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Regional rare-earth element supply and demand balanced with circular economy strategies

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The growing dependence of society on rare-earth elements poses a challenge to achieving a just low-carbon transition globally. While circular economy strategies have gained attention, their specific impacts remain unmeasured. Here we present an integrated model that quantifies how circular economy strategies can reshape global supply chains of the critical rare-earth elements such as neodymium, praseodymium, dysprosium and terbium. The model considers both in-ground and in-use stocks across ten regions from 2021 to 2050. The projections include the full deployment of three widely accepted climate scenarios. We find a considerable mismatch between in-ground stocks, supply and demand at specific region and element levels, with the mismatch for heavy rare-earth elements as a key obstacle for achieving net-zero emissions targets. We suggest that, as in-ground stocks decline among mineral suppliers, the accumulation of in-use stocks in consuming regions can foster a more balanced and less polarized geopolitical landscape for rare-earth elements, and circular economy strategies can lead to an increase of 701 kt secondary supply and a decrease of 2,306 kt demand within the next three decades. Implementing these circular economy strategies will require international cooperation in the governance of rare-earth elements amid sustainable transition.

Climate change is a common challenge for the entire world, which requires efforts from nearly all nations for a just low-carbon transition[1,2]. However, the supply of rare-earth elements (REEs), especially neodymium (Nd), praseodymium (Pr), dysprosium (Dy) and terbium (Tb), as critical raw materials of clean technologies (for example, electric vehicles (EVs) and wind power), is highly concentrated in a few countries[3–6]. This has sparked 'anxiety' about supply security and trade friction, such as in the United States[7] and the European Union[8]. Furthermore, the uneven distribution of REEs is widely concerning as it may intensify international competition and geopolitical risks and further impede global climate goals, as noted by some international organizations[9–11] and others[12,13]. To facilitate the transition towards a climate-safe future, it is essential to develop effective strategies for ensuring the stability of global REE supply chains.

Unlike fossil fuels, which are 'burnt out' and permanently lost once consumed, REEs[14] and other metals are accumulated as in-use stocks

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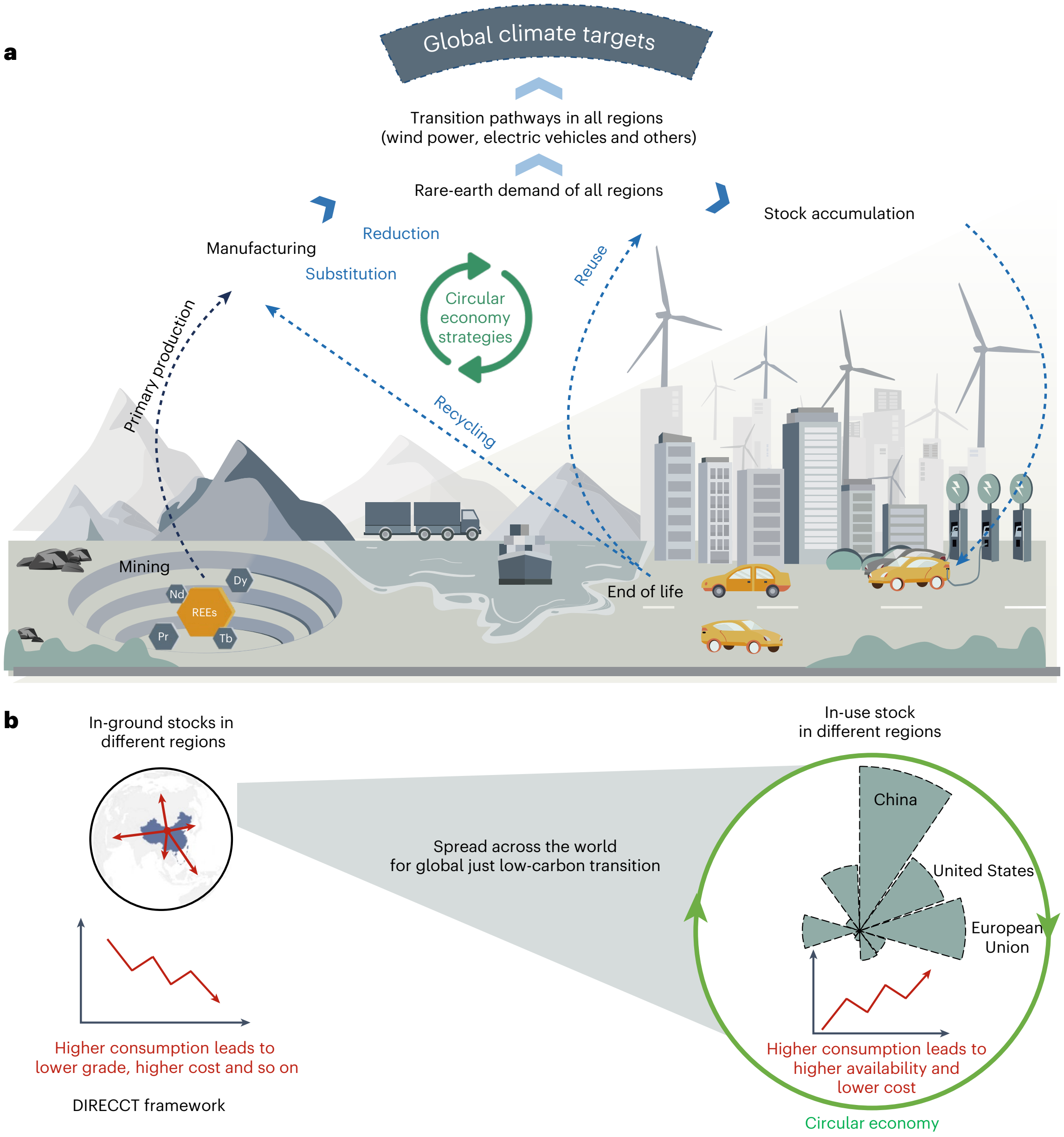


Fig. 1 | Framework of DIRECCT. This framework aims to map the REE flows from in-ground to in-use stocks for global just transition. **a**, The roles of different circular economy strategies, including reuse, reduction, substitution and recycling, in the shift of in-ground minerals to in-use stocks. **b**, How the transition of REEs can assist the clean and just transition along with its spread from mining sites to final consumers across the world.

that can be 'recovered' as alternative supply[15,16]. Given that massive REEs transfer from in-ground stocks (deposits) to in-use stocks (products), there is growing interest in extracting the in-use stocks as secondary supplies[17]. Circular economy (CE) strategies, which have been proposed to reduce supply issues across various critical materials such as cobalt and lithium[18,19], can also be applied to the case of REEs[6,20,21]. However, despite recent attention[5], the potential of rare-earth (RE) circularity in promoting just low-carbon transition remains uncertain due to limited integrated quantitative analysis.

The present focus from previous literature[4,22–24] regarding RE geopolitics is limited to the regional holdings of in-ground stocks. By contrast, the corresponding impact of in-use stocks, which refers to REEs in the final products[15], has received scant attention. Importantly, once they are used, traded and diffused globally, REE endowment will be dispersed across the world (Fig. 1b). This can form a new geopolitical chessboard. Most previous studies, from either a single regional perspective[5,25,26] or an entire global perspective[10,18,27], disregarded the disparities between regions. This may fail to capture the complexity and shifting geopolitical dynamics of the REE market that matter to global just transition.

In this Article, we present a Dynamic Integrated Model of Rare-Earth Circularity and Climate Target (DIRECCT; Fig. 1a) model to explore the linkage among climate targets, energy transition pathways and circular flows of REEs in ten global regions. The DIRECCT model considers three widely adopted climate target scenarios: the stated policies scenario (STEPS), the sustainable development scenario (SDS) and the net-zero emissions by 2050 scenario (NZE). Two types of metal stocks, in Earth's crust system (in-ground stocks) and in the societal systems (in-use stocks), are captured to quantify the dynamic changes of regional REE distribution (Fig. 1b). In each climate target scenario, the roles of different CE strategies (Fig. 1a) in reshaping global REEs supply for a just and safe low-carbon transition are explored and discussed.

Fig. 2 | RE-leveraged and pledged GHG reduction in the NZE scenario. **a**, Sketch diagram of RE-leveraged GHG reduction. **b**, Pledged GHG reduction from EV and wind power from 2021 to 2050 for each studied region (in $GtCO_2e$). **c**,**d**, RE-leveraged rate of GHG reduction for each studied region under two trade scenarios: counterfactual no-trade scenario (**c**) and free trade with priority in self-supply scenario (**d**).

REEs limiting factor to achieving climate goals

REEs play a crucial role in decarbonizing the economy (Fig. 2a). To reach the NZE target, global greenhouse gas (GHG) reduction from REE-related applications (EVs and wind power) is pledged to be 321 $GtCO_2$-equivalent (CO_2e) (Fig. 2b). We introduce the indicator 'RE leverage rate of GHG reduction' as a proxy to determine the ratio of leveraged GHG reduction supported by available REEs in achieving the pledged climate target for each region (detailed descriptions in Supplementary Information section 2.4). Considering the uneven RE distribution, we further examine the variations in the RE leverage rate under two trade scenarios (counterfactual no-trade scenario and free trade with priority in self-supply scenario; Supplementary Information section 2.4) in Fig. 2c,d, respectively.

Our results indicate that the ambitious NZE target would be severely hindered by REEs at both global and regional levels if no CE

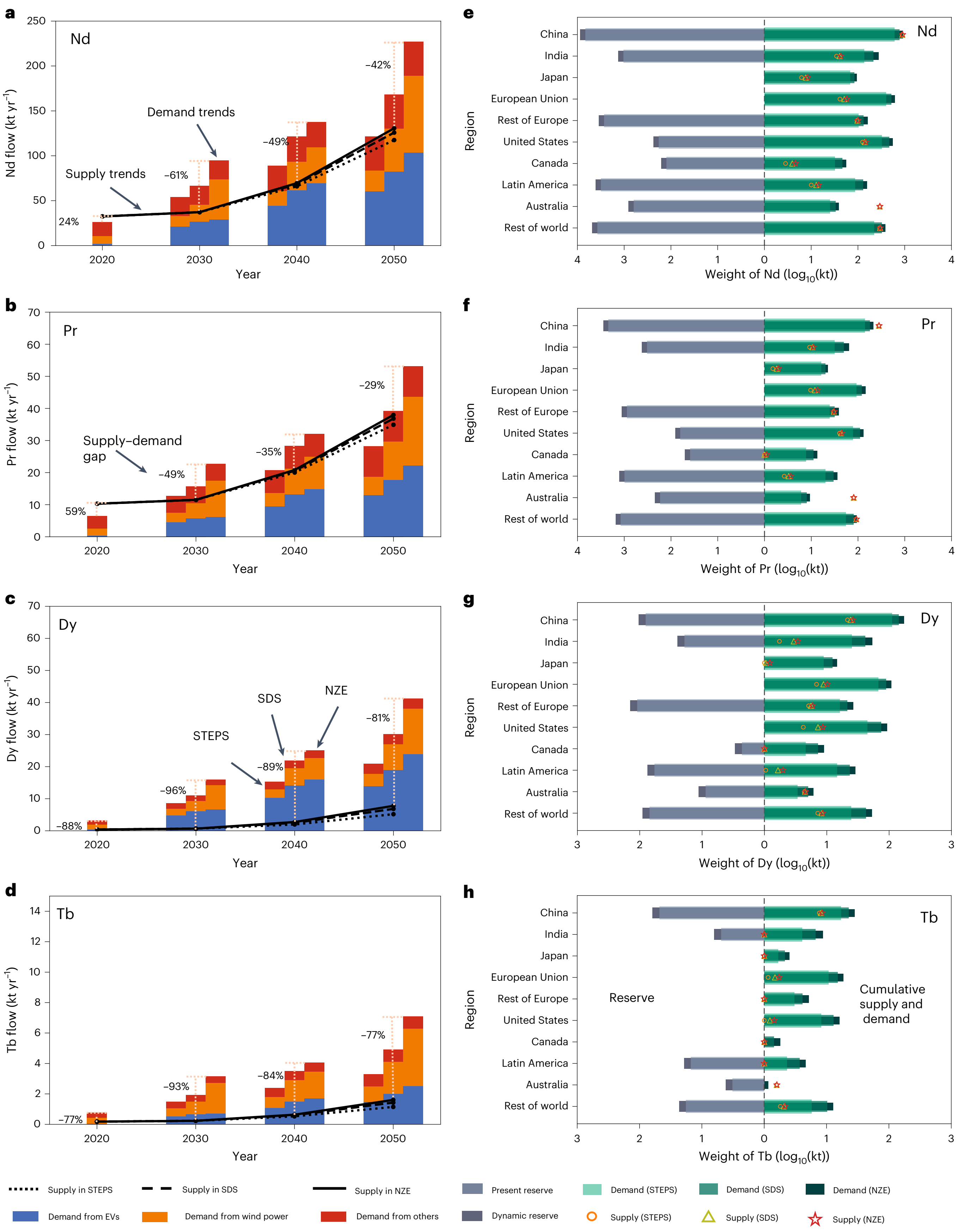


Fig. 3 | The demand, supply and reserve of REEs at global and regional levels in the baseline scenario. **a**–**d**, Global (primary plus secondary) supply and demand of Nd (**a**), Pr (**b**), Dy (**c**) and Tb (**d**) by sector in kt yr^{-1}. **e**–**h**, Regional reserves, cumulative (primary plus secondary) supply and demand of Nd (**e**), Pr (**f**), Dy (**g**) and Tb (**h**) between 2021 and 2050, represented as a base-10 logarithm.

strategies were implemented. In the absence of trade, the leverage rates for GHG reduction are as follows: 54% for Pr, 60% for Nd, 13% for Dy and 18% for Tb (Fig. 2c). However, in the 'free trade' scenario, the leverage rates for Pr and Nd can be elevated to 61% and 76%, respectively, while the rates for Dy and Tb remain unchanged (Fig. 2d). Given the attainment of climate target is contingent on all studied REEs, Dy will emerge as the most critical bottleneck raw material. Under the limitation of Dy at the no-trade scenario, China, the European Union and the Unite States can achieve only 15%, 9% and 10% of their respective pledged GHG reductions. Nevertheless, the global RE-leveraged GHG reduction rate may be limited to 13% (Fig. 2c,d), regardless of RE trade conditions.

The constraints posed by REEs on achieving climate pledges are not equal at the regional level. In the no-trade scenario, the leverage rate of GHG reduction in seven of the ten studied regions—the United States (10%), the European Union (9%), the rest of Europe (9%), Latin America (7%), Canada (8%), India (6%) and Japan (8%)—will lag behind the global average (Fig. 2c). If trade is allowed, the leverage rates of Pr, Nd and Tb for regions such as the European Union, the United States, Latin America, Canada, India and Japan show a notable increase (Fig. 2d). However, the limited availability of Dy continues to undermine these efforts. Thus, there is an urgent coordinated need for a more sufficient and balanced supply of REEs.

Regional shortages of REEs

We compare the regional demand of REEs (details in Methods) with their potential supply, including both primary (from minerals, with projected increase in different regions from literature[28]) and secondary (from end-of-life (EOL) flows) route, in Fig. 3a–d. The regional comparison between the cumulative demand of future REEs and their present reserves is given in Fig. 3e–h. Notably, the present reserve is adopted here to illustrate the gap between cumulative supply and demand, emphasizing the need for future reserve exploration and development of mining capacities, rather than the exhaustion of minerals.

Our analysis covers the period from 2010 to 2050 (negligible REE consumption of studied applications before 2010). Historically, the corresponding demand for REEs has increased rapidly from 17 kt yr^{-1} in 2010 to 37 kt yr^{-1} in 2020 driven by the global wind power and EV expansion. In line with the climate targets, global demand for Nd, Pr, Dy and Tb will increase rapidly from 26 kt yr^{-1}, 7 kt yr^{-1}, 3.2 kt yr^{-1} and 0.8 kt yr^{-1} in 2020 to 122–227 kt yr^{-1}, 28–53 kt yr^{-1}, 21–41 kt yr^{-1} and 3–7 kt yr^{-1} in 2050, respectively (Fig. 3a–d). However, our results indicate the designed expansion of capacity in light REEs (Pr and Nd) supply will soon become insufficient (Fig. 3a,b). The supplies of heavy REEs (HREEs, Dy and Tb) are much scarcer and have already been deficient since 2020, with a supply deficit ratio of 87% for Dy and 74% for Tb, indicating some unidentified sources at present (Fig. 3c,d). This requires a more radical increase in REE supply, especially to deliver the NZE climate goal, which requires 65% and 21% more REEs than the STEPS and SDS, respectively (Supplementary Table 21).

Such an REE shortage becomes more severe at regional levels (Fig. 3e–h). Among the leading global REE consumers—China, the European Union and the United States—China is projected to be the only nation capable of fulfilling its domestic demand of Pr, Nd and Tb (922 kt of Nd, 214 kt of Pr, 173 kt of Dy and 28 kt of Tb in the NZE) with its present reserve, while the present reserve of Dy is insufficient for all regions. The United States will fall far short of satisfying its domestic demand (558 kt of Nd, 131 kt of Pr, 93 kt of Dy and 16 kt of Tb), even if considering dynamic changes in reserve exploration (Methods). Both the European Union and Japan have almost no domestic reserves, exhibiting profound reliance on the global REE market. Regarding REE supply, China and Australia emerge as the sole sources, with a surplus supply of light REEs (Fig. 3b,d), while the scarcity of HREEs is widespread, with only Australia demonstrating a marginally adequate supply of Tb (Fig. 3h). As a result, the inevitable prospect of international competition for available REEs, particularly HREEs, looms large.

Redistribution of in-use REE stocks

The RE minerals are not equally distributed, with 87% in the top four nations (Fig. 4a). Our projection indicates around 71% of in-use stocks will be accumulated in the top three nations—China (32%), the European Union (21%) and the United States (18%)—by 2050 (Fig. 4b). Regional RE holdings in the form of in-ground and in-use stocks are measured in economic value[29] (details in Supplementary Information section 2.5). Notably, the European Union, the United States and Japan are predicted to accumulate US$169 billion, US$143 billion and US$23 billion of RE in-use holdings by 2050, which far exceed their present in-ground holdings (negligible for the European Union and Japan, US$44 billion for the United States; Fig. 4a,b). This implies that these regions can leverage these to offset their deficiencies of in-ground minerals.

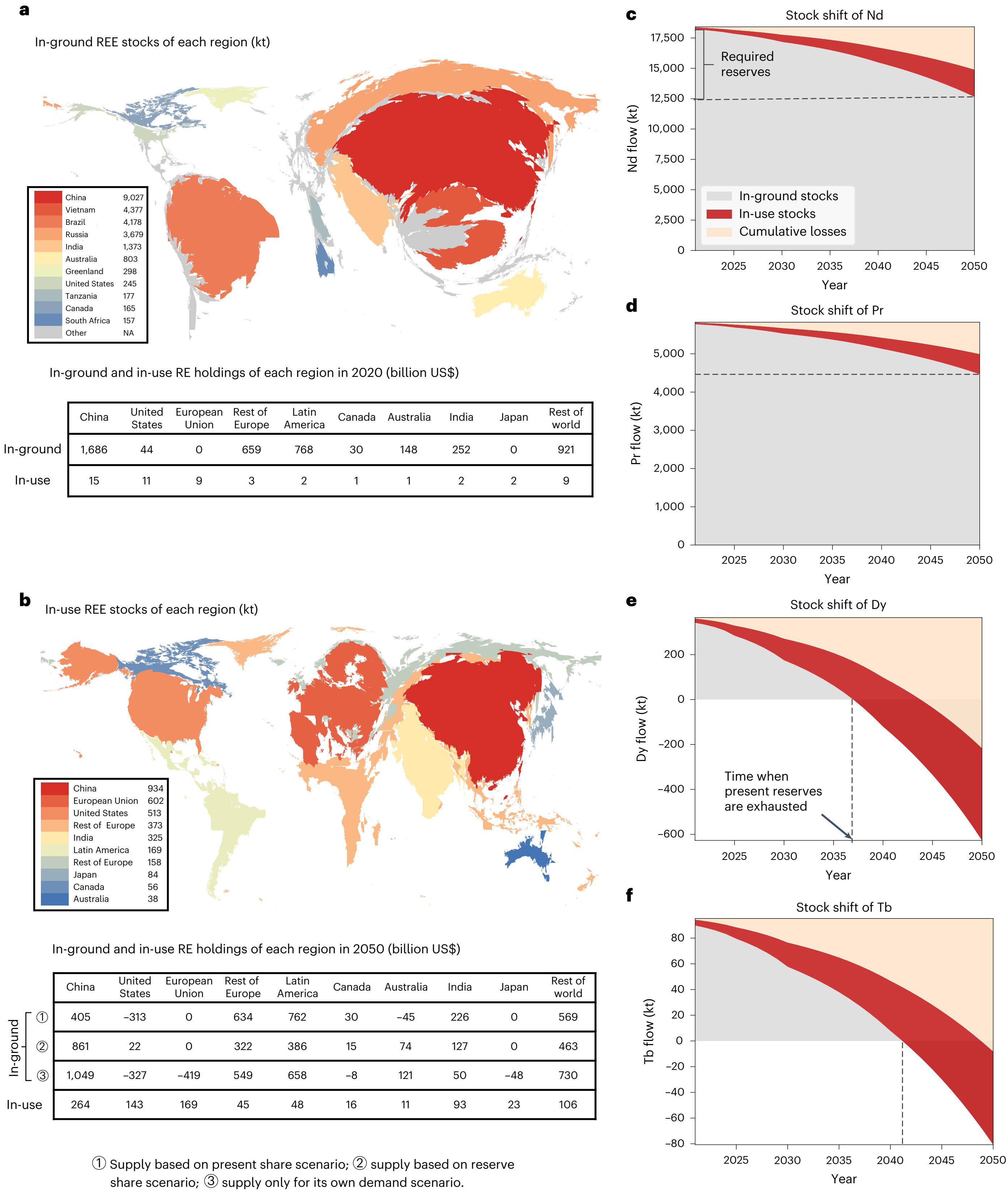
Global present in-ground stocks of REEs are predicted to decrease by 8,070 kt from 2020 to 2050 (Fig. 4c–f). At the same time, there is a notable increase in RE in-use stocks, growing from 219 kt in 2020 to 3,252 kt in 2050. In total, the stocks of studied REEs will decrease from 24,700 kt (US$4,557 billion) in 2020 to 19,660 kt (US$3,182 billion) in 2050 due to large REE losses along their life cycle[30]. This highlights the need for other supply-side strategies in reducing the production loss rates and mining from tailings and slags. Still, the in-use stocks of Nd and Pr will account for 15% and 11% of their total holdings, but the present reserves of Dy and Tb would be exhausted by around 2035–2045 to meet the NZE climate target (Fig. 4e,f). Given that reserve is a dynamic concept, our results regarding reserve exhaustion should be carefully interpreted under the strict condition of no discovery of new RE reserves (Methods). Therefore, the in-use stocks of HREEs are of great significance in international competition since their in-ground stocks are diminishing sharply.

Without CE strategies, most of the in-use stocks will end up in waste streams and cannot be used as a future resource. In this Article, we follow similar concepts from previous studies[19,31] to develop six different CE scenarios (baseline, recycling, reuse, substitution, reduction and composite with detailed assumptions in Methods and Supplementary Table 15) to explore the impact of CE in different regions in Fig. 5 (regional trends in Supplementary Fig. 27).

We map regional material flows of Nd and interregional dependencies to support the transition under the NZE target in Fig. 5a (cumulative flows during 2021–2050; other REEs in Supplementary Fig. 32), in which the CE baseline and composite scenarios are compared. There are three key major benefits from CE strategies. First, on the demand side, CE can nearly halve the required Nd demand from 3,258 kt to 1,687 kt to achieve the same GHG reduction target. Second, aside from reduction in EOL losses, the circularity of Nd can be largely enhanced with an additional supply of 492 kt of Nd, 1.7 times the 288 kt in the baseline scenario. Third, with the assistance of demand reduction and improvements in circularity, CE can largely reduce the global and regional dependency by around 60% on primary RE minerals (with high geopolitical and environmental risks[32]), the amount of which will decrease from 2,970 kt to 1,195 kt during 2021–2050.

The impacts vary among different CE strategies (Fig. 5b). As the preventive measures, the substitution and reduction strategies could reduce global REE primary demand by 1,637 kt and 961 kt, respectively (Fig. 5b). As the EOL measure, recycling can help boost the cumulative secondary supply to 932 kt, higher than that of the reuse strategy (606 kt in total). Compared with the baseline scenario, about 60% of Nd, 59% of Pr, 67% of Dy and 63% of Tb could be exempt from being mined underground by the composite strategy. This can help to conserve the scarce HREEs and ensure that their present reserves can be sufficient to meet their demand before 2050 (Supplementary Tables 19 and 21).

The CE can also benefit a more balanced regional REE supply. As indicated by the Herfindahl–Hirschman Index (HHI; Supplementary Information section 2.6), the concentration of global supply could be reduced by up to 15% for Nd, 14% for Pr, 18% for Dy and 27% for Tb by 2050 (Fig. 5c). Around 30–40% of the demand for REEs in China, the



Region	kt
China	9,027
Vietnam	4,377
Brazil	4,178
Russia	3,679
India	1,373
Australia	803
Greenland	298
United States	245
Tanzania	177
Canada	165
South Africa	157
Other	NA

In-ground and in-use RE holdings of each region in 2020 (billion US$)

	China	United States	European Union	Rest of Europe	Latin America	Canada	Australia	India	Japan	Rest of world
In-ground	1,686	44	0	659	768	30	148	252	0	921
In-use	15	11	9	3	2	1	1	2	2	9

Region	kt
China	934
European Union	602
United States	513
Rest of Europe	373
India	325
Latin America	169
Rest of Europe	158
Japan	84
Canada	56
Australia	38

In-ground and in-use RE holdings of each region in 2050 (billion US$)

		China	United States	European Union	Rest of Europe	Latin America	Canada	Australia	India	Japan	Rest of world
In-ground	①	405	−313	0	634	762	30	−45	226	0	569
	②	861	22	0	322	386	15	74	127	0	463
	③	1,049	−327	−419	549	658	−8	121	50	−48	730
In-use		264	143	169	45	48	16	11	93	23	106

① Supply based on present share scenario; ② supply based on reserve share scenario; ③ supply only for its own demand scenario.

Fig. 4 | Global shift of REEs from in-ground stocks to in-use stocks in the NZE scenario. a, Total in-ground RE stocks and RE holdings of each region in 2020. **b**, Total in-use RE stocks and RE holdings of each region in 2050 (note: rest-of-world countries are coloured on the basis of the average value due to their loose geographical relationship). **c**–**f**, REE stocks of Nd (**c**), Pr (**d**), Dy (**e**) and Tb (**f**) shift from in-ground to in-use. The results of STEPS and SDS can be found in Supplementary Information section 3.5.

