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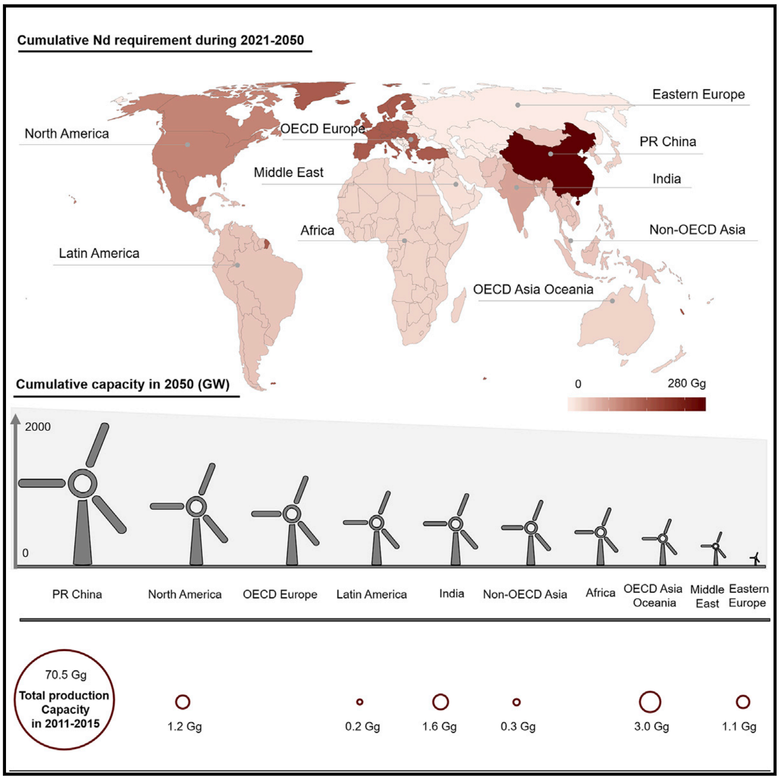
Critical Rare-Earth Elements Mismatch Global Wind-Power Ambitions

Graphical Abstract



Highlights

- 11- to 26-fold expansion of RE supply is needed for meeting global wind-power targets
- The global RE requirement is estimated at 460–902 Gg in 2021–2050
- European wind-power development faces the highest risk of RE shortage
- Governance of the RE supply chain is critical for guaranteeing wind-power deployment

Authors

Jiashuo Li, Kun Peng, Peng Wang, ..., Jing Meng, Wendong Wei, Qing Yang

Correspondence

zn928@naver.com (N.Z.),
fengkuishuang@gmail.com (K.F.),
guandabo@tsinghua.edu.cn (D.G.)

In Brief

Enhanced climate action is needed, but ambitious global wind-power-expansion targets raise concern regarding potential conflicts between the supply and demand of rare-earth elements (REs). Li et al. explore such conflicts across ten global regions through 2050 under four scenarios. They show that RE supply might not be able to meet ambitious wind-power development given the monopolistic structure of the RE supply chain and escalated geopolitical and environmental constraints. Sustainable and responsible RE supply chains are possible only via global cooperation.

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Critical Rare-Earth Elements Mismatch Global Wind-Power Ambitions

Jiashuo Li,[1,8] Kun Peng,[1,8] Peng Wang,[2] Ning Zhang,[1,*] Kuishuang Feng,[1,3,9,*] Dabo Guan,[4,5,*] Jing Meng,[5] Wendong Wei,[6] and Qing Yang[7]

[1]Institute of Blue and Green Development, Shandong University, Weihai 264209, China
[2]Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen 361021, China
[3]Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA
[4]Department of Earth System Science, Tsinghua University, Beijing 100084, China
[5]Bartlett School of Construction and Project Management, University of College London, London WC1E 7HB, UK
[6]School of International and Public Affairs, Shanghai Jiao Tong University, Shanghai 200030, China
[7]School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[8]These authors contributed equally
[9]Lead Contact
*Correspondence: zn928@naver.com (N.Z.), fengkuishuang@gmail.com (K.F.), guandabo@tsinghua.edu.cn (D.G.)
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SCIENCE FOR SOCIETY In 2019, the United Nations called for more ambitious climate action to prevent catastrophic climate change. Decarbonizing our energy systems is one of the most important actions we can take. In response, many countries have developed ambitious plans to expand wind power. However, wind turbines heavily rely on rare-earth elements (REs), and it remains unclear whether supply can meet demand. We investigated potential conflicts between RE demand and supply across ten global regions up to 2050 under four widely recognized climate scenarios. We found that RE supply capacity to support ambitious system-wide wind-power development is likely to be hindered by the monopolistic structure of the RE supply chain and intensified geopolitical and environmental constraints, and an 11- to 26-fold increase in production will be necessary to meet ambitious wind-power-expansion targets. To overcome these RE supply challenges, we highlight the importance of facilitating free trade and diversifying RE production via global cooperation.

SUMMARY

Wind power needs to be expanded rapidly across the world to stabilize our climate. However, there are increasing concerns about conflicts between the supply of rare-earth elements (REs) (mainly neodymium, praseodymium, and dysprosium) and the global expansion of wind power. Here, we provide a dynamic, technology-rich, and regional-specific approach to exploring such conflicts among ten world regions through 2050 under four widely recognized climate scenarios. We find that the significant increase in RE demand driven by the ambitious 2050 global wind-power targets cannot be achieved without 11- to 26-fold expansion in the RE production. Material recycling and efficiency, production expansion, and technical innovation are promising for alleviating RE supply shortages in the long term. However, the existing global RE supply structure, along with the intensifying geopolitical and environmental constraints, could inhibit the rapid expansion of wind power, which calls for global cooperation to foster a sustainable and responsible RE supply chain.

