data are highly aggregated and often underreported. Data on the production of manufactured goods is extracted where possible from the UK PRODCOM dataset. However, data availability has been challenging, as the nomenclature of this dataset is highly aggregated, and data are not always reported consistently. For example, there are data gaps and outliers, and often, data is suppressed due to the limited number of manufacturers in the UK. In addition, PRODCOM seems to report data on the manufacture of permanent magnets and wind turbine generators, which, based on our stakeholder analysis, can only be treated as representative of the assembly lines taking place in the UK.
v. Data on stocks and losses of materials are very limited. Data on in-use stocks are not always reported accurately or not available. The discrepancies within such data provided from different sources are common. For example, the UK cumulative wind turbine installation (MW) data in the Renewable Energy Planning Database, the National Statistics Energy Trends: UK renewables, the Global Wind Energy Council and Wind Europe do not converge, which makes it difficult to define the most suitable data source without stakeholder consultations. Also, stocks are likely to exist across every stage of the REE value chain; however, this data and information are not reported. Therefore, significant data gaps exist. Data on material losses taking place across the whole value chain are not recorded anywhere, and only through stakeholder engagement can such information be collected.
vi. Data available to describe the fate of materials at their end-of-life stage are very limited. These data are key to estimating the potential for circular economy business models to emerge. Data on waste and the fate of waste are available, but their resolution is problematic because they tend to focus on large product categories. Hence, their linkage to critical raw materials is not straightforward. Waste data are classified using the European Waste Catalogue (EWC) nomenclature, but in many cases, the product and material categories in this are highly aggregated. For example, there is no EWC code to describe traction motors or wind turbines reaching their end of life. In the case of EV traction motors, these data will likely be hidden within the 'EWC 16 01 04 end-of-life vehicle code' or possibly in one of the categories under the 'EWC 16 02 wastes from electrical and electronic equipment codes' if motors are recovered. Most importantly, we are currently unable to track end-of-life BEV, HEV/PHEV through waste statistics. The resolution of existing datasets is not sufficient to track such product flows.

There is minimal information from the existing literature to compare our results with other studies. Two data points, the electric traction motor estimation, and the neodymium annual stock estimation, can be validated through the literature. The results of electric traction motors are aligned with the UK Advanced Propulsion Centre (2023) reported figures. We estimated that 1.5 million electric traction motors were manufactured in the selected five-year period. The report from the Advanced Propulsion Centre (2023) shows that UK traction e-motor demands equated to 0.3 million e-motors in 2022 as a reference year. Annual neodymium stock in offshore wind turbines is 1143, 1404, 1448, and 1540 t between 2018 and 2021 respectively, according to our estimations. These estimations also align with Jensen et al. (2020), showing that the current Nd stock is over 1000 t. The remainder of data validation relied on extensive stakeholder consultations with UK actors that participate in this value chain and public bodies who are responsible for the official statistics (see Table S10).

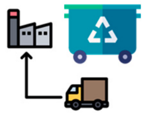
The results of this study reveal the complexity and difficulties of tracking and tracing the REE flows in the UK. They also highlight that the existing model could benefit from further detailed investigations and ongoing collaboration with industry stakeholders to improve the data availability. However, several data challenges outlined earlier cannot be resolved solely with stakeholder engagement. Changes in data reporting, related regulatory frameworks and policy, and engagement with global data providers (e.g., UN, OECD) would be essential to increase the availability and quality of data on REE and other critical raw materials. Nevertheless, the existing model serves as a good starting point for tracking the REE flows and stocks.