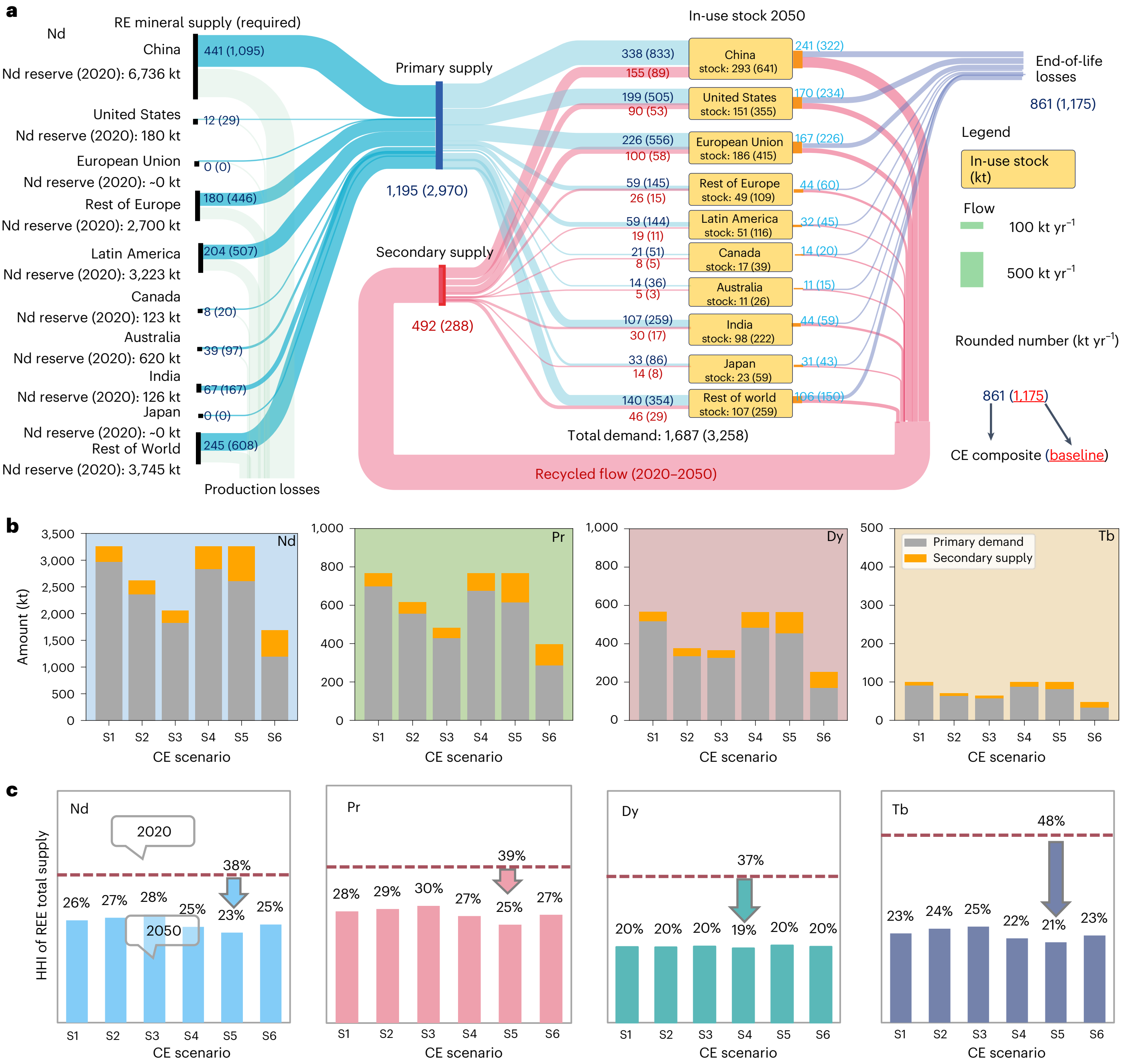


Fig. 5 | Material flows of the REEs and regional interdependence in the NZE scenario under different CE scenarios. a, Sankey diagram of material flows of Nd through the world between 2021 and 2050 in the CE composite and NZE baseline scenarios (for other REEs, see Supplementary Fig. 32). **b**, Global cumulative primary demand and secondary supply of the REEs between 2021 and 2050 (in kt). **c**. Changes in regional concentration of REE supplies, indicated by the HHI of Nd, Pr, Dy and Tb in 2020 and 2050. S1, baseline scenario; S2, reduction scenario; S3, substitution scenario; S4, reuse scenario; S5, recycling scenario; S6, composite scenario.

United States and the European Union could be met through reuse or recycling strategies by 2050 (Supplementary Fig. 27). This is particularly meaningful for the United States and the European Union, which rely highly on foreign REE sources. However, due to the long lifespan of EVs and wind turbines (Supplementary Fig. 27), it is necessary to accelerate reduction and substitution strategies to cope with RE supply risks in the short to medium term.

Under the influence of this single CE strategy, a large amount of foreign RE supply will still be required by the European Union (18–41 kt), the United States (9–30 kt), India (15–33 kt) and Latin America (7–15 kt) to achieve their NZE targets in 2050 (Supplementary Fig. 27). Therefore, the joint implementation of all CE strategies is a must, which can almost enable China, the European Union and the rest of Europe to eventually achieve a ‘closed-loop’ system (in which the circular flows from EOL REE products will exceed their final demand) of REEs by 2050 in the STEPS and SDS (Supplementary Figs. 25 and 26).

Implementation of CE strategies

The REEs play an important role in fulfilling the global common objective of climate change mitigation. Our investigation reconfirms that the availability of REEs will become an important constraint of global low-carbon transitions, especially the HREEs (Dy and Tb), which could limit the global GHG reduction to only 13% of its target (Fig. 2). Therefore, the development of HREE-free technologies is a critical and urgent necessity for related industries such as EVs and wind power.

There is growing attention from international bodies to strengthening the governance of critical minerals for global just transition[33–35]. This is particularly relevant for REEs since their in-ground stocks are considered to be accompanied by high geopolitical, economic, environmental and social risks[36–38]. Our framework (Fig. 1) can fill a gap in modelling the potentials of CE in reducing the dependence of RE mineral extraction. We show that ongoing consumption of REEs can substantially reallocate REE stocks from their origins to regions with ambitious climate goals (for example, China, the European Union and the United States together accumulate 71% of the world's in-use stocks by 2050; Fig. 4b). Through CE strategies, the newly formed REE stocks can change the geopolitical landscape behind REE supply chain towards a more balanced and less polarized one.

Compared with in-ground stocks, the supply from in-use stocks has many exceptional attributes for a just transition. For example, high demand (price) can incentivize RE mining in more environmentally and socially sensitive areas[33], accompanied by artisanal activities[39]. Despite demand reduction (halved by CE), the growing supply from in-use stock holders with a more balanced structure (HHI decreased by 14–27%) can help to stabilize REE prices. Meanwhile, secondary production in general has a much smaller environmental footprint than primary supply[40]. Notably, the quality of RE minerals is inevitably decreasing with the depletion of high-grade ore deposits[31], which further highlights the mentioned advantages of in-use stocks.

However, without CE, the in-use stocks of REEs could not be effectively mobilized. CE is already recognized as the 'third pillar' of deep decarbonization[41,42]. Our results show that CE can not only bring about more complete use of EOL REEs, but also reduce the demand for REEs through both supply-side and demand-side strategies (Fig. 5). For example, CE can substantially reduce primary mining by 60%, which can prevent the 'REE balance problem' by reducing the surplus and corresponding cost of other REEs such as cerium and lanthanum[10,43]. Moreover, CE can help some major regions such as the United States, the European Union, India and Japan reduce their dependency on foreign RE supplies by up to 100%, 93%, 91% and 88% by 2050, respectively (Supplementary Fig. 27)[44]. Thus, international cooperation on CE, such as the European Union's initiative of the Global Alliance on Circular Economy and Resource Efficiency[45,46], is welcomed.

The benefits of CE require mobilization of technologies, policies and infrastructures towards full use of secondary REE sources. There is currently a 'window of opportunity' when demands and potential tensions are still relatively lower than the anticipated challenges in upcoming decades. In particular, the CE strategies for REEs are associated with some uncertainties[47,48]. Moreover, the market of RE-containing discards will become more challenging because REEs are highly dispersed and mixed among products[43,49]. Thus, cooperation on establishing standards between upstream and downstream industries is needed. Notably, the industrialization of CE strategies is also driven by market forces; within this context, enterprises may not attach enough importance to CE in the current window of opportunity. Therefore, it is necessary to closely monitor the development of CE strategies and introduce government regulations and economic incentives to encourage technological innovation and business investment[50].

Among the limitations in our study (see 'Uncertainty and sensitivity analysis' in Methods), the analysis of supply shortage and reserve exhaustion should be carefully interpreted. Indeed, the amount of reserves can increase due to factors such as explorations, technologies and economic developments[50], such as the new RE deposit in Turkey[9] or unidentified REE reserves in Myanmar. To fill the supply gap, the importance of REE exploration is still of utmost importance. Nevertheless, the historical growth speed of RE reserves seems not fast, up from 110 million to 120 million tons in the past decade (Methods). Meanwhile, it usually takes one to two decades from the initial exploration to the operational mining for those newly discovered deposits. In this regard, the time from formation to the recovery of in-use stocks is generally less than 20 years, which highlights benefits in investing CE strategies. Still, a parallel consideration of the exploration of new REE deposits as well as the implementation of CE strategies is recommended.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41561-023-01350-9.

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Methods

This section provides an overview of our DIRECCT method, and more details can be found in Supplementary Information sections 1 and 2.

The model framework

DIRECCT is a systemic model that combines a stock-driven dynamic material flow analysis (MFA)[51] and a scenario analysis (approach (Supplementary Fig. 1). It is designed to quantify the future material flows and spatial distribution dynamics of four REEs (Nd, Pr, Dy and Tb) by end use and by region and to evaluate the role that CE strategies play in mitigating REE supply issues. The end uses of REEs can be classified into emerging sectors that deliver climate goals and low-carbon futures, including EV and wind power, and other end uses, for example, robots, elevators and air conditioners. We split the world into ten regions—China, the United States, the European Union, the rest of Europe, Latin America, Canada, Australia, India, Japan and the rest of world—which are indexed by $i(i = 1,$&hellips;,$10)$. The results shown in our study are in the period of 2020–2050, in which the time is indexed by t.

Dynamic stock-driven MFA model

A dynamic stock-driven MFA model is used to quantify the annual flows of REE-containing end uses (EVs in units or wind power capacity in GW), which is shown as follows:

$$\mathrm{inflow}_{i,t} = \mathrm{stock}_{i,t} - \mathrm{stock}_{i,t-1} + \mathrm{outflow}_{i,t} \tag{1}$$

$$\mathrm{outflow}_{i,t} = \sum_{m<t} \mathrm{inflow}_{i,m} \times L\,(t-m) \tag{2}$$

where $\mathrm{stock}_{i,t}$ is the stocks of EVs (Supplementary Fig. 4) or wind power capacity (Supplementary Fig. 5), $\mathrm{inflow}_{i,t}$ is the annual demand for EVs or newly installed wind power capacity, $\mathrm{outflow}_{i,t}$ is the amount of retired EVs or decommissioning wind power capacity, L is the lifetime probability distribution function of EVs or wind turbines, and $L(t-m)$ is the probability of the EVs or wind turbines entering the market in time m and retiring in time t, assuming that the lifespan of EVs follows a Weibull probability distribution with the most likely lifetime of 15 years (ref. 52) and wind turbines' lifespan follows the normal distribution with a mean value $\mu = 20$ years and a standard deviation of $0.25\,\mu$ (ref. 47).

Role of CE strategies in the demand for REEs

The REE inflows are calculated by multiplying the inflows of final products (EVs and wind power) and their corresponding REEs' material intensities. In the reduction strategy, the REEs' material intensities can be reduced, and in the substitution strategy, the REE-containing technologies can be substituted by the REE-free technologies. Therefore, the inflow of REEs is calculated as follows:

$$\mathrm{inflowRE}_{i,t} = \mathrm{inflow}_{i,t} \times \mathrm{MI} \times (1 - \mathrm{red}_t) \times (1 - \mathrm{sub}_t) \tag{3}$$

where MI is the material intensity of a specific REE in its corresponding application (Supplementary Table 8), red_t is the reduction rate of the REE's material intensity as a result of the reduction strategy in time t and sub_t is the rate that the REE-containing technologies are replaced with the REE-free technologies as a result of the substitution strategy.

Notably, the mainstream technologies of wind power generators include direct-drive and geared-drive permanent magnet synchronous generators, which have different REE material intensities[4]. Therefore, the REE inflows in the wind power sector are calculated by the sum of two kinds of technologies. See more details in the Supplementary Information section 2.3.

As for the other sectors, we predict their annual demand for REEs assuming that it will grow at a compound annual growth rate of 3%, given the expected annual growth in global gross domestic product[53].

The outflows and in-use stocks of the REEs are calculated as follows:

$$\mathrm{outflowRE}_{i,t} = \sum_{m<t} \mathrm{inflowRE}_{i,m} \times L\,(t-m) \tag{4}$$

$$\mathrm{stockRE}_{i,t} = \mathrm{stockRE}_0 + \sum_{m\le t} \mathrm{inflowRE}_{i,m} - \mathrm{outflowRE}_{i,t} \tag{5}$$

where $\mathrm{outflowRE}_{i,t}$ is the outflow of a specific REE in region i in time t, $\mathrm{stockRE}_{i,t}$ is the in-use stocks of the specific REE and $\mathrm{stockRE}_0$ is the initial in-use stocks of the REE. The lifespan of other sectors is assumed to follow the Weibull probability distribution with the most likely lifetime of ten years.

Role of CE strategies in the secondary supply of REEs

The secondary supply of REEs can be sourced from the reuse and recycling strategies. The reused REEs are the REEs contained in the EOL products with a reusable design that have not been reused before, which are calculated as equation (6).

$$\mathrm{reusedRE}_{i,t} = \sum_{m<t} (\mathrm{inflowRE}_{i,m} - \mathrm{reusedRE}_{i,m}) \times L\,(t-m) \times \mathrm{reusable\_rate}_m \tag{6}$$

where $\mathrm{inflowRE}_{i,m}$ is the REE inflows in time m and $\mathrm{reusable\_rate}_m$ is the share of products with reusable design in time m.

It is assumed that if an EOL product is reusable, it will be reused preferentially; otherwise, it will be recycled. Therefore, the recycled REEs are calculated as equation (7).

$$\mathrm{recycledRE}_{i,t} = (\mathrm{outflowRE}_{i,t} - \mathrm{reused}_{i,t}) \times \mathrm{recycling\_rate}_t \tag{7}$$

where $\mathrm{outflowRE}_{i,t}$ is the outflow of a specific REE, and $\mathrm{recycling\_rate}_t$ is the recycling rate of the REE in time t.

The secondary supply of REEs is then calculated as the sum of $\mathrm{reusedRE}_{i,t}$ and $\mathrm{recycledRE}_{i,t}$.

The required reserves and losses of REEs

In consideration of the yield rate of REEs (60% in the extraction stage[30], 90% in the refining and separation stage and 98% in the fabrication stage[54]), we define the required reserves (equation (8)) as the amount of REEs required to be mined from the in-ground stocks to satisfy their primary demand. The cumulative required reserves between 2021 and 2050 are calculated as equation (9), and the results are shown in Supplementary Tables 22–26. The losses of REEs here include the production losses and recycling losses, where the production losses are the amount of REEs lost in the process of refining, separation and fabrication (equation (10)), and the recycling losses are those REEs uncollected or lost in recycling process (equation (11)). The cumulative REE losses by time T are calculated as equation (12).

$$\mathrm{RR}_{i,t} = \left(\mathrm{inflowRE}_{i,t} - \mathrm{reusedRE}_{i,t} - \mathrm{recycledRE}_{i,t}\right)/\mathrm{py} \tag{8}$$

$$\mathrm{CRR}_i = \sum_{t=2021}^{2050} \mathrm{RR}_{i,t} \tag{9}$$

$$\mathrm{pl}_{i,t} = \mathrm{RR}_{i,t} \times (1 - \mathrm{py}) \tag{10}$$

$$\mathrm{rl}_{i,t} = \mathrm{outflowRE}_{i,t} - \mathrm{reused}_{i,t} - \mathrm{recycledRE}_{i,t} \tag{11}$$

$$\mathrm{CL}_{i,T} = \sum_{t\le T} \mathrm{pl}_{i,t} + \mathrm{rl}_{i,t} \tag{12}$$

where $RR_{i,t}$ is the required reserves of region i in time t, is the full-cycle yield rate of REEs (which is 53%), CRR_i is the cumulative required reserves of region i, $pl_{i,t}$ is the production losses of region i in time t, $rl_{i,t}$ is the recycling losses of region i in time t and $CL_{i,T}$ is the cumulative (production and recycling) losses of region i by time T.

Primary supply of the REEs

On the basis of Roskill's forecast of RE production before 2030 in kiloton (kt) rare-earth oxide (REO)[28], we further assume a 5% compound annual growth rate of RE production after 2030 (Supplementary Fig. 7). Notably, RE production is compounded by various REOs, which need to be disaggregated into individual REEs. To do so, we estimate the average content of the REEs (indexed by k) in different regions (indexed by i) on the basis of equation (13).

$$REE_{i,k} = \sum_{j} reserve\_share_{i,j} \times REO_{j,k} \times mf_k \tag{13}$$

where $REE_{i,k}$ is the average content of the REE k in region i, $reserve\_share_{i,j}$ is the reserve share of mine j in region i, $REO_{j,k}$ is the content of the oxide of REE k in mine j ($j = 1$,&hellips;,20) (Supplementary Table 16) and mf_k is the mass fraction of REE k in its oxide (85.7% for Nd, 82.8% for Pr, 87.1% for Dy and 89.2% for Tb). The result of the REEs' average content in different regions is shown in Supplementary Table 17. Then the primary supply of REEs in different regions can be calculated on the basis of their RE production (kt REO) and the corresponding REE average content (%), and the results are shown in Supplementary Table 18.

Reserves of the REEs

We consider two reserve scenarios in our analysis: present and dynamic reserves. The present reserves assume that there is no change in global RE reserves, which is measured by the RE reserves reported by the US Geological Survey (USGS) in 2022[55]. The present reserves of different REEs can be calculated as the product of RE reserves reported by the USGS in kt REO and the corresponding REE average content (%). The present reserves of four REEs are shown in Supplementary Table 19. The dynamic reserves assume that RE reserves can change with new mines being explored. The historical RE reserves increase from 110 million tons (reported in 2012) to 120 million tons (reported in 2022) in the past decade, with a growth rate of 9% according to the USGS[55]. We assume that the dynamic RE reserves will continue to grow at a rate of 9% per decade on the basis of present reserves.

Uncertainty and sensitivity analysis

Uncertainties of our analysis are related mainly to model assumptions about the lifespan of end uses and the REE material intensity in these end uses. Here we adopt the Monte Carlo simulation (100,000 iterations) to quantify the uncertainties of main model results, including annual regional RE demand and in-use stocks (Supplementary Figs. 34 and 35). In addition, sensitivity analysis for these key uncertainty factors is conducted (see details in Supplementary Information section 4.2), and the results are represented in Supplementary Fig. 33.

Overview of scenarios settings. Our work combines two series of scenarios in our DIRECCT modelling: climate target scenarios and circular economy scenarios. The details of scenario settings can be found in Supplementary Information section 1.2 and are summarized as follows.

Climate target scenarios. The climate goal scenarios talked about in this paper are the STEPS, SDS and NZE. STEPS reflects the current policy settings, SDS assumes that the world will reach net-zero emissions by 2070 (with many countries and regions reaching net zero much earlier) while NZE shows a pathway for the global energy sector to achieve net-zero CO_2 emissions by 2050[56,57]. The detailed definitions and objectives of the climate goal scenarios are shown in Supplementary Table 1.

Circular economy scenarios. We discuss the effects of four individual CE scenarios—reduction, substitution, reuse and recycling—and the synergistic effect of their composite strategy. Substitution and reduction are considered the preventive measures, which aim to replace the REEs in final applications or decrease their intensity through improved designs, respectively. As the EOL measures, reuse aims to fulfil demand through reusable components or products and recycling involves the recovery of REEs for further use. In addition, a baseline scenario is set as a basis for comparison with these CE scenarios.

The narratives of the CE scenarios are as follows.

Reduction strategy. Reduction strategy involves reducing the material intensity of REEs through increasing material efficiency or optimizing product design[58]. We assume a faster progress in HREE content reduction given the recent success in HREE reduction efforts[20].

Substitution strategy. Rare-earth permanent magnets (REPMs) can be substituted with REE-free magnets[24,59], where the EVs and wind turbines are assumed to have less potential to abandon the REPMs than other traditional sectors because REPMs have the advantages of compact size and high energy density that are favoured by the emerging sectors[58,60].

Reuse strategy. Reuse involves using an item again, usually for its original purpose or a similar one, without significant processing. Progressively more manufacturers will design and produce reusable REPMs, which are more implemented in EVs and wind turbines because they have large REPM sizes[5,61,62]. The reusable REPMs can be reused only once.

Recycling strategy. Recycling involves breaking down used materials to create new products or raw materials. EVs and wind turbines have a higher recycling rate than other end uses because they are easier to trace and collect due to their large sizes and clear property rights.

Composite strategy. All four single CE strategies are implemented in parallel.

The key assumptions and parameters of these scenarios are shown in Supplementary Table 15.

Limitations

This study has several limitations. Our quantification of the in-use stocks of REEs is based on an implicit assumption that all the demand for REEs can be fulfilled by 2050. However, our study also indicates that the in-ground stocks of Dy and Tb could be exhausted by around 2035–2045, which means there are not enough REE in-ground stocks to fully meet their demand. Therefore, only the development of new mines or the secondary mining of tailings and scraps can be expected to support the in-use stocks landscape shown in Fig. 4b. However, it is important to highlight that this study does not encompass the intricate market dynamics between primary and secondary supplies of REEs, nor does it fully consider the interplay of market forces affecting the equilibrium of REE supply and demand. Further research has the potential to enhance the analysis of market-driven influences that govern the relationships among REE demand, primary supply and secondary supply.

Data availability

The data generated and/or analysed in this study are provided in supplementary information and in the figshare repository (https://doi.org/10.6084/m9.figshare.24471670). The published data sources underlying the parameters used in this study are documented in supplementary information. Source data are provided with this paper. Any additional data are available from the corresponding authors.

Code availability

The code used to manipulate the data and generate the results is available from the figshare repository (https://doi.org/10.6084/m9.figshare.24471568).

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Author contributions

P.W. and Y.-Y.Y. designed the research, with steering and supervision from W.-Q.C. and L.-H.C.; P.W., Y.-Y.Y. and O.H. contributed to the methodology; P.W., Y.-Y.Y., O.H., T.F. and L.-Y.C. conducted the analysis. P.W., Y.-Y.Y., O.H. and W.-Q.C. led the drafting of the manuscript. All authors contributed significantly to the final writing of the article.

Competing interests

The authors declare no competing interests.

Additional information

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Regional rare-earth element supply and demand balanced with circular economy strategies

Supplementary information: Regional Rare Earth Element Supply and Demand Balanced with Circular Economy Strategies

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Li-Hua Chen, Tomer Fishman, and Wei-Qiang Chen

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S1 Overview

Our study is performed based on a framework called the Dynamic Integrated Model of Rare Earth Circularity and Climate Target (DIRECCT), and the detailed procedures and methods of the model are shown in **Fig. S 1**. This model serves as a multifaceted framework that goes beyond a mere testing of scenarios within the dynamic material flow context. It is built upon the linkage of climate targets, clean technologies transition pathways, with rare earth circularity system. This integrated model not only examines the intricate material flows of REEs under varying climate targets, but also delves into the intricate interplay between rare earth circularity and its leveraged greenhouse gas (GHG) reduction (the achievable GHG reduction given the limited supply of REEs). By assessing the balance between rare earth supply and demand, it reveals the constraints REEs might pose on achieving climate targets. Moreover, the model can quantitatively assess the impact of circular economy strategies on enhancing REE circularity, contributing to a comprehensive understanding of the role of circular economy strategies in achieving just and clean low-carbon transitions.

In **Section S1**, we first define our research objects and scenario settings, and give a description of the linkage of climate targets with critical rare earth elements flows along their life cycle. In **Section S2**, we give some detailed calculations and parameters related to the DIRECCT framework. The core models of the DIRECCT framework are shown in the manuscript (see Methods); here we supplement some supporting models and parameters related to our analysis. In **Section S3**, we supplement some additional results and Figures of our study. In **Section S4**, we make comparisons of our results with some previous results to validate the reliability of this study and make a sensitivity analysis and an uncertainty analysis of our results.

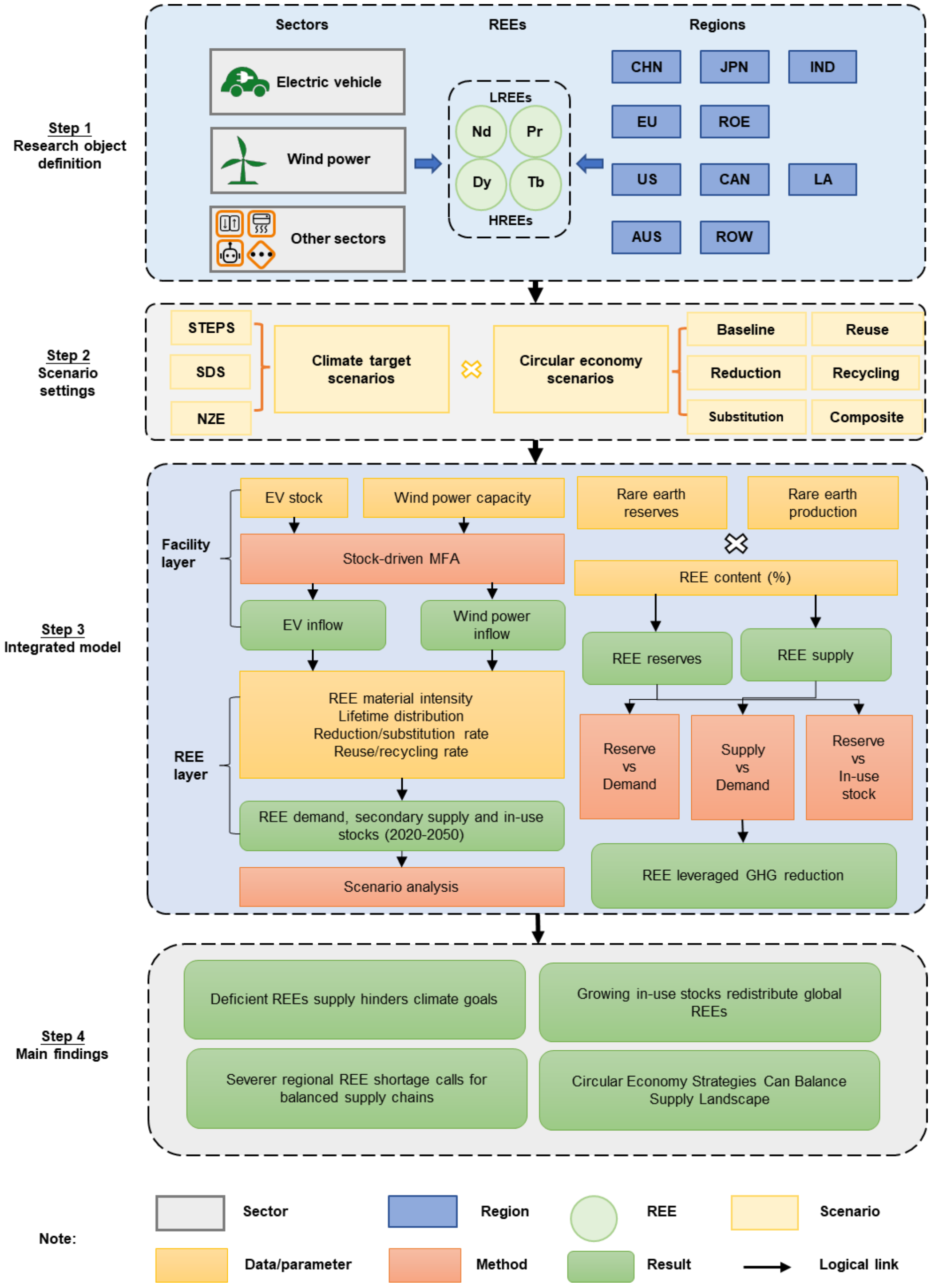


Fig. S 1 Detailed procedures and methods of the model

S1.1 Research object definition

The rare earth elements (REEs) are a group of 17 chemical elements appearing in the periodic table consisting of 15 lanthanides plus yttrium and scandium. In this paper, we focus on four REEs, neodymium (Nd), praseodymium (Pr), dysprosium (Dy), and terbium (Tb), which are critical materials for producing clean technologies, such as electric vehicles (EVs) and wind turbines.