INTRODUCTION

Wind power is widely accepted as one of the future alternatives for fossil fuels and to combat climate change.[1,2] Faced by increasingly disruptive climate, the world needs to accelerate its pace and geographic scale in wind-turbine installation.[3] Such ambitious targets have been made in various international and national roadmaps for wind-power development. In particular, the International Energy Agency (IEA) estimated that by 2050, global wind installations will reach 2,870 GW (gigawatt),[4] about five times the total capacity in 2018 (592 GW).[5] From a regional perspective, as the two largest global electricity consumers, China has announced its ambitious goal of 17% of its electricity from wind power by 2050,[6] and the United States has an even higher target of 35% by then.[7] Some nations in Africa and South America also aim to have a high share of electricity generation from wind. For example, Uruguay has set a target of 30% of electricity supply from wind energy.[8]

However, these ambitious goals cannot be achieved without the large deployment of high-performance onshore and offshore wind turbines, which heavily rely on critical minerals, particularly rare-earth elements (REs) (mainly neodymium [Nd], praseodymium [Pr], and dysprosium [Dy]), for the production of permanent magnet electric generators.[9] Those REs are critical to the efficiency and market competitiveness of wind turbines,[10] but they are relatively scarce and experiencing a vulnerable global supply chain when the whole world is relying on the production from only a few countries.[11,12] Several initial investigations have attempted to address such conflicts to meet wind-power-development targets in several countries, such as China,[13] the United States,[14,15] Denmark,[16] and Germany,[17] which all urge to incorporate RE constraint into the design of a wind-power roadmap. For instance, Fishman and Graedel found that there will be a shortage of Nd for the delivery of United States offshore wind-power targets even if the REs in retired turbines are well recycled.[14] Such RE mineral constraints could be more severe for global wind expansion.[18,19] Preliminary investigations have emerged in several system-wide studies focusing on the entire global energy system.[20–22] However, there is a lack of dynamic, spatial, and technology-specific investigation of each region toward the designed wind-power roadmaps.

Here, we carry out a comprehensive evaluation of whether the supply of REs can keep up with global wind-power pathways as required by different climate targets, in which specific factors from regional (i.e., ten specific regions), technical (i.e., direct-drive and geared-drive permanent magnet synchronous generator technologies in onshore and offshore wind turbines), and material (i.e., production expansion, material efficiency, and recycling potentials of three types of critical REs) perspectives are considered. Our findings demonstrate that the present supply capacities of Nd, Pr, and Dy are not aligned with the required global demand under all wind-power scenarios. Strategies such as production capacity expansion, material recycling, efficiency, or substitution are promising in the long term but are inhibited by existing technical progress and policy structure.

RESULTS

Conflicts between Global Wind Power and REs

Along with the rapid expansion of wind power across the world under four scenarios (Figure 1A)—the New Policies Scenario (NPS) and 450 Scenario (450S) from the IEA and the Moderate Scenario (MS) and Advanced Scenario (AS) from the Global Wind Energy Council (GWEC) (see detailed explanations in the Experimental Procedures)—the demand for a RE portfolio (i.e., Nd, Pr, and Dy together) linked to wind turbines will increase significantly from 9.5 Gg (gigagrams) during 2011–2015 to 105.9–230.9 Gg in 2046–2050, depending on the scenarios. Moreover, offshore wind power is expected to expand rapidly, inducing an increase in its share of total wind-power-related RE demand from 2.5% in 2011–2015 to 57.0–58.8% in 2046–2050 (Table S1). Notably, the demand for Nd, the main ingredient (i.e., over 70%) of REs in permanent magnets, will reach 80.7–176.0 Gg in 2046–2050 (Figure 1B), and the demand for Pr is one-quarter of that of Nd (Figure 1C) as a result of the 4:1 ratio of Nd and Pr in the permanent magnet of wind turbines.[10,11] Compared with the demand for Nd and Pr, the demand for Dy as an additive to the magnets is projected to have a much slower increasing trend from 1.1 Gg in 2011–2015 to 6.2–13.2 Gg in 2041–2045 and then decline to 5.0–11.0 Gg in 2046–2050 as a result of improvements in the utilization efficiency of REs (Figure 1D).

We also compared future RE demand (measured as total demand in every 5-year period hereafter) driven by wind power with the present global production capacity (from 2011 to 2015) (Figures 1B–1D). Under the AS scenario, which keeps the global average temperature rise below 2°C, the amount of Nd, Pr, and Dy required for wind-turbine manufacturing will be two to four times that of their current total production capacity. Given the fierce competition with other newly emerging industries, such as electronics, electric vehicles, and industrial robots,[23,24] all of the produced REs flowing into the wind-power industry would be unrealistic, implying the future potential shortage of REs to meet the ambitious wind-power-development goals without rapid expansion of the RE production capacity. However, the observed historical average mine production growth rates of Nd, Pr, and Dy remained at an extremely low level during 1998–2016[25] because of environmental and geopolitical constraints. Thus, meeting the 11- to 26-, 11- to 26-, and 7- to 12-fold expansion ratios of the required Nd (total demand in 2046–2050), Pr (total demand in 2046–2050), and Dy (total demand in 2036–2040) associated with wind-power development to that in 2011–2015 would be challenging (see Tables 1 and S2–S6).

Regional Disparities in Wind Power and RE Supply

At the regional level, our results show that China's demand for REs will be the largest (over one-third of the global total) under all four wind-power scenarios given its leading position in projected installation capacities (Figure 1A). China's cumulative demand for REs is estimated to be in the range of 159.8–357.2 Gg (53.1%–54.2% for offshore wind power) during 2021–2050, including 118.0–264.2 Gg for Nd (Figure 2A), 29.5–66.0 Gg (Figure 2C) for Pr, and 12.3–27.0 Gg (Figure 2E) for Dy. Moreover, China, endowed with abundant RE minerals (37% of global reserves in 2018),[26] is also the only country with a complete RE supply chain from mineral mining to magnet production.[27] Nevertheless, China's wind-power deployment could still face a RE shortage posed by its production quota[28] given that the production capacity of REs in 2046–2050 must be expanded by 6–15 times their production level in 2011–2015 (Tables 1 and S2–S6) to meet its wind-power targets.