5.2. UK challenges with the REE supply chain

The analysis of the REE flows and stocks in the UK has identified several hotspots in which significant reliance on global markets currently exist. The key challenges identified from our analysis are:

- Despite some limited geological occurrences in the UK, REE have never been commercially extracted in the UK, and no systematic exploration for REE has ever taken place.
- The UK actively participates in alloy manufacturing, but most UK REE metal and alloy production is exported to global REPM manufacturers. The lack of UK REPM manufacturing is a significant missing link in the UK REE value chain.
- The UK relies heavily on imports of REPM from international markets (primarily China). REPM are essential for manufacturing electric traction motors in the UK, but they also used for various applications. Any tension in the global REPM market can result in significant bottlenecks for the UK value chain.
- There is no manufacturing taking place in the UK for wind-power generators. Considering the significant global competing demand for these components, the UK is in a potentially risky position if any market disruption occurs, and it would benefit from building a supply chain that includes manufacturing stages within the UK.
- The in-use stocks of EV and wind turbines are building rapidly, and they will reach their end-of-life in the coming decades. The development of circular economy businesses would require multiple

Table 3
Recommendations on how to capture value from REE flows and stocks in the UK.

Capture value from REE flows and stocks in the UK		
Collection and Reverse Logistics Infrastructure		• Scale up electric vehicle collection schemes • Establish infrastructure to dismantle e-motors and REPM • Establish infrastructure to decommission wind turbines and dismantle generators
Product Sorting and Inspection		• Assess the composition of products • Assess the condition of returned items • Identify reusable components • Segregate components that require repair, refurbishment, recycling, or disposal
Management of Components for Repair and Refurbishment Operations		• Components that can be repaired or refurbished need to be sent through appropriate processes to restore their functionality and extend their lifespan • Repair centres or service providers should be equipped to extract REPM, e-motors and generators
REE Recycling and Recovery		• Establish recycling facilities and specialised REE recyclers to extract valuable REE oxides and metals from returned components • Ramp up UK-based REE recycling capacity and investments
Collaboration and Partnerships		• Collaboration across the supply chain, including designers, manufacturers, brand owners, logistics providers, waste collectors, recyclers, and regulatory bodies • Information sharing, knowledge development and diffusion • Resource pooling, and the development of shared infrastructure and processes

actors and reverse supply chains to advance, which also takes time and coordination. Hence, it is crucial for the UK that such actions take place rapidly, especially as other nations across the globe are undergoing comparable expansion trajectories at the same time.

- Currently, REE embedded in products are not recovered when they reach end-of-life. The lack of any substantial recovery and recycling activities could have detrimental impacts on the UK as the in-use stocks are developing, both from a loss of material and residual value that the UK could benefit from, but also from a waste management point of view.

5.3. Capturing value from REE flows and stocks in the UK

Table 3 lists recommendations on how to capture economic value from REE flows and stocks based on the mapping of potential CE flows (Fig. 1), the identified hotspots and leakage points from the results (Fig. 2) and stakeholder consultations.

The REE in-use stock from EV and wind turbines in the UK in 2021 are estimated to be around 4.2kt. Based on a BGS estimation, Nd, Dy, Pr shares in the global average REE mine production (metal content) between 2018 and 2020 are about 15 %, 1 %, 5 %, respectively, which equals approximately to 44 kt (British Geological Survey (BGS), 2023). The latter figure indicates that about 10 % of this global annual mine production (Nd, Dy, Pr in metal content) is found in the UK 2021 in-use stocks of EV and wind turbines. There are most probably additional in-use stocks in other applications such as electronics. Therefore, the potential for extracting value through circular economy routes is significant.

The development of REE reverse supply chains involves the management of EoL products, the dismantling and recycling, and the reintegration of products and materials back into the supply chain, which is currently in development in the UK. For example, REPM recyclers (HyProMag and Ionic Technologies) are in the process of scaling up recycling capacity to 130 t per annum of end-of-life REPM in 2024/2025 (Ionic Technologies, 2023; University of Birmingham, 2023). The Pensana refinery is looking to produce around 4500 to 5000 t of NdPr oxide by 2025, mainly from primary sources (Pensana PLC, 2023), but the potential to utilise feedstock from secondary sources also exists. End-of-life vehicle recyclers like European Metal Recycling (EMR), with the largest UK network of authorised treatment facilities (ATFs), are developing processes to enable dismantling and processing of key components such as traction motors from EV. There is, therefore, capacity development for reverse supply chain that acts as an enabler of CE.

Table 4
Proposed policy on a circular economy for CRM.

