Environmental Science & Technology

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Evaluating Rare Earth Element Availability: A Case with Revolutionary Demand from Clean Technologies

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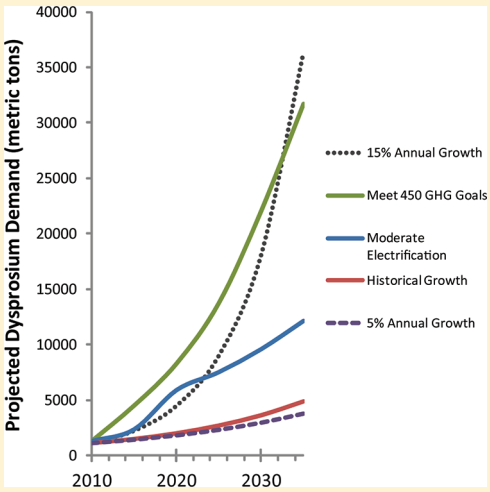
Supporting Information

ABSTRACT: The future availability of rare earth elements (REEs) is of concern due to monopolistic supply conditions, environmentally unsustainable mining practices, and rapid demand growth. We present an evaluation of potential future demand scenarios for REEs with a focus on the issue of comining. Many assumptions were made to simplify the analysis, but the scenarios identify some key variables that could affect future rare earth markets and market behavior. Increased use of wind energy and electric vehicles are key elements of a more sustainable future. However, since present technologies for electric vehicles and wind turbines rely heavily on dysprosium (Dy) and neodymium (Nd), in rare-earth magnets, future adoption of these technologies may result in large and disproportionate increases in the demand for these two elements. For this study, upper and lower bound usage projections for REE in these applications were developed to evaluate the state of future REE supply availability. In the absence of efficient reuse and recycling or the development of technologies which use lower amounts of Dy and Nd, following a path consistent with stabilization of atmospheric CO_2 at 450 ppm may lead to an increase of more than 700% and 2600% for Nd and Dy, respectively, over the next 25 years if the present REE needs in automotive and wind applications are representative of future needs.



INTRODUCTION

Increasing concerns about the environmental impacts and reliability of supply of fossil fuels are motivating a global drive toward introduction of emerging technologies such as photovoltaics, fuel cells, and wind turbines. However, the availability of materials required for these technologies is a source of concern.[1−8] The adoption of new technologies can lead to rapid changes in materials demand. Historically, new, or "revolutionary", changes in demand for materials have led to market instability and price spikes.[9,10] For example, the platinum market experienced a surge when three-way catalytic converters were adopted by the automotive industry to meet environmental regulations requiring emissions controls.[11,12] Market instability is detrimental to manufacturers that depend upon a reliable supply of materials and can deter the introduction of new technologies.[9] The implications of revolutionary demand for materials cannot be understood from historical ("evolutionary") demand information alone.[9]

Rare earth elements (REEs) have recently received much attention regarding the reliability of their supply.[13,14] The International Union of Pure and Applied Chemistry (IUPAC) defines the rare earth metals as a group of 17 elements consisting of the 15 lanthanoids [La, Ce, Pr, Nd, *Pm*, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu] plus Sc and Y.[15] Data are mainly available for only 10 of the 17 elements, and therefore the following analysis focuses on these: La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, and Y. The commercial significance of REEs is not reflected in the volume in which they are used; their annual primary production tonnage is approximately 2 orders of magnitude less than copper and 4 orders of magnitude less than iron.[16] REEs are important because they provide critical functionality in a wide variety of applications[17] and are used in relatively large amounts in key technologies being developed to provide sustainable mobility and energy supply.[18]

Unfortunately, the availability of REEs appears to be at risk based on a number of factors. Of particular significance, one country (China) controls 98% of current supply (production).[13,19] Historically, much lower levels of market concentration have harmed manufacturing firms. For example, in 1978 Zaire controlled 48% of the cobalt supply and yet political unrest in Zaire resulted in a disruption to global supply that became known as the "Cobalt Crisis".[20−22] Another contributor to supply risk for REEs is the fact that they are comined;

Received: October 4, 2011
Revised: January 6, 2012
Accepted: February 3, 2012
Published: February 3, 2012

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individual REEs are not mined separately. REEs are found together in geological deposits, rendering mining of individual elements economically inefficient. The supply of any individual REE depends on the geology of the deposits, the costs of the extraction technology employed, and the price of the basket of rare earths (RE). Finally, REEs have come under global scrutiny due to the environmental and social conditions under which they are mined, further increasing their supply risk.[23−25]

The literature contains a number of reports that evaluate different aspects of RE availability. The USGS has published detailed reports on RE resources.[18,26,27] Industry reporting has focused on projected demands for REEs, with a focus on the political efforts in China to limit exports.[28−30] Recent material flow analysis by Du and Graedel[17,31] have quantified global secondary resources for possible future recycling of REE. They evaluated REE flows through end-use products such as computers and automobiles to estimate both REE stocks and flows. A number of reports have highlighted the political implications of high geographic concentration of RE production.[13,23,32,33] Finally, a number of materials survey studies have identified REEs as having high risks.[6,34,35]