As the second-largest consumer of REs related to wind power, OECD Europe will require 89.7–106.4 Gg of Nd, 22.4–26.6 Gg of Pr, and 9.5–11.5 Gg of Dy, accounting for 16.0%–26.5% of the global total. In particular, the RE requirement in offshore wind power will reach 72.1–83.9 Gg, accounting for approximately 60% of the total wind-power-related REs in OECD Europe. OECD Europe is an early adopter and leader in RE-related wind-turbine technologies.[9] However, this region has a limited amount of RE reserves and very low production capacity, making the region highly dependent on the import of REs (especially from China) and their related products for their wind-turbine production.[29]

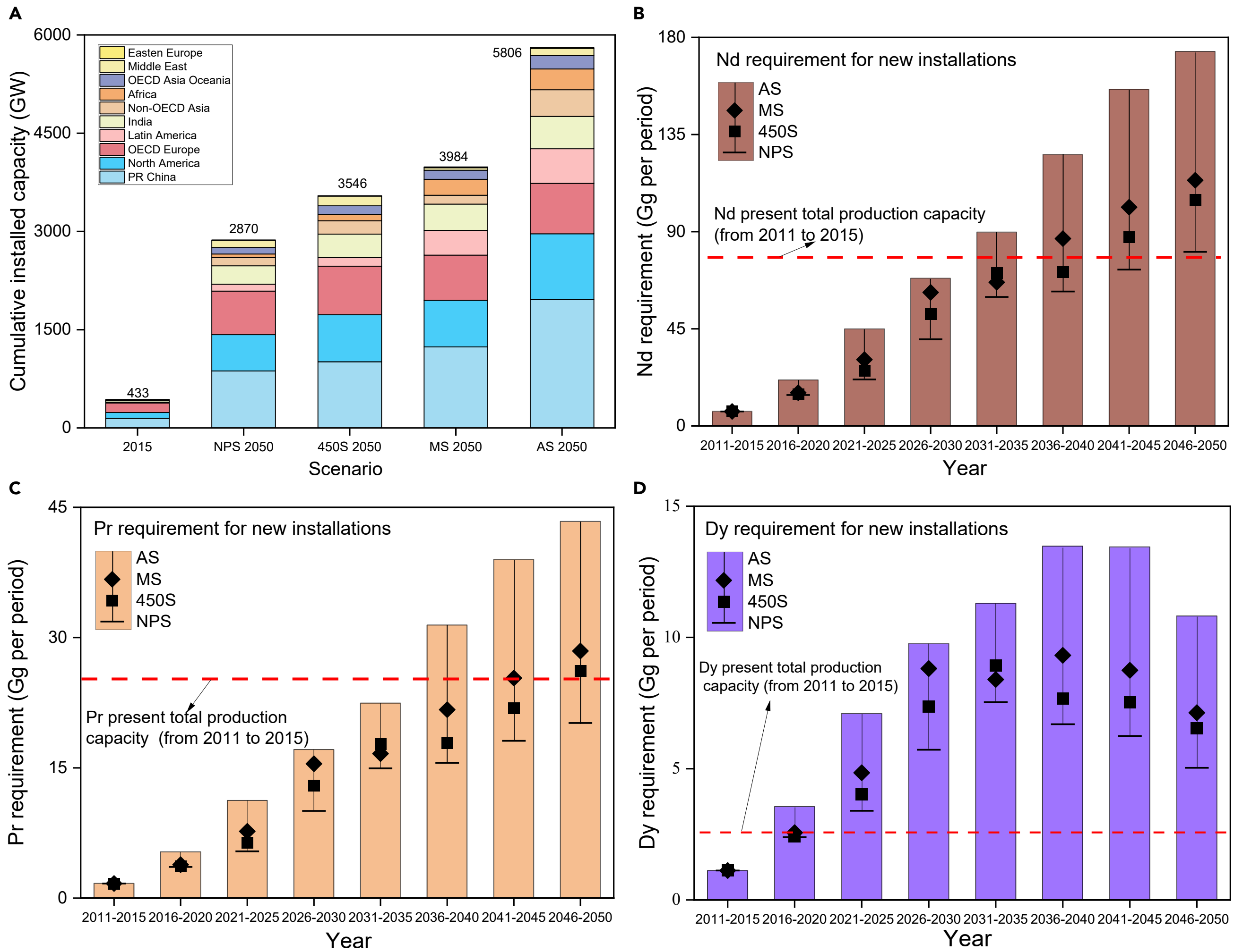


Figure 1. Global Cumulative Installed Capacity and RE Demand Associated with Wind-Power Development

(A) Global cumulative installed capacity for the years 2015 and 2050 in the IEA New Policies Scenario (NPS), IEA 450 Scenario (450S), GWEC Moderate Scenario (MS), and GWEC Advanced Scenario (AS).

(B–D) Global demand trend (total amount in every 5-year period) of (B) Nd, (C) Pr, and (D) Dy associated with wind-power scenarios. Note that because opening a new mine or adjusting production capacity requires a long time period (around 5–10 years),[21] we compare the future trends on an every-5-year basis rather than an annual basis to better guide future mineral and energy planning.

Given that offshore wind technology is more reliant on REs, the wind-power pathway chosen by OECD Europe will face a higher risk of RE shortage.