Proposed policy on a circular economy for critical raw materials (CRM)	
Improving traceability of individual CRM	• Improve the current statistics by segregating the product and waste categories • Conduct annual enterprise surveys • Establish a digital product passport platform[*] • Establish a new CRM data monitoring platform to track the origins of individual CRM, material composition and secondary CRM • Combination with blockchain technology and collaborations between industry and government
Establishing a Regulatory Framework	• Develop a circular economy action plan on critical raw materials • Set CRM recycling targets • Establish Extended Producer Responsibility (EPR) schemes • Implement policies to provide economic incentives for using recycled CRM or substitute materials
Supporting further Research and Innovation	• Support research and innovation in areas such as material science, recycling technologies, and product design for circularity • Encourage collaboration between industry, academia, and research institutions to develop new processes, technologies, and business models that enable resource efficiency, material recovery, and the reduction of critical raw materials dependency • Revalorisation opportunities would need to develop in parallel to fast-growing in-use stock to ensure efficient use of CRM • Capacities and skills need to be scaled in sync with the likely release of CRM stock
Monitoring CE progress	• Establish mechanisms to monitor the progress, effectiveness, and impact of policies and initiatives related to CE on CRM flows • Regular evaluations to provide insights into the success of implemented measures and guide future policy adjustments or interventions
International Cooperation	• Share best practices • Harmonise data and standards • Participant in international initiatives aimed at resource productivity, CRM recycling, and responsible sourcing

[*] (Koppelaar et al., 2023)(e.g., EU digital product passport (European Commission, 2023) and battery passport pilot (Global Battery Alliance, 2023)).

5.4. Policy requirements on CE for CRM

Given the substantial challenges identified by the MFA, we suggest policymakers to focus on the following priorities in this fast-changing industrial setting shown in Table 3. Although this study focuses on the REE, these policy priorities can be applicable to several critical raw materials (Table 4).

6. Conclusions

Our proposed UK REE material flow analysis model provides an initial baseline of the stocks and flows of REE used in the REPM for EVs and wind turbines from a supply chain perspective. The development of the model relied on several different datasets, stakeholder engagement and assumptions. The latter are inevitable as the challenges associated with data availability and data quality are many and complex. However, through stakeholder engagement, we were able to validate assumptions and estimations done during this work. The model provides an insight into the dependencies that the UK faces with the REE supply chain, which are significant for permanent magnets required for both decarbonisation applications (EV and wind turbines). The model also clearly outlines the disconnected patterns in which the UK participates in the REE supply chain. For example, the production of REE metal alloys for permanent magnets in the UK leaves the country for the production of magnets elsewhere, which are later imported for use in EV manufacture. The potential for the in-use stock to serve as feedstock for REE and REPM in the future is significant, if reverse supply chains are developed in time. However, currently, there is no recovery of REE and REPM from the end-of-life of these products, with REE being lost during the waste management processes. The UK REE MFA model can be used to identify and guide interventions for policy priorities as discussed earlier, which would be essential for improving security of supply and moving towards a circular economy ecosystem in the UK. The presented model is far from complete, as several product streams are currently missing from this. Future research is suggested to further expand this REE MFA model by tracking additional products (e.g., conventional vehicles, MRIs, HDDs and e-bikes), and developing dynamic stock models for foresight studies to estimate the future demand and potential secondary supply, as well as conducting scenario analysis to understand different potential circular scenarios.

CRediT authorship contribution statement

Wan-Ting Hsu: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Evi Petavratzi:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Markus Zils:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization. **Stefán Einarsson:** Writing – review & editing, Writing – original draft, Data curation. **Esmaeil Khedmati Morasae:** Writing – review & editing, Writing – original draft. **Oliver Lysaght:** Data curation. **Peter Hopkinson:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of competing interest

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

Acknowledgment

The authors would like to thank the UKRI Interdisciplinary Circular Economy Centre for Technology Metals, Met4Tech project (EP/V011855/1) for funding. The authors express gratitude to the value chain stakeholders, including Less Common Metals, Bunting Magnetics, Dr. James Edmondson from IDTechEX, Driver and Vehicle Licensing Agency (DVLA), The Society of Motor Manufacturers & Traders (SMMT), Jaguar Land Rover (JLR), Offshore Renewable Energy (ORE) Catapult, and Department for Energy Security and Net Zero, Department for Environment Food and Rural Affairs, Department for Business and Trade, Environment Agency, HyProMag, and Ionic Technologies, for validating the results and sharing their experiences and knowledge with us.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.03.027.

