SAND2015-5732C

Simulating the Neodymium Supply Chain Using Explicit Dynamic Supply and Demand

Abstract

America's clean energy technologies rely on materials with highly specialized properties that allow them to compete in a dynamic energy economy. These materials are often referred to as 'critical materials' and are vital to enabling modern innovations but are surrounded by uncertain supply and demand, as indicated by dramatic changes in the price of materials. In order to meet growing energy demands with projected clean energy technologies an in-depth understanding of supply and demand for critical materials is required. In 2011, DOE released a report identifying five high risk materials necessary for clean energy technology advancement in the United States. Neodymium, europium, terbium, dysprosium, and yttrium, each with significant supply chain vulnerabilities. To mitigate the risks associated with these vulnerabilities, three strategies are generally accepted: 1) increase supply by recycling material, 2) decrease demand by developing substitute materials or technologies, or 3) increase extraction efficiency and productivity. In this paper, we explore the potential of all three strategies in meeting long term clean energy technology projections goals. Additionally, we explore an alternative method to investigating market dynamics within system dynamics that seeks to improve cooperation between system dynamicists and orthodox economists.

1. Introduction

The global supply chain for rare earth elements (REE) is a complex and vulnerable system filled with supply uncertainty, market unpredictability, and dynamically changing agendas. Because REEs possess unique chemical and physical properties they lend well to advancing modern technology through increased efficiency, miniaturization and durability. In particular, REEs are important to clean energy technologies including permanent magnets for wind and electric vehicles, phosphors for energy efficient lighting, and high-output batteries.

From 2010 to 2011, due to an export limitation by China, the price of REEs increased dramatically. The price of processed dysprosium oxide rose from $310/kg to almost $3500/kg and the price of neodymium oxide rose from $42/kg to $283/kg in this period (Achterbergh, Espejo, Regtering, & Schwaninger, 1997). Similar increases were displayed in praseodymium, terbium, and yttrium. These price increases prompted concern from U.S. electronics and clean energy technology manufacturing industries. Most experts attribute the 2010 price increase to a shrinking supply from the Chinese export quota exacerbated by an increase in demand through company stockpiling (Jha, 2014). Current

REE production is primarily conducted in China, but this has not always been the case. From the late 1960s through the mid-1980s, California's Mountain Pass Mine (which stopped production in 2002) was the primary world REE producer, but since the mid-1980s, Chinese mines have grown to more than 90% of global REE production (Morrison, 2012). Since the price spike of 2010 and 2011, the opening of the Mount Weld Mine in Western Australia and recent re-opening and improvements to Mountain Pass have captured 7% of global REE production (Kingsnorth, 2014).

In addition to dynamics of competition in the global REE market, the composition of REEs varies greatly among the world's mineral deposits. Experts posit that production of the heavy REEs (e.g. samarium, europium, terbium, dysprosium, yttrium) will remain primarily in Northern China's Bayan Obo mine due to the rich nature of its deposit and the complexity to separate heavy REEs. Conversely, the light REEs (e.g. lanthanum, cerium, praseodymium, neodymium) could have a more diversified source of production in the future pending the successful rollout of non-Chinese mines (Adamas, 2014; Humphries, 2013). Other sources for REEs, such as material substitution and end-of-life product recycling, are also potential supply options that are currently less well-researched.

Fear that the tumultuous market will limit industrial activities has lead several organizations to initiate plans to mitigate shocks and shutdowns caused by the unreliable nature of the REE global supply chain. For example, the U.S. Department of Energy (US DOE) has funded the Critical Materials Institute (CMI) as one of its Energy Innovation Hubs. CMI is pursuing research in three strategic areas: diversifying supply, developing substitutes, and recycling (DOE, 2011). US DOE is interested in whether the United States can meet clean energy growth targets, especially if there are supply disruptions in the future. Furthermore, they want to know how CMI's research portfolio contributes to the United States' resilience to future price shocks.

In this study, we explore how the CMI strategy could contribute to the future balance of REE supply and demand, particularly in terms of meeting U.S. targets for manufacturing of clean energy technologies. We do so while contrasting two system dynamics methods for simulating commodity markets: the generic system dynamics commodity market method (herein: generic SD commodity market model) employed and professed by Sterman (2000) and a new method that explicitly creates dynamic supply and demand curves (Jeffers, Jacobson, & Searcy, 2013). The goal of the new method is to develop a system dynamics market simulation approach that will be more acceptable and translatable between system dynamicists and orthodox economists.

Diversifying Supply

Diversifying the supply of REEs entails the development of new REE sources outside of China. This includes both mining projects and refining capacity, with an emphasis on the former. The main issues associated with diversifying the supply of REE ore are the long

timeframe of mine project development, co- and byproduct supply, uncertain market conditions, resource quality, and more stringent environmental standards in developed nations.