In the present work, we evaluate future potential demand scenarios for REEs with a focus on the issue of comining. REE demand scenarios are presented and compared to past demand, estimated future production, and known resources. In particular, resource requirements for electric vehicles and wind turbines (revolutionary demand areas for REEs) were estimated from performance specifications and vehicle sales or turbine deployment projections. Future demand is estimated for a range of scenarios including one developed by the International Energy Agency (IEA) with adoption of electric vehicles and wind turbines at a rate consistent with stabilization of CO_2 in the atmosphere at a level of 450 ppm.[36,37]

The present work is a top-down analysis of RE flows which complements previous analyses.[17,31] We present a detailed analysis of the implications of comining of REEs on future REE availability and the first projections of REE demand where revolutionary and evolutionary demand are explicitly considered. Finally, we describe several RE demand estimates spanning a range of conservative to aggressive demand scenarios that provide lower and upper bounds on expected global RE demand. The present work had two goals: (1) identify the conditions where REEs may experience unprecedented demand growth, and (2) assess the implications of comining on RE availability under rapid demand growth in specific industries

■ MATERIALS AND METHODS

To evaluate future RE availability, a set of demand projections was developed and compared to production and reserve statistics and projections. The projection scenarios were developed to present a range of potential REE demand levels for the next 25 years. In particular, the scenarios were designed to identify evolutionary (historical) versus revolutionary (new-technology) demand trends for REs. The implications of some of the present assumptions about future technologies and growth paths for REE demand are quantified. This Malthusian evaluation of market balance is a preliminary step for understanding potential risks for scarcity.

Estimating Supply and Demand for Rare Earth Elements and Oxides. The models used here for calculating production (supply) and consumption (demand) and for transforming oxide to elemental mass are presented as follows. We define the following variables: S_i = production of REO in a mine, for each ith mine (supply), O_j = Oxide fraction of jth REE, f_j = mass fraction of REE in oxide for j^{th} REE, D_k = demand for REO for the kth demand category, g_k = growth rate for REO demand in the kth demand category, y = year, t = time.

$$\text{total supply of REO} = S_{\text{REO}} = \sum_i S_i = \sum_i \sum_j S_i{}^*O_{ij} \tag{1}$$

$$\text{total supply of REE} = S_{\text{REE}} = \sum_i \sum_j S_i{}^*O_{ij}{}^*f_j \tag{2}$$

$$\text{total demand of REO} = D_{\text{REO}} = \sum_k D_k = \sum_k \sum_j D_k{}^*O_{kj} \tag{3}$$

$$\text{total demand of REE} = D_{\text{REE}} = \sum_k \sum_j D_k{}^*O_{kj}{}^*f_j \tag{4}$$

Historical demand growth was estimated as an exponential growth rate that could be evaluated either for individual rare earth demand industry sectors (e.g., k = magnets or phosphors) or for aggregate global production.The growth rate for REO demand by industry, k, g_k, was estimated from recent historical data using standard least-squares regressions. A compound annual growth rate (CAGR) equation was used to calculate g_k:

$$g_{k,\text{historical}} = \left(\frac{D_{k,t=T}}{D_{k,t=0}}\right)^{(1/(y_T - y_0))} - 1 \tag{5}$$

Global growth, g_t, was estimated by CAGR and statistical regression.

Supply and demand data for REEs, and where possible, information about individual elements, were obtained from published sources. The literature data are expressed either in terms of rare earth oxide (REO) or rare earth element (REE) mass. We assumed that for each REE, the oxide mass fraction was based on a single REO molecular formula as described elsewhere.[38]

Just as each ore body has a typical REO portfolio, each demand application depends on a unique portfolio of REEs. For example, automotive catalysts primarily use Ce, while magnets use Nd, Pr, and Dy. We combined the information on market share[39] with the REO portfolios[27] to estimate the total global REE demand portfolio. Since the portfolio data did not distinguish between different applications of catalysis, we estimated that 30% of the catalyst market went to the petroleum industry, with the balance going to automotive catalysts based on U.S. average usage numbers between 1995 and 2008 from the USGS mineral commodity summaries.[16] We split the Metal Alloys demand category such that 40% of the metal alloy used went to battery applications, based on an approximation from 2006 usage numbers, with the balance going to other alloy applications.[29] Finally, for the portfolio of REEs of the market segment of "Other" applications, which accounted for 6.9% of 2008 REE demand, we selected a portfolio such that the total demand profile was representative of REE supply for 2008. This assumes that REE stockpiling in 2008 was minimal.

