Agent-based modeling of supply disruptions in the global rare earths market

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HIGHLIGHTS

- Rare earth supply disruption scenarios simulated with dynamic agent-based model
- Results feature effects on individual rare earths, magnet supply chain, and trade
- Dysprosium market significantly affected by curtailment of China illegal supply
- Supply disruptions could foster new mine capacity that is not sustainable

ABSTRACT

Several independent assessments have identified rare earth elements (REEs) as critical materials, notably neodymium (Nd), praseodymium (Pr), and dysprosium (Dy) used in permanent magnets. Factors affecting their criticality include expected growth in demand arising from their unique performance-enhancing properties in consumer, energy, and military applications and the supply risk associated with China's dominance in their production. We demonstrate the use of Argonne's Global Critical Materials (GCMat) agent-based model to explore the possible consequences to REE market dynamics of different types of regional supply disruptions including a temporary loss of production, shutdown of capacity, and diversion of supply. Results suggest that supply disruptions may foster earlier and more REE mine starts outside of China, although some of these mines may not be able to sustain operations post disruption. Further, price and associated market responses such as production, capacity, and demand tended to extend beyond the disruption period. Such market impacts in the magnet supply chain could affect the costs and availability of a number of emerging clean energy technology applications such as electric vehicles and wind turbines. In the future, GCMat could be used to evaluate the effectiveness of mitigation strategies — including recycling, conservation, product substitution, and diversification of supplies — on reducing the severity of disruptions in REE markets.

Keywords:
rare earth
critical material
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supply disruption
supply chain

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1. INTRODUCTION

Modern technologies have complex supply chains that are sensitive to global markets and geopolitics. Many of these supply chains contain materials and components with small or highly concentrated markets, increasing the risk of disruptions to supply. Supply disruptions are defined here broadly as any disturbance that can result in a loss or delay in the delivery of materials or products meeting quality requirements throughout the supply chain. They can arise from many different sources, including those internal to the supply chain, such as operational problems or logistics failures, and those external to the supply chain, such as natural disasters or government actions. Figure 1 presents examples of supply disruption causes, informed by the supply risk management literature (Jüttner et al. 2003, Chopra and Sodhi 2004, Rao and Goldsby 2009, Ellis et al. 2011, Johansson 2013, Heckmann et al. 2015, Ho et al. 2015). These causes may result in a variety of different types of disruptions and associated consequences, such as a loss of production or a diversion of supply. Further delineations of supply disruptions consider the scale of affected supply chain entities and supply, as well as the geographic scope, duration, and timing of the disruption.

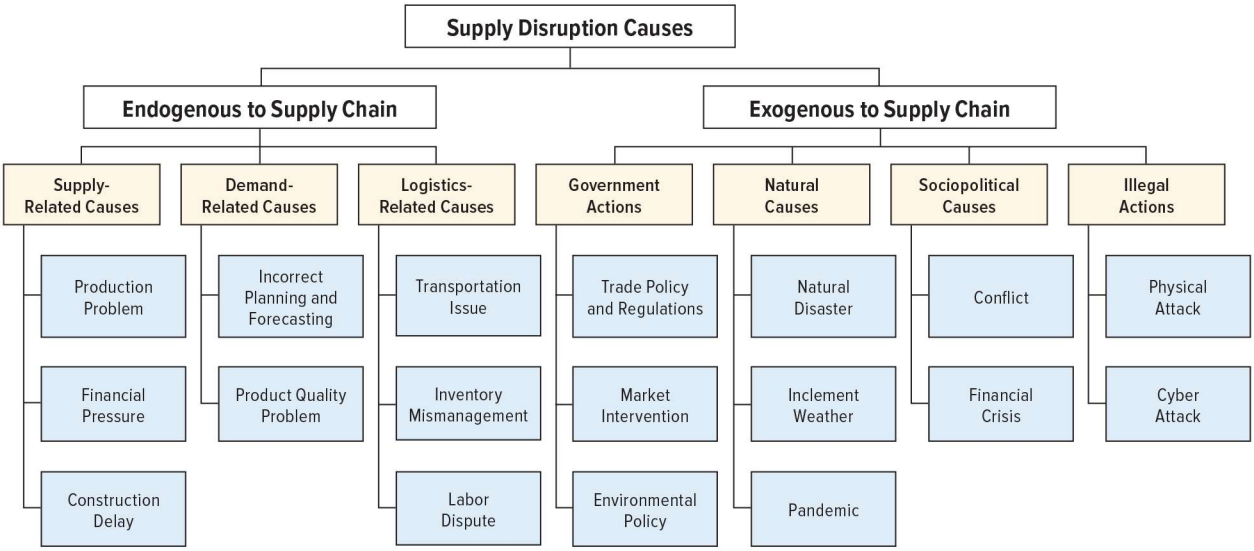

Figure 1. Causes of supply disruptions. Broad categories of endogenous and exogenous supply disruption causes (yellow boxes) and example (blue boxes). Note that neither the supply disruption causes nor the categorization approach are inclusive of all those documented in the literature.

In contrast to the literature on supply risk management, papers on modeling supply disruptions are sparse. In a comprehensive literature review on mathematical models for supply risk management, Paul et al. (2016) comment on the importance and need for quantitative disruption models of real-life supply chains. Researchers have applied various approaches for modeling supply disruptions including systems dynamics (e.g., Wilson 2007, Bueno-Solano and Cedillo-Campos 2014), discrete-event simulations (e.g., Melnyk et al. 2009, Schmitt and Singh 2012), petri-net (e.g., Wu et al. 2007, Zegordi and Davarzani, 2012), game theory (e.g., Bakshi and Kleindorfer 2009), and agent-based modeling (e.g., Behdani et al. 2012, Zhao et al. 2019). Parunak et al. (1998) posit that agent-based modeling (ABM) is uniquely adept at simulating behaviors specific to individual decision makers in the supply chain, yielding results that pertain to disruptive events. In their review, Chen et al. (2013) conclude that while ABM is a useful modeling approach for supply chain risk management, few studies employ this approach. On a related topic, Bollinger et al. (2011) compare ABM and equation-based simulation (e.g., systems dynamics) for material flow analysis. The authors note advantages of using ABM in modeling regional differences, technology evolution, and diversity in competitive environments. Knoeri et al. (2013) present a framework for integrating ABM with material

flow analysis for dynamic criticality assessment. Blos et al. (2015) apply ABM to inform mitigation of supply chain disruption risks for a manufacturing firm.

The purpose of this paper is to examine supply disruption scenarios in the rare earth elements (REEs) supply chain. While reasonably abundant in the Earth's crust, REEs typically occur in low concentrations of mined ores (Van Gosen et al. 2017). Processes for recovering REE concentrates from these ores are complex, capital intensive, and challenged by environmental issues (USEPA 2012, García et al. 2017). Further, lead times from preliminary exploration to construction can be as long as 10–15 years (Adamas 2016). China dominates the REE supply chain. In 2019, China supplied ~85% of global demand for refined REE (Roskill 2019). China is also the largest global producer of RE-containing downstream products, such as REE metals, magnets, glass polish, alloys, and phosphors (Roskill 2016, 2019).

REEs have unique magnetic, catalytic, and phosphorescent properties that significantly improve performance of a wide range of technologies, spanning aerospace, clean energy, telecommunications, electronics, transportation, defense, and other diverse applications. Different studies employing a variety of analytic methods and metrics identified REEs as critical materials (DOE 2011, Nassar et al. 2015, EU 2017, Fortier et al. 2018, Nassar et al. 2020).

The 2010–2011 REE price behaviors observed after a trade dispute between China and Japan spurred several REE supply-and-demand studies, including Riddle et al. (2015) to which this paper extends. Several papers provide historical background on REE global markets (see for examples: Du and Graedel 2011, Tse 2011, Humphries 2013, Massari and Ruberti 2013). Alonso et al. (2012) present projections of REE supply and demand associated with evolutionary and revolutionary adoption of clean energy technologies, for which REEs enhance their performance. The researchers identify REEs in neodymium-iron-boron (NdFeB) magnets to be at greatest risk of negative consequences with specific applicability to wind turbines and electric vehicles. Eggert et al. (2016) describe policies and innovations targeted at mitigating supply shortages, including new mines, improved REE separations, recycling, and substitution. Regarding the latter, Smith and Eggert (2016, 2018) analyze material substitution alternatives for the NdFeB magnets deployed in these technologies.