References

Adamas Intelligence, 2022. Rare earth magnet market outlook to 2035.
Advanced Propulsion Centre, 2023. Q4 2022 Automotive industry demand forecast.
Alonso, E., Sherman, A.M., Wallington, T.J., Everson, M.P., Field, F.R., Roth, R., Kirchain, R.E., 2012. Evaluating rare earth element availability: a case with revolutionary demand from clean technologies. Environ. Sci. Technol. 46 (6), 3406–3414. https://doi.org/10.1021/es203518d.
Alonso, E., Pineault, D.G., Gambogi, J., Nassar, N.T., 2023. Mapping first to final uses for rare earth elements, globally and in the United States. J. Ind. Ecol. 27 (1), 312–322. https://doi.org/10.1111/jiec.13354.
Bai, J., Xu, X., Duan, Y., Zhang, G., Wang, Z., Wang, L., Zheng, C., 2022. Evaluation of resource and environmental carrying capacity in rare earth mining areas in China. Sci. Rep. 12 (1), 6105. https://doi.org/10.1038/s41598-022-10105-2.
Ballinger, B., Stringer, M., Schmeda-Lopez, D.R., Kefford, B., Parkinson, B., Greig, C., Smart, S., 2019. The vulnerability of electric vehicle deployment to critical mineral supply. Appl. Energy 255, 113844. https://doi.org/10.1016/j.apenergy.2019.113844.
Bandara, H.M.D., Darcy, J.W., Apelian, D., Emmert, M.H., 2014. Value analysis of neodymium content in shredder feed: toward enabling the feasibility of rare earth magnet recycling. Environ. Sci. Technol. 48 (12), 6553–6560. https://doi.org/10.1021/es405104k.
British Geological Survey (BGS), 2023. World mineral statistics database. https://www2.bgs.ac.uk/mineralsuk/statistics/wms.cfc?method=searchWMS.
Brunner, P.H., Rechberger, H., 2016. Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers. CRC Press.
Busch, J., Steinberger, J.K., Dawson, D.A., Purnell, P., Roelich, K., 2014. Managing critical materials with a technology-specific stocks and flows model. Environ. Sci. Technol. 48 (2), 1298–1305. https://doi.org/10.1021/es404877u.
Carrara, S., Alves Dias, P., Plazzotta, B., Pavel, C., 2020. Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system doi, 10, 160859.
Chen, W., Nie, Z., Wang, Z., Gong, X., Sun, B., Gao, F., Liu, Y., 2018. Substance flow analysis of neodymium based on the generalized entropy in China. Resources, Conservation and Recycling 133, 438–443. https://doi.org/10.1016/j.resconrec.2018.02.019.
Chen, C., Jiang, Z., Li, N., Wang, H., Wang, P., Zhang, Z., Zhang, C., Ma, F., Huang, Y., Lu, X., Wei, J., Qi, J., Chen, W.-Q., 2022. Advancing UN comtrade for physical trade flow analysis: review of data quality issues and solutions. Resources, Conservation and Recycling 186, 106526. https://doi.org/10.1016/j.resconrec.2022.106526.
Chen, C., Li, N., Qi, J., Wei, J., Chen, W.-Q., 2023. Material flow analysis of dysprosium in the United States. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.3c07496.
Ciacci, L., Vassura, I., Cao, Z., Liu, G., Passarini, F., 2019. Recovering the “new twin”: analysis of secondary neodymium sources and recycling potentials in Europe. Resour. Conserv. Recycl. 142, 143–152. https://doi.org/10.1016/j.resconrec.2018.11.024.
Cui, J., Ormerod, J., Parker, D., Ott, R., Palasyuk, A., McCall, S., Paranthaman, M.P., Kesler, M.S., McGuire, M.A., Nlebedim, I.C., Pan, C., Lograsso, T., 2022. Manufacturing processes for permanent magnets: part I—sintering and casting. JOM 74 (4), 1279–1295. https://doi.org/10.1007/s11837-022-05156-9.
Deetman, S., Pauliuk, S., van Vuuren, D.P., van der Voet, E., Tukker, A., 2018. Scenarios for demand growth of metals in electricity generation technologies, cars, and electronic appliances. Environ. Sci. Technol. 52 (8), 4950–4959. https://doi.org/10.1021/acs.est.7b05549.
Du, X., Graedel, T.E., 2011. Uncovering the global life cycles of the rare earth elements. Sci. Rep. 1 (1), 145. https://doi.org/10.1038/srep00145.
Edmondson, J., Wyatt, D., Gear, L., 2022. Electric Motors for Electric Vehicles 2022–2032 (Sample Pages) (IDTechEx, Cambridge, UK), Tech. Rep, Issue.
Eheliyagoda, D., Ramanujan, D., Veluri, B., Liu, Q., Liu, G., 2023. Tracing the multiregional evolution of the global dysprosium demand-supply chain. Resources, Conservation and Recycling 199, 107245. https://doi.org/10.1016/j.resconrec.2023.107245.
European Commission, 2023. Ecodesign for sustainable products regulation. https://commission.europa.eu/energy-climate-change-environment/standards-tools-and