DEMAND SCENARIOS

Assessing future demand is inherently challenging given the evolution of underlying technological and contextual conditions. To accommodate this reality, this work explores a broad range of scenarios of future REE demand and tries to draw conclusions from the common observations that emerge from the results of these scenarios.

To construct these scenarios, we applied two methods to project potential future demand over the next 25 years. The first method, evolutionary demand growth, projects commodity demand based on historic patterns of commodity use. The second method, revolutionary technology demand growth, projects demand for products within a specific market sector, then maps that to commodity demand based on expected commodity use per product within that sector. The different scenario assumptions examined are described in Table 1.

For Scenarios A, B, and C, the demand for REO in industry k in year T is calculated as:

$$\begin{aligned} &D_{k,t=T,\text{historical/expert}} \\ &\quad = \exp((y_T - y_0)^{*}\ln(1 + g_{k,\text{historical/expert}}) \\ &\qquad + \ln(D_{k,t=0})) \end{aligned} \tag{6}$$

Total projected demand for REO in industry k is translated to demand for each REE by multiplying by the appropriate oxide fraction (O_{kj}) and elemental mass fraction (f_j). Scenarios A and B use historical trends as a predictor of future trends in RE markets and may be described as estimates for evolutionary demand growth. For Scenario C, the contribution of new technologies to growth projections is not explicitly given; rather, it is implicit in the projection which is based on expert input.[28,29] We assume that industry experts have, to some degree, considered the evolution of individual market sectors and the technologies used by those sectors including revolutionary sectors like those explored explicitly herein. As such, Scenario C is characterized as a revolutionary demand growth based projection.

In Scenarios D and E, revolutionary demand was limited to two widely discussed REE applications: automotive and renewable wind electricity generation. Other emerging clean energy applications that rely on REEs such as high efficiency lighting, solid oxide fuel cell systems, maglev trains, and electric scooters could also be considered in an analogous manner, but were outside the scope of this study, in part due to lack of data.

The IEA's Blue Map/450 Greenhouse Gas (GHG) scenario was used to evaluate aggressive RE requirements for future vehicle sales and wind energy.[36,37,40] This scenario sets out an energy pathway consistent with the goal of limiting increase in average global temperature to 2 °C. The Blue Map scenario presents a detailed scenario of vehicle sales,[37] where 80% of sales were electrified (i.e., including hybrid electric vehicles (HEV), plug-in hybrids (PHEV), and battery electric vehicles (BEV)) by 2035. In the Blue Map scenario, the wind turbine capacity additions are provided over five-year periods; we assumed that installation occurs at a constant annual rate over each five-year period.

The scenarios from Gruber et al.[8] were used to evaluate moderate revolutionary REE requirements for electric vehicles. These scenarios assume electrified vehicles increase from 6% of total vehicle sales in 2015, to 27−35% in 2035, and 35−48% in 2050.

RE demand by new technology, n, was calculated as follows:

$$\text{demand for REE} = D_{\text{REE}} = \sum_n \sum_j N_{nj} \tag{7}$$

where the nth technology is either one of the different auto technologies (gasoline, diesel, BEV, HEV...) or wind, and N_{nj} = j^{th} is the unit content of REEs per new car sold or wind turbine built in kilograms. The RE content per vehicle or wind turbine are assumed to be static. This is clearly a simplification. While it is expected that future technologies will likely improve their REE content performance, it is also expected that the number of applications that require REs, at least within a car, will also increase.

Our recent estimate of RE content in representative sedan vehicles with different electrification technologies was used in addition to the US Department of Energy (DOE) estimates for the RE content of nickel metal hydride (NiMH) batteries.[6,41] NiMH batteries were assumed for HEVs up to 2020 and all other electric vehicles were assumed to contain lithium batteries (HEVs after 2020, all BEVs, PHEVs).

The REE content of a wind turbine using a synchronous motor with a permanent magnet has been reported to be 600 kg per average 3.5MW turbine.[39] On the basis of this figure, we assume an average of 171 kg of REEs per MW of built wind capacity.[39] The portfolio of REEs in the wind turbine was assumed to follow the average magnet REE portfolio.[27] It has been reported that wind energy capacity can also be built without permanent magnet technology, if it is too costly.[4,42] The use of REEs for wind turbines could therefore also be reduced to zero. In designing Scenario E as a moderate scenario, it was

Table 1. Future REE Demand Projection Scenarios

	evolutionary demand scenarios	assumptions
A	Aggregated evolutionary demand: overall historical production (supply) rate of growth projected into future.	All RE production markets experience uniform demand growth at historical rates.
B	Disaggregated evolutionary demand: individual demand industry sector-level historical growth rates projected into the future.	Each RE consumption market experiences demand growth at its historical rate.
	Revolutionary + evolutionary demand scenarios.	
C	Implicit revolutionary demand: market reported expectations for industry sector-level growth rates are projected into the future.	Each RE consumption markets grows at rates predicted by industry experts.
D	Aggressive revolutionary demand: growth rate scenario B is supplemented with IEA Blue Map scenario for wind and automotive electrification.	Aggressive automotive electrification, all wind uses permanent magnets, other RE market demand grows at historical rates.
E	Moderate revolutionary demand: growth rate scenario B is supplemented with Gruber et al. 2−3% GDP growth automotive electrification scenario.	Moderate automotive electrification, wind does not use permanent magnets, other RE market demand grows at historical rates.