Several studies have applied equation-based simulation models, such as systems dynamics (SD), to project future REE markets. For example, Sprecher et al. (2014) evaluate the effects of Nd markets on recycling computer hard disk drives and Sprecher et al. (2017) apply SD modeling to quantify resilience metrics for NdFeB magnet supply chains. They evaluate disruption mitigation strategies, including stockpiling, recycling, material substitution, and new mine starts. Mancheri et al. (2019) build on this work to explore the effect of Chinese policies on REE prices, global supply, and supply chain resilience. Among the policies they investigate are stockpiling, production and export quotas, export taxes, and Chinese imports and overseas investments. Nguyen and Imholte (2016) also deploy a SD model to assess possible outcomes of Chinese government policies (quotas and resource taxes) and different REE demand growth scenarios. They also apply their model to analyze how adoption of an aluminum-cerium alloy for automotive light-weighting might affect the REE markets (Nguyen et al. 2019). Fishman et al. (2018) and Fishman and Graedel (2019) also use SD modeling to evaluate the impact of increased demand for alternative vehicles and wind turbines on the market for REEs, respectively. Though not a SD model, Brown and Eggert (2018) employ an equation-based Stackelberg model to simulate producer responses to Chinese rare earth policies.

While the equation-based models deployed in previous studies present reasonable projections of future REE markets, ABM provides the unique capability for bottom-up modeling of the diverse, complex business-driven decisions of REE supply chain agents who adapt their behaviors based on market signals and changes (North and

Macal 2007). Riddle et al. (2015) use ABM to study how reliance on REE markets (specifically neodymium and dysprosium) affects the adoption of clean energy technologies. This paper extends this model to explore plausible market consequences associated with supply disruptions in REE markets. The model is well-suited to address these questions because of its ability to capture dynamic, non-linear market responses to disruptions and explicitly model the behavior of individual decision-making agents in the supply chain that adapt to (and determine) prevailing market conditions at each time step. These agents include over 60 specific rare earth deposits with detailed data on each individual project and a variety of specific intermediate producers and end users. The interactions of these agents across the supply chain determine market signals, such as average prices of individual oxides.

Questions we seek to answer through this study include:

- How might the consequences of supply disruptions differ by disruption type and why?
- How might the dominance of China in the NdFeB magnet supply chain affect these consequences?
- How could supply disruptions affect REE trade?

The remainder of the paper is structured as follows. Section 2 provides a summary of the GCMat model design. The supply disruption scenarios are described, and scenario results are presented in Section 3. Section 4 concludes with discussion and future work.

2. METHODOLOGY

The GCMat agent-based market model used for this study is an extended version of the model described in Riddle et al. (2015), which was developed for a study assessing the effect of Nd, Dy and NdFeB magnet markets on clean energy technologies. Argonne's Repast Simphony ABM toolkit provides a framework for implementing and using agent-based models (North et al. 2013) and is the basis for GCMat.

Rare earth (RE) materials modeled are cerium (Ce), lanthanum (La), neodymium (Nd), praseodymium (Pr), samarium (Sm), yttrium (Y), terbium (Tb), europium (Eu), gadolinium (Gd), and dysprosium (Dy) oxides and metals. Also modeled are didymium (a mix of Nd/Pr) oxide and metal, and other mixed oxides (Ce/La and Ce/La/Nd/Pr) and their associated mischmetals (alloys of REEs). Figure 2 shows the supply chain agents and their decision behaviors modeled.

The first step in the supply chain is mines. More than 60 REE deposits are modeled using detailed data (see Riddle et al. 2015, 2020 for sources) on reserves, mineral compositions, capital and operating costs, and operational statuses. Mine agents forecast profitability and off-take contracting to inform decisions on when to start deposit development, when to start construction of a new mining facility, when to shut down a mining facility, or when to restart it. For mining facilities that are operating, mine managers make decisions on the tonnage of ore to mine and process, the prices and quantities of RE oxides (REOs) offered to each potential buyer, and the management of their inventories. As currently modeled, refining to produce individual REOs in not represented as a separate supply chain step from mines.

China mine production is exogenously limited by production quotas set by the Chinese Ministry of Industry & Information Technology (MIIT). Future production quotas are informed by MIIT's 2016 REE industry development plan. Additionally, REE mined outside of China but refined in China, for example REE mined from Mountain Pass post-2017, are included in China REE production.

Mine agents sell REOs to metal refiners and to producers of REE-containing products. Producers of REE-containing products sell their products to final demand agents. Metal refiner agents sell RE metals to NdFeB magnet

producers and to producers of RE metal-containing products, with the latter selling to final demand agents. NdFeB magnet producers supply magnets to manufacturers of wind turbines, electric and hybrid electric vehicles, and electric bikes and to final demand agents. The final demand agents are split into multiple categories of NdFeB magnet demand, including consumer, industrial, and non-drivetrain automotive applications. Each of the producer agents has business decision-making behaviors for updating price offers, buying and selling products, choosing technologies, setting production rates, managing inventories, and investing in new production capacities. Final demand agents respond to prices in their purchases of end-use products.

While the model's agent decision behaviors are grounded in common business practices, the sparsity of data limits the capability to capture all of the variability and uncertainty in them across the supply chains in China, ROW, and US regions. Further, the model does not represent every production step in the complex REE supply chain. For example, the modeled supply chain does not include recycling, though there is evidence that some REE are recovered for reuse - for example Nd, Pr, and Dy from metal refining, magnet swarf, and other sources.

The model executes with time steps of one week, beginning in January 2010 and ending in January 2030. The model is calibrated to historical REO price data, including Chinese internal and export prices. The model has been validated using conceptual, computerized and operational validation, as documented in the SI. Detailed descriptions of the model design, agent representations, input data and sources, and calibration are documented in Riddle et al. (2020).

By design, the model captures market dynamics arising from the autonomous decision-making and interactions of supply chain agents. These market dynamics are explored in greater depth by modeling scenarios of interest.

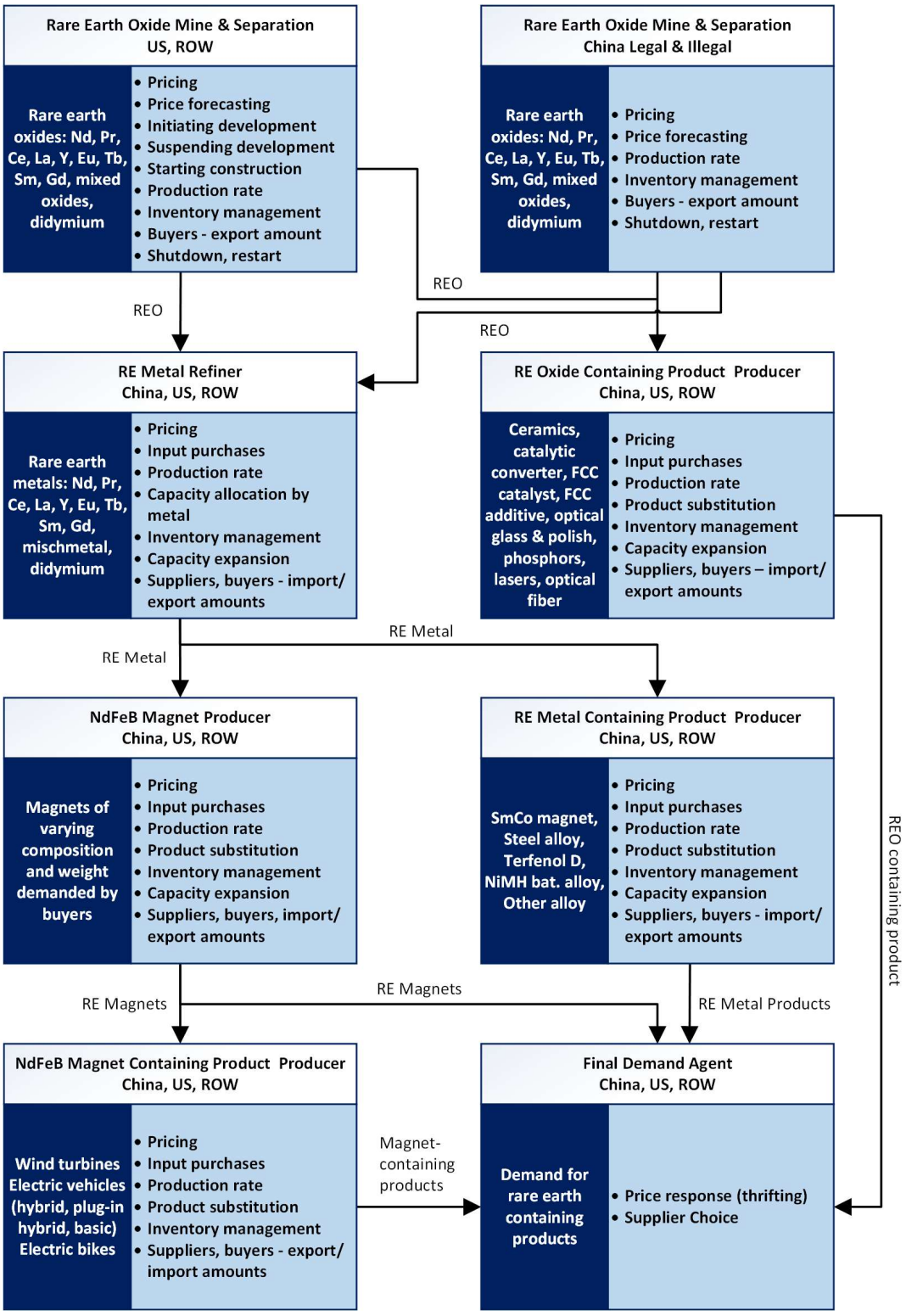

Figure 2. GCMat model agents (white boxes), products (dark blue boxes), and key decisions made by each agent type (light blue boxes). Three regions are modeled: China, the United States (US), and the rest of world (ROW). The paper's use of "non-China" refers to the US and the ROW.