RE consumption by North America and India will amount to 67.2–121.9 and 46.2–79.2 Gg, respectively, together accounting for 22%–25% of the global total. These two regions also lack enough RE mineral reserve and production capacity to support their local wind-power deployment (Figures 2B, 2D, and 2F). The Nd, Pr, and Dy supply would need to be expanded by 16–82 times through 2050 to keep pace with the regional corresponding wind-power targets (Tables 1, S2, and S3). In particular, RE minerals in these two regions are characterized by high Nd and Pr content yet very low Dy content (Figure 2). Therefore, Dy could be the most critical metal affecting wind-power deployment in North America and India. In particular, their wind-power pathways are more reliant on onshore wind farms, and approximately 60% and 70% of RE consumption are associated with onshore wind power in North America and India, respectively.

OECD Asia Oceania, non-OECD Asia, Latin America, and Eastern Europe own higher RE reserves but consume fewer RE minerals than OECD Europe (Figure 3). More specifically, RE demand for each of these four regions accounts for less than 4% of the global total. It should be noted that OECD Asia Oceania (Australia mainly) has abundant RE minerals (e.g., 528 Gg of Nd and 145 Gg of Pr in their reserve), which can support approximately 23–53 times more than their required demands. However, this region's Dy reserve is very low (Table S3), which meets only around —three to seven times its demand requirement (1.1–2.2 Gg) (Figure 2E), indicating that OECD Asia Oceania could fail to meet its wind-power-development requirements as a result of the Dy supply constraint. Non-OECD Asia, with abundant RE minerals, will consume many fewer REs than it can provide, making it one of the most significant RE suppliers in the global wind-power market.

Table 1. The Reserve, Production, Demand, and Required Supply Expansion Ratio of Nd

Region	Nd in RE Reserve (Gg)	Total Production Capacity in 2011–2015 (Gg)	Cumulative Nd Demand in 2021–2050 (Gg)				Expansion Ratio[a] of the Required Nd Demand Associated with Wind Power in the Future to That of 2011–2015			
			NPS	450S	MS	AS	NPS	450S	MS	AS
World	16,575.5	77.8	339.7	415.0	465.1	668.0	2–11	2–16	2–17	2–26
North America	140.4	1.2	49.7	63.5	63.9	90.2	4–43	3–60	4–55	5–83
Latin America	3,488.0	0.2	9.1	11.1	34.3	45.8	2–12	2–16	2–49	2–73
OECD Europe	0.0	0.0	89.7	98.7	94.2	106.4	6–21	6–24	6–21	6–24
Africa	0.0	0.0	4.8	8.4	21.4	27.5	2–34	2–62	3–164	3–216
Middle East	0.0	0.0	9.0	12.7	3.2	8.7	6–4,201	7–4,812	5–1,400	6–3,904
Eastern Europe	1,542.6	1.1	0.3	0.6	1.0	1.3	1–13	1–29	1–54	1–70
India	1,182.7	1.6	34.1	43.9	46.1	58.6	2–14	2–19	2–22	2–27
Non-OECD Asia	3,017.0	0.3	13.8	23.1	14.1	42.8	14–259	15–425	13–306	15–944
People's Republic of China	6,676.6	70.5	118.0	138.1	172.1	264.2	1–6	1–7	1–8	1–15
OECD Asia Oceania	528.3	3.0	11.2	14.7	14.8	22.5	1–19	1–26	1–29	1–42

The total production capacity is the total Nd production during the past 5 years that supplied all end-use applications (electric vehicles, catalyst, ceramics, etc.), whereas our estimated future required supply of Nd considers only the portion for wind power. Because opening a new mine or adjusting production capacity requires a long time period (around 5–10 years),[21] we compare the future trends on an every-5-year basis rather than annual basis to better guide future mineral and energy planning. The results for Pr and Dy are given in Tables S2 and S3, respectively. Additionally, the expansion ratio refers to the following: expansion ratio = material demand (n^{th} period)/material demand (first period: 2011–2015), where n means the periods 2016–2020, 2021–2025, …., and 2046–2050. Material demand (n^{th} period) is the cumulative material demand in every 5-year period.
[a]The range of the expansion ratio covers the period of 2016–2050.

For each scenario, Eastern Europe's demand for Nd, Pr, and Dy accounts for only 0.1% of their reserves (1,543 Gg for Nd, 497 Gg for Pr, and 63 Gg for Dy) (Figure 2). Thus, Eastern Europe might be able to become a potential source of REs to sustain global wind-power development. However, for Africa, it is very challenging to meet the wind-power targets because of its poor RE mineral endowment and lack of trade connection to those suppliers.