-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en.
Gao, C., Xu, Y., Geng, Y., Xiao, S., 2022. Uncovering terbium metabolism in China: a dynamic material flow analysis. Resources Policy 79, 103017. https://doi.org/10.1016/j.resourpol.2022.103017.
Gauß, R., Burkhardt, C., Carencotte, F., Gasparon, M., Gutfleisch, O., Higgins, I., Karajić, M., Klossek, A., Mäkinen, M., Schäfer, B., 2021. Rare Earth Magnets and Motors: A European Call for Action. A Report by the Rare Earth Magnets and Motors Cluster of the European Raw Materials Alliance, Berlin.
Geng, J., Hao, H., Sun, X., Xun, D., Liu, Z., Zhao, F., 2021. Static material flow analysis of neodymium in China. J. Ind. Ecol. 25 (1), 114–124. https://doi.org/10.1111/jiec.13058.
Geng, Y., Sarkis, J., Bleischwitz, R., 2023. How to build a circular economy for rare-earth elements. nature 619 (7969), 248–251.
Gielen, D., Lyons, M., 2022. Critical Materials for the Energy Transition: Rare Earth Elements. International Renewable Energy Agency, Abu Dhabi, United Arab Emirates, p. 48.
Global Battery Alliance, 2023. Battery passport. https://www.globalbattery.org/battery-passport/.
Guyonnet, D., Planchon, M., Rollat, A., Escalon, V., Tuduri, J., Charles, N., Vaxelaire, S., Dubois, D., Fargier, H., 2015. Material flow analysis applied to rare earth elements in Europe. J. Clean. Prod. 107, 215–228. https://doi.org/10.1016/j.jclepro.2015.04.123.
Habib, K., Schibye, P.K., Vestbø, A.P., Dall, O., Wenzel, H., 2014. Material flow analysis of NdFeB magnets for Denmark: a comprehensive waste flow sampling and analysis approach. Environ. Sci. Technol. 48 (20), 12229–12237.
IEA, 2023. Critical Minerals Market Review 2023. https://www.iea.org/reports/critical-minerals-market-review-2023.
Ionic Technologies, 2023. Our Plant. Retrieved 09 Jan from. https://ionictechnologies.com/process/.
Jensen, P.D., Purnell, P., Velenturf, A.P.M., 2020. Highlighting the need to embed circular economy in low carbon infrastructure decommissioning: the case of offshore wind. Sustainable Production and Consumption 24, 266–280. https://doi.org/10.1016/j.spc.2020.07.012.
Jin, H., Afiuny, P., Dove, S., Furlan, G., Zakotnik, M., Yih, Y., Sutherland, J.W., 2018. Life cycle assessment of neodymium-iron-boron magnet-to-magnet recycling for electric vehicle motors. Environ. Sci. Technol. 52 (6), 3796–3802. https://doi.org/10.1021/acs.est.7b05442.
Koppelaar, R.H.E.M., Pamidi, S., Hajósi, E., Herreras, L., Leroy, P., Jung, H.-Y., Concheso, A., Daniel, R., Francisco, F.B., Parrado, C., Dell'Ambrogio, S., Guggiari, F., Leone, D., Fontana, A., 2023. A digital product passport for critical raw materials reuse and recycling. Sustainability 15 (2), 1405. https://www.mdpi.com/2071-1050/15/2/1405.
Laner, D., Feketitsch, J., Rechberger, H., Fellner, J., 2015. A novel approach to characterize data uncertainty in material flow analysis and its application to plastics flows in Austria. J. Ind. Ecol. 20 (5), 1050–1063.