3. SUPPLY DISRUPTION SCENARIOS and RESULTS

As exemplified in Figure 1, numerous occurrences or actions, either endogenous or exogenous to the supply chain, can cause supply disruptions. The consequences of these disruptions will depend on their duration, geographic scope, market share, and impact on individual supply chain stages or entities. In this study, we model a baseline and three supply disruption scenarios:

- **Temporary production loss**: A 2-year shutdown of the Mt Weld mine in Australia and Lynas Advanced Materials Plant (LAMP) separation facility in Malaysia, as could be a result of financial pressures. The main products of the LAMP facility are oxides of didymium, Ce, La, and mixtures thereof (Roskill 2018, Lynas undated). This source of separated REEs is the largest outside of China, accounting for more than half of non-China demand (see Table SI-1). This scenario will shed light on how a temporary loss of production representing less than 10% of global REE demand, but a significant percentage of non-China demand, could affect REE markets.
- **Permanent capacity shutdown**: An 80% curtailment of illegal REO supply with no end year, as could result from government market intervention. A significant quantity of illegal artisanal mining from heavy REE-rich mineral ores is believed to occur in southern China (Yang et al. 2013). Over the past several years, the Chinese government has reportedly taken actions to limit illegal production (Wübbeke 2013, Packey and Kingsnorth 2016). Reports (Adamas 2016, Roskill 2018) suggest that more heavy REOs (HREOs) from the southern Chinese provinces are sold illegally than are light REOs (LREOs) from the northern and western provinces. This scenario will examine how the effects of an extended shut-down of production might differ from those of a temporary shut-down, and how the illegal REO supply curtailment might affect HREO markets differently from LREO markets.
- **Supply diversion**: Temporary (1-year) export stoppages from China as could result from government trade policy. Export stoppages are modeled as a temporary shutdown of legal exports of REOs and RE metals from China, accompanied by a crackdown on illegal exports that is modeled as an increase in the costs of smuggling goods out of China illegally. Scenarios include (1) export stoppages of separated REOs only, and (2) export stoppages of separated REOs and produced RE metals. These scenarios will provide insights on how the impact of trade stoppages may be different from loss of production, and how REE markets might respond differently when two stages of the REE supply chain versus one stage are disrupted.

These scenarios are modeled for the period 2010 to 2030 with different start dates and durations for the supply disruptions as detailed in Table 1. Taken together, the scenarios vary disruption characteristics of supply loss relative to existing capacity (different supply sources affected and start years), regional scope (global and non-China supply chains), affected supply (REOs and RE metals), and duration (1-yr, 2-yr, and >10-yr shutdowns or stoppages).

Table 1. Supply disruption scenarios modeled with GCMat

Scenario Name	Scenario	Start Year	End Year
BaselineNoDisrupt	No supply disruption		
MtWeldShut2yr2021	2-yr Mt Weld shutdown in 2021	2021	2023
MtWeldShut2yr2024	2-yr Mt Weld shutdown in 2024	2024	2026
IllegalCurtail2021	Chinese illegal supply curtailed by 80% in 2021	2021	----
IllegalCurtail2024	Chinese illegal supply curtailed by 80% in 2024	2024	----
China1yrREOEx2021	1-yr China REO export stoppage in 2021	2021	2022
China1yrREOEx2024	1-yr China REO export stoppage in 2024	2024	2025
China1yrREO_MEx2021	1-yr China REO and RE metal export stoppage in 2021	2021	2022
China1yrREO_MEx2024	1-yr China REO and RE metal export stoppage in 2024	2024	2025

We focus our analysis on didymium and Dy oxides and on metals and La and Y oxides. Didymium and Dy are key components of NdFeB magnets used in consumer, industrial, automotive, and clean energy technologies. Relevant to these REEs, we explore the effects of disruptions on metal refining and magnet production. La oxide is used in the production of fluid-cracking catalysts used in petroleum refining to produce gasoline, catalytic converters, and alloy, glass, and ceramic products. Important applications of Y oxides are ceramic capacitors, thermal barrier coatings, and phosphors in lighting. Focusing on these REEs allows us to observe the variety of different impacts that may result from different supply disruption scenarios.

For each scenario, we ran 1000 simulations using Argonne's high-performance computing (HPC) resources to capture the effect of uncertainties in parameter values and input data. These uncertainties include projected growth rates in final demand for products; production and demand shares among China, the United States (US), and ROW; production costs; price elasticities; and clean energy technology choices. HPC results are presented in the Supplemental Information (SI). For deeper analysis, we simulated each scenario with the same parameter and input data values on a desktop computer, from which week-by-week results are generated covering demands, offers, sales, imports, exports, prices, inventories, production rates and capacities, and technology compositions. Figures presented in the main body of the report are from the desktop simulations.

Results for the BaselineNoDisrupt scenario (see Figure SI-1) illustrate that our calibrated model replicates historical price patterns from 2010–2018. The 2010–2012 price spikes are modeled to be partly driven by inventory builds whose timing and size were derived from calibration to historical price data (see Riddle et al. 2020 for details on the calibration process). Similar inventory builds were not included in the 2021 or 2024 supply disruption scenarios that we model due to the difficulty in predicting the amount of speculative buying that may occur in response to market disruptions.

3.1 How might the consequences of supply disruptions differ by disruption type and why?

The graphs shown in Figure 3 illustrate the non-China price responses observed from the desktop simulations for each of the supply disruption scenarios compared to the BaselineNoDisrupt scenario (in red). In this figure, prices are charted from 2010 to 2030 for comparison of the modeled REE price behaviors with the price spikes observed in 2010–2012. All other results in the paper and the SI are charted from 2020 to 2030 to accentuate the modeled disruption effects.

Prices in GCMat are driven by the amount produced and made available to sell relative to the amount of demand, as well as the amount of excess production capacity. Imbalances between supply and demand lead to depletion or accumulation of inventories, which lead to accelerated price increases if inventories are low or to persistent low prices if inventories are high. Each agent sets its own prices — keeping them competitive with other suppliers so

that the prices from different suppliers do not differ greatly. If there are no restrictions on exports, prices in different regions tend to stay fairly close to each other, with differences driven by the cost of exporting products between regions, including tariffs, export taxes, and transportation costs. Prices are limited on the low end by those necessary to justify continuing production and sales as determined from historical pricing.