Here, we separately forecast the demand of the four REEs from EVs, wind power, and other sectors. The EVs and wind power represent emerging clean technologies that underpin global climate targets, so they are attached to particular importance in this study. As for the other sectors, we treat them as an entirety and make a rough prediction of their demand for REEs.

As for the studied regions, we divide the world into 10 regions/countries, which are China (CHN), the United States (US), the European Union (EU), the rest of Europe (ROE), Latin America (LA), Canada (CAN), Australia (AUS), India (IND), Japan (JPN), and the rest of world (ROW). Such a classification is limited by the available data, but it covers main economies that contribute to global climate goals, thereby can provide valuable insights into the international landscape of REEs.

S1.2 Scenario settings

The demands for EVs and wind power are closely related to countries' climate goals, because these two industries are one of the most important pathways to mitigate climate change. In order to quantify the demand for EVs and wind power under different climate targets, we adopt three climate target scenarios proposed by the International Energy Agency (IEA). In ascending order of ambition, they are the Stated Policies Scenario (STEPS), Sustainable Development Scenario (SDS), and Net Zero Emissions by 2050 Scenario (NZE)[1,2], with NZE being the most ambitious one. The definitions and objectives of these climate targets are shown in **Table S 1**. In this paper, we take the NZE scenario as a normative scenario, and our results shown in the manuscript are mainly under the NZE scenario unless exceptions are stated, and the additional results under the STEPS and SDS are shown here.

Table S 1 Definitions and objectives of the climate target scenarios[1,2]

Scenarios	STEPS	SDS	NZE
Definitions	A scenario that reflects current policy settings based on a sector-by-sector and country-by-country assessment of the specific policies that are in place, as well as those that have been announced by governments around the world.	A scenario describes the broad evolution of the energy sector that would be required to reach the key energy-related goals of the United Nations, including the climate goal of the Paris Agreement, universal access to modern energy by 2030, and a dramatic reduction in energy-related air pollution and the associated impacts on public health.	A scenario that sets out a pathway for the global energy sector to achieve net zero CO_2 emissions by 2050. It does not rely on emissions reductions from outside the energy sector to achieve its goals. Universal access to electricity and clean cooking are achieved by 2030.

Objectives	To provide a benchmark to assess the potential achievements (and limitations) of recent developments in energy and climate policy.	To limit the global temperature rise to below 1.8°C with a 66% probability if CO_2 emissions remain at net zero after 2070.	To show what is needed across the main sectors by various actors, and by when for the world to achieve net zero energy-related and industrial process CO_2 emissions by 2050 while meeting other energy-related sustainable development goals such as universal energy access.

To quantify the role of circular economy (CE) strategies in rare earth circularity, we set the reduction scenario, substitution scenario, reuse scenario, recycling scenario, and composite scenario (which covers all the CE strategies in parallel), and compare them with a reference scenario. **Table S 2** lists some practical cases of these strategies, which have varying degrees of progress.

Table S 2 Practical cases of circular economy (CE) strategies

CE strategies	Cases
Reduction	Toyota has created a new type of magnet for motors that can reduce the use of neodymium by half using lanthanum and cerium instead, which cost 20 times less than neodymium, and at the same time eliminate other elements like terbium and dysprosium[3].

Substitution	At Tesla's 2023 Investor Day on March 1st, the company revealed that its next-generation PMSM traction motors would not use rare earth permanent magnets.[4]
Reuse	To our best knowledge, there is no industrial practice of reuse strategy, but relevant research has been studied lot[5,6].
Recycling	Nissan has developed a new, more efficient recycling process to recover REEs from EV motor magnets, which can recover 98% of REEs and shave work time by 50% compared to manual disassembly[7].

S1.3 The linkage of climate targets with critical REEs flows

Fig. S 2 shows the linkage of climate targets with critical rare earth elements flows along their life cycle, which covers the material production, manufacturing, in-use, and end-of-life stages.

In the material production stage, the rare earth metals are produced through a series of processes including extraction, refining, and separation, whereby part of them are supplied for the downstream manufacturers, and the rest are inevitably lost in tailings and factory waste. In the manufacturing stage, rare earth metals are fabricated into various essential components, such as permanent magnet synchronous motors (PMSMs), direct-drive/gear-drive permanent magnet synchronous generators (DDPMSGs/ GDPMSGs), etc. These components are then used in EVs (mainly PMSMs) and wind turbines (mainly DDPMSGs/GDPMSGs), which are important sectors contributing to the climate targets, and some other sectors. Some inevitable losses are generated during the fabrication processes. The reduction and substitution strategies can be implemented in this stage by developing REE-less or REE-free technologies. In the in-use stage, the REEs are stored in society in the form of products for many years until their end-of-life. In the end-of-life stage, the REE-containing components can be directly reused for their original purpose or a similar one, or be recycled to extract the secondary materials, in the principle of reuse or recycling strategies. However, it's worth noting not all REEs can be reused or recycled due to incomplete collection and inevitable losses during the recovery processes.

In this study, all the mentioned REE inflows, outflows, in-use stocks, in-ground stocks, secondary supplies, and losses (shown in **Fig. S 2**) are systemically quantified by the DIRECCT method.

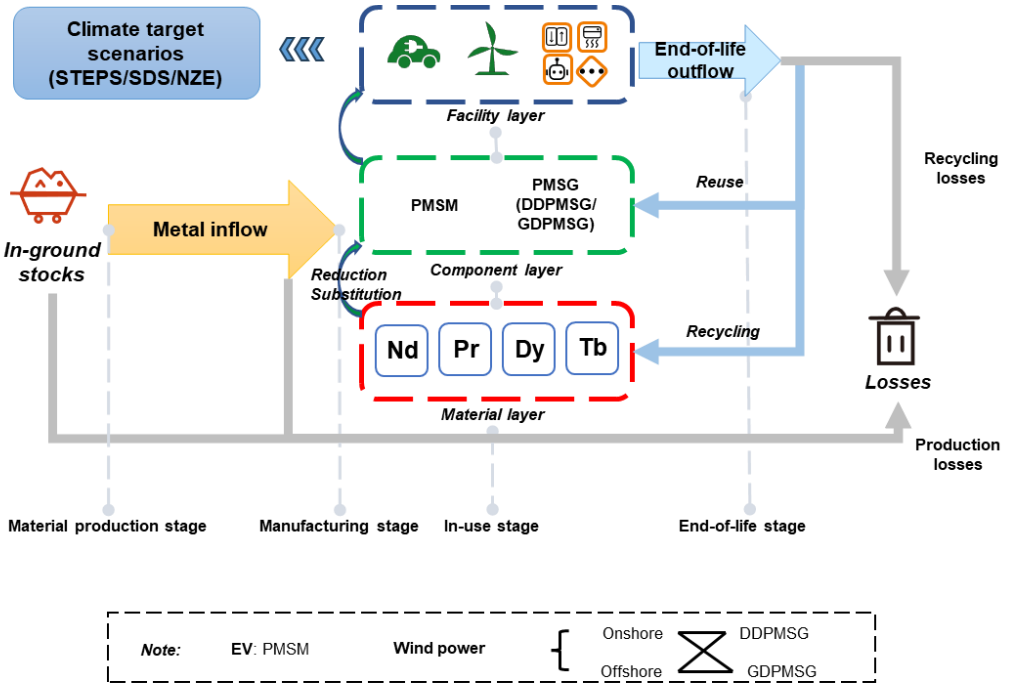


Fig. S 2 The linkage of climate targets with critical rare earth elements flows along their life cycle

S2 Supplementary Methods

S2.1 EV stock prediction model

Gompertz function is a sigmoid function which describes growth as being slowest at the start and end of a given time period, which is used to predict the vehicle stock in many different regions/countries, as shown in equation (S1).

$$x_{i,t} = s_i \times e^{\alpha e^{\beta PGDP_{i,t}}} \tag{S1}$$

where $x_{i,t}$ is the vehicle ownership per capita (measured in vehicles per 1000 people), s_i is the vehicle ownership saturation level (measured in vehicles per 1000 people), $PGDP_{i,t}$ is the GDP per capita, α ($\alpha < 0$) determines vehicle stock demands at low or zero income levels, and β ($\beta < 0$) is a curvature parameter that controls the slope of the function at high-income levels[8].

The vehicle ownership of a specific region ($X_{i,t}$) is calculated by the product of its vehicle ownership per capita ($x_{i,t}$) and population ($P_{i,t}$) (equation (S2)).

$$X_{i,t} = x_{i,t} \times P_{i,t} \tag{S2}$$

The EV stock ($EVstock_{i,t}$) is then calculated as the product of vehicle ownership ($X_{i,t}$) and EV penetration rate ($pr_{i,t}$) (equation (S3)).

$$EVstock_{i,t} = X_{i,t} \times pr_{i,t} \tag{S3}$$

The key parameters used above to predict the EV stocks, including vehicle ownership saturation level (s_i), vehicle ownership per capita ($x_{i,t}$), GDP per capita ($PGDP_{i,t}$), and EV penetration rate ($pr_{i,t}$), are shown in **Table S 3**, **Fig. S 3**, **Table S 4**, and **Table S 5**, respectively. The results of the EV stocks in different climate target scenarios are shown in **Fig. S 4**.

(1) Vehicle ownership saturation

The vehicle ownership saturation level is closely related to the population density and the urbanization rate of a region. In this paper, the vehicle ownership saturation levels of different regions/countries are collected from literature[9-12], as shown in **Table S 3**.

Table S 3 Vehicle ownership saturation level (per 1000 people)

Country/Region	**CHN**	**EU**	**ROE**	**US**	**JPN**	**KOR**	**CAN**
Saturation level	500	789	785	852	732	646	845
Country/Region	**AUS**	**NZ**	**CHI**	**IND**	**MX**	**ZA**	**BRA**
Saturation level	785	812	810	200	840	852	831

Note: KOR: Korea, NZE: New Zealand, CHI: Chile, MX: Mexico, and ZA: South Africa. The region classification here is different from our defined research region classification, because here is just an intermediate process to predict the EV stocks. The reason we list these regions is that the historical EV stock data published by the IEA only covers these regions[13]. In the following steps, we will merge some regions to adapt to our defined research region classification.

(2) Vehicle ownership per capita

The historical vehicle ownership per capita is calculated through the vehicle stock data from the International Organization of Motor Vehicle Manufacturers (OICA)[14], and the population data (medium variant) from the United Nations, Department of Economic and Social Affairs [15]. The prospective vehicle stock per capita is predicted using the Gompertz function model (equations S1-S2). The vehicle ownership per capita both historical and predicted are shown in **Fig. S 3**, with the solid blue line indicating the predicted data, and the dotted orange line indicating the historical data.

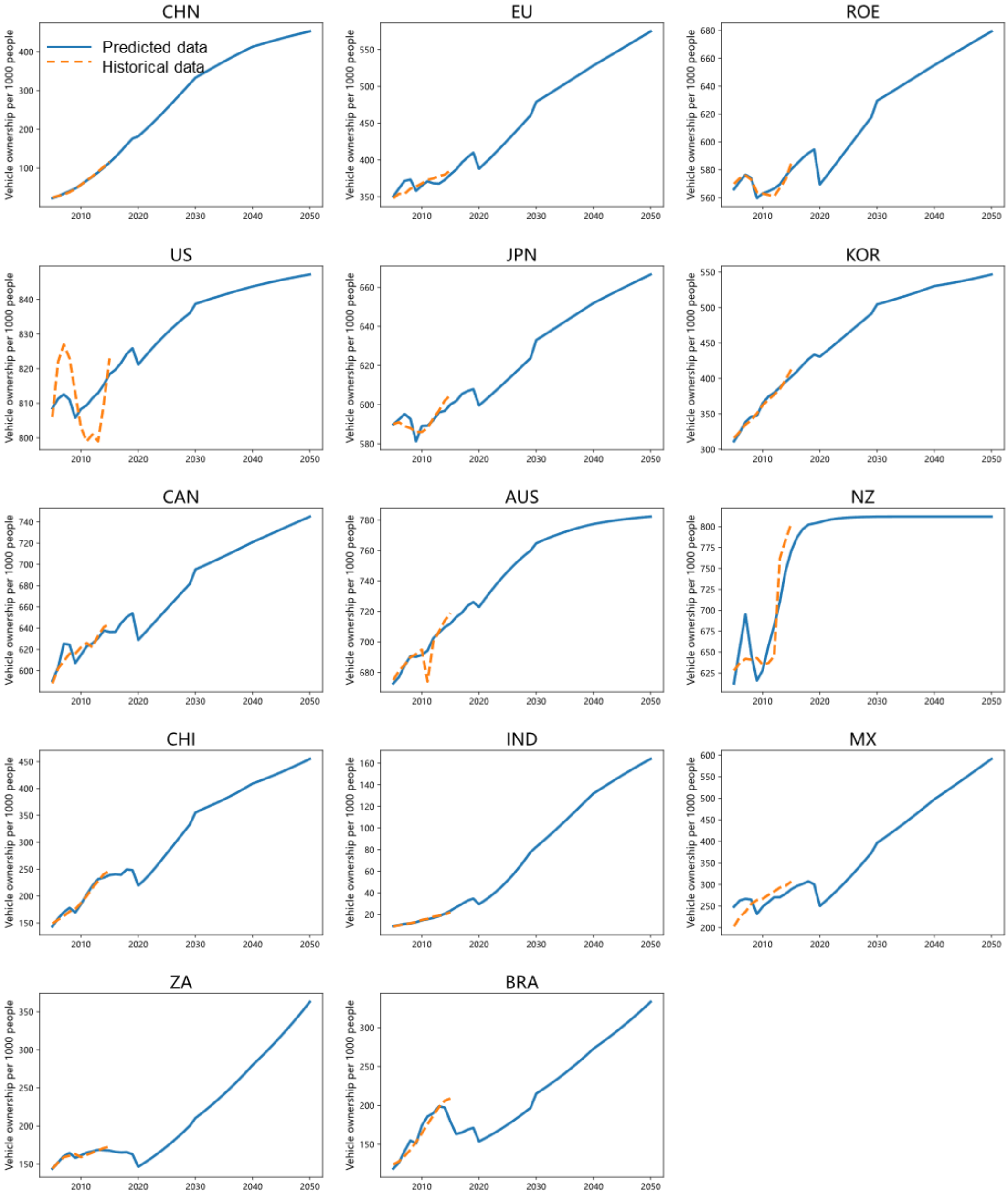


Fig. S 3 Vehicle ownership per 1000 people.

(3) GDP per capita

The GDP per capita is calculated by dividing the GDP data from World Bank[16] (historical) and OECD (prospective)[17], with the population data from the United Nations, Department of Economic and Social Affairs[15], and the results are shown in **Table S 4**.

Table S 4 GDP per capita (constant 2015 million US $)

	CHN	EU	ROW	US	JPN	KOR	CAN	AUS	NZ	CHI	IND	MX	ZA	BRA
2005	3322	18684	48604	52890	32956	20969	38668	50872	35052	10350	954	8878	5588	7352
2010	5519	19537	48096	52814	32821	25455	40983	53246	35250	11809	1244	8879	6085	8702
2015	7863	20422	50975	56839	34730	28841	43204	56431	38588	13574	1606	9617	6260	8814
2020	10166	20871	49153	58148	34637	31674	42402	58470	42404	12954	1812	8910	5659	8229
2025	12587	23226	53778	63484	37114	35394	45655	64374	46112	14835	2430	10058	6408	8730
2030	15716	26602	60373	70947	41466	40667	50443	72383	51455	17197	3207	11573	7381	9598
2035	17816	28306	63203	74317	43772	42479	52280	78008	54549	17976	3814	12491	8167	10143
2040	20319	30166	66321	78144	46338	44763	54439	84412	58135	18934	4574	13575	9091	10790
2045	22164	32001	69536	82084	48571	46078	56574	90458	61977	19643	5184	14601	10006	11351
2050	24305	34002	73045	86410	50925	47816	58915	97113	66308	20498	5911	15798	11075	12003

(4) EV penetration

The EV penetration rate refers to the stock share of EVs here, which before 2030 is based on IEA assumptions[13,18], and that after 2030 is based on our reasonable extrapolation, which is shown in **Table S 5**.

Table S 5 EV penetration rate assumptions

Region	Scenario	2020	2025	2030	2040	2050
China	STEPS	1.70%	8.00%	18.00%	45.00%	65.00%
	SDS	1.70%	12.00%	22.00%	55.00%	80.00%
	NZE	1.70%	14.00%	25.00%	60.00%	95.00%
Europe	STEPS	1.20%	6.00%	15.00%	42.00%	65.00%
	SDS	1.20%	10.00%	20.00%	54.00%	80.00%
	NZE	1.20%	12.00%	23.00%	60.00%	95.00%
US	STEPS	0.80%	3.00%	8.00%	20.00%	40.00%
	SDS	0.80%	9.00%	18.00%	45.00%	70.00%
	NZE	0.80%	12.00%	22.00%	55.00%	90.00%
India	STEPS	0.03%	1.00%	6.00%	20.00%	40.00%
	SDS	0.03%	5.00%	17.00%	40.00%	65.00%
	NZE	0.03%	8.00%	20.00%	50.00%	85.00%
ROW	STEPS	0.20%	0.90%	3.00%	15.00%	35.00%
	SDS	0.20%	3.00%	8.00%	25.00%	55.00%
	NZE	0.20%	5.00%	11.00%	30.00%	65.00%
World	STEPS	0.80%	4.00%	10.00%	28.00%	50.00%
	SDS	0.80%	8.00%	16.00%	44.00%	70.00%
	NZE	0.80%	10.00%	20.00%	50.00%	86.00%

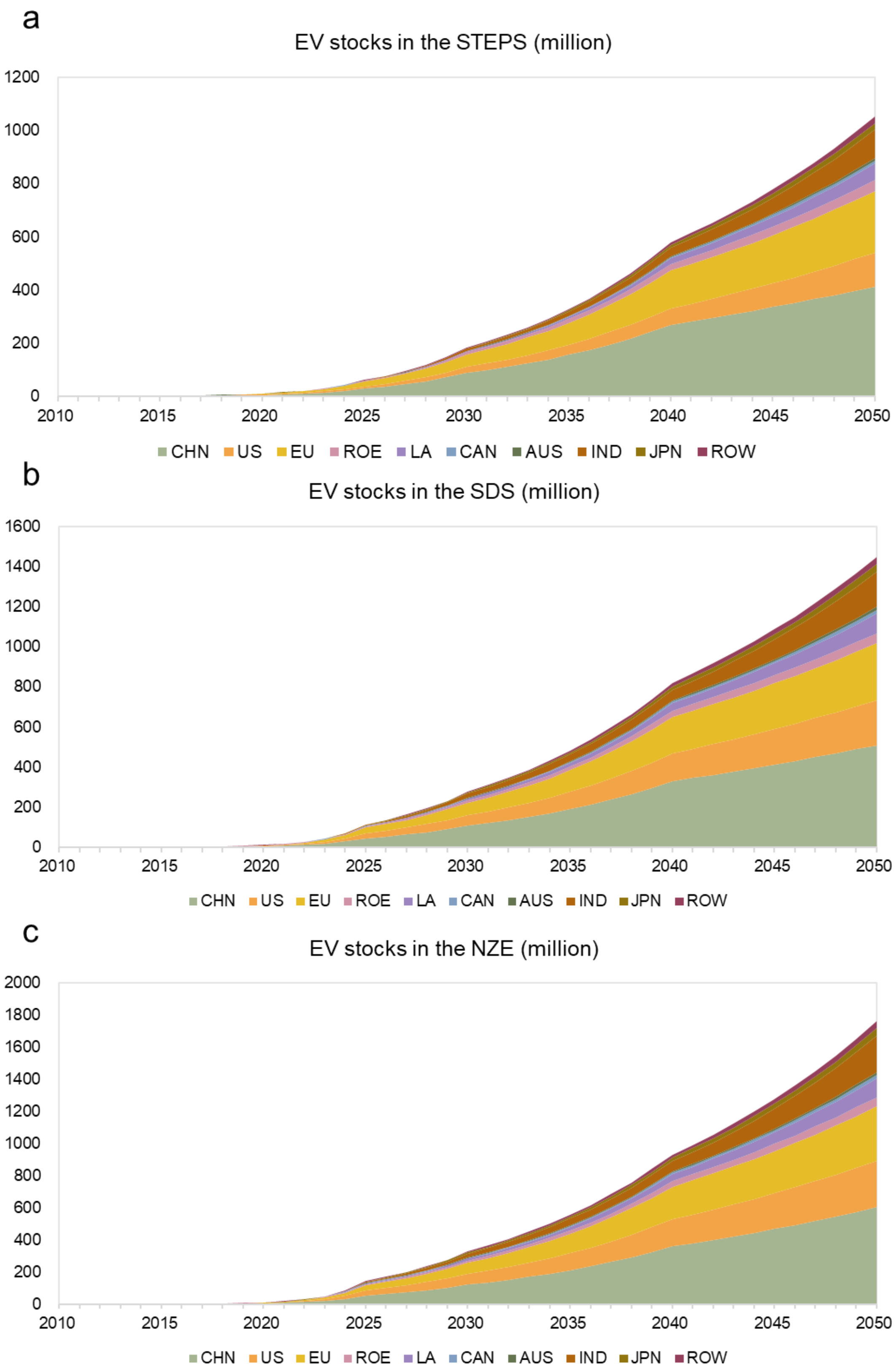


Fig. S 4 EV stocks in the STEPS (a), SDS (b), and NZE (c).

S2.2 Wind power generation prediction model

The regional wind power generation in different scenarios is published by IEA in the World Energy Outlook 2021 (wind generation)[19], as shown in **Table S 6**. However, the unit of these data is terawatt hours (TWh), which needs to be converted into gigawatts (GW) for further calculation. The conversion coefficient between TWh and GW is calculated based on the world total wind generation capacity published in the World Energy Outlook 2021 (world electricity sector), which has two versions of data, one is in TWh and the other is in GW. The ratio of the two versions of data is then taken as conversion coefficient between TWh and GW. The World Energy Outlook 2021 published historical wind generation in 2010 and 2020 and the predicted wind generation in 2030 and 2050, and here we fill in the data for the unpublished time period by assuming an exponential growth trend. The wind power generation in GW under different climate target scenarios are shown in **Fig. S 5**.

Table S 6 Wind power generation (TWh) [19].

STEPS	**CHN**	**US**	**EU**	**ROE**	**CAN**	**AUS**	**JPN**	**IND**	**LA**	**ROW**
2010	45	95	140	14	10	-	4	20	4	10
2019	406	298	367	96	46	-	8	68	78	54
2020	471	340	398	119	51	17	8	68	78	46
2030	1414	688	844	304	99	42	45	200	190	276
2050	2631	1179	1365	580	220	127	205	916	393	1189
SDS	**CHN**	**US**	**EU**	**ROE**	**CAN**	**AUS**	**JPN**	**IND**	**LA**	**ROW**
2010	45	95	140	14	10	-	4	20	4	10
2019	406	298	367	96	46	-	8	68	78	54
2020	471	340	398	119	51	17	8	68	78	46
2030	1778	1187	1083	392	175	62	68	382	247	741
2050	4236	2759	2706	953	440	233	306	1557	835	3552
NZE	**CHN**	**US**	**EU**	**ROE**	**CAN**	**AUS**	**JPN**	**IND**	**LA**	**ROW**
2010	45	95	140	14	10	-	4	20	4	10
2019	406	298	367	96	46	-	8	68	78	54
2020	471	340	398	119	51	17	8	68	78	46
2030	2328	1554	1418	513	229	81	89	500	323	971
2050	5973	3890	3816	1344	620	329	431	2195	1177	5008

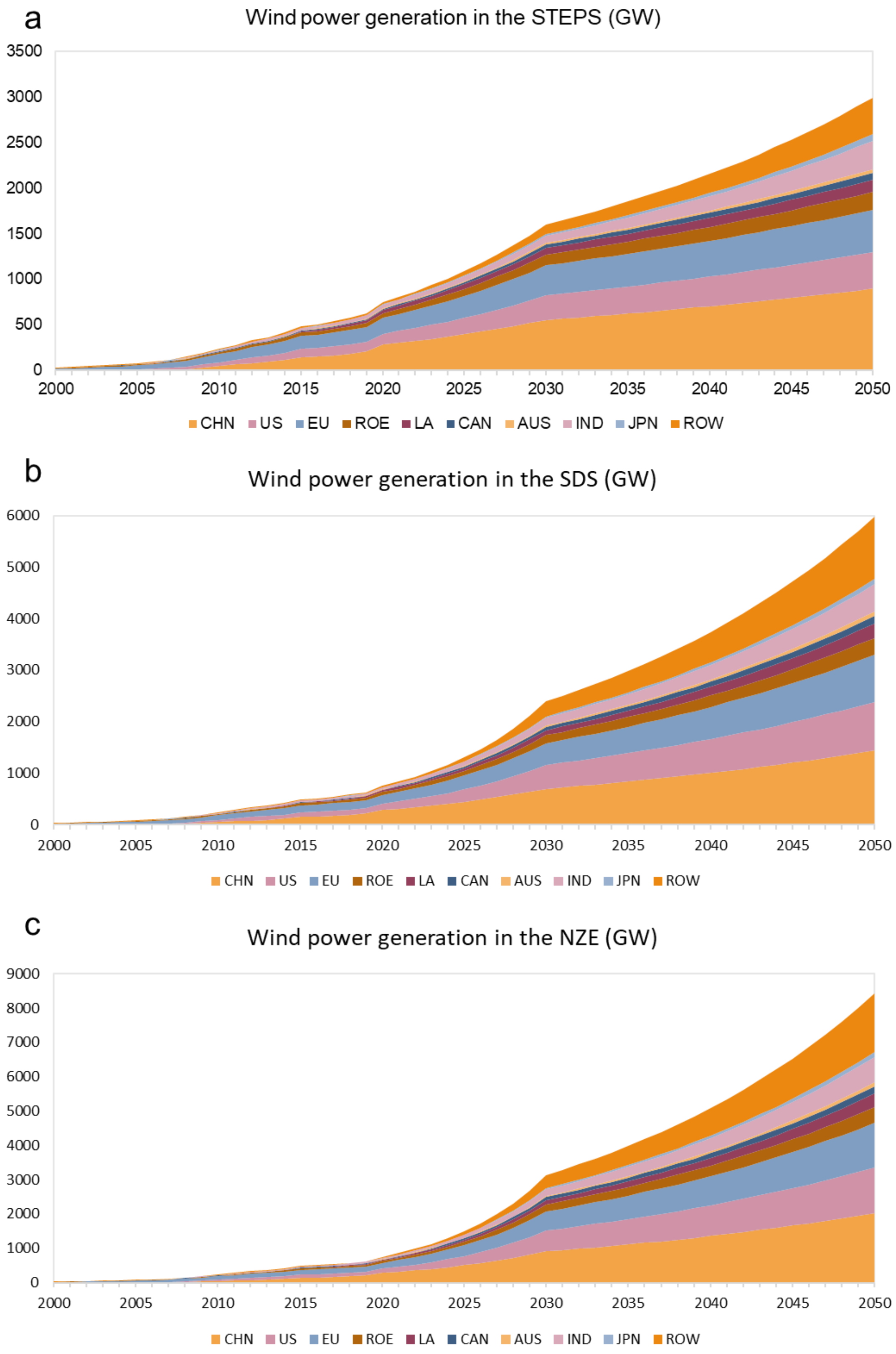


Fig. S 5 Wind power generation in the STEPS (a), SDS (b), and NZE (c)

S2.3 REE inflows required by wind power

Here, we make a detailed description about the calculation of REE inflows in the sector of wind power. The mainstream technologies of wind power generators include direct drive (DDPMSG) and geared drive permanent magnet synchronous generators (GDPMSG), which have different market shares in the onshore and offshore wind power, as shown in **Table S 7.** The REE material intensities of a wind turbine depend on its generator technology, which are shown in **Table S 8**.