Table 2. Estimated Industry-Level Growth Rates (Per Annum) of Key RE Demand Categories[28,29]

growth rates (%)	magnets	metal alloys	catalysts	polishing	glass	phosphors	ceramics	other
scenario A: historical overall growth for 2006−2010 (USGS 2011)	3.7							
scenario B: historical by industry for 2006−2010 (Roskill 2007 and Kingsnorth 2010)	6.1	6.7	3.3	7.9	−4.1	0	6.2	−3.3
scenario C: projections used for 2010−2015 (Kingsnorth 2010)	12.5	10	4	8.5	0	8	7	7
scenario C: projections used for 2015−2035 (Kingsnorth 2010)	12.5	6	4	10	0	4.5	6	6

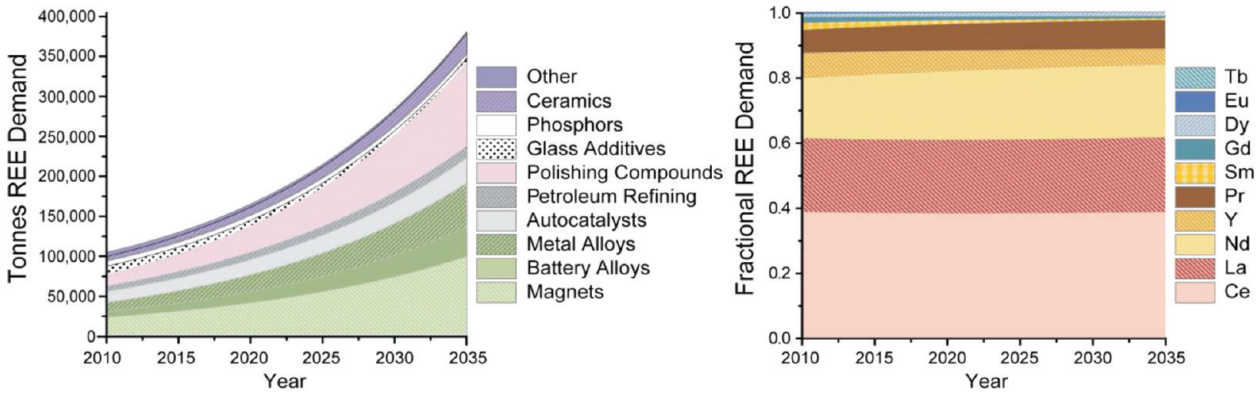

Figure 1. Scenario B, evolution of market distribution of REE demand: Totals (left) and individual REE market share (right). Average annual growth between 2010 and 2035 is 5.3%.

assumed that wind energy would use nonpermanent magnet technology.

For Scenarios D and E, total projected demand was calculated as a sum of revolutionary and evolutionary demand:

$$D_{\mathrm{REE},t=T} = D_{\mathrm{REE\ revolutionary},t=T} + \sum_k \sum_j D_{k,t=T,\mathrm{evolutionary}} {}^{*} O_{kj} {}^{*} f_j \quad (8)$$

To calculate the evolutionary demand, an estimate was made for the use of rare earths in batteries and motors in electric vehicles sold in 2010. This value was subtracted from the 2010 historical RE demand in batteries and motors, respectively, and an evolutionary growth rate was estimated from the 2006−2010 data so that evolutionary demand could be calculated using eq 6.

For calculating revolutionary demand, the requirements for vehicle electrification (e.g., electric motor, loss of catalyst for BEV) were separated from the evolutionary requirements (e.g., radio speakers). Revolutionary RE content per vehicle sold was defined as the RE content that differed from the conventional gasoline or diesel engine vehicle.

$$N_{\mathrm{revolutionary\ auto}} = N_{\mathrm{auto},n} - N_{\mathrm{conventional\ ICE\ or\ diesel}} \quad (9)$$

RESULTS AND ANALYSIS

Status of Rare Earth Market. Historically, RE production has grown rapidly to meet the upsurge in demand.[16] World production growth rate, measured between 1970 and 2010, was 5.6%. Annual growth rates, averaged over 5 year periods, have been as high as 12%, but the more recent growth rate, measured between 2006 and 2010, was only 3.7% (Table 2).