Lee, I.S., Kim, J.G., 2014. Industrial demand and integrated material flow of terbium in Korea. Int. J. Precis. Eng. Manuf.-Green Technol. 1 (2), 145–152. https://doi.org/10.1007/s40684-014-0019-y.
Liu, Q., Sun, K., Ouyang, X., Sen, B., Liu, L., Dai, T., Liu, G., 2022. Tracking three decades of global neodymium stocks and flows with a trade-linked multiregional material flow analysis. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.2c02247.
Lusty, P., Shaw, R., Gunn, A., Idoine, N., 2021. UK Criticality Assessment of Technology Critical Minerals and Metals.
Morris, N., Ellerington, I., Paterson, A., Howard, M., Gifford, S., 2020. UK Electric Vehicle and Battery Production Potential to 2040. Faraday Institution.
Nansai, K., Nakajima, K., Kagawa, S., Kondo, Y., Suh, S., Shigetomi, Y., Oshita, Y., 2014. Global flows of critical metals necessary for low-carbon technologies: the case of neodymium, cobalt, and platinum. Environ. Sci. Technol. 48 (3), 1391–1400. https://doi.org/10.1021/es4033452.
van Nielen, S.S., Sprecher, B., Verhagen, T.J., Kleijn, R., 2023. Towards neodymium recycling: analysis of the availability and recyclability of European waste flows. J. Clean. Prod. 394, 136252 https://doi.org/10.1016/j.jclepro.2023.136252.
Peiró, L.T., Méndez, G.V., Ayres, R.U., 2013. Material flow analysis of scarce metals: sources, functions, end-uses and aspects for future supply. Environ. Sci. Technol. 47 (6), 2939–2947. https://doi.org/10.1021/es301519c.
Pensana PLC, 2022. Pensana breaks ground at Saltend and secures ATF funding. https://pensana.co.uk/wp-content/uploads/2022/07/Pensana-Plc-RNS-Saltend-Ground-Breaking-22-July-2022-1.pdf.
Pensana PLC, 2023. Building an independent and sustainable supply of rare earths. https://pensana.co.uk/wp-content/uploads/2023/02/Pensana-Plc-BMO-Presentation-February-2023.pdf.
Rademaker, J.H., Kleijn, R., Yang, Y., 2013. Recycling as a strategy against rare earth element criticality: a systemic evaluation of the potential yield of NdFeB magnet recycling. Environ. Sci. Technol. 47 (18), 10129–10136. https://doi.org/10.1021/es305007w.
Reimer, M.V., Schenk-Mathes, H.Y., Hoffmann, M.F., Elwert, T., 2018. Recycling decisions in 2020, 2030, and 2040—when can substantial NdFeB extraction be expected in the EU? Metals 8 (11), 867. https://www.mdpi.com/2075-4701/8/11/867.
Restrepo, E., Løvik, A.N., Wäger, P., Widmer, R., Lonka, R., Müller, D.B., 2017. Stocks, flows, and distribution of critical metals in embedded electronics in passenger vehicles. Environ. Sci. Technol. 51 (3), 1129–1139. https://doi.org/10.1021/acs.est.6b05743.
Rollat, A., Guyonnet, D., Planchon, M., Tuduri, J., 2016. Prospective analysis of the flows of certain rare earths in Europe at the 2020 horizon. Waste Manag. 49, 427–436. https://doi.org/10.1016/j.wasman.2016.01.011.
Serrano-González, J., Lacal-Arántegui, R., 2016. Technological evolution of onshore wind turbines—a market-based analysis. Wind Energy 19 (12), 2171–2187. https://doi.org/10.1002/we.1974.