Table S 7 The market share of different wind power technologies[17,20,21]

2020	**CHN**	**US**	**EU**	**ROE**	**CAN**	**AUS**	**JPN**	**IND**	**LA**	**ROW**
Onshore	84%	98%	81%	81%	98%	93%	84%	98%	98%	98%
DDPMSG in onshore	35%	15%	29%	29%	15%	18%	35%	35%	18%	18%
GDPMSG in onshore	15%	10%	24%	24%	10%	12%	15%	15%	12%	12%
Offshore	16%	2%	19%	19%	2%	7%	16%	2%	2%	2%
DDPMSG in offshore	84%	84%	84%	84%	84%	84%	84%	84%	84%	84%
GDPMSG in offshore	0%	4%	6%	6%	4%	0%	0%	0%	0%	0%

2050	**CHN**	**US**	**EU**	**ROE**	**CAN**	**AUS**	**JPN**	**IND**	**LA**	**ROW**
Onshore	68%	71%	40%	40%	68%	68%	68%	85%	68%	68%
DDPMSG in onshore	60%	40%	50%	50%	40%	40%	60%	60%	40%	40%
GDPMSG in onshore	30%	30%	35%	35%	30%	30%	30%	30%	30%	30%
Offshore	32%	29%	60%	60%	32%	32%	32%	15%	32%	32%
DDPMSG in offshore	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
GDPMSG in offshore	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Note: Market share of offshore wind turbines before 2040 is assumed based on the Offshore Wind Outlook 2019[20] and World Energy Outlook 2019[21] published by IEA, and afterwards is based on reasonable extrapolation. The market shares of DDPMSG and GDPMSG are collected from the literature[17].

Table S 8 REE material intensities of EVs and wind turbines [17,22-26]

Type	PM	REE material intensity (kg/vehicle or kg/MW)							
	(kg)	Nd	Nd	Dy	Dy	Pr	Pr	Tb	Tb
		(w%)	(kg)	(w%)	(kg)	(w%)	(kg)	(w%)	(kg)
EV	2	28%	0.56	6.40	0.12	6.00	0.12	0.68	0.013
DDPMS	650	27.00	175.	4.50	29.2	6.75	43.8	1.08	7
GDPMS	120	27.00	32.4	4.50	5.4	6.75	8.1	3.33	4

The inflow of REEs in the wind power sector is calculated as equation (S4).

$$\begin{aligned} inflowRE_{i,t} = inflow_{i,t} & \\ & \times \left(\left(ms_{on} \times D_{on} + ms_{off} \times D_{off} \right) \times MID_t \right. \\ & \left. + \left(ms_{on} \times G_{on} + ms_{off} \times G_{off} \right) \times MIG_t \right) \\ & \times (1 - red_t) \times (1 - sub_t) \end{aligned} \tag{S4}$$

where ms_{on} and ms_{off} are the market shares of onshore and offshore wind turbines, respectively; D_{on} and D_{off} are the market shares of DDPMSG in the onshore and offshore wind turbines, respectively; G_{on} and G_{off} are the market shares of GDPMSG in the onshore and offshore wind turbines, respectively; MID_t and MIG_t are the material intensities of a specific REE in the DDPMSG and GDPMSG, respectively.

S2.4 Pledged and rare earth leveraged GHG reduction

(1) Pledged GHG reduction from EVs

According to the International Council on Clean Transportation (ICCT)[27], the life-cycle GHG emissions over the lifetime of battery electric vehicles (BEVs) registered in 2021 are lower than a comparable gasoline internal combustion engine vehicle (ICEV) by 37%-45% in China, 60%-58% in the US, 66%-69% in Europe. As the electricity mix continues to decarbonize, the life-cycle emissions between BEVs and ICEVs will increase to 48%-64% in China, 62-76% in the US, and 74%-77% in the Europe by 2030. In addition, compared to average BEVs in China, the US, and Europe, the life-cycle GHG emissions are 39%-58%, 43%-64%, and 123%-138% higher for a PHEV registered in 2021, and 94%-166%, 53%-100%, and 171%-197% higher for a PHEV to be registered in 2030. Based on data from ICCT, we estimated the average life-cycle GHG emissions reduction compared with ICEVs for BEVs and PHEVs registered in 2021 and 2030, which are shown in **Table S 9**.

Table S 9 Life-cycle GHG reduction of BEVs and PHEVs

		China	**Europe**	**US**	**Average**
Average annual mileage (km/year)		19000	13500	17400	16633
Life-cycle GHG emissions for different kinds of vehicles registered in 2021(g CO2 eq/km)	ICEV	260	245	255	253
	BEV	153	80	92	108
	PHEV	228	184	141	184
Life-cycle GHG reduction compared to ICEVs for EVs registered in 2021 (t CO2 eq/year*vehicle)	BEV	2.0	2.2	2.8	2.4
	PHEV	0.6	0.8	2.0	1.2

Life-cycle GHG emissions for different kinds of vehicles registered in 2030 (g CO2 eq/km)	ICEV	215	240	230	228
	BEV	95	59	71	75
	PHEV	215	167	126	169
Life-cycle GHG reduction compared to ICEVs for EVs registered in 2030 (t CO2 eq/year*vehicle)	BEV	2.3	2.4	2.8	2.6
	PHEV	0.0	1.0	1.8	1.0

Note: the other regions except for China, Europe, and the US adopt the average data. Data between 2022 and 2029 and data between 2031 and 2050 are determined based on the assumption of a linearly changing trend.

BEVs accounted for about two-thirds of new registrations of EVs in 2020[28]. Accordingly, we assume that the market shares of BEVs and PHEVs are 2/3 and 1/3 in 2020, respectively; they will increase to 75% and 25% by 2030 and 90% and 10% by 2050, respectively. In consideration of the market share of BEVs and PHEVs, the average GHG emissions reduction of an EV compared with a gasoline ICEV is depicted as **Fig. S 6**.

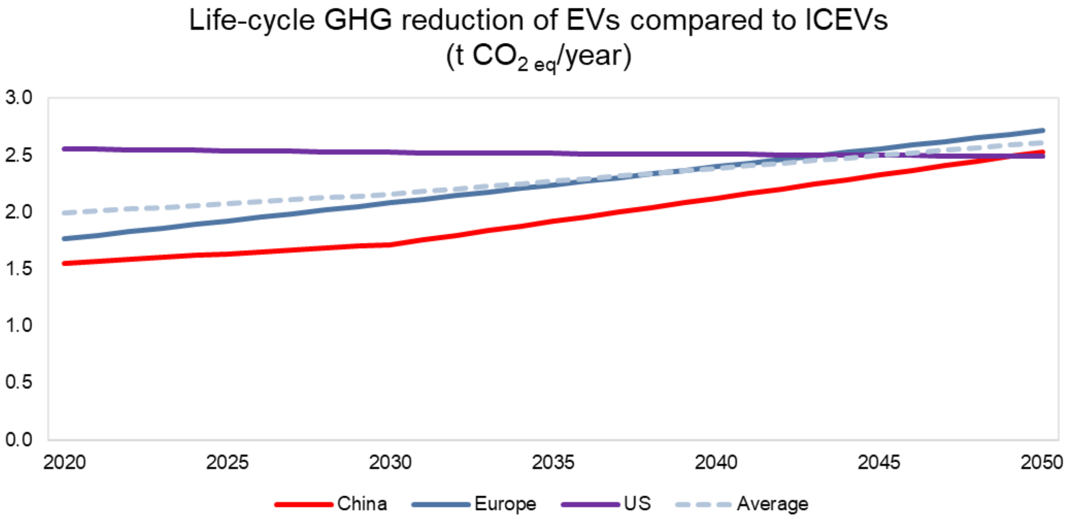


Fig. S 6 Life-cycle GHG reduction of EVs compared to ICEVs

The accumulative pledged GHG emissions reduction from EVs between 2021 and 2050 (GR_{EV}) is then calculated as equation (S5).

$$GR_{i,EV} = \sum_{2021}^{2035} inEV_{i,t} \times AR_{i,t} \times life_{EV} + \sum_{2036}^{2050} inEV_{i,t} \times AR_{i,t} \times (2051 - t) \tag{S5}$$

Where $inEV_{i,t}$ is the inflow of EVs of region i in time t, $AR_{i,t}$ is the life-cycle GHG emissions reduction of EVs compared to ICEVs in year t, and $life_{EV}$ is the average lifetime of EVs, which is assumed to be 15 years.

(2) Pledged GHG reduction from wind power

The GHG emissions reduction from wind power depends on the comparative generation pathway. In 2020, coal-fired and gas-fired generation accounts for 74% (9.1 Gt) and 22% (2.7 Gt) of the CO_2 emissions from electricity generation worldwide (total 12.3 Gt), respectively[18]. Therefore, we take the coal-fired and gas-fired generation as comparative subjects, to calculate the GHG emissions reduction from wind generation. The relative ratio of natural gas generation and coal generation of different regions in 2020 is obtained from IEA's World Energy Outlook 2021, as shown **Table S 10**.

Table S 10 The relative ratio of natural gas and coal generation in 2020[19]

	CHN	**US**	**EU**	**ROE**	**LA**
Natural gas generation	4.4%	66.1%	59.0%	58.4%	78.6%
Coal generation	95.6%	33.9%	41.0%	41.6%	21.4%
	CAN	**AUS**	**IND**	**JPN**	**ROW**
Natural gas generation	83.8%	46.6%	5.8%	53.7%	46.6%
Coal generation	16.2%	53.4%	94.2%	46.3%	53.4%

According to IEA, compared with unabated coal generation, onshore wind power can avoid annual direct CO_2 emissions per 1 GW of installed capacity by 2.8 Mt, and which for offshore wind power is 3.5 Mt. Compared with natural gas generation, onshore and offshore wind power can avoid annual direct CO_2 emissions per 1 GW of installed capacity by 1.3 Mt and 1.6 Mt, respectively[29]. **Table S 11** shows the average CO_2 emissions reduction by replacing the main fossil fuel power generation paths (coal generation and natural gas generation) with onshore and offshore wind power per 1 GW per year, taking into account the share of coal-fired and gas-fired generation.

Table S 11 CO₂ emissions reduction of wind power (unit: Mt/GW*year)

	CHN	**US**	**EU**	**ROE**	**LA**
Onshore wind power	2.7	1.8	1.9	1.9	1.6
Offshore wind power	3.4	2.2	2.4	2.4	2.0
	CAN	**AUS**	**IND**	**JPN**	**ROW**
Onshore wind power	1.5	2.1	2.7	2.0	2.1
Offshore wind power	1.9	2.6	3.4	2.5	2.6

The accumulative pledged GHG reduction from wind power between 2021 and 2050 (GR_{wind}) is then calculated as equation (S6)(S11).

$$GR_{i,wind} = \sum_{2021}^{2030} \left(onIC_{i,t} \times onAR_i + offIC_{i,t} \times offAR_i\right) \times life_{wind} + \sum_{2031}^{2050} \left(onIC_{i,t} \times onAR_i + offIC_{i,t} \times offAR_i\right) \times (2051 - t) \tag{S6}$$

where $onIC_{i,t}$ and $offIC_{i,t}$ are the inflow capacity of onshore and offshore wind power of region i in time t, respectively; $onAR_i$ and $offAR_i$ are the average CO₂ emissions reduction per 1 GW and per year by onshore and offshore wind power, respectively; and $life_{wind}$ is the average lifetime of wind turbines, which is assumed to be 20 years.

(3) RE leveraged rate of GHG reduction

The RE leveraged GHG reduction depends on how the rare earth supplies (see Methods) are traded and allocated around the world, thereby we consider two trade scenarios here. The first scenario entails a counterfactual no trade approach, which is an extreme portrayal of resource nationalism. Within this scenario, each region exclusively depends on its own REE supplies, devoid of any interregional trade. The second scenario is characterized as free trade with priority in self-supply, wherein regions boasting REE surpluses cater to the needs of deficit regions proportionally, based on their individual shortages.

The RE leveraged rate of GHG reduction refers to the ratio of RE leveraged GHG reduction and the pledged GHG reduction, which can be calculated as equation (S7).

$$LR_i = \frac{S_i}{D_i} \tag{S7}$$

where the regions are indexed by i ($i = 1,2, \dots, 10$), LR_i is the RE leveraged rate of GHG reduction, S_i is the REE supply that region i can obtain from 2021 to 2050, and D_i is the REE demand of region i from 2021 to 2050.

The global RE leveraged rate of GHG reduction equals to the weighted average of leveraged GHG reduction share of all regions and their respective RE leveraged rate of GHG reduction, which is calculated as equation (S11).

$$LR_g = \sum_i \frac{GR_i}{\sum_i GR_i} \times LR_i \tag{S8}$$

where GR_i is the pledged GHG reduction from EV and wind power in region i.

S2.5 Rare earth holdings in economic value

We define the rare earth (RE) holdings as the economic value of available RE stocks including in-ground stocks and in-use stocks. We set three supply pattern scenarios to estimate the future in-ground RE holdings, which are 1) supply based on present share, 2) supply based on reserve share, and 3) supply only for its own demand. The narratives of three supply pattern scenarios are shown as **Table S 12**.

Table S 12 Narratives of the supply pattern scenarios

Supply pattern scenario	**Assumptions**	**In-ground stocks by 2050 ($\boldsymbol{Res}_{i,\mathbf{2050}}$)**
Supply based on present share	By 2050, countries will maintain their supply share as 2020 (see **Table S 13**), and fully cater to global rare earth demand.	$\boldsymbol{Res}_{i,\mathbf{2020}} - \boldsymbol{RR} \times ss_i$
Supply based on reserve share	By 2050, countries will supply based on their reserve share in 2020 (see **Table S 13**), and fully cater to global rare earth demand.	$\boldsymbol{Res}_{i,\mathbf{2020}} - \boldsymbol{RR} \times rs_i$
Supply only for its own demand	An isolated supply system that countries will only and completely supply to their local demand.	$\boldsymbol{Res}_{i,\mathbf{2020}} - \boldsymbol{RR}_i$

Note: $\boldsymbol{Res}_{i,\mathbf{2050}}$ is a vector of the remaining in-ground stocks of four REEs in region i by 2050, $\boldsymbol{Res}_{i,\mathbf{2020}}$ is a vector of the reserves of four REEs in region i in 2020 (**Table S 19**), $\boldsymbol{RR}$ is a vector of the world total required reserves of four REEs in the next 3 decades (**Table S 22**), $\boldsymbol{RR_i}$ is a vector of the required reserves of four REEs in the next 3 decades in region i (**Table S 23-26**); ss_i is the supply share of region i, and rs_i is the reserve share of region i in 2020 (**Table S 13**).

Table S 13 Rare earth supply and reserve share[30]

	CHN	**US**	**EU**	**ROE**	**LA**	**CAN**	**AUS**	**IND**	**JPN**	**ROW**
supply share	57%	16%	0%	1%	0%	0%	9%	1%	0%	16%
reserve share	37%	1%	0%	15%	17%	1%	3%	6%	0%	20%

We measure the rare earth holdings in two parts, including the economic value of REE in-ground stocks and in-use stocks based on their current prices[31] (**Table S 14**). The rare earth holdings of in-ground and in-use stocks are calculated as equations (S9) and (S10), respectively.

$$CapG_{i,t} = \boldsymbol{Res'_{i,t}} \times \boldsymbol{P} \tag{S9}$$

$$CapU_{i,t} = \boldsymbol{Stock'_{i,t}} \times \boldsymbol{P} \tag{S10}$$

where $CapG_{i,t}$ is the in-ground REE holdings in region i in time t, $CapU_{i,t}$ is in-use REE holdings in region i in time t, $\boldsymbol{Stock'_{i,t}}$ is the transpose of the in-use stocks vector of the four REEs in region i in time t, and $\boldsymbol{P}$ is the price vector of the four REEs.

Table S 14 Current prices of the four rare earth metals (USD/kg)[31]

REE	**Nd**	**Pr**	**Dy**	**Tb**
Price	168.9	163.7	551.2	3126.6

S2.6 Supply concentration

We use the Herfindahl–Hirschman Index (HHI) to measure the concentration of REE supplies[32], which is calculated as the sum of the squares of REEs' supply shares, as described as follows:

$$HHI(s) = \sum_{i} {s_i}^2 \tag{S11}$$

where s_i is the share of region i in the REE supply. Higher HHI means higher supply concentration.

S2.7 Other supplementary parameters

In this subsection, we supplement the parameters mentioned in the manuscript.

Table S 15 Key parameters of the circular economy scenarios

	Baseline scenario	Reduction scenario	Substitution scenario	Reuse scenario	Recycling scenario	Composite scenario
Material intensity reduction (Nd/Pr/Dy/Tb)	0%/0%/0%/0%	30%/30%/50%/50%	0%/0%/0%/0%	0%/0%/0%/0%	0%/0%/0%/0%	30%/30%/50%/50%
Substitution rate (EV/Wind turbine/ Other)	0%/0%/0%	0%/0%/0%	50%/50%/80%	0%/0%/0%	0%/0%/0%	50%/50%/80%
Recycling rate (EV/Wind turbine/ Other)	40%/48%/24%	40%/48%/24%	40%/48%/24%	40%/48%/24%	95%/95%/57%	95%/95%/57%
Reusable design share (EV/Wind turbine/ Other)	0%/0%/0%	0%/0%/0%	0%/0%/0%	80%/80%/30%	0%/0%/0%	80%/80%/30%

Table S 16 Rare earth oxide content of individual minerals (% of rare earth oxide)[33,34]

	China									
REO	Bayan Obo, Inner Mongolia	Weishan, Shandong	Dechang, Sichuan	Maoniuping, Sichuan	Longnan, Jiangxi	Xunwu, Jiangxi	Xinfeng, Jiangxi	Pingyuan, Guangdong	Xinfeng, Guangdong	Nangang, Guangdong
Nd_2O_3	18.50%	10.90%	13.10%	15.20%	3.47%	30.20%	17.60%	29.50%	23.30%	17.00%
Pr_6O_{11}	6.20%	3.95%	4.73%	4.42%	1.08%	7.41%	5.62%	7.00%	6.60%	4.10%
Dy_2O_3	0.10%	0.00%	0.09%	0.21%	7.48%	1.77%	3.71%	2.60%	3.60%	0.80%
Tb_4O_7	0.10%	0.14%	0.06%	0.12%	1.33%	0.46%	0.68%	0.60%	0.60%	0.70%
	China			**US**	**Russia**	**Australia**	**Malaysia**	**India**	**Brazil**	
REO	Chongzuo, Guangxi	Shanghang, Fujian	Jianghua, Hunan	Mountain Pass, CA	Revda, Murmansk Oblast	Mount Weld, Western Australia	-	Manavalakurichi, Tamil Nadu	Minasu County, Goias	Araxa, Minas Gerais
Nd_2O_3	51.80%	19.80%	10.40%	11.70%	15%	18.10%	1.61%	20.00%	13.20%	13.90%
Pr_6O_{11}	5.60%	5.80%	4.40%	4.20%	5%	5.16%	0.50%	5.50%	4.40%	4.50%
Dy_2O_3	4.70%	3.80%	6.20%	0.05%	0.60%	0.25%	8.44%	0.18%	1.90%	0.28%
Tb_4O_7	0.50%	0.70%	1.00%	0.06%	0.00%	0.09%	0.92%	0.06%	0.63%	0.07%

S3 Supplementary Results

S3.1 Primary supply and present reserves of the REEs

(1) REE content

Table S 17 Average REE content in different regions (% of REE)

	Nd	Pr	Dy	Tb	Sum
China	15.31%	4.92%	0.18%	0.11%	20.52%
United States	10.03%	3.48%	0.04%	0.05%	13.50%
Australia	15.51%	4.27%	0.22%	0.08%	20.08%
Russia	12.86%	4.14%	0.52%	0.00%	17.52%
Malaysia	1.38%	0.41%	7.35%	0.82%	9.97%
India	20.00%	5.50%	0.18%	0.05%	25.73%
Rest of the world	14.87%	4.68%	0.28%	0.07%	19.90%

Note: The REEs' mass fractions in their corresponding REOs are 85.7% for Nd, 82.8% for Pr, 87.1% for Dy, and 89.2% for Tb.

(2) REE primary supply

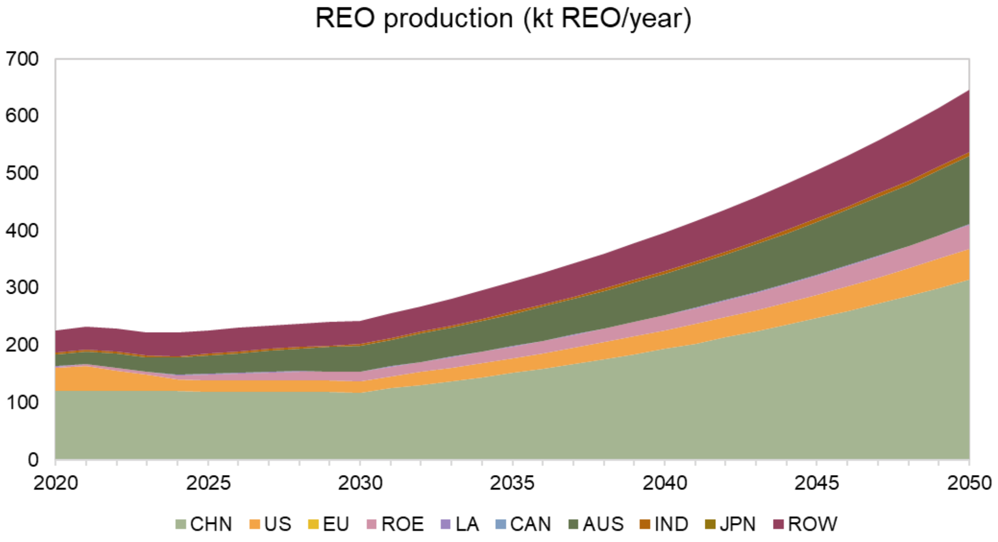


Fig. S 7 Rare earth oxide production (kt REO/year)

Table S 18 Cumulative primary supply of the REEs (2021-2050) (kt)

	CHN	US	EU	ROE	LA	CAN	AUS	IND	JPN	ROW	World
Nd	813	94	0	85	3	0	291	26	0	271	1585
Pr	261	33	0	27	1	0	80	7	0	85	495
Dy	9.7	0.4	0.0	3.5	0.1	0.0	4.1	0.2	0.0	5.0	23
Tb	5.8	0.5	0.0	0.0	0.0	0.0	1.5	0.1	0.0	1.3	9
Sum	1090	127	0	116	4	0	377	33	0	363	2111

(3) REE reserves

Table S 19 Present reserves of the REEs (kt)

	CHN	US	EU	ROE	LA	CAN	AUS	IND	JPN	ROW	World
Nd	6736	180	0	2700	3123	123	620	1026	0	3745	18254
Pr	2163	63	0	869	982	39	171	323	0	1178	5787
Dy	80	0.7	0	110	58	2	9	19	0	69	347
Tb	48	1	0	0	15	1	3	5	0	18	90
Sum	9027	243	0	3679	4178	165	803	1373	0	5010	24479

Table S 20 Dynamic reserves of the REEs (kt)

	CHN	US	EU	ROE	LA	CAN	AUS	IND	JPN	ROW	World
Nd	8724	234	0	3496	4045	160	804	1329	0	4850	23640
Pr	2801	81	0	1126	1272	50	221	418	0	1525	7495
Dy	104	0.9	0	142	75	3	11	25	0	90	451
Tb	62	1.3	0	0	20	1	4	6	0	24	118
Sum	11690	317	0	4764	5412	214	1040	1778	0	6489	31704

S3.2 Global cumulative demand and required reserves

Table S 21 Global cumulative primary demand, secondary supply, and total demand of the REEs between 2021 and 2050

		Primary demand (kt)					Secondary supply (kt)					Total demand (kt)				
Scenarios		Nd	Pr	Dy	Tb	Sum	Nd	Pr	Dy	Tb	Sum	Nd	Pr	Dy	Tb	Sum
STEPS	**Reference**	1797	424	289	49	**2559**	197	47	31	5	**279**	1994	470	320	54	**2857**
	Reduction	1439	340	190	35	**2004**	175	41	25	5	**246**	1613	381	215	40	**2265**
	Substitution	1075	252	180	30	**1538**	150	35	24	4	**214**	1225	288	204	34	**1765**
	Reuse	1703	410	266	47	**2426**	291	60	54	7	**411**	1994	470	320	53	**2856**
	Recycling	1544	364	250	42	**2200**	450	106	70	12	**638**	1994	470	320	54	**2857**
	Composite	684	165	90	17	**957**	332	74	54	9	**468**	1016	239	143	26	**1435**
SDS	**Reference**	2454	578	418	72	**3521**	255	60	42	7	**364**	2709	638	460	80	**3981**
	Reduction	1961	462	275	52	**2749**	227	54	35	6	**322**	2188	515	310	58	**3150**
	Substitution	1508	354	264	46	**2171**	198	47	34	6	**285**	1706	400	298	51	**2526**
	Reuse	2334	558	389	69	**3350**	375	79	71	10	**536**	2709	638	460	80	**3981**
	Recycling	2130	502	364	64	**3059**	578	136	96	16	**826**	2709	638	460	80	**3981**
	Composite	976	234	136	27	**1373**	434	97	73	12	**617**	1411	331	209	39	**2047**
NZE	**Reference**	2970	699	517	91	**4277**	288	68	49	8	**413**	3258	767	566	100	**3981**
	Reduction	2359	556	337	64	**3316**	257	61	40	7	**365**	2617	616	377	71	**3150**
	Substitution	1828	429	326	57	**2640**	226	53	39	7	**325**	2054	482	366	64	**2526**
	Reuse	2835	677	485	88	**4084**	423	90	81	12	**606**	3258	767	566	100	**3981**
	Recycling	2608	614	455	81	**3758**	650	153	110	19	**932**	3258	767	566	100	**3981**
	Composite	1195	286	170	34	**1685**	492	111	84	14	**700**	1687	396	253	47	**2047**

Table S 22 Global cumulative required reserves of the REEs between 2021 and 2050 (kt)

		Nd	Pr	Dy	Tb
STEPS	**Reference**	3391	799	546	93
	Reduction	2714	641	359	67
	Substitution	2029	476	340	57
	Reuse	3213	774	502	88
	Recycling	2912	686	472	80
	Composite	1291	312	169	33
SDS	**Reference**	4630	1090	788	137
	Reduction	3700	872	518	97
	Substitution	2845	667	499	86
	Reuse	4403	1053	733	131
	Recycling	4019	947	686	120
	Composite	1842	442	257	50
NZE	**Reference**	5604	1319	975	172
	Reduction	4452	1049	635	121
	Substitution	3449	810	616	108
	Reuse	5349	1277	915	165
	Recycling	4920	1159	859	153
	Composite	2255	539	321	63