A REE demand portfolio was calculated and compared to recently published information about the flows of different REEs into use for 2007[17] and the supply distribution estimate published for 2010.[43] Our calculated portfolio and the published portfolios are within 15% for the majority of the REEs. These percentages are comparable to the differences between the published data portfolios and the projected changes that can occur over time. Given the uncertainty inherent for different sets of data, and the differences between using different approaches,[44,45] it would appear that the approach used in this work provides a good order of magnitude estimate and a reasonable comparison among different RE demand volumes.

Rare Earth Projected Growth. The annual growth rates used for Scenarios A, B, and C are presented in Table 2.

With Scenario A, all industries would maintain the same market share over time while growing at the rate of 3.7%/year. With Scenario B, modeled demand for RE grows at an overall rate of 5.3% between 2010 and 2035, which would correspond to an approximate doubling of demand between 2010 and 2025, as plotted in Figure 1. The modeled market shares of magnets and polishing compounds grow most, while those of automotive catalysts, petroleum catalysts, and glass additives shrink. However, as shown in the right-hand panel of Figure 1, despite these changes to the underlying sectoral demand, the changes to the REE portfolio are modest, with small increases in Nd, Pr, and Dy and small decreases in Y, Sm, and Gd demand.

Scenario C is based on predictions by industry insiders ("experts"). Implicitly, such predictions take into account changes in demand for goods which use REs from evolving markets including the effects of technological and materials substitution. In other words, revolutionary demand is implicitly considered in these reported growth values, but cannot be explicitly delineated. While such predictions may be more accurate in cases where historical demand patterns are not expected to be repeated, they may also reflect systematic biases. In past projections by rare earth industry insiders (covering the period from 2006 to 2010), actual average yearly growth rates were below the projected growth rates in 6 of the 8 reported sectors.[28,29]

Figure 2 shows that some within the RE industry expect magnets could grow to represent 50% of the market of rare

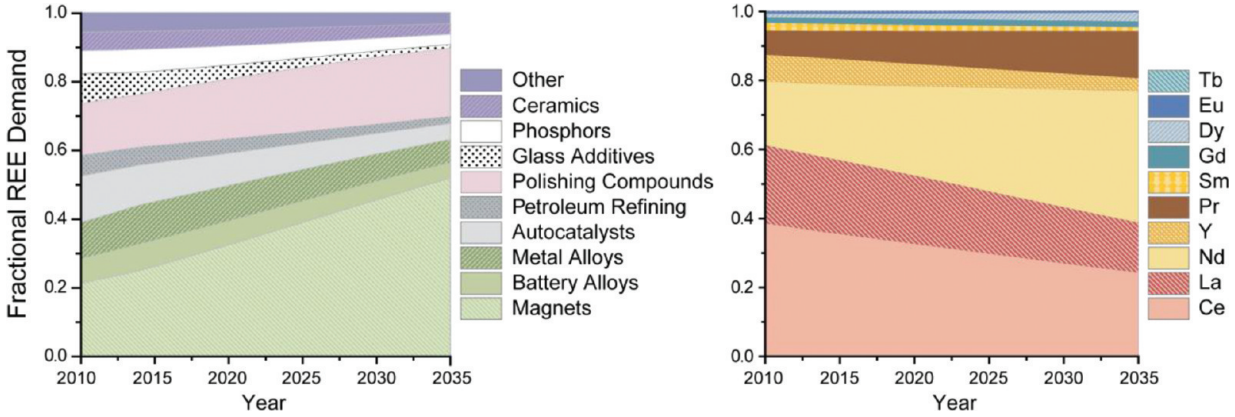

Figure 2. Scenario C, market share (Left), REE distribution (Right). Average Expert Preditions (Kingsnorth 2010) for future annual growth rates were used to project demand. Average annual growth rate between 2010 and 2035 is 8.6%.

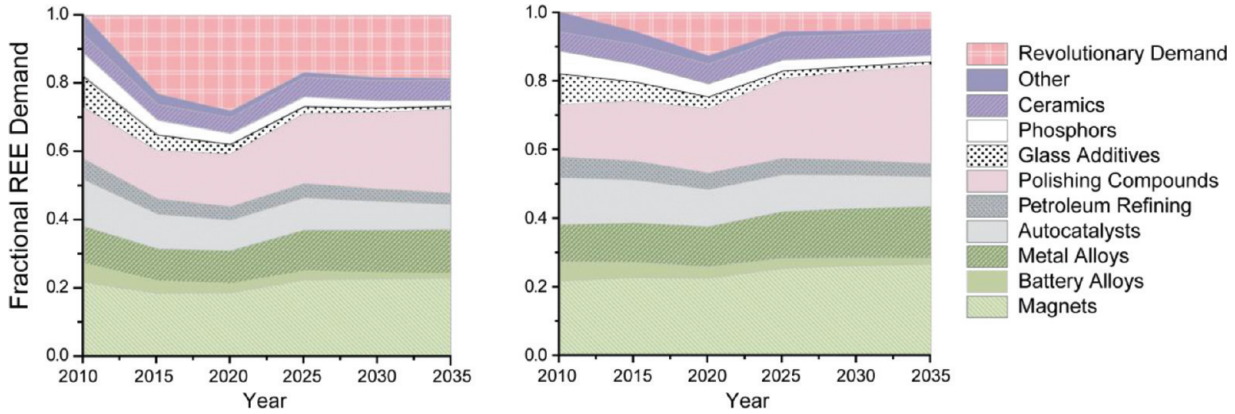

Figure 3. Scenario D (Left) and E (Right): Projected market share based on Industry-sector demand.