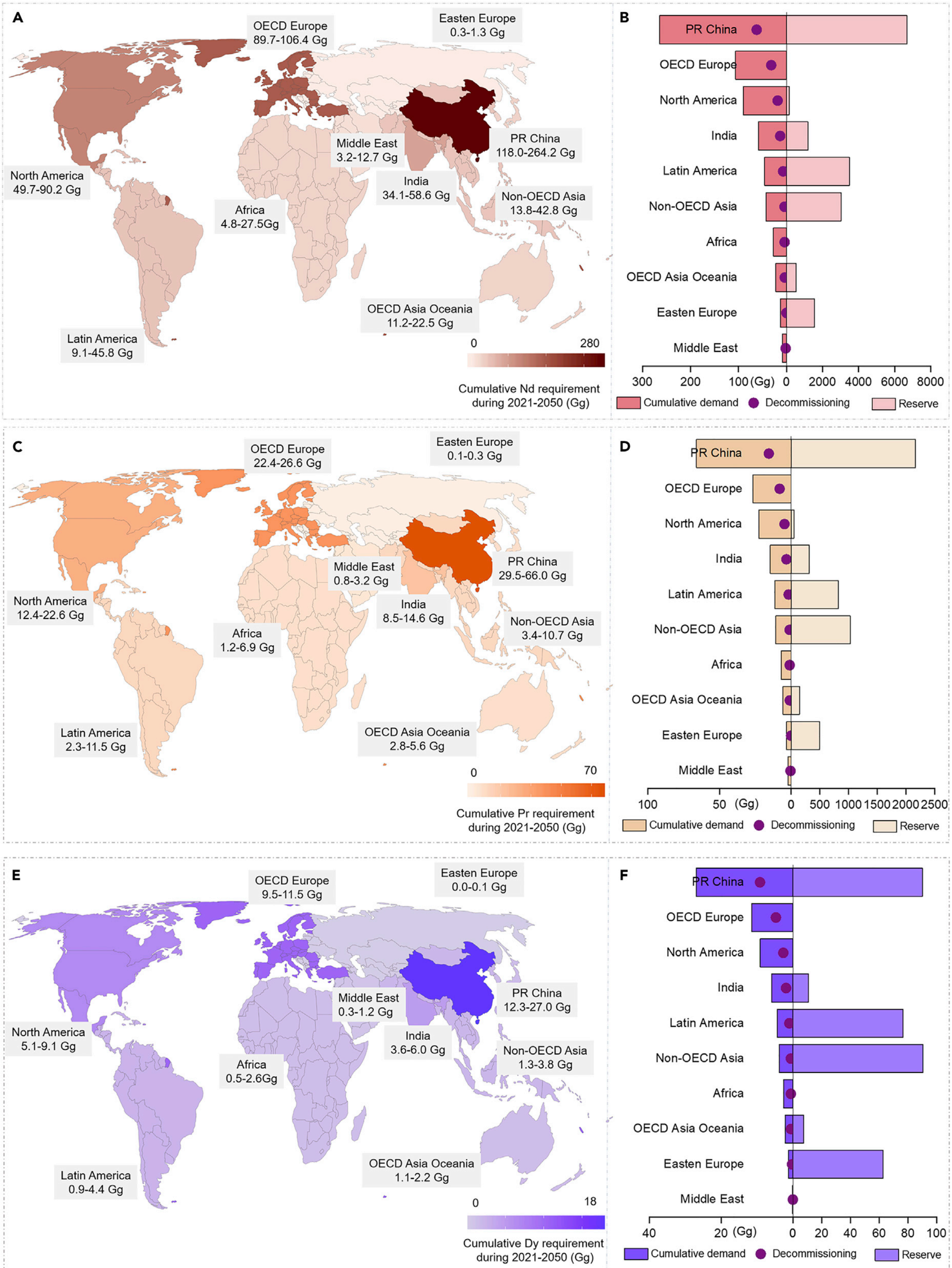
DISCUSSION

Model Validation and Sensitivity Analysis

The economy-wide approach and technology-specific approach are popular approaches to estimating and projecting the demand for materials or minerals related to the transition to a low-carbon energy system. The economy-wide approach, such as the input-output-based life-cycle analysis in de Koning et al.,[21] focuses on the entire economic system and estimates the material demand associated with the social-economic transition. Thus, this approach can help to provide an aggregative quantification of the amount of materials required by the entire sector but fails to uncover the dynamics of infrastructure installation, operation, and decommission according to specific wind-power targets. By contrast, the technology-specific approach (i.e., dynamic material flow analysis)[14] offers a dynamic, technology-rich, and regional-specific framework for tracing the flows of metals directly used by different wind-turbine technologies, and for this reason we selected this approach in our study. By using the technology-specific modeling framework, we can incorporate various technical parameters such as the lifetime of the wind turbine, regional market shares of wind-turbine technologies, and material intensity of different wind-turbine technologies to estimate RE demand.

Similar to other studies,[14,16] our predictions on future wind-power development and its corresponding RE demand are subjective to the scenario assumptions and model uncertainty. To validate the dynamic material-flow-analysis model we used in this study, we collected and reviewed all relevant studies in Table S7 to compare results, and we found that our estimated global Nd demand is consistent with most previous studies (Figure S1). Nevertheless, this study should not be considered an actual estimation but rather a forward-looking analysis of potential trends to urge current actions. Moreover, we performed a sensitivity analysis (i.e., NPS scenario as a proxy and extension of the NPS scenario into four "sensitivity analysis" scenarios, including a base scenario, a high-material-intensity scenario, a high-geared scenario, and a high-lifespan scenario). Their detailed settings are shown in Table S8, and the results are shown in Figures S2–S12, which show that the future RE demand is very sensitive to the market share and material intensity of wind-turbine technologies. For example, the reducing market share of permanent magnet synchronous generators (PMSGs) (high-geared scenario versus base scenario) will significantly decrease global RE demand (total demand in 2021–2050) by 57%–58% (i.e., 58% for Nd, 58% for Pr, and 57% for Dy). Besides, if the material intensity of the same wind-turbine technology remains constant over time (high-material-intensity scenario versus base scenario), the global wind-power industry's cumulative Nd, Pr, and Dy demand in 2021–2050 will increase by 22%, 22%, and 97%, respectively (Figure S2).

In addition, we do not consider the competition from other emerging technologies, such as electric vehicles, on RE demand. This study is a material-based estimation that does not consider the constraints from geopolitical, technical, or environmental factors, which are discussed in the following sections.



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More Stringent Constraints in China's RE Supply

China's current domination in global RE production will undoubtedly affect the future market stability of REs for wind power. Implementation of any domestic RE policies in China could have a significant impact on the global RE supply chain. China has treated REs as a strategic resource and has imposed restrictions on the production and trade of REs since the 2000s (and the trade quota was abandoned after 2015).[30,31] These policy reinforcements immediately led to a substantial decline in the amount of REs exported from China to the international market. In particular, China blocked the export of its RE products to Japan, causing a price spike and global panic between 2010 and 2011.[32] The recent trade disputes between the United States and China could also induce large uncertainties in global RE supply and hinder the designed expansion of global wind power. Meanwhile, the Chinese government is expected to impose more stringent environmental restrictions to internalize environmental costs into RE production.[12] Moreover, there will also be rapid growth in electric vehicles, electric motors, and consumer electronics in China, increasing the competition for REs.[24] Thus, the global wind-power ambitions could potentially face more severe RE constraints than our result indicated.