Swain, B., Kang, L., Mishra, C., Ahn, J., Hong, H.S., 2015. Materials flow analysis of neodymium, status of rare earth metal in the Republic of Korea. Waste Manag. 45, 351–360. https://doi.org/10.1016/j.wasman.2015.07.020.
UK Government, 2022. Resilience for the Future: The UK's Critical Minerals Strategy.
UK Government, 2023a. Offshore wind net zero investment roadmap. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1167856/offshore-wind-investment-roadmap.pdf.
UK Government, 2023b. PM recommits UK to Net Zero by 2050 and pledges a "fairer" path to achieving target to ease the financial burden on British families. https://www.gov.uk/government/news/pm-recommits-uk-to-net-zero-by-2050-and-pledges-a-fairer-path-to-achieving-target-to-ease-the-financial-burden-on-british-families.
University of Birmingham, 2023. Birmingham to become UK's first centre for rare earth magnet recycling. https://www.birmingham.ac.uk/news/2023/birmingham-to-become-uks-first-centre-for-rare-earth-magnet-recycling.
Walton, A., Anderson, P., Harper, G., Mann, V., Beddington, J., Abbott, A., Bloodworth, A., OudeNijeweme, D., Schofield, E., Wall, F., 2021. Securing technology-critical metals for Britain. http://epapers.bham.ac.uk/3450/1/policy-commission-securing-technology-critical-metals-for-britain.pdf.
Wang, Q.-C., Chen, W.-Q., Wang, P., Dai, T., 2022a. Illustrating the supply chain of dysprosium in China through material flow analysis. Resources, Conservation and Recycling 184, 106417. https://doi.org/10.1016/j.resconrec.2022.106417.
Wang, Y., Sun, B., Gao, F., Chen, W., Nie, Z., 2022b. Life cycle assessment of regeneration technology routes for sintered NdFeB magnets. Int. J. Life Cycle Assess. 27 (8), 1044–1057.
Wang, P., Yang, Y.-Y., Heidrich, O., Chen, L.-Y., Chen, L.-H., Fishman, T., Chen, W.-Q., 2024. Regional rare-earth element supply and demand balanced with circular economy strategies. Nat. Geosci. https://doi.org/10.1038/s41561-023-01350-9.
Xiao, S., Geng, Y., Rui, X., Su, C., Yao, T., 2000. Anthropogenic cycles of praseodymium in China: 2000-2020. Chang and Yao, Tianli, Anthropogenic Cycles of Praseodymium in China 2020.
Xiao, S., Geng, Y., Pan, H., Gao, Z., Yao, T., 2022. Uncovering the key features of dysprosium flows and stocks in China. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.1c07724.
Yao, T., Geng, Y., Sarkis, J., Xiao, S., Gao, Z., 2021. Dynamic neodymium stocks and flows analysis in China. Resources, Conservation and Recycling 174, 105752. https://doi.org/10.1016/j.resconrec.2021.105752.
Zaimes, G.G., Hubler, B.J., Wang, S., Khanna, V., 2015. Environmental life cycle perspective on rare earth oxide production. ACS Sustain. Chem. Eng. 3 (2), 237–244. https://doi.org/10.1021/sc500573b.
Zapp, P., Schreiber, A., Marx, J., Kuckshinrichs, W., 2022. Environmental impacts of rare earth production. MRS Bull. 47 (3), 267–275. https://doi.org/10.1557/s43577-022-00286-6.