earths. As a result, the modeled relative demand for Ce and Y decreases while the relative demand for Dy, Nd, and Pr is expected to increase over the next 25 years. Moreover, the industry predicted growth rate is generally higher than the overall historical rates, resulting in a total projected average annual growth of 8.6% over the next 25 years.

For Scenario D, which represents an electrification strategy to meet 450 ppm CO_2 GHG goals, RE use in the revolutionary demand sectors is projected to grow to over 25% of RE demand in the short term. Modeled short-term (10 years) growth in revolutionary demand is driven by the use of REEs in NiMH batteries for HEVs, and is modeled to diminish as that technology is phased out in favor of lithium-ion batteries. In fact, it was estimated that NiMH batteries for hybrid vehicles have accounted for most of the growth in rare earth demand in the battery sector between 2006 and 2010.

When coupled with growth in the evolutionary sectors, these trends project a long-term growth rate of 5.9% per year over the next 25 years, notably, a less than 1% increase in the growth rate from historical levels (Figure 3). However, in Scenario E, revolutionary demand would account for only a small fraction of total rare earth demand, peaking at 13% of total demand before NiMH batteries are phased out.

Finally, two interesting conclusions emerge from these projections. First, the projected demand for REs for wind energy is small compared to projected demand for vehicle applications. In other words, the automotive industry is expected to be a more significant driver of the change in RE demand than wind power generation over the next 25 years. Second, the increase in demand for magnets from these wind and automotive products, especially in the case of Scenario D, results in higher ratios of Nd, Pr, and most significantly, Dy (Figure 4).

Evaluating Rare Earth Availability. To evaluate the implications of the projected demand growth for the RE market, we compare our projected demand with data on RE supply. RE primary production for 2010 was approximately 127 000 tonnes REO, which corresponds to 107 000 tonnes of RE metals.[43] The expected supply in 2015 from current mines and mines that are already being developed is 188 000 tonnes REO or 157 000 tonnes rare earth metals, an average annual increase of 8.1%. The portfolio of REEs mined is not expected to change significantly in the next 5 years, with Ce and La accounting for over 55% of supply for all mines.

The USGS estimates REO total reserves are approximately 110 million tonnes.[16] It has been reported[46] that large amounts of RE are present in deep ocean sediments; however, the commercial feasibility of exploiting such deposits is unclear. While 50% of RE reserves are concentrated in China, significant quantities are also found in the U.S. and the Commonwealth of Independent States (former Soviet bloc countries). The static depletion index of REO (reserves/present production) is approximately 870 years. To place this value in perspective, copper, a key industrial metal that has been the focus of some recent studies of availability, has a static depletion index of 34 years.[47−49] The known reserves for RE are therefore not expected to be constraining in the next 25 years.

Moreover, at present, although RE recycling is limited to new scrap,[50] this would be expected to change as prices rise and as

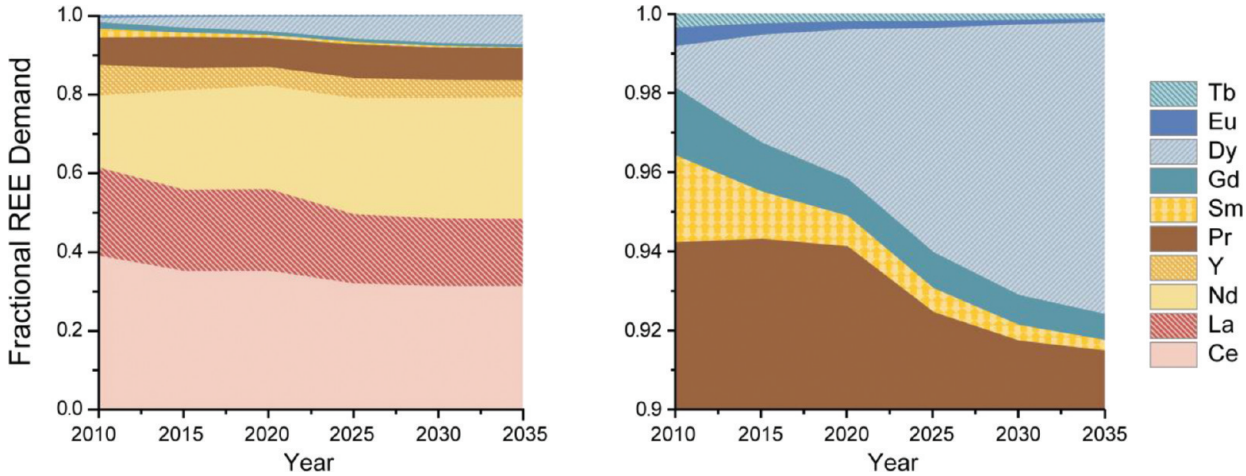

Figure 4. Scenario D: Evolution of projected REE demand distribution based on reported REE content by application estimate (right part is a zoom in on the 0.9 to 1.0 of the *y*-axis).