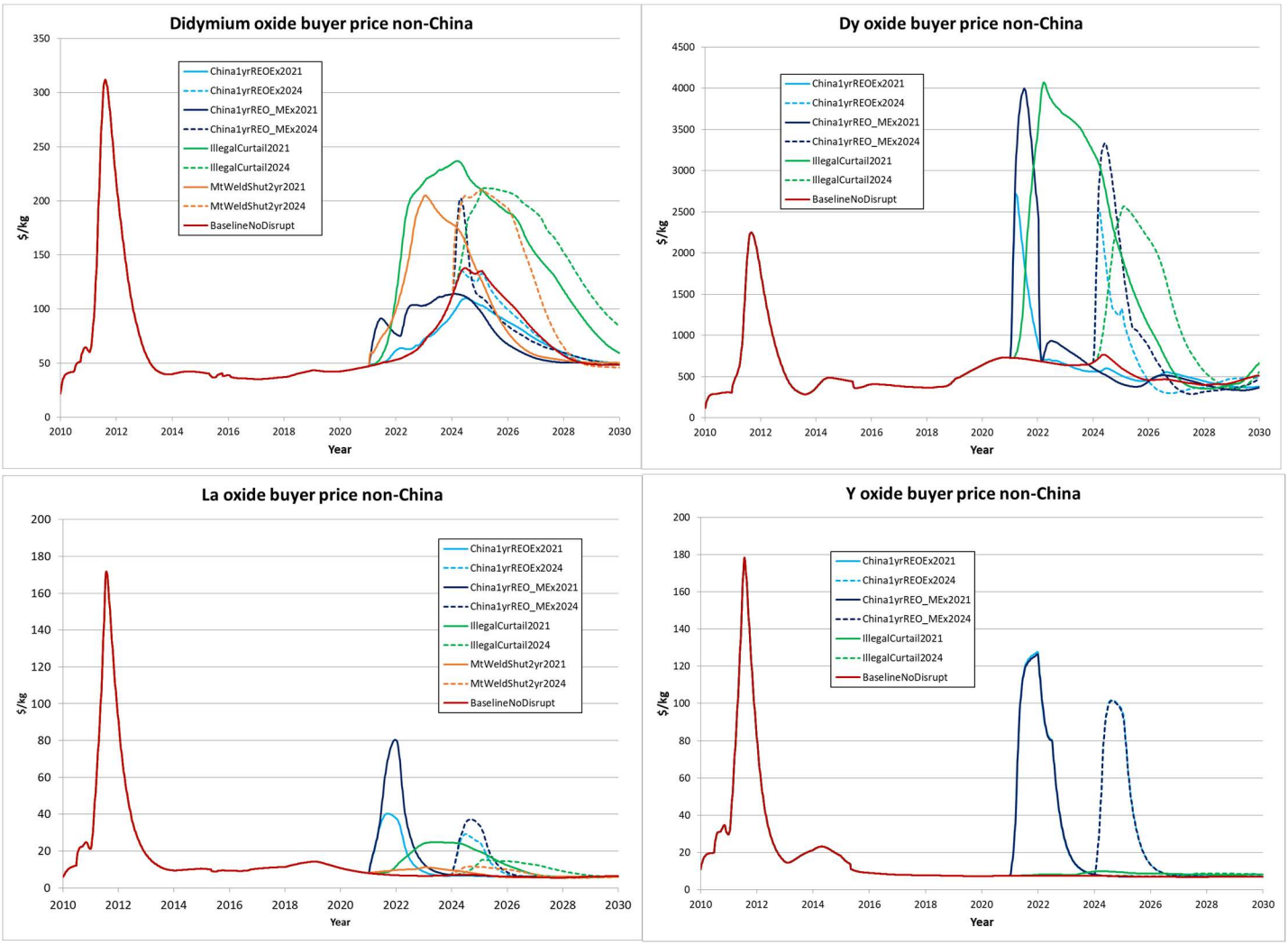

Figure 3. Price results for baseline and supply disruption scenarios. (See Figures SI-2, -3, and -4 for desktop and HPC oxide and metal price results for the Mt Weld shutdown; curtailment of illegal exports; and Chinese export stoppage scenarios, respectively.) The content of the Dy and Y oxides in the Mt Weld ores are negligible, so they are omitted from analysis of the Mt Weld shutdown scenarios. We note that the high Dy oxide prices observed in some scenarios are outside historical precedence and that market responses not represented in the model might occur. However, they are defensible as comparative responses among the supply disruption scenarios.

The supply disruptions affect the different RE prices to varying extents. Some of the differences can be explained by the disruption duration and the portion of worldwide production affected. The largest and most extended increase in prices is observed for the Dy oxide in the curtailment of illegal exports scenarios. Illegal production accounts for 53% of worldwide Dy oxide production in 2021, so it is not surprising that Dy oxide prices would rise dramatically when 80% of this supply is no longer available in the market. The higher prices extend several years, although they decline as non-China HREO-rich mines open and ramp-up their production.

In the export stoppage scenarios, Dy oxide prices also see large increases in price, largely driven by the lack of Dy oxide production outside of China. Dy oxide is the only oxide which is projected to see a larger price increase than was observed during the historical price spike. The relatively larger increase in Dy oxide prices compared to the historical period partly reflects differences in how the two events are modeled. In 2011, export quota impact on prices were similar for all oxides covered by each quota, leading to larger percentage increases for low-value oxides. The future export stoppage scenarios, on the other hand, are modeled as a complete shut-off in legal exports, leading to larger price differentials for high value oxides such as Dy for which non-China supply is insufficient to meet demand. The Chinese government also makes more effort to limit increases in illegal exports in the future export stoppage scenarios, which disproportionately affects heavy rare earths such as Dy oxide.

On the other hand, the curtailment of illegal exports has a lesser effect on Y oxide prices. While sales of Y oxide are about five times the sales of Dy oxide, demand for the Dy oxide drives the illegal production of HREOs. Nearly 100% of the Dy oxide produced is sold. By comparison, less than 80% of the Y oxide produced is sold. Hence, Y oxide inventories build up and are available to fill the supply gap caused by reduced illegal oxide production. During the China export stoppages, however, these inventories are not available to non-China buyers who rely on China for >95% of their supply, and non-China Y oxide prices increase significantly.

Didymium oxide prices increase most significantly in the illegal curtailment and Mt Weld shutdown scenarios. In the model, >99% of didymium oxide is refined to metals and consumed in the manufacture of NdFeB magnets. Demand growth for the NdFeB magnets drives the price behaviors of the didymium oxide and metal. In the BaselineNoDisrupt scenario, didymium oxide prices start to increase around 2022. Their price climb correlates to the point where mine inventories of didymium oxide cross below those of the co-produced La oxide, and non-China mine capacity utilization increases beyond 95%. The combination of low inventories and high capacity utilization drives mines to increase didymium oxide prices. The removal of illegal or Mt Weld's supply from the market exacerbates this already tight demand situation, driving up prices by more than 200 USD/kg in each scenario — about 70% of the maximum price reached in 2011.

La oxide prices, on the other hand, decline after 2019 as inventories build up due to the imbalance in demand for the different REEs. Consequently, we observe a lesser price response to the curtailment of illegal exports and Mt Weld shutdown of the La oxide than was observed for didymium oxide. The opposite occurs with the Chinese export stoppage. One reason for this higher response of La oxide prices is that the non-China share of world demand for La oxide (~35%) is higher than it is for didymium oxide (~10%). Further, a significantly larger fraction of non-China La oxide demand (~45%) compared to didymium oxide demand (~12%) is met by China supply in 2021 and 2024 (see Figure SI-5).

Differences in the price behaviors are observed for the two China export stoppage scenarios. Market effects depend both on the Chinese share of world production and on how much of that production is exported. The REO price responses, with the exception of Y oxide prices, are greater when metal exports are also restricted. Restricting metal exports from China causes non-China RE metal refiners to increase their production to compensate for lost Chinese supplies, and hence non-China REO demand increases, leading to increases in oxide price. If only oxide exports are restricted, the reverse occurs. In these scenarios, Chinese metal refiners are able to increase metal production and export more in metal form, and non-China metal refiners consequently produce less and purchase fewer oxides.

Didymium oxide prices are not significantly affected by a stoppage of Chinese REO-only exports because non-China demand is comparatively low. As modeled in GCMat, nearly 100% of didymium oxide is refined into metals for NdFeB magnet production. Consequently, didymium oxide demand is dependent on metal refining, for which less than 15% of global capacity is in non-China. In 2021, only 8%, falling to 3% in 2024, of non-China didymium oxide

demand is sourced from China in the BaselineNoDisrupt scenario (see Figure SI-5). However, when both China REO and RE metal exports are stopped, a higher dependence on Chinese didymium metal results in higher prices.

The rising RE prices caused by supply disruptions affect both their supply and demand. The supply disruption scenarios spawn earlier non-China mine start-ups after the disruptions compared to the BaselineNoDisrupt scenario (see Figure SI-6 for desktop and HPC results). As modeled, individual mines have incomplete information on competing mines. They decide to move ahead with construction (modeled as the final 2.5 years of the development process) based on forecasted prices, which depend on current and past prices, projected capacity and projected demand. If a disruption leads to reduced production capacity and higher price forecasts, this can encourage additional mines to enter the construction phase. The earlier mine start-ups are most prominent for the illegal curtailment scenarios, which cause significant reductions in capacity and sustained high prices, improving the economics of moving ahead with construction. The mine start-ups, however, may result in too much capacity in the long-term. By the time that they open, particularly after 2026, demand has dropped in response to high prices. As a result, mines operate at a lower utilization rate and in some runs, mines fail to meet sustainable revenues and shutdown, most prevalently in the IllegalCurtail2021 scenario.

For REO demand, GCMat models producers' product substitution for NdFeB magnets, lighting, glass polish, and fluid catalytic cracking (FCC) catalysts. Producer agents, motivated by price increases, adopt new production processes designed to generate savings. GCMat also models reductions in consumer purchases of REE-containing products in response to the increased prices of these products. The extent of the reduction depends both on the price elasticities of demand for the REE-containing products (Gallaway et al., 2003) and on the relative cost of the REE to the cost of the final price of the product. For example, the contribution of material costs to final product prices is small for products like wind turbines and electric vehicles, which leads to a small increase in final product prices when rare earth prices rise, and therefore a small demand response. The combined effect of producers' product substitution and consumers' purchasing reduction is observable by comparing the REE embedded in final product demands during the disruption with the baseline results, which we refer to as "demand reduction." Non-China demand reductions observed in the desktop simulations are shown graphically in Figure 4, and HPC results are provided in Figure SI-7. As a quantitative measure of demand responsiveness, we divide the maximum demand reduction reached by the maximum price increase reached after the disruption. Table SI-2 shows results of this demand responsiveness calculation for the oxides and scenarios from the desktop simulations.