Challenges in Diversifying Global RE Supply

RE reserves are not all located in China but are unevenly distributed across the globe. Countries such as Australia and Russia are also rich in RE reserves.[26] However, a lack of mature electrolysis (i.e., deoxidizing RE oxides into pure metals) and technologies for the disposal of radioactive waste (controlling the spread of radioactive pollutants in wastewater, waste gas, and tailings to the environment) to meet environmental standards prevent RE production in these countries.[33] For example, Molycorp, the only United States producer at the time, was forced to close as a result of water leakages containing radioactive waste in 2002.[34] Australia's Lynas Corporation, one of the largest suppliers outside China at present, operates its RE refinery in Malaysia. This plant now faces closure as a result of rising public awareness of the treatment of radioactive waste.[35] Evidence shows that global RE supply is locked by green processing technology, indicating that nations with abundant RE reserves and high wind-power ambition need to strengthen the development of green production technology to establish a responsible and sustainable RE supply chain.[36]

Challenges in RE Recycling and Efficiency Improvement

REs are considered protected and strategic mineral resources by some governments because of their non-renewability and preciousness properties, which makes it difficult to significantly expand the short-term output of REs. In response to the RE bottlenecks for the future deployment of wind power, it is critical to determine additional sources for REs other than exploiting mines. The secondary supply of REs from retired wind turbines has the potential to reduce the RE supply deficit. The lifespan of a wind turbine is usually 20 years,[14] which means that in 2040 there will be a ramp up of decommissioned RE magnets from the recently installed wind turbines. As shown in Figure 3, the annual amounts of recyclable REs Nd, Pr, and Dy from decommissioned wind turbines between 2021 and 2050 will increase from about 0.06, 0.02, and 0.01 Gg to 8.9–16.1, 2.2–4.0, and 1.2–2.1 Gg, respectively. More importantly, we found that the annual decommissioning amount of Dy will exceed the annual demand under NPS by the end of 2050 (Figure 3I). Over the next three decades, if all decommissioned REs are recycled and reused, 22.1%–25.9% of Nd demand (88.1–146.7 Gg), 22.1%–25.9% of Pr demand (22.0–36.7 Gg), and 31.8%–37.1% of Dy demand (13.0–21.4 Gg) could be met (Table S9). However, RE recovery still faces challenges such as the collection of the RE permanent magnets used in offshore wind turbines, a significant loss of REs during remelting and recasting, and high recycling costs.[37] More efforts need to be exerted into the centralized recovery of retired wind turbines and the development of technologies that have lower costs and higher recovery rates.

Increasing the material efficiency of REs in wind turbines is another promising option that can potentially reduce the use of REs. Assuming there is no technological advancement in the material efficiency of REs through 2050 (high-material-intensity scenario versus base scenario), the cumulative requirement of Nd, Pr, and Dy in the wind-power industry in 2021–2050 would increase by 22%, 22%, and 97%, respectively (Figure S2). However, with the current technologies, the improvement in RE efficiency remains challenging. Fortunately, several manufacturers have taken a series of substitution measures to reduce the dependence of wind turbines on REs, including material substitution for REs and component substitution for PMSGs.[38] These alternatives could reduce the future RE demand for wind-power development but at the cost of performance losses.

Renewable Expansion Calls for Global Cooperation

Adjusting wind-power-development goals and replacing wind power with other technologies that generate renewable energy can also help to reduce RE dependence. However, these other technologies are also subject to relevant environmental and resource constraints.[39,40] For example, the shortages in the supply of crystalline silicon can be a bottleneck in photovoltaics technology.[41] Thus, such mineral constraints also apply to solar power, electric vehicles, and other emerging sustainable technologies,[42] which calls for integrated investigations of minerals, energy planning, and climate mitigation to avoid burden shifting.

Notably, the aforementioned strategies—the expansion of production capacity, material recycling, efficiency, or substitution—cannot be significantly improved in the short term because

Figure 2. Cumulative Demand and Decommissioning Flows of Nd, Pr, and Dy in Ten Regions during 2021–2050 Related to Regional Reserves of Nd, Pr, and Dy

(A) Cumulative Nd requirement.
(B) Nd demand, decommissioning amounts, and reserve.
(C) Cumulative Pr requirement.
(D) Pr demand, decommissioning amounts, and reserve.
(E) Cumulative Dy requirement.
(F) Dy demand, decommissioning amounts, and reserve.