applications that use concentrated amounts of RE grow in importance. Any increase in recycling would further increase the REE depletion index.

Belying their name, rare earth elements are not rare. The key concern with RE availability is not their geophysical abundance, but rather whether the RE supply base can expand at a sufficient pace to meet future demand particularly for individual RE metals. In particular, we wish to identify (a) the conditions where REEs may experience unprecedented demand growth and (b) the implications of comining on RE availability under rapid demand growth in specific industries.

Ability of Supply to Grow Rapidly. We compare the overall REE demand path for Scenarios A, B, C, D, and E in Figure 5. Scenario A is a conservative lower bound projection of future REE demand, while Scenarios C and D are upper bound projections. For this analysis, we considered how projected demand growth rates compare with historical supply growth rates.

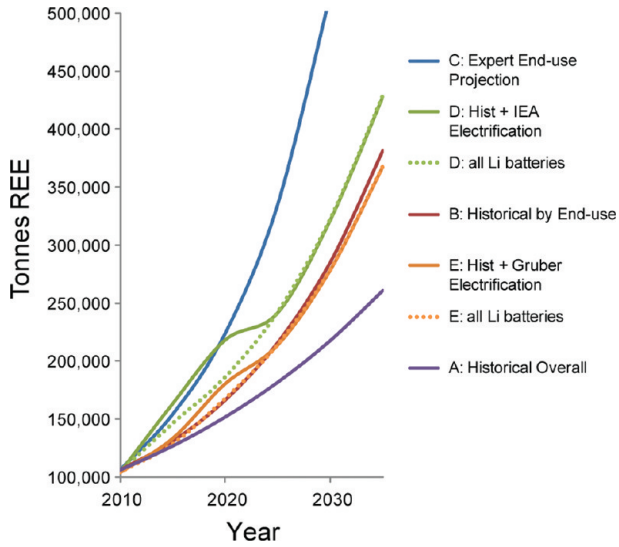

Figure 5. Comparison of demand projections for REE (total summed).

Global total REE production has averaged 6.5% annual growth, but ranged between −21% and 34% annual growth since 1970.[16] As mentioned previously, the overall long-term annual growth rate (curve fit) was 5.4%. These rates are indicative of the strong growth in applications for REEs over the past 40 years and of the large historical fluctuations experienced in the REE market as this growth has occurred. While no guarantee can be made that future rare earth supply can grow at these historical rates, it is an indicator that growth at these rates would not be unprecedented.

Scenario D would require relatively rapid growth in total rare earth supply, 5.9%/year, yet this rate is within 1% of the historical overall production growth rate. Until lithium-ion batteries replace NiMH batteries in HEVs, rapid adoption of HEVs results in fast demand growth for REEs. In particular, in Scenario D, REE markets experience high growth rates relative to historical levels (8%/year between 2010 and 2020) followed by a significant slowdown in demand (2.4%/year between 2020 and 2025). Such changes may be accompanied by volatile prices.

Satisfying the demand projected by Scenario C would require 8.6%/year supply growth over the next 25 years, which is very challenging. While market dynamics are expected to play a role in all scenarios, Scenario C is most likely to lead to increased pressure on primary supply and, therefore, increased prices.

Finally, by accounting for evolutionary and revolutionary demand explicitly the growth rates for Scenario E result in a lower REE demand in 2035 than Scenario B because some of the recent historical growth in rare earth demand may be attributed to the NiMH batteries in HEV. Since lithium-ion technology is projected to replace NiMH, future RE demand growth is expected to slow correspondingly.

Limitations of Co-Mining. Even in the most aggressive growth scenarios, total RE demand growth is projected to exceed historic norms by no more than 3% per year. However, closer examination of the results reveals significant deviation from historic norms for individual elements. REEs are comined and are produced in a portfolio that is determined based on the geology of RE reserves and the economics of recovery and separation technologies. When examining the future of REs, concern arises from emerging dislocations in relative demand among specific elements particularly for Dy and Nd. Vehicles and wind turbines rely very heavily on Dy, Pr, and Nd. Presently exploited ores are over 70% Ce, La, and Nd.