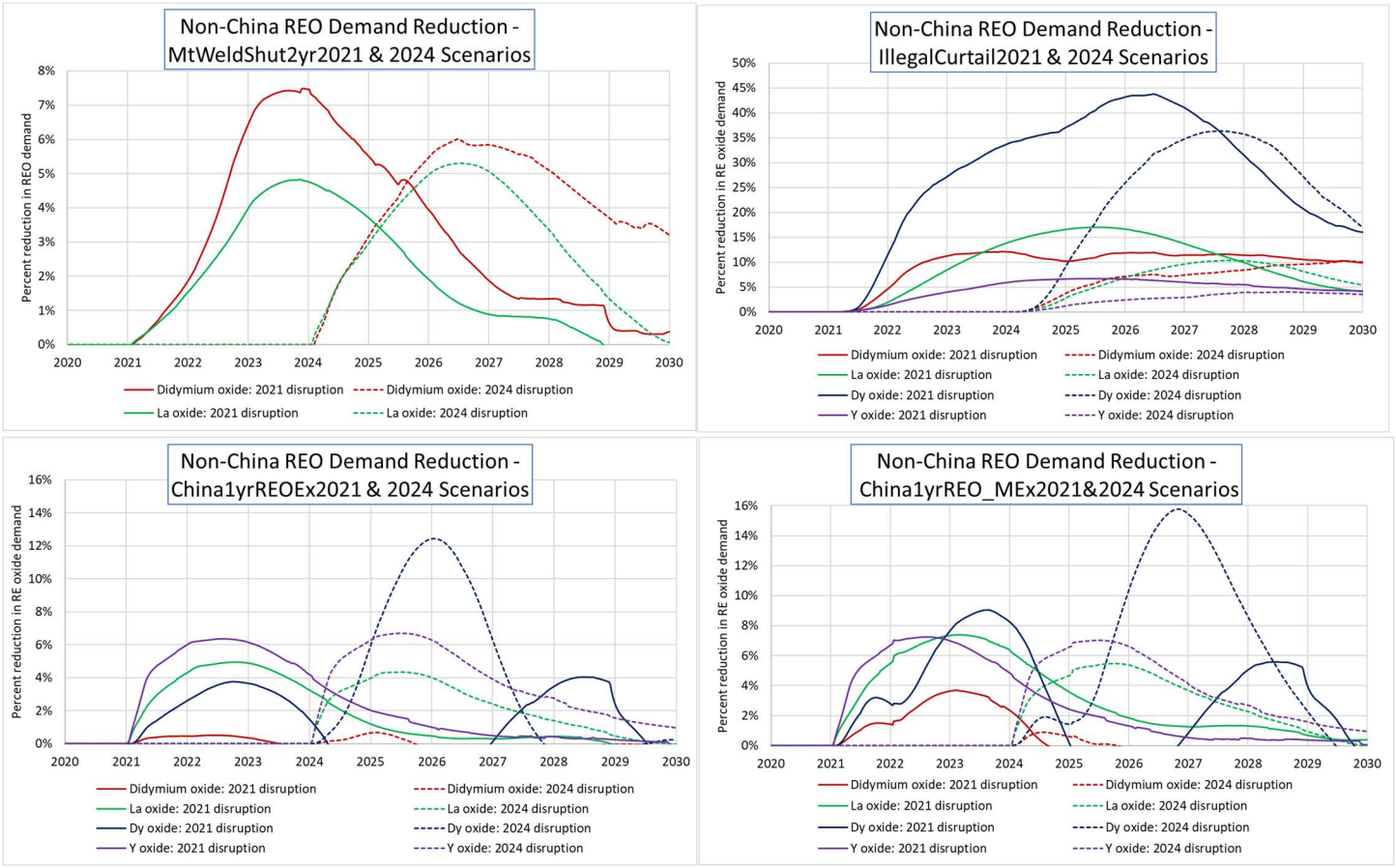

Figure 4. Reduction in non-China demand for selected REOs in response to price increases caused by disruption scenarios. Demand reduction is calculated as the (baseline tonnage minus scenario tonnage) divided by (baseline tonnage). Associated HPC graphs and statistics are provided in Figure SI-7.

Much of the variation in the magnitude and duration of the non-China demand reduction among the REOs and supply disruption scenarios studied is similar to their associated price response. The highest level and persistence of demand reduction is observed for the Dy oxide in the curtailment of illegal exports scenarios, which also showed the largest and lengthiest increase in price. The lowest level of demand reduction is observed for didymium oxide in the Chinese export stoppage of oxides only.

Some differences between the demand reduction and price results are apparent, however. Didymium oxide demand is not very price responsive because it is difficult to substitute away from, and its cost makes up a small portion of the price of most of the final products produced from the oxide, namely, NdFeB magnet-containing products. As currently modeled, didymium content cannot be reduced in magnets without replacing it with similarly priced Nd or Pr metals or higher-priced Dy metals. In fact, the amount of didymium per NdFeB magnet may rise slightly during a disruption as agents substitute away from Dy. Technology choice associated with NdFeB magnets for wind turbines, electric vehicles, and electric bicycles is a major contributor to didymium and Dy demand, and leads to some reduced magnet use in response to high prices (see Riddle et al. 2015 for details).

La oxide demand is more responsive to price compared to didymium oxide because of substitution away from the La oxide in the production of FCC catalysts and because some products containing La oxide, such as glass polishes, have prices that are largely driven by the prices of their REE content. Dy oxide demand also is more responsive than didymium oxide demand because magnet producers can reduce the amount of Dy used per magnet as prices rise, in addition to the same reductions in magnet demand as seen for didymium oxide. Y oxide demand reductions

are also relatively high compared to the price increases observed due to greater demand response to prices of final products containing the Y oxide.

The difference in price responsiveness between didymium and the La oxide is apparent in the Mt Weld shutdown scenarios. Demand reduction is higher for the former, but by a modest amount compared to the relative price impacts of the disruption. In the 2021 Mt Weld shutdown scenario, although the La oxide price increase looks small compared to historical prices, it is still a significant increase relative to the baseline: at its maximum, La oxide prices are 73% more than the baseline, leading to a maximum demand reduction of 4.8%. The didymium oxide price increases much more, reaching 201% above the baseline and leading to a 7.5% demand reduction.

The export stoppage scenarios generally show less demand reduction compared to the other scenarios, and the amount of non-China demand reduction is not as closely related to the size of non-China price increases. In an export stoppage scenario, different regional markets are affected differently. While oxide prices paid by non-China buyers increase, oxide prices paid by Chinese producers of downstream products do not increase as much. As a result, buyers of downstream products such as magnets or glass polish can shift to buying more products from China rather than reducing their demand.

3.2 How might supply disruptions affect the magnet supply chain during and after the disruption?

The NdFeB magnet supply chain modeled in GCMat involves REO mines, metal refiners, magnet block producers, and final demand consumers. Figure SI-8 provides a magnet supply chain diagram and GCMat model inputs for China and non-China metal refining and magnet production capacity and world production shares at model start in 2010. The metal refiners produce all RE metals, not just those sold to NdFeB magnet producers.

The different supply disruption scenarios affect the magnet supply chain in different ways. In some scenarios, non-China producers lose business and do not fully recover once the disruption is over; in others, the reduction is shorter-term. In some scenarios, producers at certain stages in the supply chain benefit, while others do not.

In the BaselineNoDisrupt scenario post 2020, China metals production capacity increases in 2022, and non-China metals production capacity increases in 2026 (see Figure SI-9). Further, non-China metal refiners are steadily increasing their production of didymium metal. China shares of world didymium metal production in 2021 and 2024, respectively, are 90% and 87% and of Dy metal are 89% and 88%. Didymium metal constitutes 50–51% of China RE metal production from 2021 to 2024, while Dy metal accounts for about 2–3% during that period. Among non-China sources, didymium metal accounts for 38% of RE metal production in 2021, growing to 57% in 2024 As modeled, >99% of didymium oxide and ~93% of Dy oxide purchases are consumed in the production of RE metals for NdFeB magnets. Consequently, their production is closely tied to NdFeB demand.

NdFeB magnet prices (see Figure SI-10) tend to track the prices of their didymium and Dy metal supply. In response to increases in their prices, magnet demand and subsequent capacity utilization are reduced, and additions to non-China magnet production capacity are pushed into later years. Responses of non-China metal refiners are more varied. The China oxide and metal export stoppage leads to the most significant change — earlier and greater increases in non-China metal refining capacity as well as sustainably higher production.