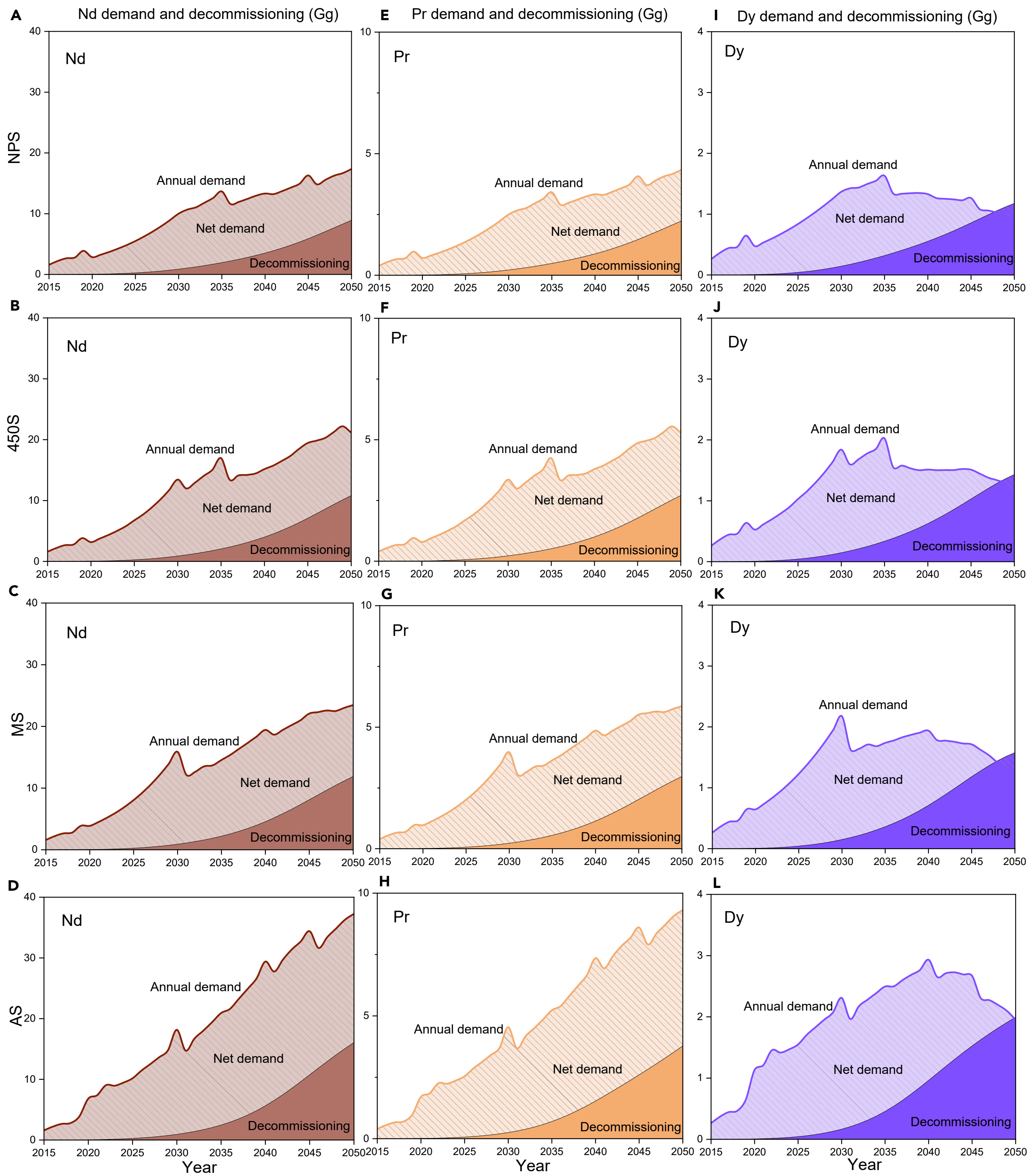

Figure 3. Comparison of RE Annual Demand and Decommissioning Flows in the Wind-Power Industry

(A–D) Nd in the (A) NPS, (B) 450S, (C) MS, and (D) AS scenarios.

(E–H) Pr in the (E) NPS, (F) 450S, (G) MS, and (H) AS scenarios.

(I–L) Dy in the (I) NPS, (J) 450S, (K) MS, and (L) AS scenarios.

REs in decommissioning wind turbines are widely considered one of the most important sources for meeting RE future demand in regions without primary production capacities. Thus, we present our results on an annual basis to better illustrate the trend of increasing decommissioning flows and the narrowing gap between RE demand and decommissioning flows.

of technical and political constraints. For instance, the decommissioning of REs will become available for recycling at a substantial scale only after 2040 in all scenarios. The expansion of RE mineral production in or outside China can lag around decades,[21] but such a decision is quite sensitive to the present mineral market. At present, concerns about global competition of these critical and strategic minerals are intensifying.[43] Given that climate change is affecting the globe as a whole, global responses are needed to balance the regional disparity in renewable and mineral endowments and to spur technical innovation and diffusion in mineral production and renewable generation. Thus, there should be an urgent need for international cooperation, rather than competition, with regard to REs as well as other critical minerals across national borders.

EXPERIMENTAL PROCEDURES

Resource Availability

Lead Contact

Further information and requests for resources should be directed to and will be fulfilled by the Lead Contact, Kuishuang Feng (fengkuishuang@gmail.com).

Materials Availability

This study did not generate new unique materials.

Data and Code Availability

The data on the four wind-power scenarios (NPS and 450S from the IEA and MS and AS from the GWEC) were obtained from Global Wind Energy Outlook.[4] The data on historical market share of direct-drive and geared-drive permanent magnet generators were obtained from the Joint Research Centre of the European Commission (Tables S10 and S11).[44] The data on historical rare-earth oxide (REO) production and reserves were published by the United States Geological Survey.[26] The material coefficients for different types of wind-turbine technologies, such as the amount of Nd, Pr, and Dy required per unit of wind-power capacity, are summarized in Table S12. The data and code are available for academic use at http://dx.doi.org/10.17632/zdgtky97cz.5.

Model Description

We developed a bottom-up, dynamic, technology-rich, and regional-specific model based on a dynamic material-flow analysis[14,45] to explore RE flows and stocks in each of ten regions' wind-power pathways under global climate scenarios. This model covers four wind-power scenarios (NPS, 450S, MS, and AS) and three types of REs (Nd, Pr, and Dy) and incorporates the technical innovation of direct-drive and geared-drive permanent magnet technologies in onshore and offshore wind turbines into our analysis for future projection from 1990 to 2050.