Table S 23 Regional cumulative required reserves of Nd between 2021 and 2050 (kt)

Nd		CHN	US	EU	ROE	LA	CAN	AUS	IND	JPN	ROW
STEPS	**Reference**	1025	547	667	175	150	55	43	238	115	376
	Reduction	820	440	536	141	118	44	34	185	93	304
	Substitution	641	313	409	106	88	32	24	143	65	208
	Reuse	967	517	630	166	144	52	41	230	109	357
	Recycling	868	468	567	149	134	48	37	217	100	324
	Composite	398	199	257	68	58	21	16	97	42	135
SDS	**Reference**	1299	794	874	224	225	79	57	376	143	558
	Reduction	1038	638	701	180	177	63	46	294	115	448
	Substitution	822	479	546	139	136	48	34	232	83	326
	Reuse	1229	751	828	214	216	76	55	363	136	534
	Recycling	1111	681	751	194	202	70	50	342	124	494
	Composite	520	307	350	90	91	32	22	156	54	220
NZE	**Reference**	1572	953	1049	274	272	96	67	489	163	668
	Reduction	1251	762	838	219	213	77	53	379	130	529
	Substitution	995	580	657	171	165	59	40	298	95	389
	Reuse	1495	904	998	262	262	92	65	474	155	643
	Recycling	1362	824	912	239	246	86	60	449	142	600
	Composite	637	375	426	112	110	39	26	203	62	265

Table S 24 Regional cumulative required reserves of Pr between 2021 and 2050 (kt)

Pr		CHN	US	EU	ROE	LA	CAN	AUS	IND	JPN	ROW
STEPS	**Reference**	236	131	156	42	35	13	10	55	28	93
	Reduction	189	105	125	34	28	11	8	43	22	75
	Substitution	147	75	95	25	20	8	6	33	16	51
	Reuse	226	128	150	40	34	13	10	54	27	92
	Recycling	200	112	133	36	31	12	9	50	24	80
	Composite	93	49	61	17	14	5	4	23	11	35
SDS	**Reference**	300	188	205	54	52	19	14	87	34	138
	Reduction	240	151	164	43	41	15	11	68	27	111
	Substitution	190	113	127	33	31	11	8	53	20	80
	Reuse	287	181	197	52	51	19	13	84	33	135
	Recycling	257	161	176	46	47	17	12	79	29	122
	Composite	122	74	84	22	21	8	5	36	13	56
NZE	**Reference**	364	224	246	66	63	23	16	113	39	165
	Reduction	290	180	197	53	49	18	13	87	31	131
	Substitution	230	136	154	41	38	14	9	69	22	96
	Reuse	350	217	237	64	61	23	16	110	38	162
	Recycling	316	194	214	58	57	21	14	103	34	148
	Composite	149	90	101	27	26	10	6	47	15	67

Table S 25 Regional cumulative required reserves of Dy between 2021 and 2050 (kt)

Dy		CHN	US	EU	ROE	LA	CAN	AUS	IND	JPN	ROW
STEPS	**Reference**	188	77	113	27	26	8	6	44	15	43
	Reduction	124	51	75	18	16	5	4	28	10	28
	Substitution	121	46	72	17	15	5	3	27	9	24
	Reuse	174	69	104	25	24	7	5	43	14	37
	Recycling	159	66	96	23	23	7	5	41	14	37
	Composite	60	22	36	9	8	2	2	15	4	12
SDS	**Reference**	242	127	152	36	41	13	9	73	21	74
	Reduction	160	85	101	24	26	8	6	46	14	49
	Substitution	156	80	98	23	25	8	5	45	13	45
	Reuse	225	116	142	34	39	12	8	70	19	68
	Recycling	207	109	131	32	37	11	8	67	19	66
	Composite	79	40	50	12	13	4	3	24	6	24
NZE	**Reference**	295	159	186	45	50	16	11	96	25	93
	Reduction	193	105	123	30	32	10	7	59	16	60
	Substitution	190	100	119	29	31	10	6	59	15	56
	Reuse	277	147	174	43	48	15	10	92	23	86
	Recycling	255	138	162	40	46	14	10	88	22	85
	Composite	98	51	62	15	16	5	3	32	8	30

Table S 26 Regional cumulative required reserves of Tb between 2021 and 2050 (kt)

Tb		CHN	US	EU	ROE	LA	CAN	AUS	IND	JPN	ROW
STEPS	**Reference**	29	14	18	5	4	2	1	7	3	10
	Reduction	21	10	13	4	3	1	1	5	2	7
	Substitution	18	8	11	3	2	1	1	4	2	6
	Reuse	27	13	17	5	4	1	1	7	3	10
	Recycling	24	12	15	4	4	1	1	7	3	9
	Composite	10	5	7	2	1	1	0	3	1	3
SDS	**Reference**	38	22	26	7	7	2	2	12	4	18
	Reduction	28	16	18	5	5	2	1	8	3	12
	Substitution	25	14	16	4	4	2	1	7	2	11
	Reuse	36	21	24	7	6	2	2	11	4	17
	Recycling	33	19	22	6	6	2	1	11	3	16
	Composite	14	8	10	3	2	1	1	5	1	6
NZE	**Reference**	48	28	32	9	8	3	2	15	4	23
	Reduction	34	20	23	6	6	2	1	11	3	15
	Substitution	31	17	20	6	5	2	1	10	3	14
	Reuse	46	26	30	9	8	3	2	15	4	22
	Recycling	42	24	28	8	7	3	2	14	4	21
	Composite	18	10	12	3	3	1	1	6	2	8

S3.3 Demand, supply and reserves of REEs at global and regional scales

(1) Reduction scenario

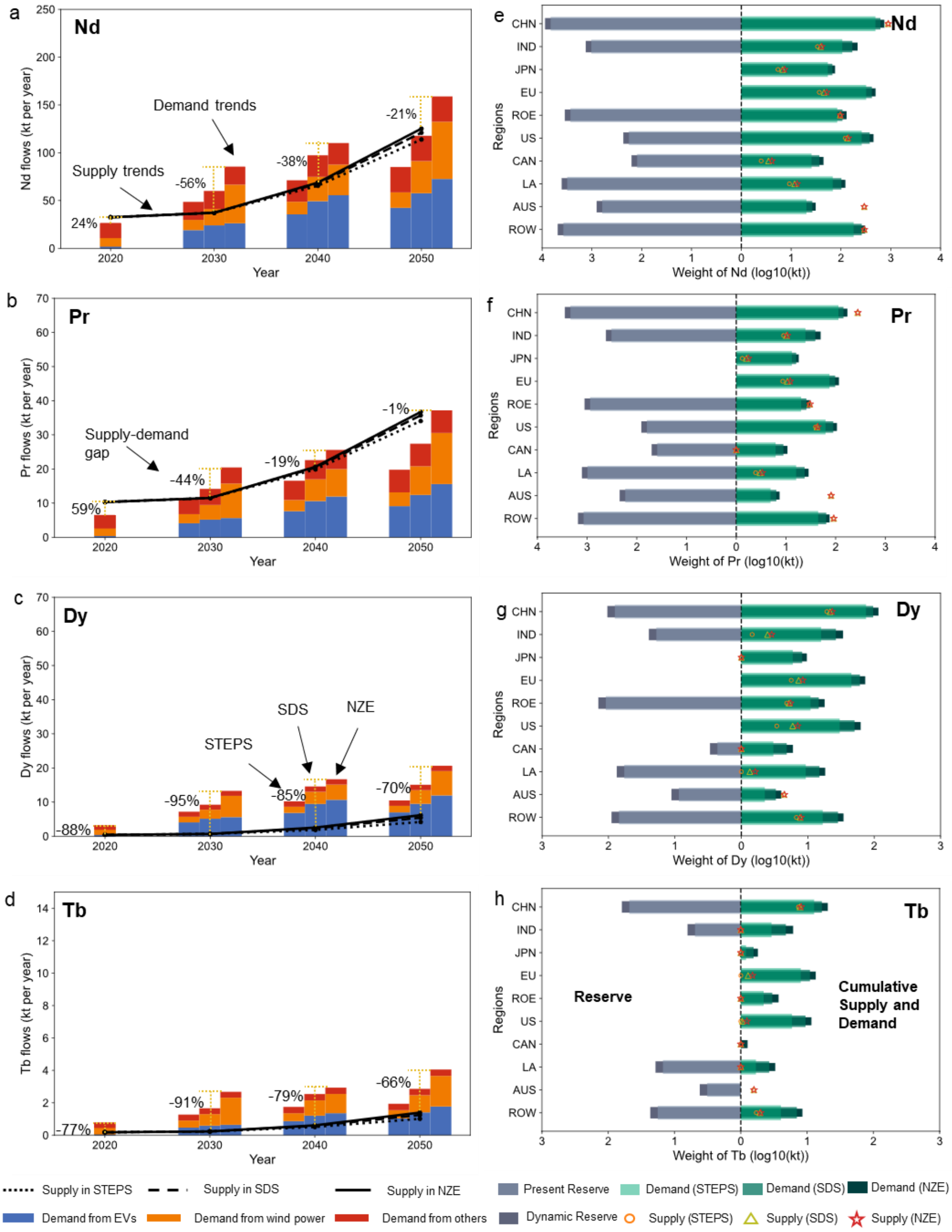


Fig. S 8 The demand, supply, and reserves of REEs at global and regional scales in the reduction scenario. a-d Global (primary plus secondary) supply and demand of Nd (a), Pr (b), Dy (c), and Tb (d) by sector in kt/year, and **e-h** regional reserves, cumulative (primary plus secondary) supply and demand of Nd (e), Pr (f), Dy (g) and Tb (h) between 2021 and 2050, represented as a base-10 logarithm.

(2) Substitution scenario

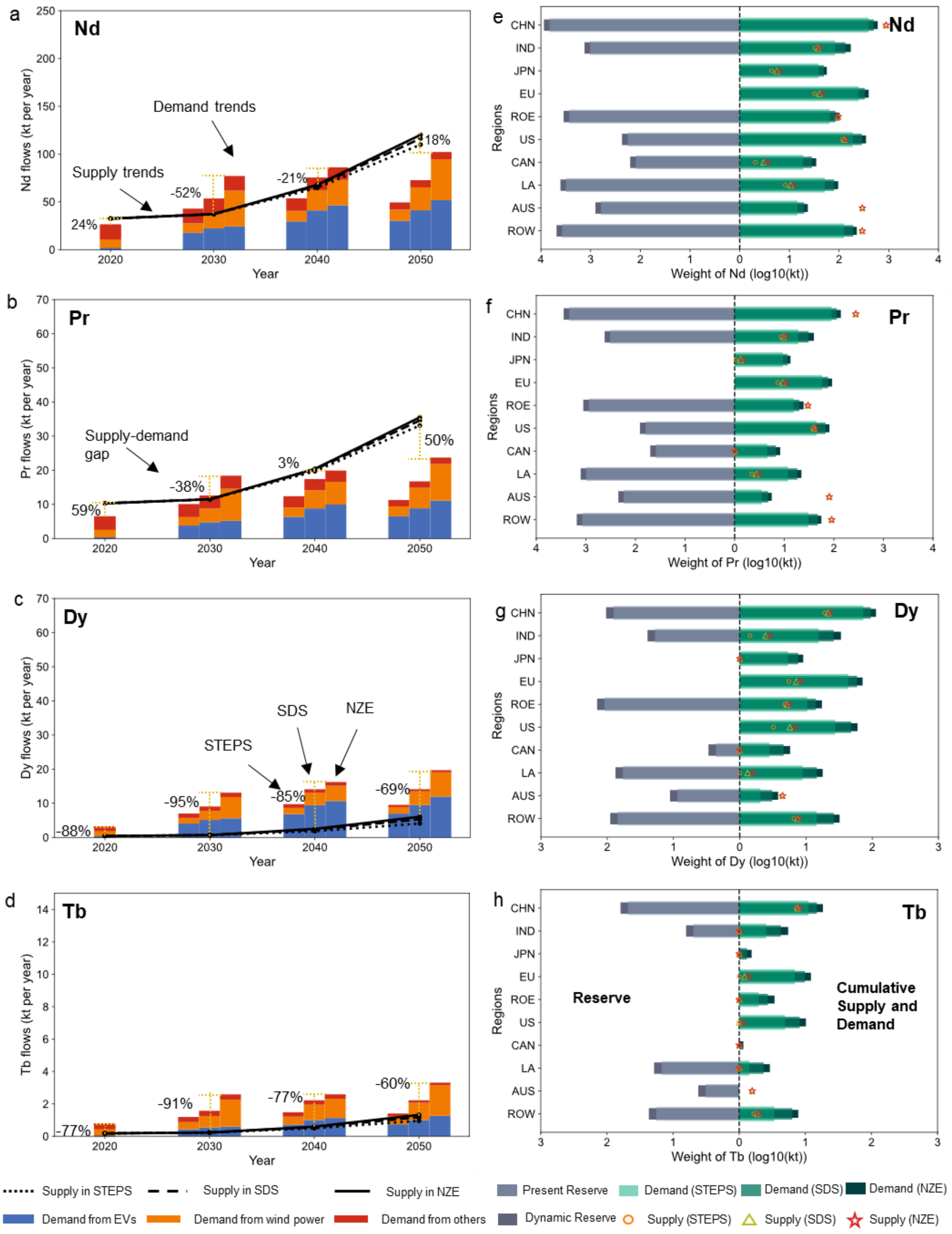


Fig. S 9 The demand, supply and reserves of REEs at global and regional scales in the substitution scenario. a-d Global (primary plus secondary) supply and demand of Nd (a), Pr (b), Dy (c), and Tb (d) by sector in kt/year, and **e-h** regional reserves, cumulative (primary plus secondary) supply and demand of Nd (e), Pr (f), Dy (g) and Tb (h) between 2021 and 2050, represented as a base-10 logarithm.

(3) Reuse scenario

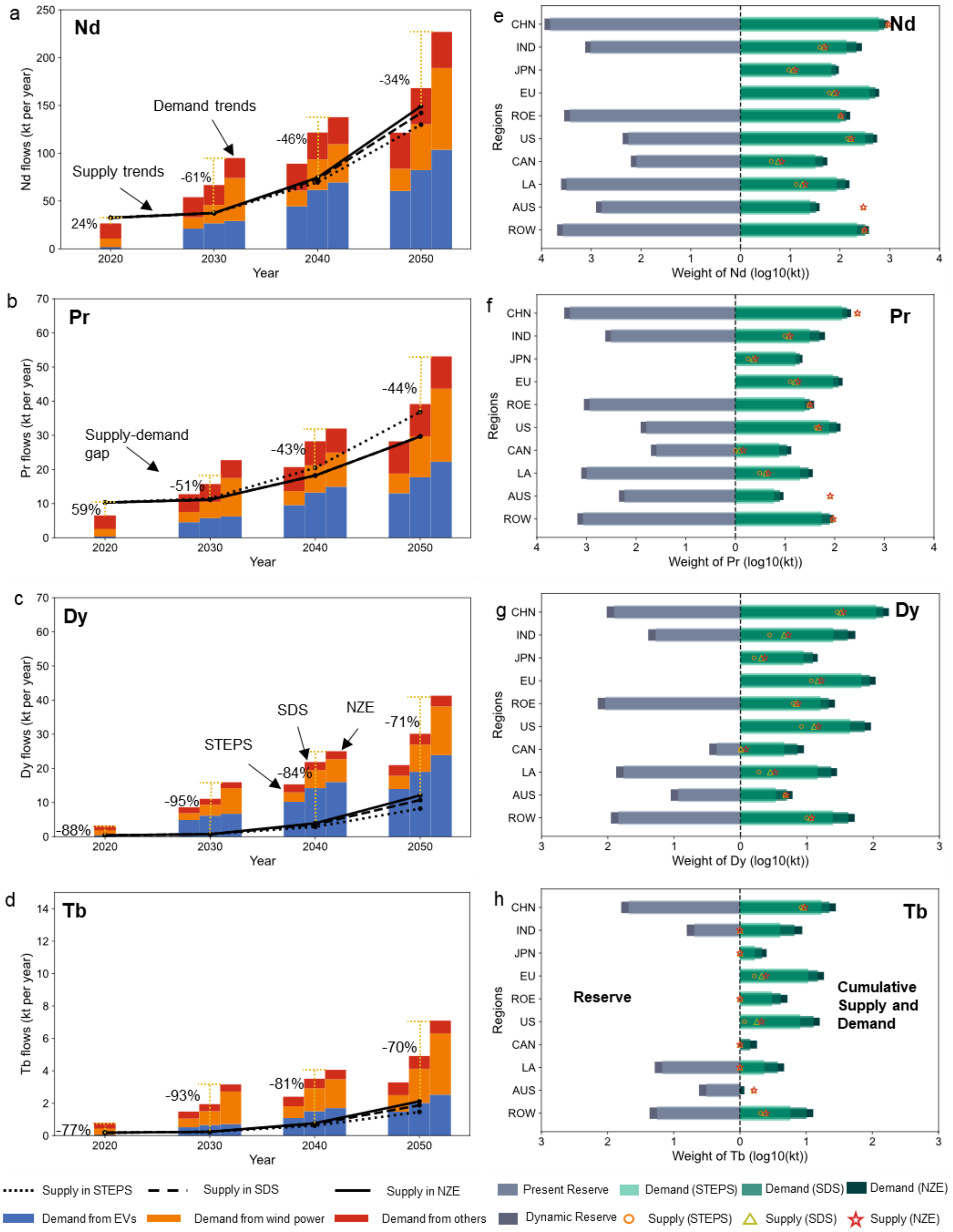


Fig. S 10 The demand, supply, and reserves of REEs at global and regional scales in the reuse scenario. a-d Global (primary plus secondary) supply and demand of Nd (a), Pr (b), Dy (c), and Tb (d) by sector in kt/year, and **e-h** regional reserves, cumulative (primary plus secondary) supply and demand of Nd (e), Pr (f), Dy (g) and Tb (h) between 2021 and 2050, represented as a base-10 logarithm.

(4) Recycling scenario

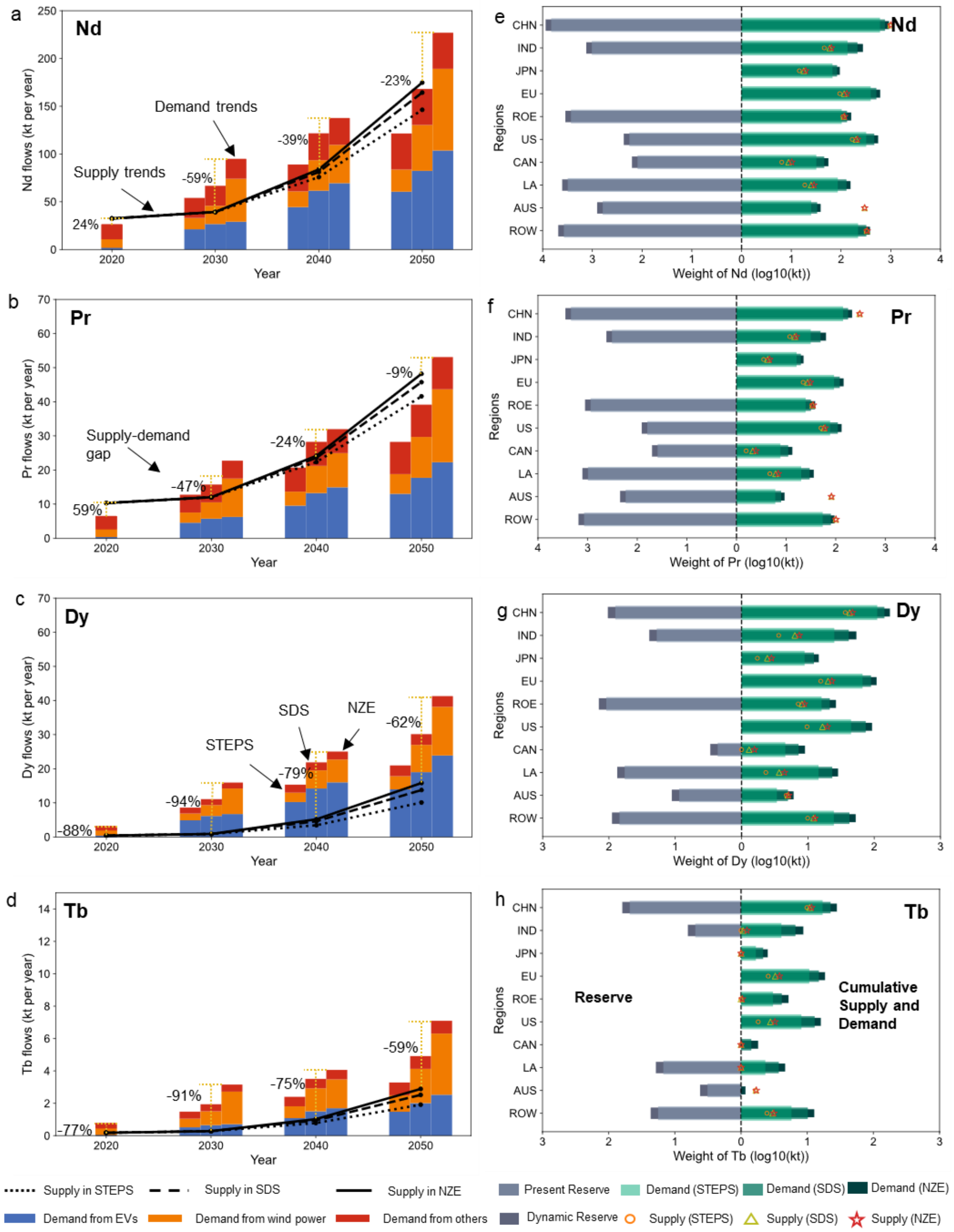


Fig. S 11 The demand, supply and reserves of REEs at global and regional scales in the recycling scenario. a-d Global (primary plus secondary) supply and demand of Nd (a), Pr (b), Dy (c), and Tb (d) by sector in kt/year, and **e-h** regional reserves, cumulative (primary plus secondary) supply and demand of Nd (e), Pr (f), Dy (g) and Tb (h) between 2021 and 2050, represented as a base-10 logarithm.

(5) Composite scenario

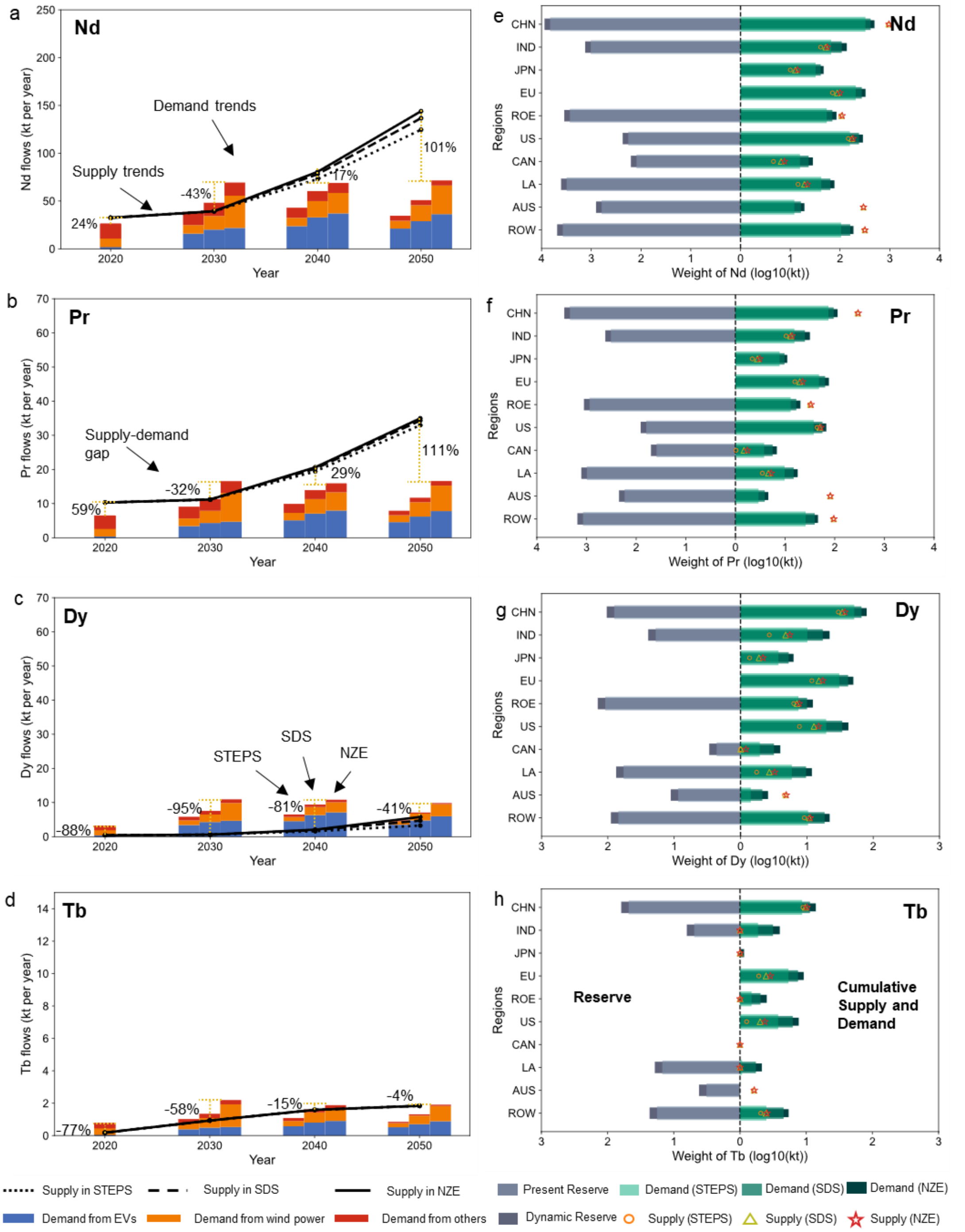


Fig. S 12 The demand, supply, and reserves of REEs at global and regional scales in the composite scenario. a-d Global (primary plus secondary) supply and demand of Nd (a), Pr (b), Dy (c), and Tb (d) by sector in kt/year, and **e-h** regional reserves, cumulative (primary plus secondary) supply and demand of Nd (e), Pr (f), Dy (g) and Tb (h) between 2021 and 2050, represented as a base-10 logarithm.