To quantify this potential supply constraint, we compared demand for each element in the different scenarios and divided

Table 3. Ratio of Demand to Supply for Scenarios A–E (eq 10)

REE	T = 2010, base year =2010	T = 2035, base year =2010		T = 2015, base year =2015				T = 2020, base year =2015		T = 2035, base year =2015		
	(%)	D (%)	A (%)	B (%)	C (%)	D (%)	E (%)	B (%)	C (%)	B (%)	D (%)	E (%)
Ce	99	327	75	77	83	91	81	98	133	229	223	226
Dy	92	2630	99	111	148	332	175	149	314	317	2353	909
Eu	95	78	86	68	97	68	68	65	151	51	59	59
Gd	90	145	87	71	107	83	71	73	188	93	119	107
La	81	249	66	68	75	82	71	87	121	174	197	197
Nd	106	724	87	97	124	156	105	130	252	272	510	361
Pr	140	669	114	128	160	170	128	172	322	356	472	429
Sm	99	47	83	62	92	61	61	58	142	54	55	55
Tb	167	249	133	116	157	125	116	122	256	134	167	158
Y	115	267	124	116	139	116	116	135	217	189	239	239
total	98	402	80	82	96	106	87	105	166	219	290	251

by supply for that element (see Table 3). The percentages shown in Table 3 represent calculated demand in year T compared to current (2010) or projected (2015) supply in a base (comparison) year for the jth REE, calculated in the table as follows:

$$\text{ratio for } j^{th}\text{element} = R_{j,T:\text{base}} = \frac{D_{j,y=T}}{S_{j,y=\text{base}}} \times 100\% \tag{10}$$

The final row in Table 3 shows the ratio of total projected demand to total supply (actual in 2010, projected in 2015). Although the more standard practice is to compare future projected demand to current supply, we elected to also compare with projected 2015 supply to incorporate the most updated available information on supply. Supply projections for a 5-year period are considered somewhat reliable, given the long time frame required to plan and build a mine.[51−53]

In the second column of Table 3, we verify our assumptions by comparing the 2010 demand estimate with the reported 2010 supply. The fact that our demand estimates for the individual elements are generally within 20% of the reported supply in 2010 provides confidence in the methods used. The larger discrepancies (e.g., for Pr and Tb) presumably reflect either the impact of stockpiling, or uncertainties in the literature data used in our analysis, or both.

For each scenario, the total 2015 REE demand is within 20% of the projected total 2015 supply (Table 3, bottom row). However, for some specific REEs, in particular Pr, Nd, Dy, Tb, and Y, the rate of demand growth is challenging. For example, the projected demand for Dy for 2015 under Scenario D is expected to be over 300% of the projected 2015 Dy supply. To meet 2035 demand, the growth rate for Dy supply would need to be between 9% (Scenario E) and 14% (Scenario D) per year, when revolutionary demand is considered explicitly, nearly double the historic total REE supply growth rate.

The applications that will be most negatively affected by constraints in these REEs (i.e., increased costs) will be those dependent upon high performance magnets. Applications such as petroleum refining, which depend on elements whose supply is projected to exceed demand, may be positively affected if primary producers increase overall production to meet the higher demand for specific elements. If a secondary market emerges to meet the higher demand for specific elements (i.e., recycling of magnets, but not catalysts), then, given that the portfolio of recycled REEs would be significantly different from the portfolio of primary supply, the overall supply portfolio of REEs could change.

MITIGATING EFFECTS

A key aspect of material markets is that price signals encourage both suppliers and users to be adaptive. As demand for Nd and Dy increases disproportionately to demand for other RE, the prices of individual REEs will change encouraging manufacturers to reduce their net Nd and Dy use. This may be achieved through materials substitution, improved efficiency, and the increased reuse, recycling, and use of scrap.[14,54−56] Du and Graedel[31] have estimated that in 2007 the global in-use stocks of Pr, Nd, Tb, and Dy were four times the annual extraction rate of the individual elements. Moreover, wind turbines and electric vehicles may be more amenable to recycling due to their concentration of REE in single parts. Due to the inherent delay between consumption and recycling and the growing nature of REE demand, the impact of such recycling will likely only be significant in the long term. Although suppliers of RE are somewhat constrained by the geological concentration of REO in the ore, they can also adapt to prices by increasing yield of higher priced REEs. In the end, prices are not the only forces that will influence the REE markets. Government intervention in this market is prevalent. Also, corporate social responsibility policies may influence some firm's decisions to use REE unless environmental concerns around their mining are addressed. These issues should be considered carefully by interested stakeholders and future research on this topic.

ASSOCIATED CONTENT

Supporting Information

Supplemental the data provided in the Methodology section. This material is available free of charge via the Internet at http://pubs.acs.org.

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ACKNOWLEDGMENTS

We thank our colleagues Renata Arsenault, Mike Degner, Kelly Keller, Ted Miller, and Bing Xu at the Ford Motor Company for helpful discussions.

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