Four Wind-Power Scenarios

The four wind-power scenarios (the IEA's NPS and 450S and the GWEC's MS and AS) were derived from the latest GWEC report,[4] in which the global wind-power targets were divided into ten different regions: the People's Republic of China, OECD Europe, North America, India, non-OECD Asia, the Middle East, OECD Asia Oceania, Latin America, Africa, and Eastern Europe. AS has the most ambitious scenario, in which the global cumulative wind-power installed capacity will reach 5,806 GW and contribute 36% (207,879 TWh) of the global electricity generation by 2050 to keep global temperature rise below 2°C above the pre-industrial level. Following AS, the global wind-power installation targets under MS and 450S are 3,984 and 3,546 GW, respectively. NPS assumes that the whole world will continue with the current energy and climate policies; consequently, the wind-power target under this scenario is the most conservative at just about half of that in AS. Notably, there is a sudden drop in wind-power deployment from 2030 to 2031 under the AS scenario. As mentioned previously, the AS scenario is an externally taken scenario designed in the Global Wind Energy Outlook[4] to show the most ambitious climate-mitigation pathway. However, the scenario setting of this study starts from the year 2019, when the wind-power installed capacity was smaller than that under the projection of AS scenario. That is to say, to meet the designed capacity target in 2030, the future path of new capacity installment will be more radical to follow that of the AS scenario. This has induced market plummeting. Hence, our study should be considered an explorative estimation rather than an actual projection, and the results of single years should be applied with caution. More details about the four scenarios can be found in the Global Wind Energy Outlook.[4]

Simulation of Wind-Power Installed Capacity

We adopt the dynamic material-flow-analysis model to estimate the annual installations and decommissioning of wind-power capacity, which involves three key parameters—stock, inflow, and outflow—to represent the accumulation of, newly added, and the decommissioning of wind-power installed capacity, respectively. First, the outflow is quantified according to the historical inflow and wind turbines' lifetime:

$$\text{outflow}_{\text{MW}}(t_n) = \sum_{t_0}^{t_{n-1}} \left(\text{inflow}_{\text{MW}}(t_i) \times [\text{survival}(t_{i-1} - t_0) - \text{survival}(t_i - t_0)]\right), \quad \text{(Equation 1)}$$

where the outflow in t_n ($\text{outflow}_{\text{MW}}(t_n)$) is the sum of decommissioning of past inflow vintages t_i from t_0 to t_{n-1}. Survival(t) is the complementary cumulative distribution function of the normal distribution.[13] According to the principle of conservation of mass, the inflow ($\text{inflow}_{\text{MW}}(t_n)$) must equal a combination of the changes of stock ($\text{stock}_{\text{MW}}(t_n) - \text{stock}_{\text{MW}}(t_n - 1)$) and all outflow during this period:

$$\text{inflow}_{\text{MW}}(t_n) = \text{stock}_{\text{MW}}(t_n) - \text{stock}_{\text{MW}}(t_{n-1}) + \text{outflow}_{\text{MW}}(t_n). \quad \text{(Equation 2)}$$

RE Flow in the Wind-Power Industry

With the simulated new installation of capacity ($\text{inflow}_{\text{MW}}(t_n)$), annual RE demand by the wind-power industry ($\text{inflow}_{\text{REs}}(t_n)$) is quantified by multiplying the market share of direct-drive train ($\text{market}_{\text{D}}(t_n)$) or geared-drive train ($\text{market}_{\text{G}}(t_n)$) PMSGs (Table S13) and material coefficient ($\text{coe}_{\text{D}}(t_n)$ or $\text{coe}_{\text{G}}(t_n)$) (Tables S12 and S14):

$$\text{inflow}_{\text{REs}}(t_n) = \text{inflow}_{\text{MW}}(t_n) \times [\text{market}_{\text{D}}(t_n) \times \text{coe}_{\text{D}}(t_n) + \text{market}_{\text{G}}(t_n) \times \text{coe}_{\text{G}}(t_n)]. \quad \text{(Equation 3)}$$

The $\text{outflow}_{\text{REs}}(t_n)$ is determined by the historical inflow and wind turbines' lifetime:

$$\text{outflow}_{\text{REs}}(t_n) = \sum_{t_0}^{t_{n-1}} \left(\text{inflow}_{\text{REs}}(t_i) \times [\text{survival}(t_{i-1} - t_0) - \text{survival}(t_i - t_0)]\right). \quad \text{(Equation 4)}$$

Global RE Mineral Endowments

Notably, the REs mentioned in the production are the sum of 17 different REs in the form of REOs. Given that wind-power turbines use only three types of REs (Nd, Pr, and Dy), here we further refine these three REs' production data by the following equation:

$$R_{m,k} = \sum_j F_m T_{m,j} P_{j,k}, \quad \text{(Equation 5)}$$

where $R_{m,k}$ is the present production capacity of RE m (Nd, Pr, or Dy) in year k, F_m is the RE or REO atomic weight fraction for element m, $T_{m,j}$ is the fraction of element m in the ore of mine j (Table S15), and $P_{j,k}$ is the RE mineral production of mine j in year k. Because about 30% of the RE content of ores is lost to the production stage,[46] calculating $R_{m,k}$ permits processing losses to be estimated as well.

The equation of estimate reserve amount of REs (Nd, Pr, or Dy) is as follows:

$$\text{reserve}_m = \sum_j F_m T_{m,j} G_j, \quad \text{(Equation 6)}$$

where G_j is the RE mineral reserve of mine j.

SUPPLEMENTAL INFORMATION

Supplemental Information can be found online at https://doi.org/10.1016/j.oneear.2020.06.009.

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AUTHOR CONTRIBUTIONS

J.L., K.P., K.F., D.G., and N.Z. designed the research. J.L., J.M., P.W., W.W., and Q.Y. conducted the analysis. J.L., K.P., P.W., K.F., D.G., and N.Z. led the drafting of the manuscript. All authors contributed significantly to the final writing of the article.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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