S3.4 Rare earth leveraged GHG reduction

(1) Reduction scenario

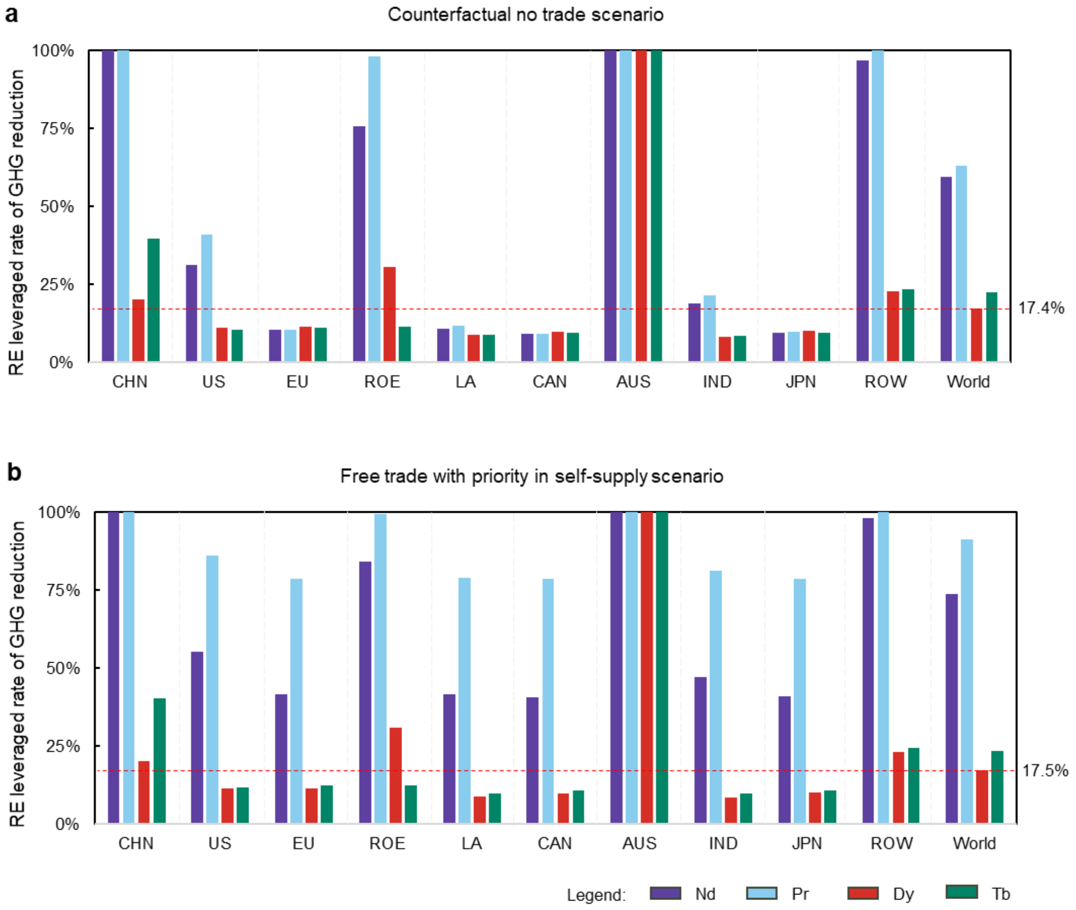


Fig. S 13 RE leveraged rate of GHG reduction for each studied region in the reduction scenario under no trade scenario (a) and free trade with priority in self-supply scenario (b).

(2) Substitution scenario

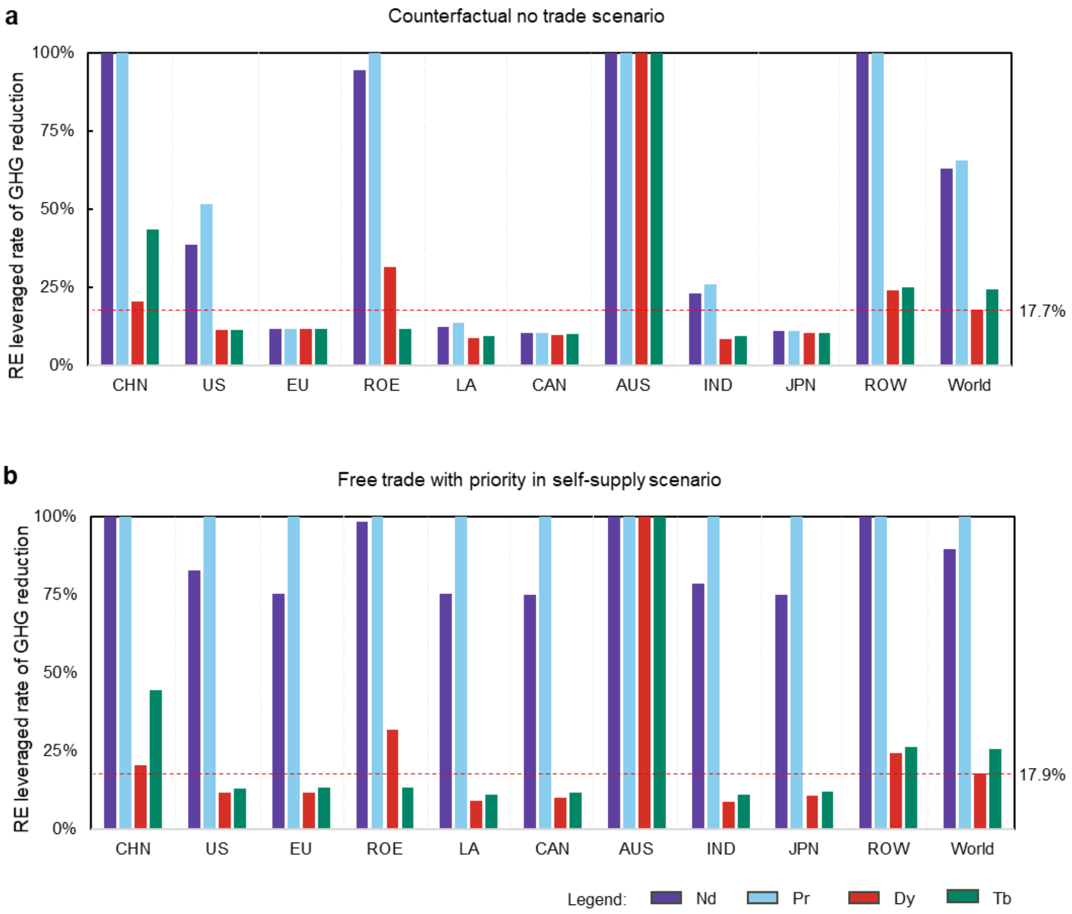


Fig. S 14 RE leveraged rate of GHG reduction for each studied region in the substitution scenario under no trade scenario (a) and free trade with priority in self-supply scenario (b).

(3) Reuse scenario

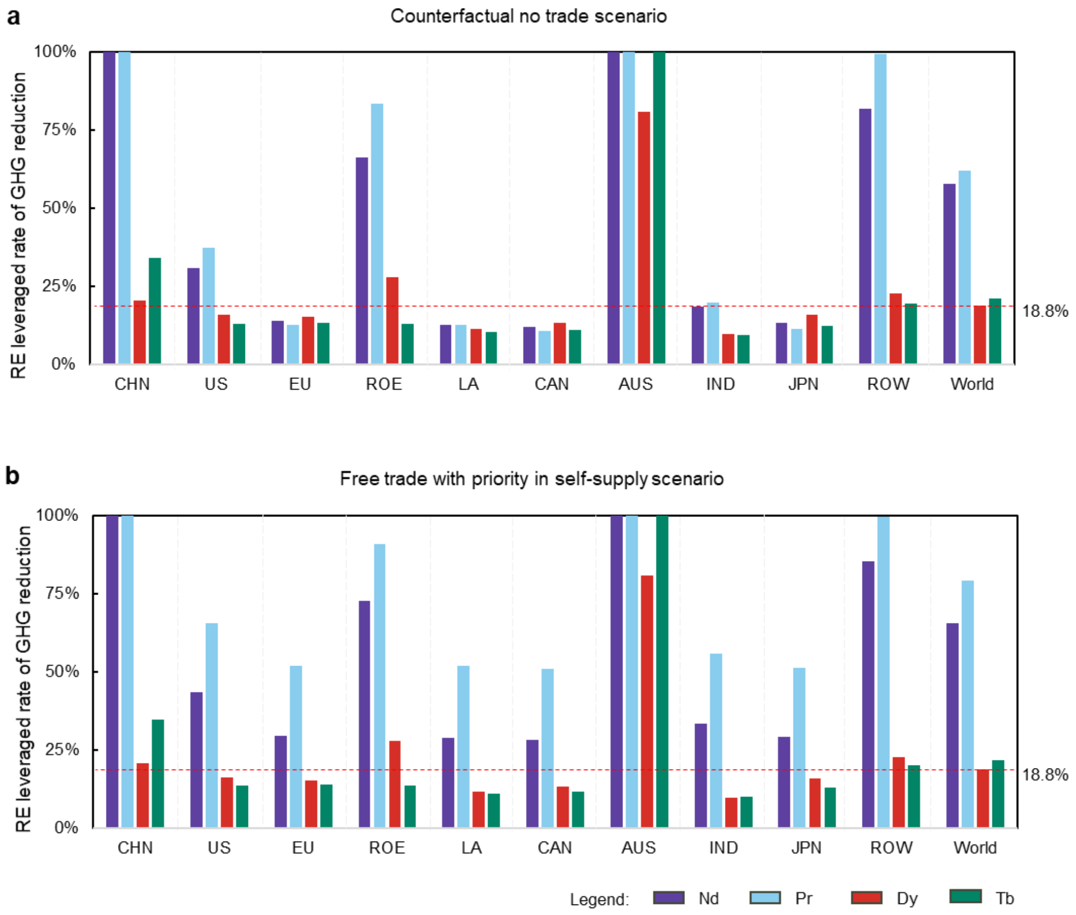


Fig. S 15 RE leveraged rate of GHG reduction for each studied region in the reuse scenario under no trade scenario (a) and free trade with priority in self-supply scenario (b).

(4) Recycling scenario

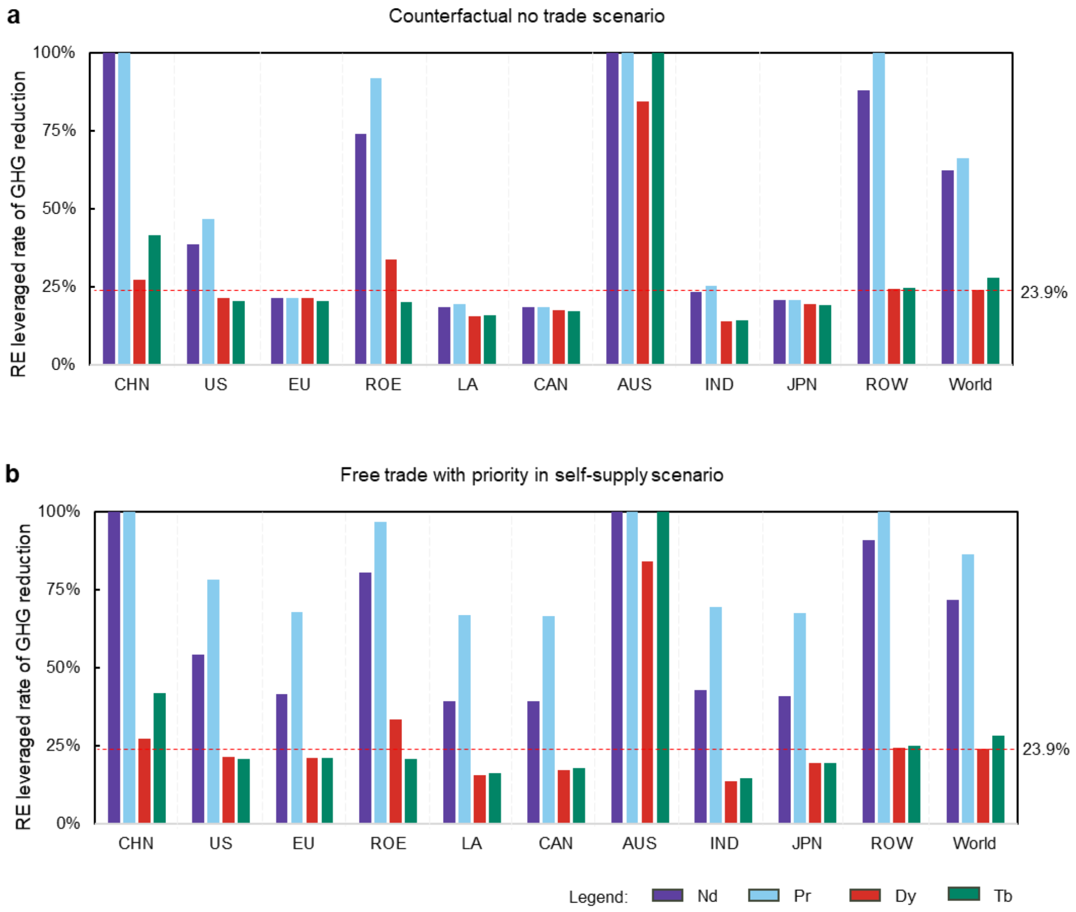


Fig. S 16 RE leveraged rate of GHG reduction for each studied region in the recycling scenario under no trade scenario (a) and free trade with priority in self-supply scenario (b).

(5) Composite scenario

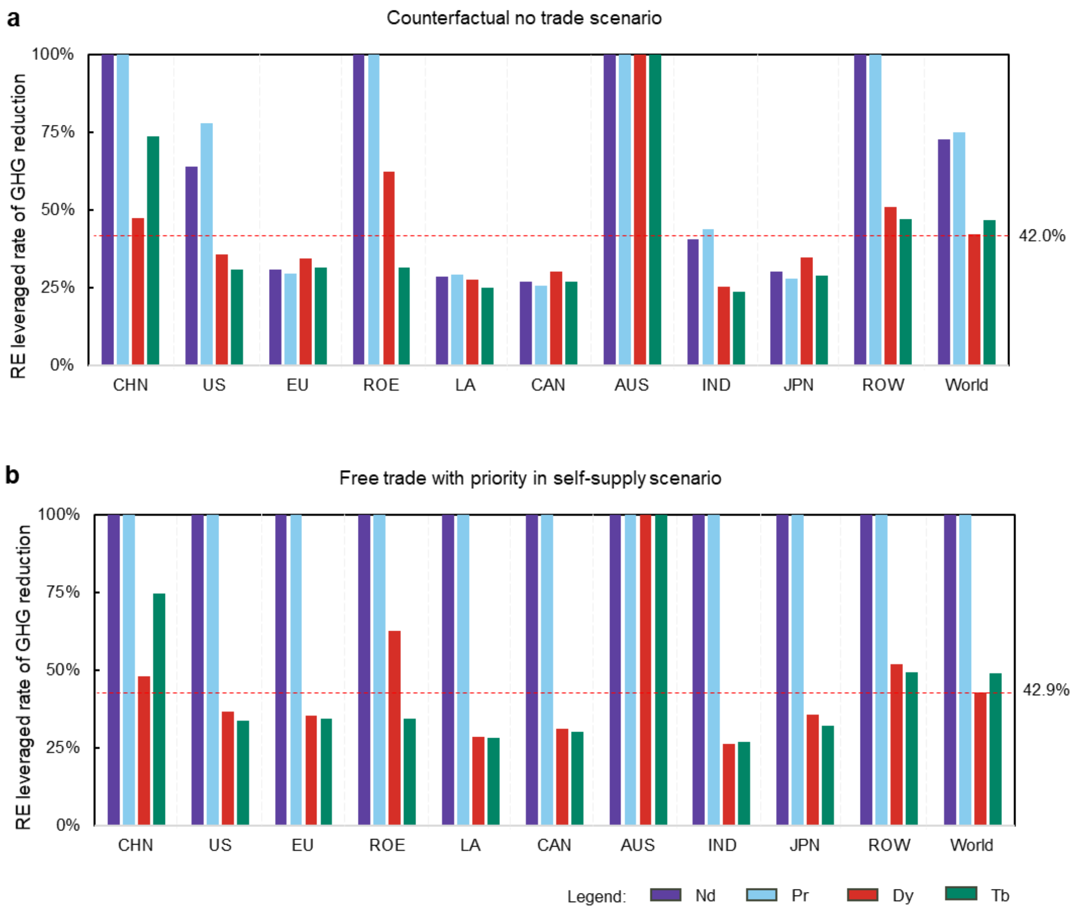


Fig. S 17 RE leveraged rate of GHG reduction for each studied region in the composite scenario under no trade scenario (a) and free trade with priority in self-supply scenario (b).

S3.5 Shift of REEs from in-ground stocks to in-use stocks

(1) STEPS

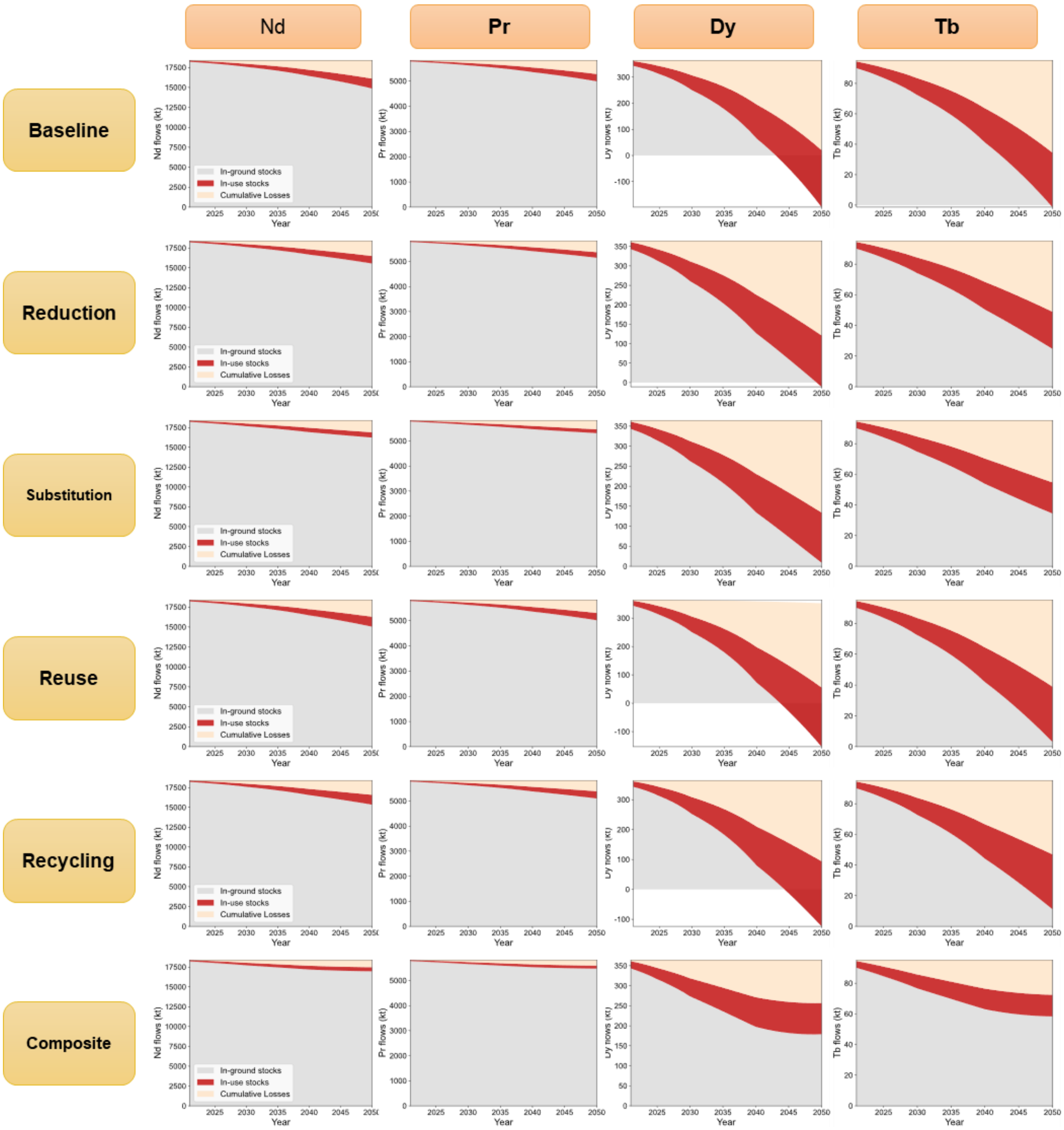


Fig. S 18 Shift of REEs from in-ground stocks to in-use stocks in the STEPS in different circular economy scenarios.

(2) SDS

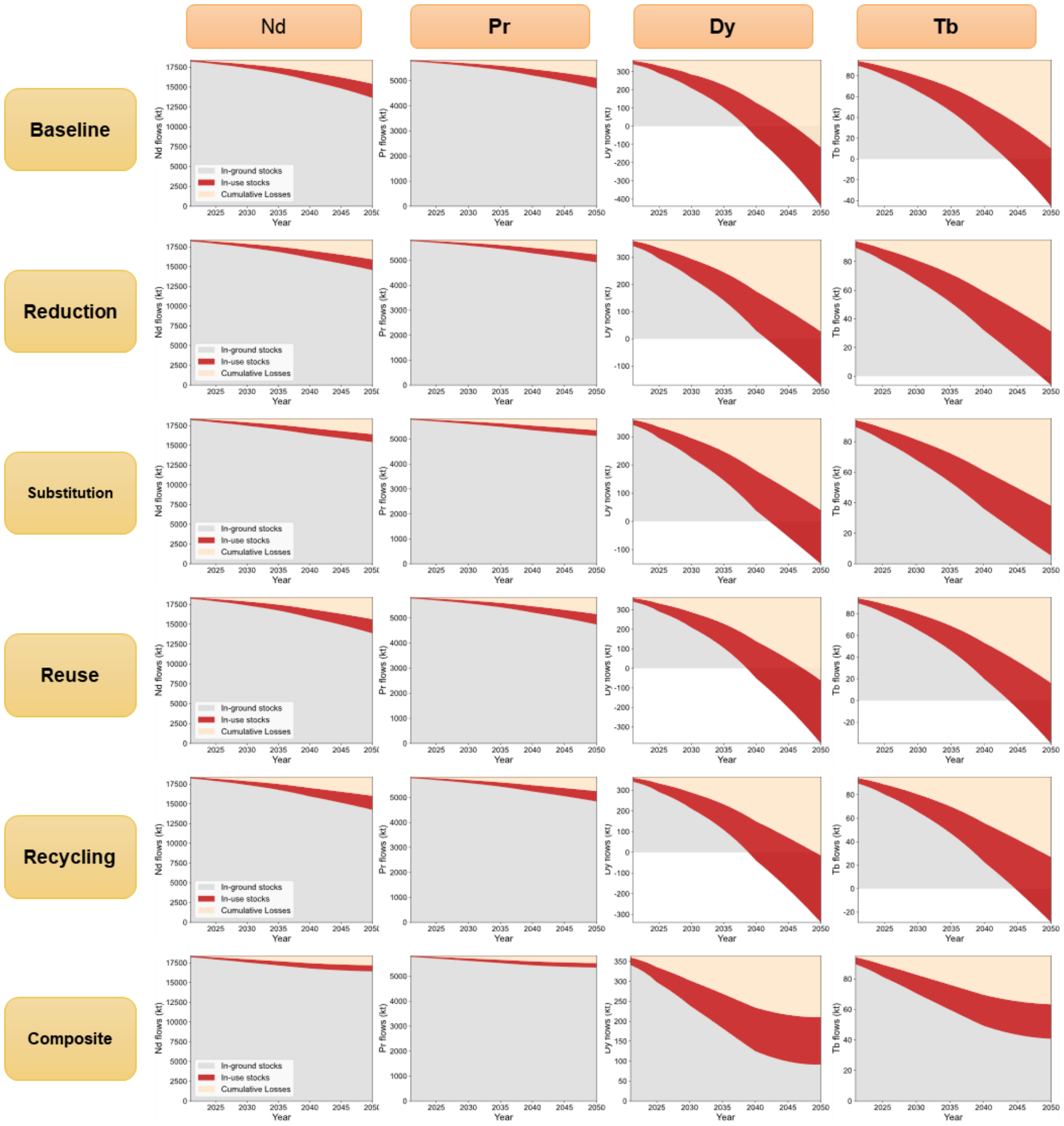


Fig. S 19 Shift of REEs from in-ground stocks to in-use stocks in the SDS in different circular economy scenarios.

(3) NZE

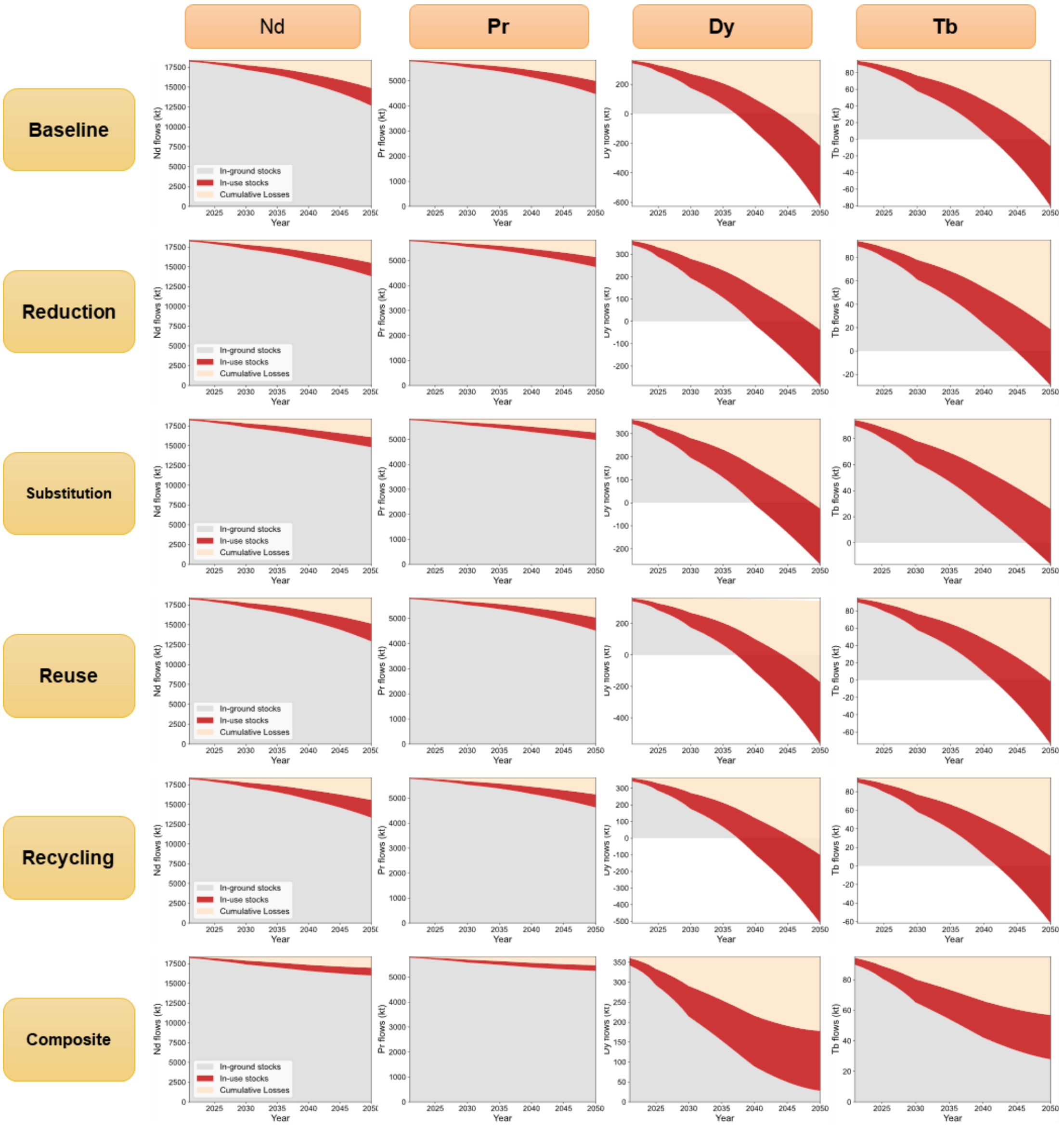


Fig. S 20 Shift of REEs from in-ground stocks to in-use stocks in the NZE in different circular economy scenarios.