In all of the disruption scenarios, the higher NdFeB magnet prices lead to reductions in global magnet sales, followed by some delay in reductions of production, which affects both China and non-China producers. Figure 5 illustrates the magnitude of these reductions for each of the scenarios. The curtailment of illegal exports scenarios cause the largest and most sustained reductions in magnet sales and production.

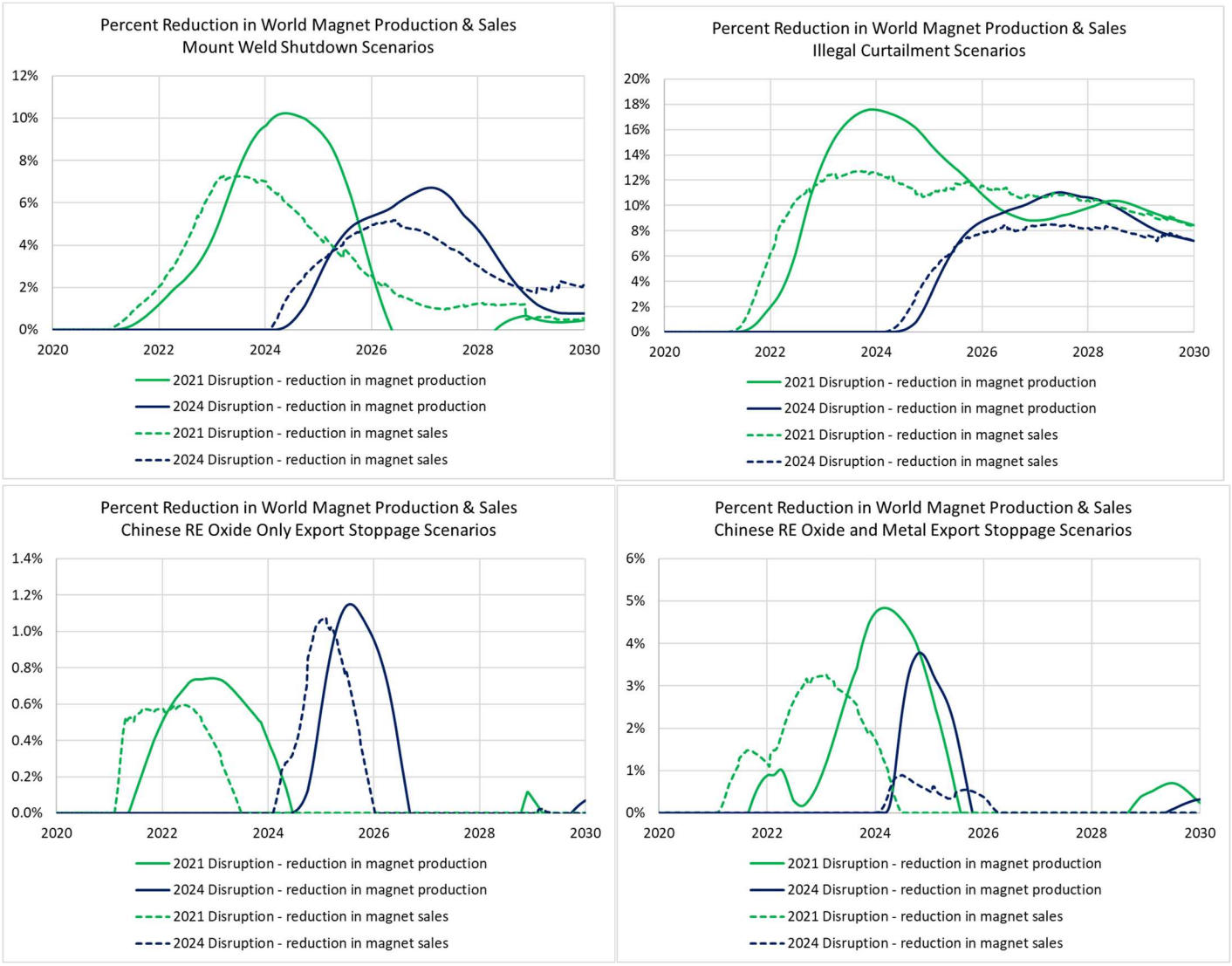

Figure 5. Reduction in world NdFeB magnet production and sales for the supply disruption cases.

While the worldwide impacts of the export stoppage supply disruptions do not last as long as the illegal curtailment scenario, the impacts on some non-China producers can be relatively larger and more persistent due to the different prices faced by China and non-China producers. The shifts in the location of metal and magnet production depend on the products that are covered by the export stoppage, as shown in Figure 6 (see Figures SI-9 and SI-10 for HPC results). In the two export stoppage scenarios that cover both metals and oxides, there is a shift in magnet production from non-China sites to China. With metals more difficult to obtain outside of China, non-China magnet production drops by about 40% relative to baseline production following the export stoppage, while Chinese magnet production increases to make up the difference. When the export stoppage is over, non-China magnet production recovers, but remains about 5–15% below baseline levels. In the oxide and metal export stoppage scenarios, increases in non-China magnet production capacity are delayed by several years.

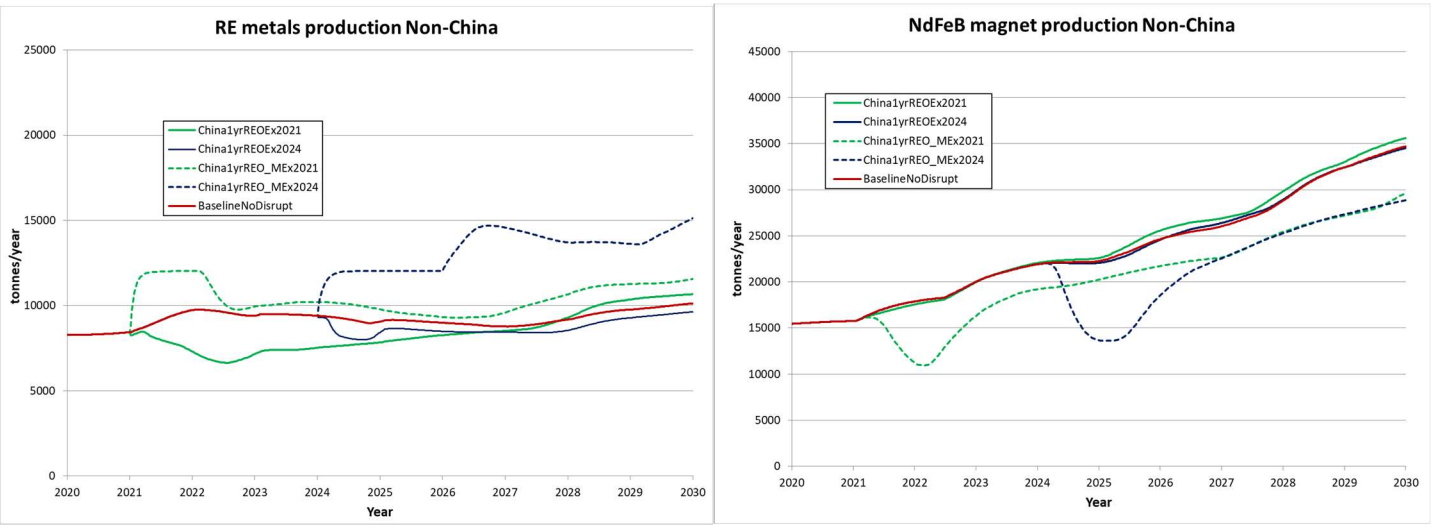

Figure 6. Non-China REE metal and NdFeB magnet production for the 2021 and 2024 export stoppage scenarios. Associated HPC results are provided in Figures SI-9 (RE metals) and SI-10 (NdFeB magnets).

The effect on metal refining in the oxide and metal export stoppage scenarios is the reverse: when Chinese metal exports stop, metal demand is increasingly met by non-China refiners, causing increases in their production capacity utilization and triggering decisions to build capacity. In later years, these capacity additions lead to lower capacity utilization among both the both China and non-China refiners.

However, in the export stoppage scenarios that cover only oxides, non-China metal refining decreases due to the reduced availability of oxides outside of China. Non-China magnet production is not significantly affected as these producers are still able to obtain needed metal from China.

The impacts of the Mt Weld shutdown and the curtailment of illegal exports scenarios on regional production shares are more limited. Without restrictions on trade between regions, the reductions in REO production affect both Chinese and non-Chinese metal and magnet producers, and there are less significant shifts in the locations of metal and magnet production.