S3.6 Regional in-use stocks of the REEs by 2050

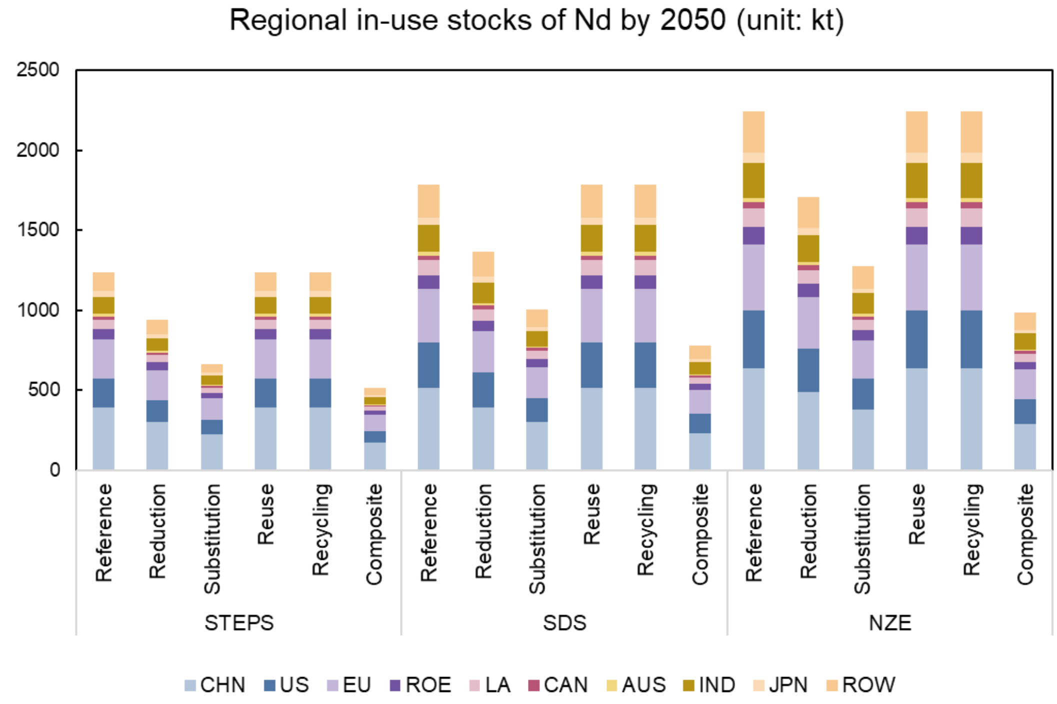


Fig. S 21 Regional in-use stocks of Nd by 2050 (unit: kt)

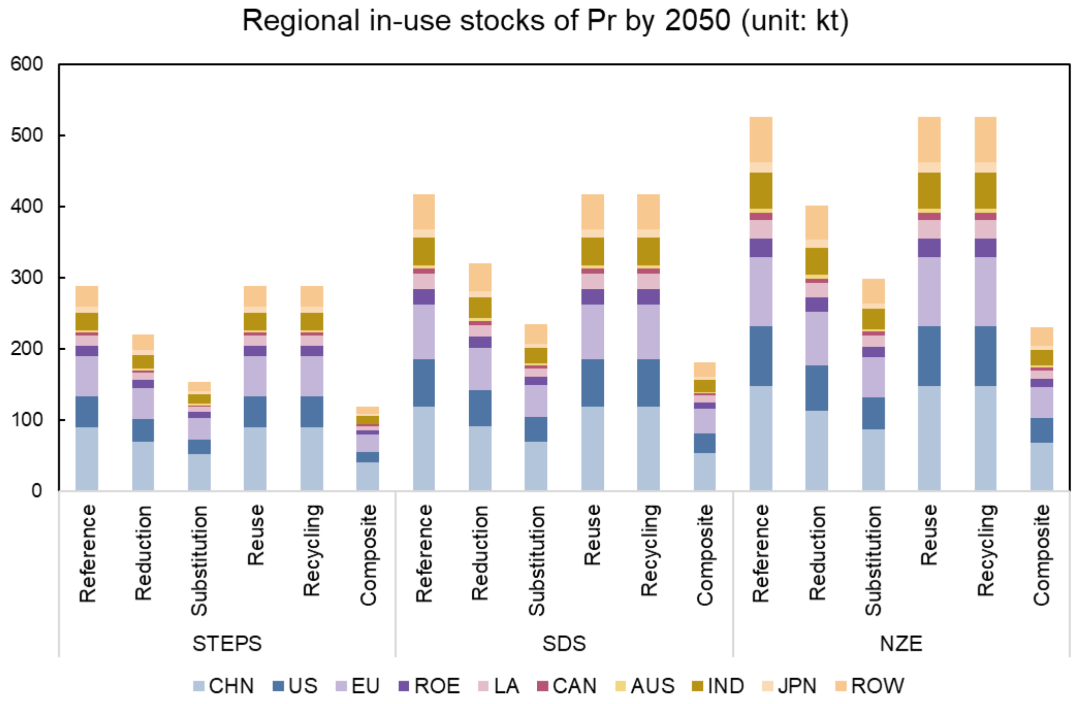


Fig. S 22 Regional in-use stocks of Pr by 2050 (unit: kt)

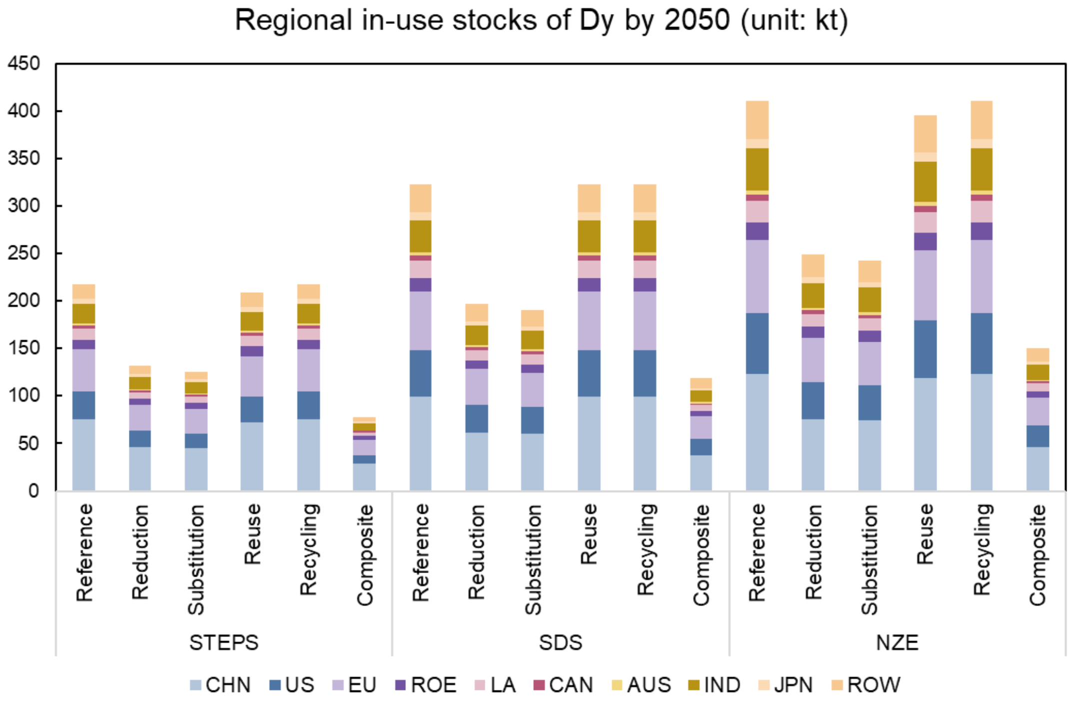


Fig. S 23 Regional in-use stocks of Dy by 2050 (unit: kt)

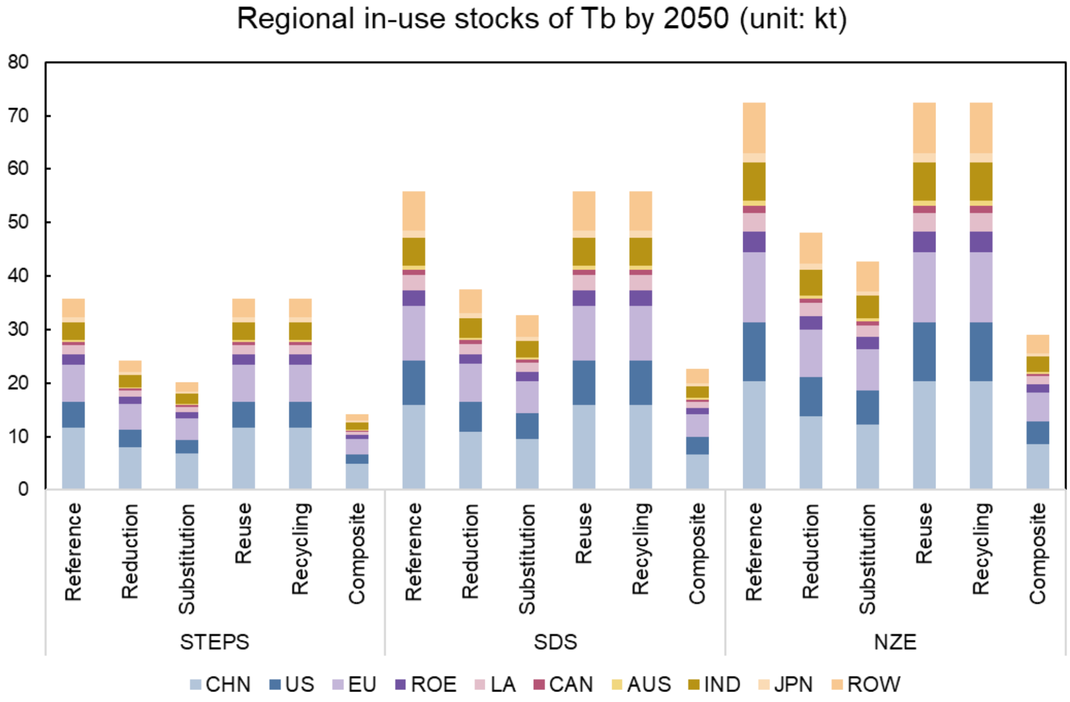


Fig. S 24 Regional in-use stocks of Tb by 2050 (unit: kt)

S3.7 Prospective primary demand and secondary supply of the REEs

(1) STEPS

Fig. S 25 Prospective primary demand and secondary supply of all the REEs (in total) in the STEPS in different circular economy scenarios. a Global cumulative primary demand and secondary supply of the REEs between 2021 and 2050 (unit: kt), and **b** regional primary demand, primary supply and secondary supply of the REEs from 2020 to 2050, unit: kt/year.

(2) SDS

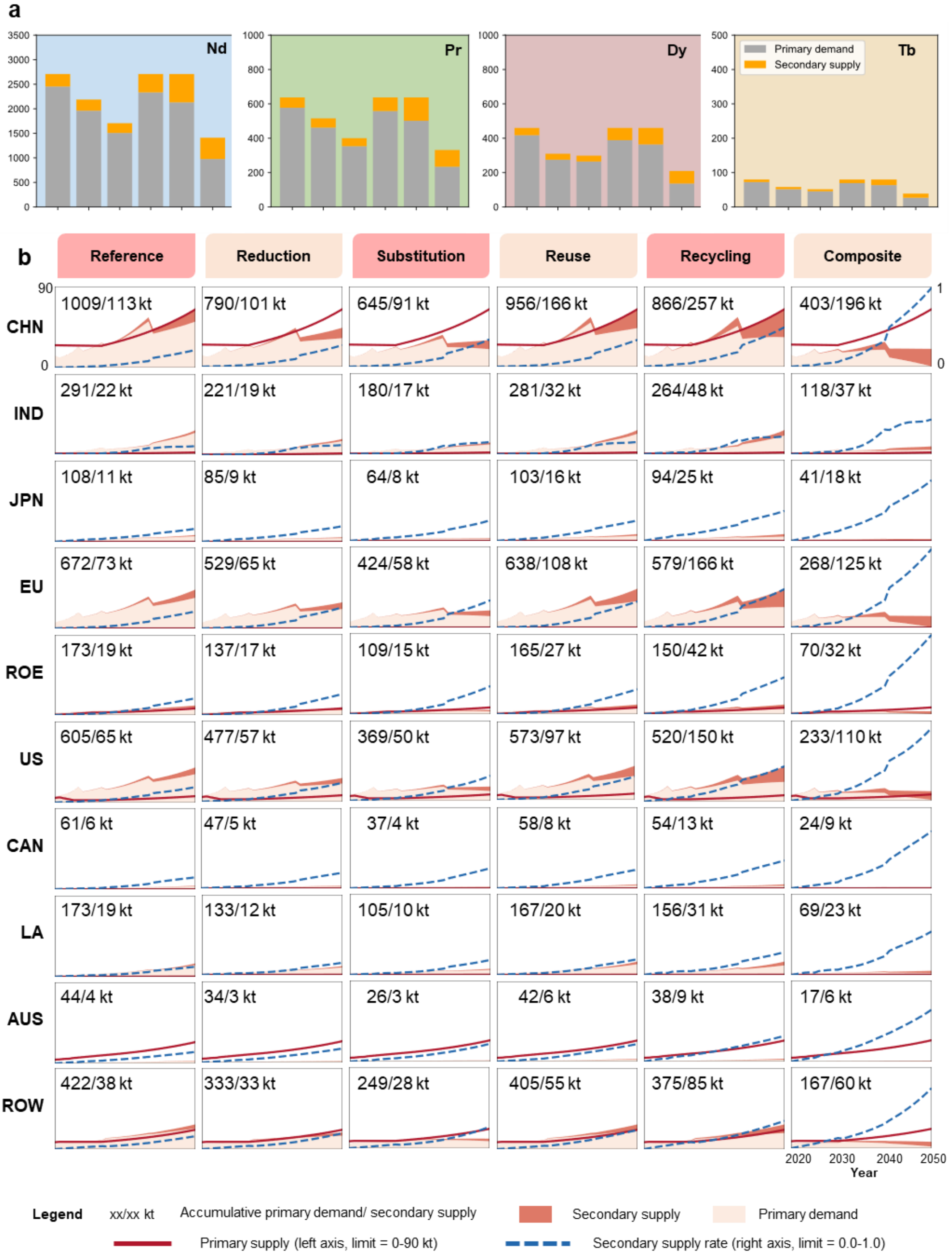


Fig. S 26 Prospective primary demand and secondary supply of all the REEs (in total) in the SDS in different circular economy scenarios. a Global cumulative primary demand and secondary supply of the REEs between 2021 and 2050 (unit: kt), and **b** regional primary demand, primary supply and secondary supply of the REEs from 2020 to 2050, unit: kt/year.

(3) NZE

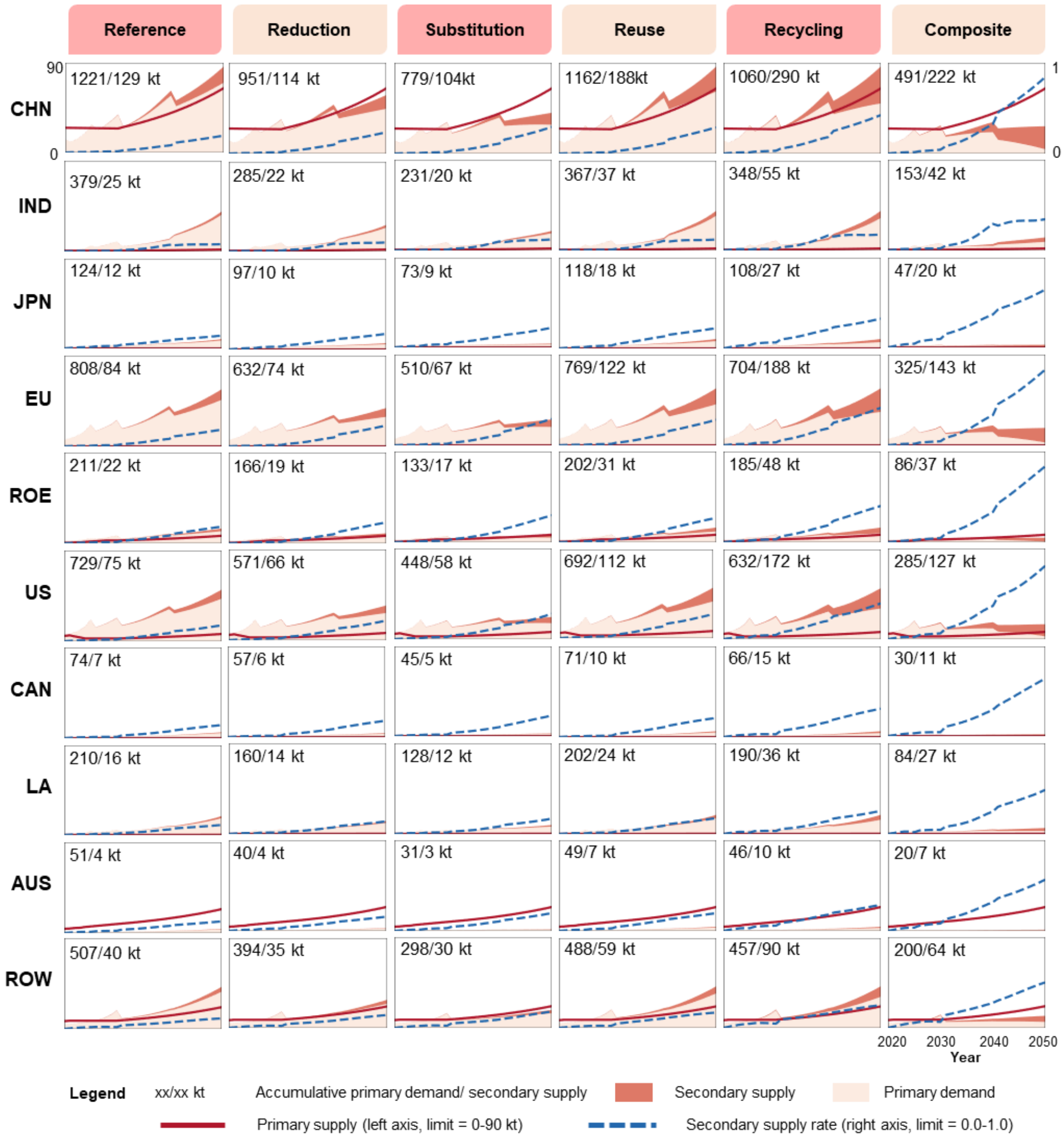


Fig. S 27 Regional primary demand, primary supply and secondary supply of all the REEs (Nd, Pr, Dy, and Tb in total) in the NZE scenario from 2020 to 2050 (unit: kt/year).

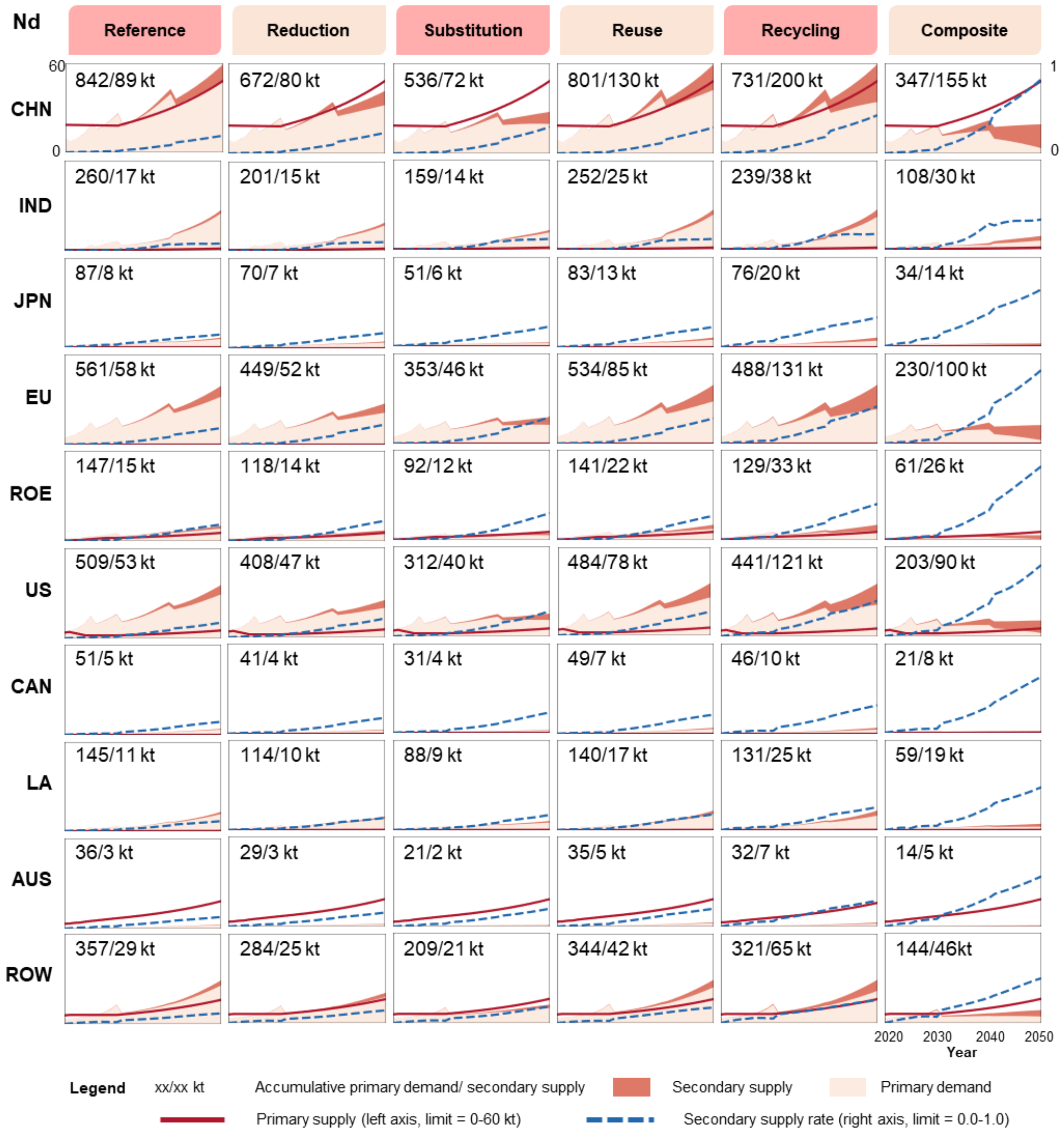


Fig. S 28 Regional primary demand, primary supply and secondary supply of Nd in the NZE scenario from 2020 to 2050 (unit: kt/year).

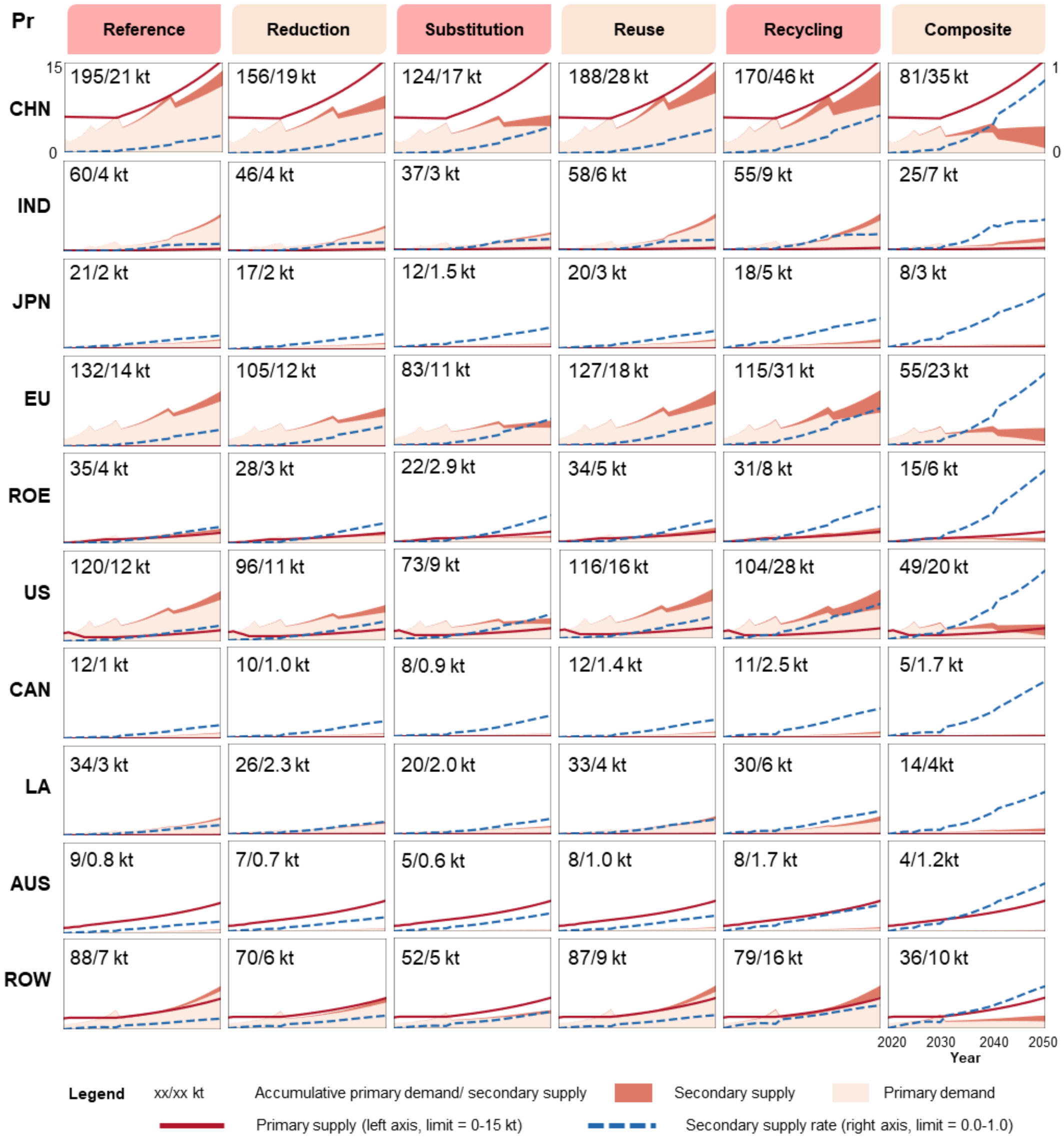


Fig. S 29 Regional primary demand, primary supply and secondary supply of Pr in the NZE scenario from 2020 to 2050 (unit: kt/year).