Figures 7 and SI-11 show simulation results for NdFeB magnet composition. The curtailment of illegal exports and China export stoppage scenarios result in lower Dy content in non-China magnets. While the magnet price increases associated with the China oxide and metal export stoppage scenarios are modest in comparison to other scenarios, the reduction in Dy metal content per magnet produced by non-China producers is quite dramatic. This response is driven by a significant rise in non-China Dy metal prices. China magnet producers, on the other hand, slightly increase the Dy content in their magnets. In that scenario, with less Dy metal being exported, more becomes available to use in China at competitive pricing. In response to the Mt Weld shutdowns, on the other hand, didymium prices drive magnet markets, since Mt Weld produces significant amounts of didymium oxide but lower amounts of Dy oxide. The result is that China and non-China magnet producers increase the Dy content in their magnets slightly because of the reduced price incentive to substitute didymium for Dy. This result depends on model assumptions about the magnet producers' substitution behavior: specifically, that Dy use adjusts gradually toward a target level that is calculated based on the relative prices of Dy and Nd/Pr/didymium and on the benefits of higher Dy contents. Actual magnet producers' decisions will likely also depend on their technologies and processes that we have not captured in this model. For example, once a magnet producer has invested in a new capability such as grain boundary diffusion, it may not make sense for them to stop using this process if Dy prices fall relative to didymium prices.

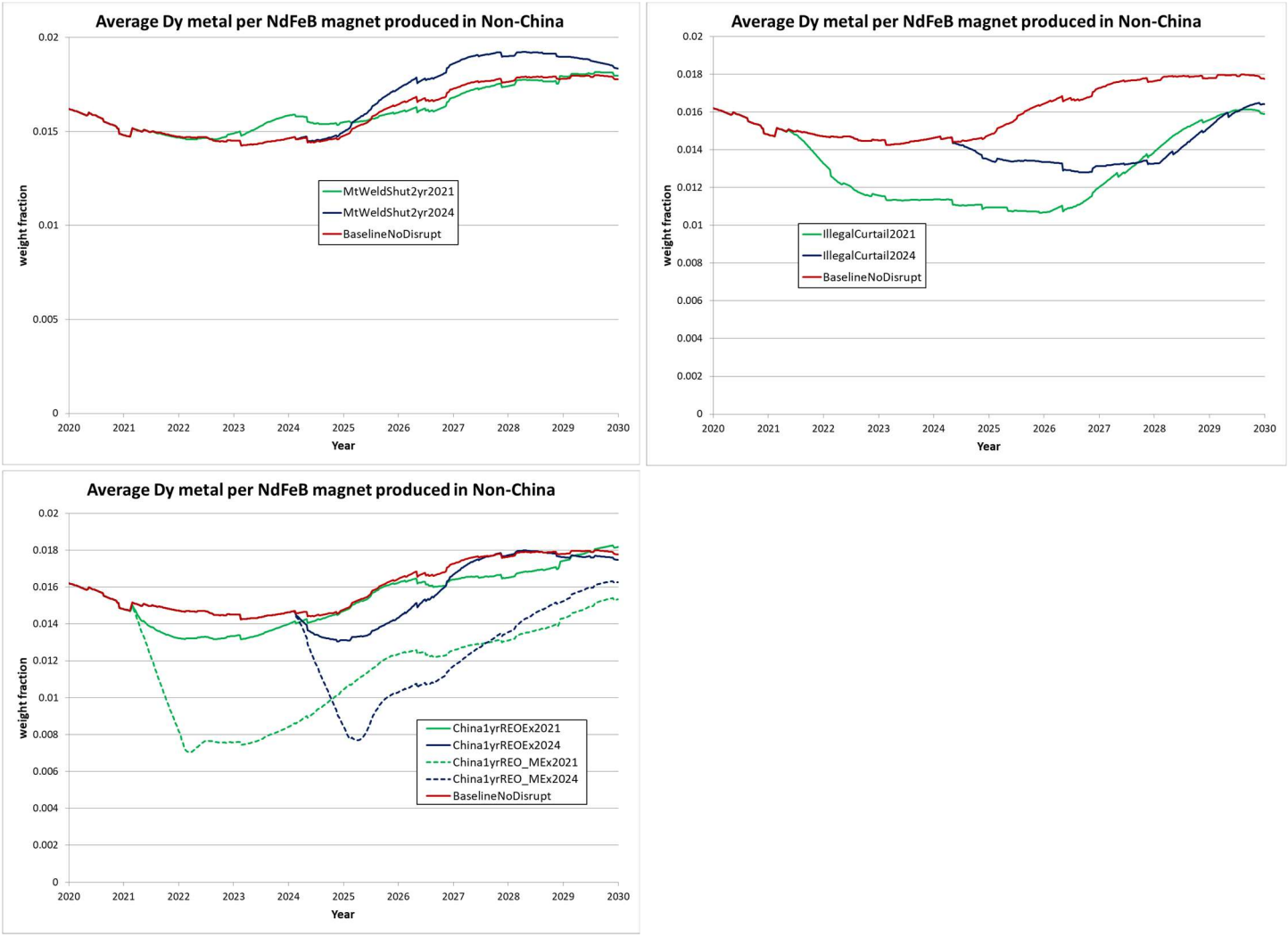

Figure 7. Desktop results of Dy metal content in NdFeB magnets produced by non-China suppliers for all scenarios. Associated HPC results are provided in Figure SI-11.

3.3 How might supply disruptions affect trade during and after the disruption?

Our particular interest with this question is to ascertain how supply disruptions might affect the dependence of non-China producers on Chinese-supplied REOs and RE metals. The approach to modeling trade in GCMat affects these results. Trade involves supplier choice, which as modeled depends on price offers, transaction costs, export limits, and contracts. Agents switch gradually to suppliers who offer the lowest prices, after accounting for transportation costs, taxes, and tariffs. They choose suppliers based on their previous period purchases and the relative prices offered. The share of demand that comes from each supplier adjusts gradually from its previous value based on the difference between prices in the two regions.

Trends in trade prior to the 2021 and 2024 disruptions affect the market conditions during and after the supply disruptions as seen in Figures 8 and SI-12. In the BaselineNoDisrupt scenario, the dependence of non-China buyers on China-supplied LREO steadily decreases after 2020, reducing the percentage of China-supplied didymium oxide, didymium metal, and La oxide in 2024 from that in 2021.

Non-China producers purchase significantly less tonnage of Dy oxide than didymium and La oxides; however, the fraction of supply from China is higher. Their dependence on Chinese Dy oxide supply declines as new mines, particularly HREO-rich mines, start-up in the region after 2024. In the desktop BaselineNoDisrupt scenario, about

67% of non-China Dy oxide demand is sourced from China in 2021, falling to 56% after new mines start up in 2024. On the other hand, non-China dependence on China Dy metal supply increases in the period from 2021 to 2024, from 28% to 36%. Non-China producers rely most heavily on China for the Y oxide supply: 97% and 96% in 2021 and 2024, respectively, in the BaselineNoDisrupt scenario.

For the baseline and disruption scenarios, Figures 8 and SI-12 present model results of China to non-China trade for the featured REOs and RE metals. These results show different trade behaviors for didymium and Dy oxides feeding the NdFeB magnet supply chain compared to La and Y oxides, which we accredit to the relatively higher NdFeB magnet demand growth.