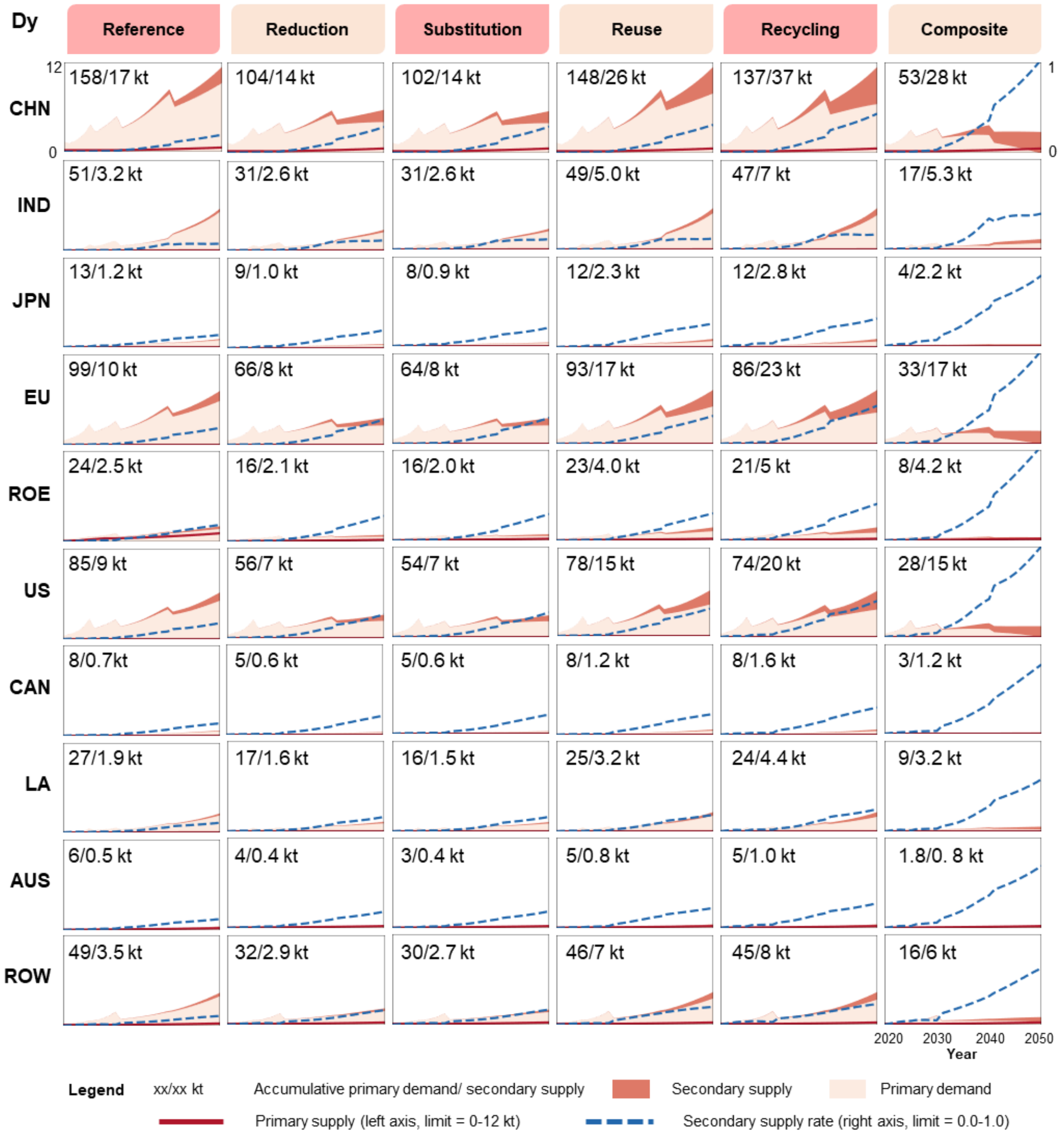


Fig. S 30 Regional primary demand, primary supply and secondary supply of Dy in the NZE scenario from 2020 to 2050 (unit: kt/year).

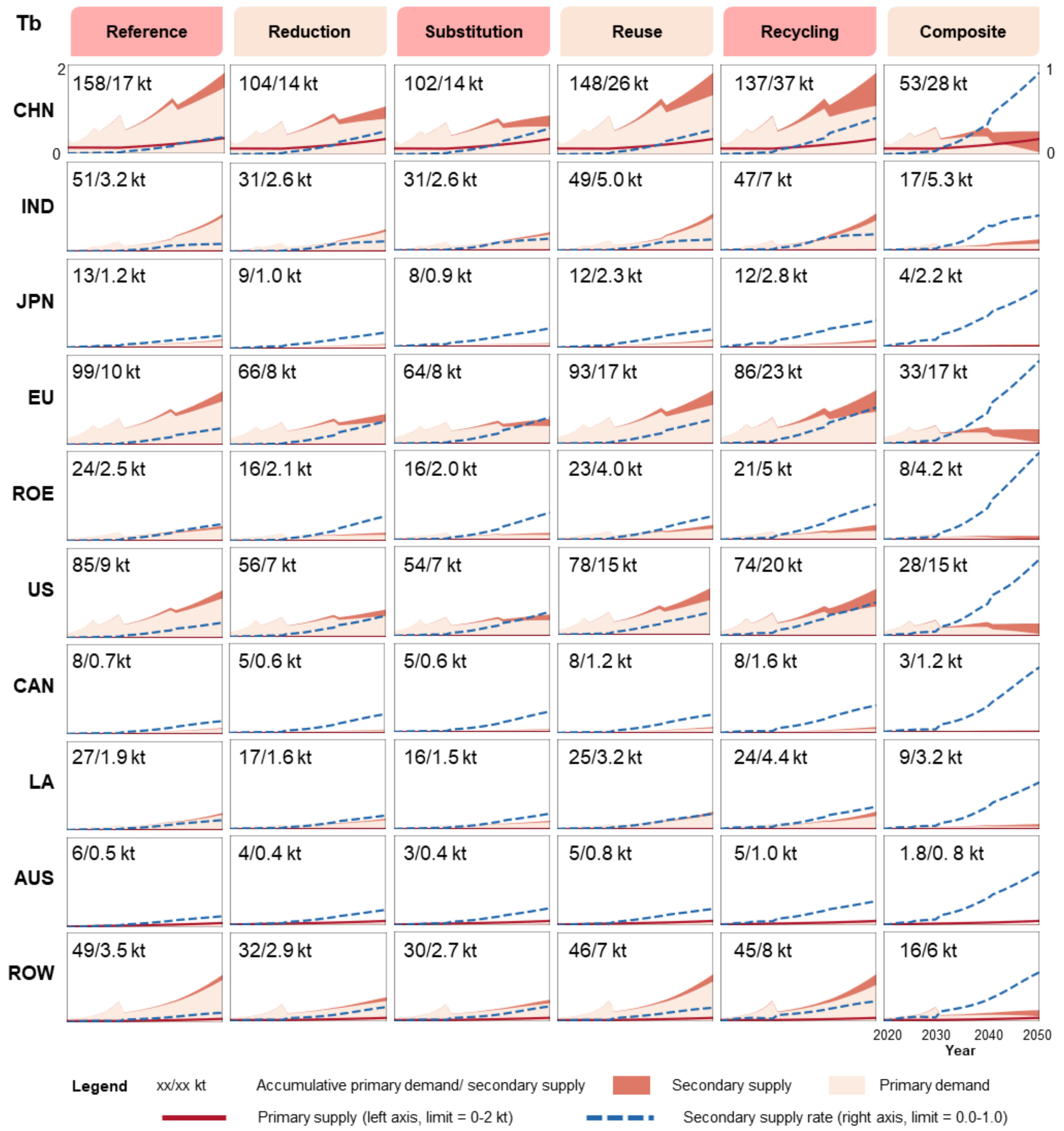


Fig. S 31 Regional primary demand, primary supply and secondary supply of Tb in the NZE scenario from 2020 to 2050 (unit: kt/year).

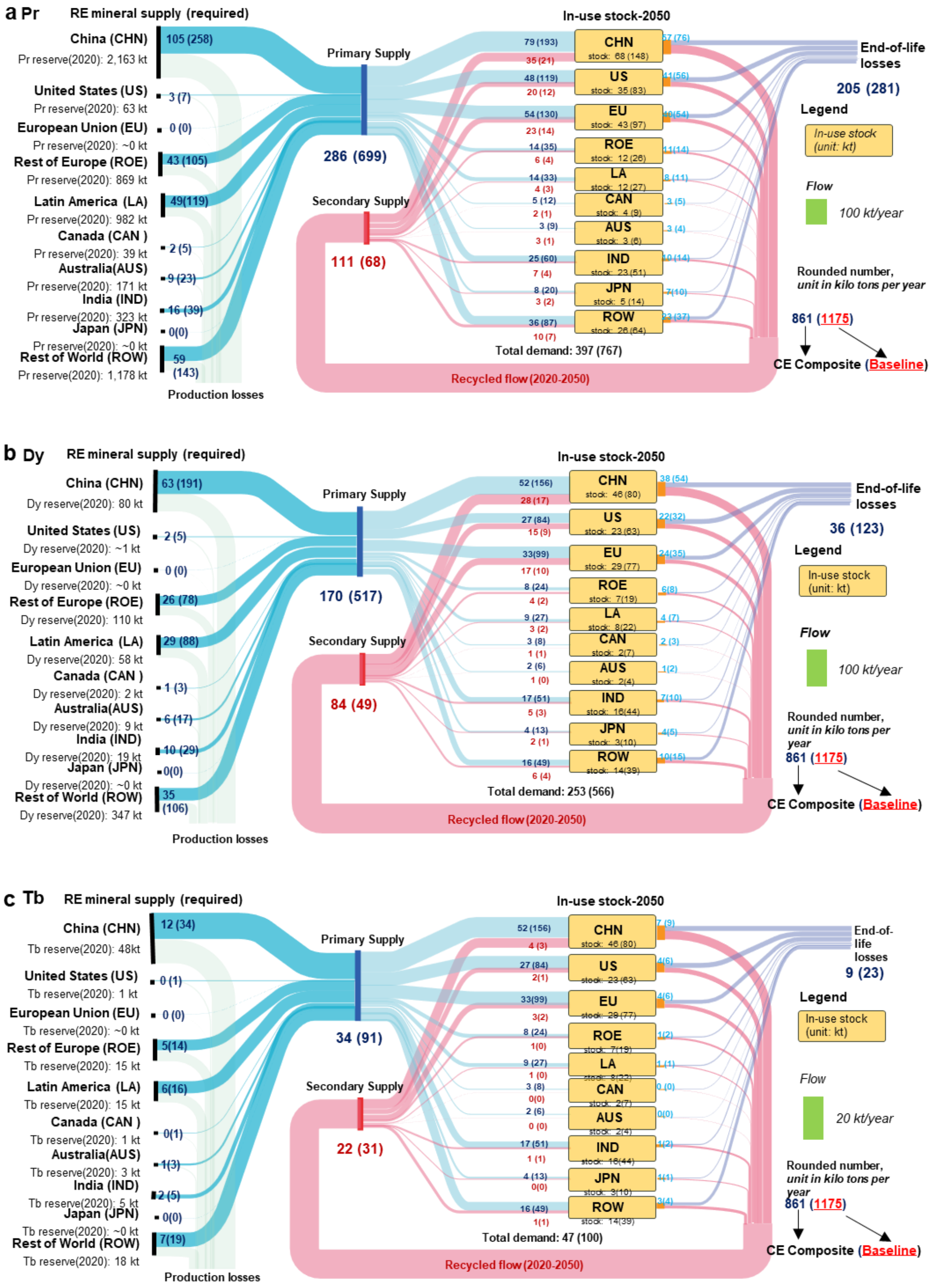


Fig. S 32 Sankey diagram of material flows of Pr (a), Dy (b), and Tb(c) through the world between 2021 and 2050 in the CE composite and NZE baseline scenarios

S4 Model Validation

The predictions are inherently subjective to uncertainties associated with the model assumptions and parameters. In this section, we first make comparisons with some previous studies, to validate the reliability of our predictions about the demand for REEs. Further, we conduct a sensitivity analysis and an uncertainty analysis using the normative scenario, i.e., the NZE scenario, as a base scenario.

S4.1 Comparisons with previous studies

Limited by the comparable data, we provide a global comparison of the REE demand from EVs and wind power (**Table S 27**), and a regional comparison of the REE demand from wind power (**Table S 28**). The comparison results verify that our results are reliable.

Table S 27 Global comparisons of the annual REE demand by 2050

	EV			**Wind power**		
	our study	**Habib et al.** [24]	**Elshkaki** [35]	**our study**	**Habib et al.** [24]	**Elshkaki** [35]
Nd	61-104	25-100	200-310	23-85	3-22	11-28
Pr	13-22	-	-	6-21	-	3-10
Dy	14-24	4-15	25-50	4-14	0-2.2	1-3
Tb	1.5-2.5	-	-	1-3.8	-	0.5-3

Table S 28 Regional comparisons of the accumulative demand for Nd, Pr, and Dy between 2021 and 2050 from wind power

		CHN	**IND**	**US**	**CAN**	**LA**	**EU**	**ROE**	**AUS**	**JPN**	**ROW**
Nd	Our study	138-307	41-99	45-147	9-25	16-46	82-214	34-76	5-13	9-19	47-194
	Li et al. [17]	118-264.2	34.1-58.6	49.7-90.2*		9.1-45.8	90-107.7**		33-105.5***		
Pr	Our study	35-77	10-25	11-37	2-6	4-12	20-54	8-19	1-3	2-5	12-48
	Li et al. [17]	29.5-66	8.5-14.6	12.4-22.6*		2.3-11.5	22.5-26.9**		8.2-26.4***		
Dy	Our study	23-51	7-17	8-24	1-4	3-8	14-36	6-13	1-2	2-3	8-32
	Li et al. [17]	12.3-27	3.6-6	5.1-9.1*		0.9-4.4	9.5-11.6**		3.2-9.8***		

Note:

* indicates North America in the comparative article;

** indicates the OECD Europe and Eastern Europe;

*** indicates Non-OECD Asia, OECD Asia Oceania, Middle East and Africa.

S4.2 Sensitivity analysis

We extend four sensitivity analysis scenarios by two key parameters, lifetime and material intensity, which are shown in **Table S 29**.

Table S 29 Sensitivity analysis scenarios

	High material intensity	**Low material intensity**
Long lifetime	S I	S II
Short lifetime	S III	S IV

A longer lifetime for products can result in reduced demand for REEs due to fewer replacements needed. Various assumptions regarding the lifetime of EVs and wind turbines have been studied in the literature, as shown in **Table S 30**. The lifetime of wind turbines is assumed to be 18 to 25 years typically, while the lifetime of EVs is mostly assumed to be 15 years. In this section, we adopt a short-lifetime scenario of 18 years for wind turbines, 12 years for EVs, and 8 years for other sectors, and a long-lifetime scenario of 25 years for wind turbines, 18 years for EVs, and 12 years for other sectors.

Table S 30 Lifetime assumptions of wind turbines and EVs

	Reference	**Lifetime assumption**
Wind turbines	Cooperman et al.[36]	20 years
	Jensen et al.[37]	20-25 years
	Anaële et al.[38]	25 years
	Liu et al.[39]	18/20/25 years
	Chen et al.[40]	18 years

EVs	Xu et al.[41]	15 years
	Baars et al.[42]	15 years
	Hao et al.[43]	>10 years
	Ziemann et al. [44]	15 years

Based on a review conducted by Liang et al.26, there appears to be a significant variance in the material intensity of applications, as shown in **Table S 31**. Given such a significant variance, we consider scenarios in the sensitivity analysis that assume a 10% increase or decrease in material intensity, as presented in **Table S 32.**

Table S 31 Material intensity of applications[26]

	Nd	**Pr**	**Dy**	**Tb**
BEV (g/vehicle)	200-969	0.5-192	34-336	34
DDPMSG (kg/MW)	23.2-310	1-75	1-50	0.55-30
GDPMSG (kg/MW)	12-49.6	4	1.4-3.7	1

Table S 32 Parameter settings for sensitivity analysis

	Lifetime	**Material intensity**
Base scenario	EV: 15 years Wind power: 20 years Other sectors:10 years	See **Table S 8**
S I	EV: 18 years Wind power: 25 years Other sectors: 12 years	10% higher than the base scenario
S II	Same as S I	10% lower than the base scenario
S III	EV: 12 years Wind power: 18 years Other sectors: 8 years	Same as S I
S IV	Same as S III	Same as S II

The sensitivity analysis results are shown in **Fig. S 33**, which indicates that longer lifetime and lower material intensity can lead to an around 14%-18% reduction of regional accumulative demand for REEs, while shorter lifetime and higher material intensity can lead to an around 10%-20% increase of regional accumulative demand for REEs.

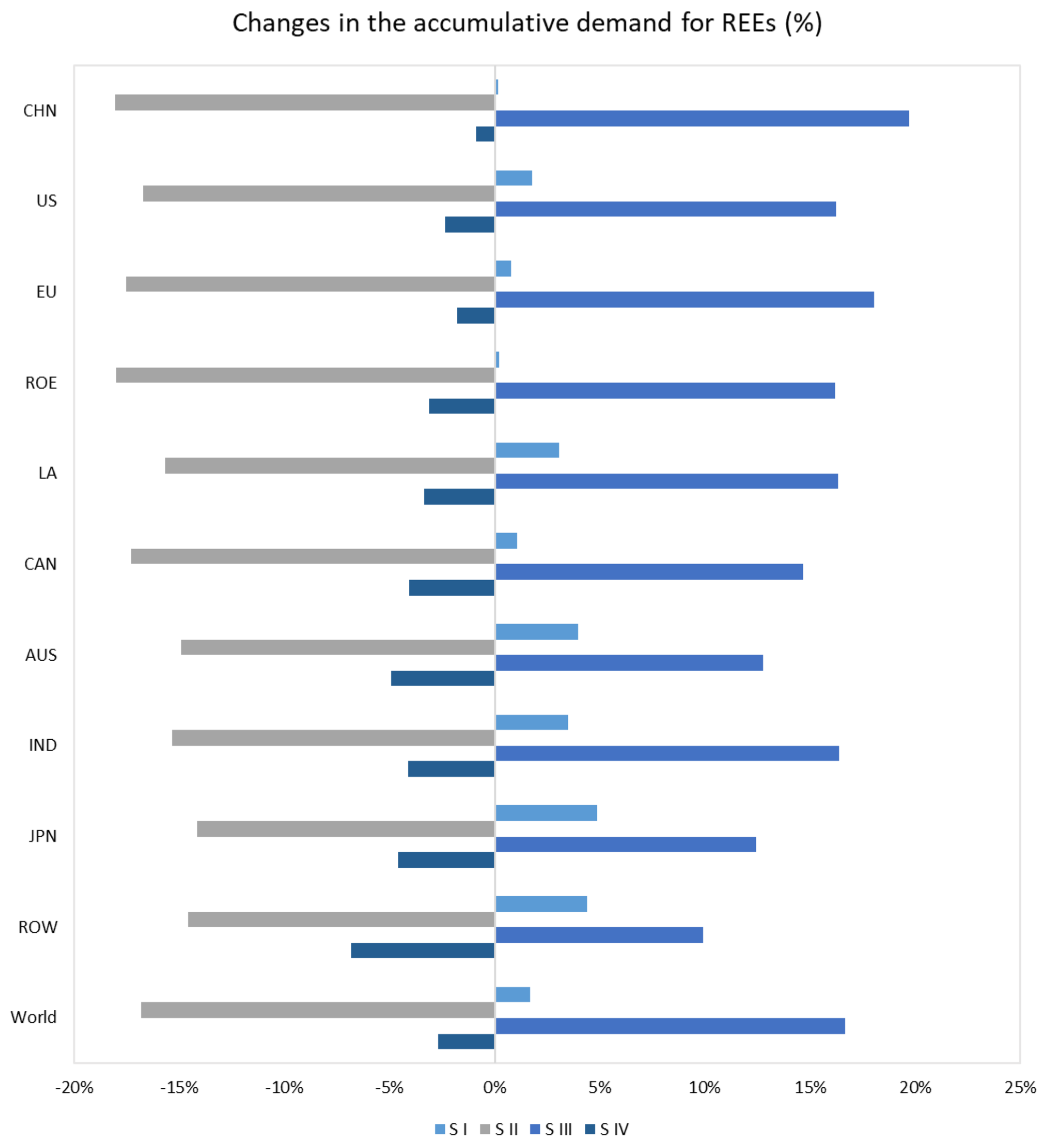


Fig. S 33 Sensitivity analysis for the accumulative demand for REEs from 2020 to 2050 in the NZE baseline scenario.

S4.3 Uncertainty analysis

Uncertainty analysis results of the REE annual inflows and in-use stocks are shown in **Fig. S 34** and **Fig. S 35**, respectively.

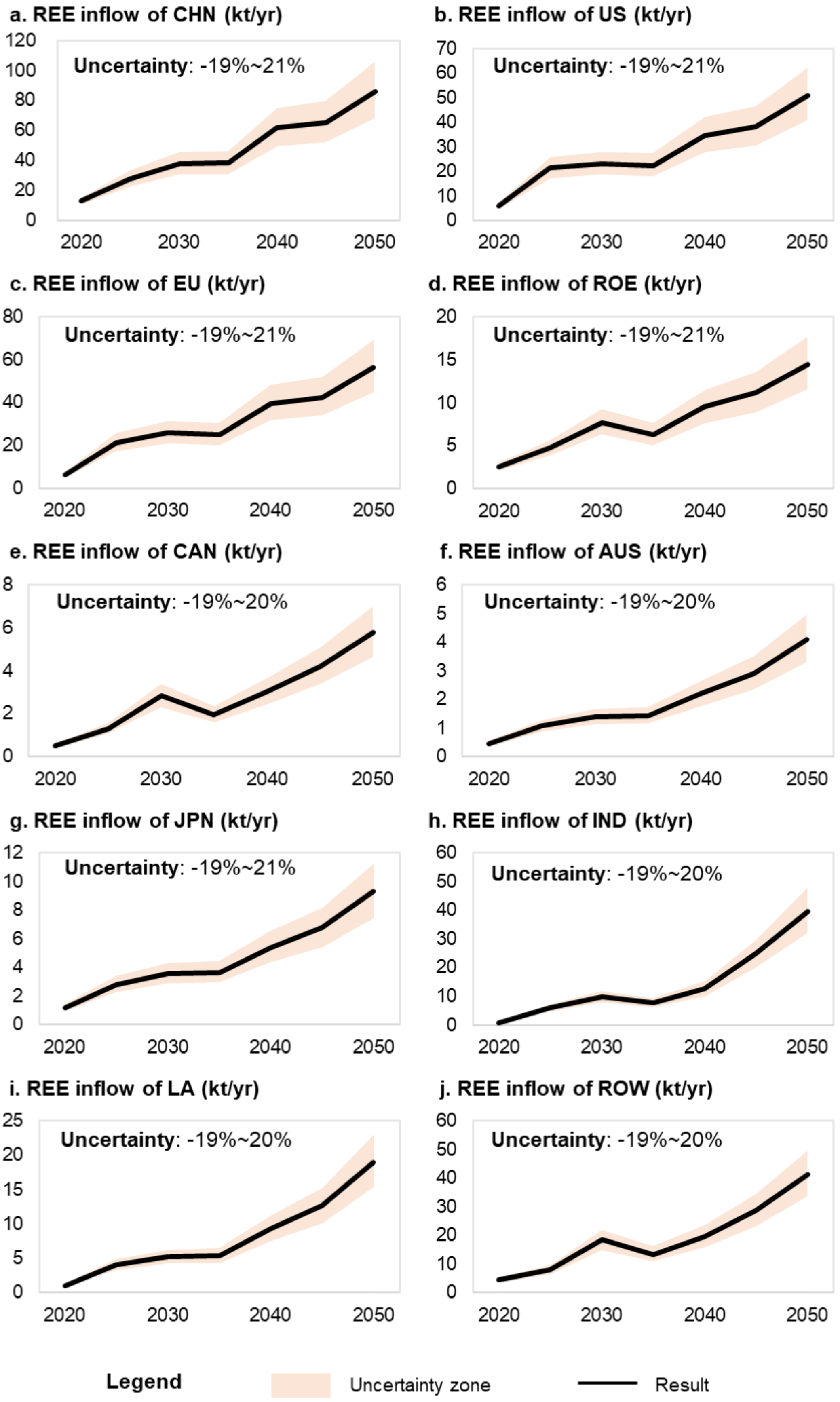
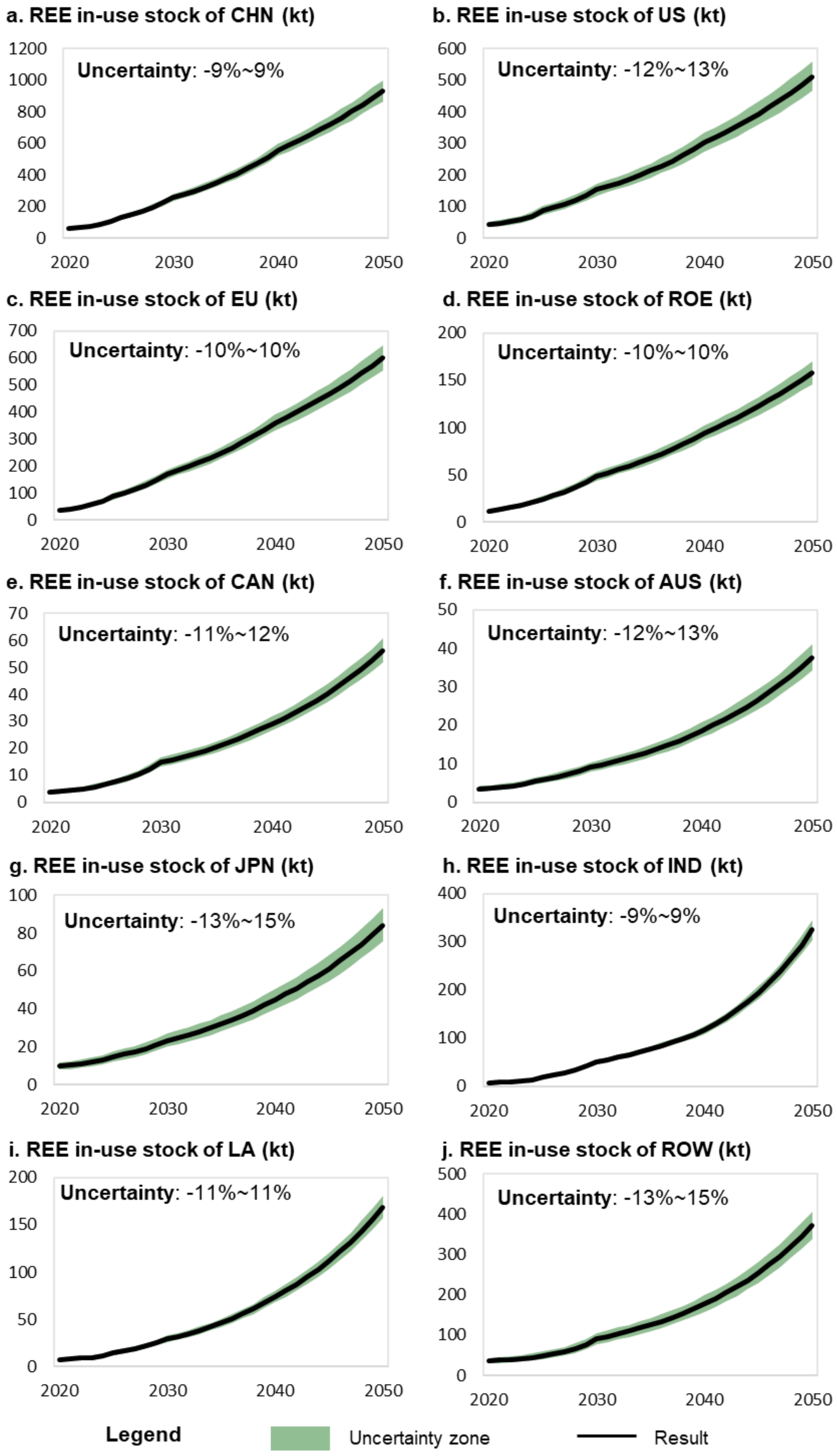


Fig. S 34 Uncertainty analysis of annual REE inflows



a. REE in-use stock of CHN (kt)

b. REE in-use stock of US (kt)

c. REE in-use stock of EU (kt)

d. REE in-use stock of ROE (kt)

e. REE in-use stock of CAN (kt)

f. REE in-use stock of AUS (kt)

g. REE in-use stock of JPN (kt)

h. REE in-use stock of IND (kt)

i. REE in-use stock of LA (kt)

j. REE in-use stock of ROW (kt)

Fig. S 35 Uncertainty analysis of REE in-use stocks

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