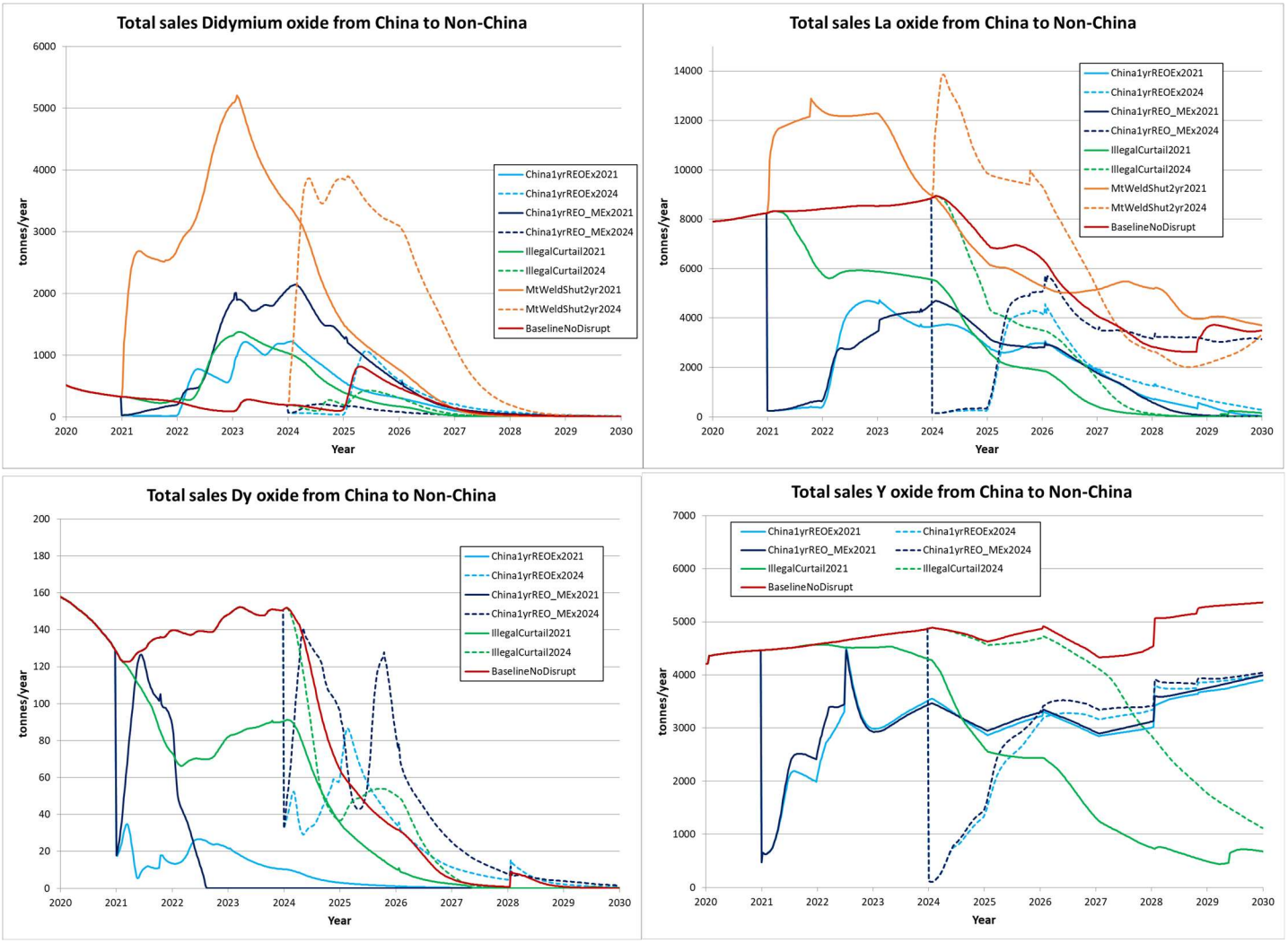

Figure 8. Desktop results of REO sales from China to non-China buyers for all scenarios. Figure SI-12 shows desktop results for RE metals and all associated HPC results.

In the case of the Mt Weld shutdown, non-China buyers of didymium and La oxides must purchase more from China to compensate for the loss of that mine's production. Imports from China remain higher than the baseline, particularly for didymium oxide until new REO mines open in the non-China region.

The legal and illegal Chinese export supply disruption scenarios lead to reduced dependency of non-China producers on Chinese supply of the La and Y oxides. The observed trade behaviors for the NdFeB magnet

components are more complex. In the curtailment of illegal exports scenarios, the results show an eventual increase in didymium oxide exports from China to non-China buyers, with the largest increases occurring if the disruption occurs in 2021. This response is driven by contracts to buy didymium oxide at stable prices that are held by non-China metal refiners, which allow them to keep their didymium metal prices relatively low as un-contracted world didymium oxide prices rise. Because of these contracts, non-China metal refiners gain market share and increase purchases of didymium oxide from China. The increases in exports from China decline over the course of 4–5 years after non-China mines start up in 2024. With these start-ups, the 2024 supply disruptions have a lesser effect on didymium oxide trade. The China REO and RE metal stoppages have the most significant effects on didymium metal trade. Earlier start-ups of non-China refining capacity lead to significant reductions in imports from China of didymium metal.

The effect of supply disruptions on the Chinese Dy oxide and metals trade do not mirror those of didymium oxide and metals. Results suggest that Dy oxide sales from China to non-China buyers initially decline after the disruptions and, particularly for the 2021 disruptions, remain lower than the baseline. Dy metal imports from China, on the other hand, reach higher levels in the out years. The rise in Chinese exports that was observed for didymium oxide does not occur for the Dy oxide because there are fewer contracts for the small amount of non-China Dy oxide production.

4 DISCUSSION and CONCLUSIONS

This paper describes the application of a dynamic, agent-based simulation model to explore the possible impacts of supply disruptions in the REE markets. Given the economic and societal criticality of REE materials, understanding the potential consequences of supply disruptions is important. In this study, we have applied the model to analyze a number of plausible supply disruption scenarios ranging in duration, geographic scope, and affected production and have discovered some interesting and diverse results.

Although differing in scope and duration, most of the supply disruption scenarios modeled in the desktop and HPC simulations resulted in price increases for the materials affected. In many cases, the price impact of disruptions reached multiple times prior years' prices. This finding is unsurprising and matches expectations based on the REE market response to the Chinese export quota reduction and export embargo to Japan in 2010 (Humphries 2013, Klossek et al. 2016). However, using GCMat to explore different types and characteristics of supply disruptions showed that their impacts could differ significantly. For example, disruptions of Chinese exports of REOs only versus those of both REOs and RE metals resulted in different effects on the NdFeB magnet supply chain, with non-China magnet producers being more severely affected when both oxide and metal exports were stopped. In fact, non-China magnet production is not significantly affected when only the oxide exports are stopped, as these producers are still able to obtain needed metal from China. When oxide and metal exports are stopped, non-China magnet production drops relative to baseline production. When China exports resume, non-China magnet production recovers, but remains below baseline levels.

The results from these simulations also help to highlight which REs may be most vulnerable to disruptions. The Dy oxide market showed the highest increases in prices during the long-term Chinese illegal curtailment and the 1-year China REO and RE metal export stoppage scenarios - more than experienced during the 2010-2011 REE market disturbance. GCMat does not model all market player behaviors, particularly speculative actions taken during disruptive periods, which could cause prices to spike even more dramatically. What the model does expose, though, are potential consequences to non-China Dy oxide and metal markets from the facts that: (1) China supplies more than 90% of Dy oxide and metal, (2) a large share of Chinese Dy oxide is produced illegally, and (3) Dy oxide production may be constrained by co-production of other REOs with lesser relative demand, as is the case with Y oxide. This suggests that products that rely on Dy oxide may continue to be at risk of shortages or high

prices in the event of disruptions to supply, in spite of progress that has been made in substituting away from Dy oxide over the past ten years.

Didymium oxide also remains vulnerable to price surges if there is a drop in production, largely because demand is growing, and there is limited potential for substitution away from didymium. However, the availability of some supply outside of China combined with relatively little use of didymium metals or oxides outside of China helps to limit the impacts of a Chinese export stoppage. Y oxide prices may also be impacted, but under different scenarios. Excess supplies help to cushion the effects of a drop in production, even in the illegal curtailment scenario where about 40% of Y oxide production is removed. However, because of the heavy reliance on China for supplies, Y oxide users outside of China could face shortages if exports from China are cut off. La oxide prices may also surge, especially in the export stoppage scenario, though the maximum prices are not as high as for the other oxides.

Further, the study found that supply disruptions may foster earlier and more non-China REO mine starts, some of which may not be able to sustain profitable capacity utilization and operations post disruption. Such outcomes may result from non-China mine owners having incomplete information on competing mines and on how demand will respond to high prices, and thereby constructing more capacity than needed to meet future market demand.

Results indicate that higher REO and RE metal prices occurring during supply disruptions trigger reductions in demand for RE-containing products, including NdFeB magnets, which continue after supplies are restored. Substitution away from NdFeB magnets, which are key components of high performance motors, could have a lasting effect, reducing the energy efficiency of wind turbines, electric vehicles, and consumer, industrial, and non-drivetrain electronics.

The scenario studies show that the geographical scope of the disruption affects trade, with GCMat enabling examination of the impact of various disruptions on sales of material between regions. A disruption outside of China resulted in increased sales of material from China to the rest of the world. Unsurprisingly, a disruption of production and thus supply from China resulted in reduced sales of material from China to rest of the world. At the end of the disruption, however, trade from China rebounds for some REOs while not for others. The effects on trade were found to last several years after the disruption ended, in some cases creating a tipping point in non-China sourcing of REOs and RE metals.

Last, in the scenarios where the disruption was temporary, price impacts tended to extend years beyond the disruption period; and the effects on production, capacity, and demand could last longer. One reason for the extended impacts on prices is that inventories depleted during the disruption period remain low and continue to impact prices after supplies become available. Shifts in production caused by the disruption that lead to the development of new capacity can have longer-lasting impacts. Consequent responses in the magnet supply chain could affect future growth in clean energy technologies.

Overall, this study has relevance for REE stakeholders who are concerned about the sustainable management of the REE supply chain. The results of this study illustrate how and why outcomes from different types of supply disruptions vary by their geographical scope, duration, and affected supply. While this study explored a range of global and regional supply disruptions, many other possible disruption scenarios could be modeled and could lead to different insights. Moreover, additional analysis could evaluate the effectiveness of different supply disruption mitigation strategies, such as recycling, product or technology substitution, and supply diversification.

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