Developing new mining projects takes a considerable amount of time due to large startup and capital investment costs. Before a potential mining project produces ore, it must go through stages of exploration, resource classification, feasibility assessments, and development studies. This process occurs through performing various pre-feasibility studies and feasibility studies to assess the long term profitability. These feasibility studies evaluate ore extraction capabilities, environmental compliance, and social acceptability. Only after a project has demonstrated ability to meet all requirements will it move into the development stages, which can take several additional years. Since mines are costly and long-term endeavors, uncertain market conditions exacerbate the long timeframe issue, particularly for lower quality, marginal deposits which are only feasible when prices are high.

Recent concerns for continued availability of REEs has increased interest in mining projects and over 50 projects outside of China have been proposed, most of which are still highly speculative (TMR, 2015). Of these, only 2 have actually come into production as of 2015. These include the expansion of Mountain Pass mine (operated by Molycorp) in California and the Mount Weld mine (operated by Lynas) in Western Australia. Because the Mountain Pass mine was a pre-existing REE mine that quit production in 2002 due to increased environmental regulations and low REE prices, this project was unusually quick to come into production (Molycorp, 2015). Some of the more promising projects on the near-horizon include Browns Range in Western Australia, Steenkampstaal in South Africa, and Bear Lodge in Wyoming (TMR, 2015).

Specific REEs are not the primary resource at most REE mines and at many proposed sites, leading to concerns that their production is largely dependent upon the market for the primary co- product. For example, Bayan Obo produces rare earths along with niobium as a byproduct of iron, its primary product. This type of multi-use mining is referred to as co-mining, and creates a complex economic system which is not explored in this study. The two currently operating mines outside of China both consider rare earth elements as their primary assets (Molycorp, 2015; Proaviceinvestors.com, 2014).

Recycling

Recycling refers to the ability of manufacturers to source their materials from secondary sources. Recycling of REEs is generally done in three ways. The first is to recover the material itself from an existing product so that it can be reused and transformed into something else. An example of this would be the recovery of europium from phosphor dusts obtained from spent fluorescent lamps. The second is to recover the specific item of interest from a larger product so that it can be reused in a similar application, such as the recovery of the NdFeB magnet from a discarded hard drive. Finally, recycling of

scrap occurs during processing manufacturing using REEs, and can be represented as an improvement to processing or manufacturing efficiency.

There are several challenges associated with recycling, namely, that many products are not designed to be disassembled and recycled, REE recycling technology is in its infancy, secondary sources of REEs depend on the supply of end-of-life products, and that oftentimes the profitability of recycling lies in other materials in a given product, not in the REEs (Binnemans et al., 2013).

Substitution and Increased Manufacturing Efficiency

Substitution refers to the ability of end-users to use one material or technology in place of another and (for our purposes can be thought of in two ways. The first is *material substitution*, which can be thought of as element-for-element substitution. An example of material substitution is in neodymium (NdFeB) magnets, where the usage of dysprosium can be reduced with the addition of more neodymium. The decrease in dysprosium, however, is associated with a loss of the magnet's heat resistance properties. The second type of substitution is *system substitution*, which can be thought of as the substitution of one technology for another. An example of system substitution is the substitution of NdFeB magnets for samarium cobalt (SmCo) magnets in wind turbines. In an even broader sense, or, at a higher level, direct drive wind turbines can be substituted for gearbox turbines. Similar to the example of material substitution, there are tradeoffs associated with system substitution.

There are two main challenges facing REE substitution in clean energy technologies. The first challenge is the issue of obtaining similar properties from materials and technologies which use fewer or no REEs. The second challenge is that new technology takes a long time to create, meaning that viable commercial alternatives to current technology may not be able to alleviate material availability concerns in the near future.

2. Contrasting Methods for Material Supply Chain Economics

This analysis is based on a system dynamics approach to resource economics implemented using the Powersim Studio simulation tool from Powersim Software.

Fundamentally, economics as a field aims to explain how individuals allocate resources to satisfy needs by considering the production, trade and consumption of goods and services (John M. Hartwick, 1997). Forrester's article titled "Economic theory for the new millennium" stressed great opportunity for applying system dynamics to system-scale economics (Forrester, 2003). Until recently, the application of system dynamics has been considered a heterodoxical economic approach because of its perceived ideological differences with orthodox economics (Crookes & De Wit, 2014; Radzicki, 2003). Our new method for representing materials markets seeks to bridge this gap.

This model of critical material supply chain economics uses stocks to represent important storage of critical materials in different forms, as shown in Figure 1. The model is highly generic, able to be configured for many alternative materials, suppliers, and consumers. Its origins are the exploratory model of Pruyt (2010), which was used to experiment with the growth of a recycling industry to alleviate mineral scarcity. The structure of the Pruyt model was studied and found to have important differences to the generic system dynamics structure for commodity markets outlined by Sterman (2000) and interpreted in Figure 2. Furthermore, important characteristics of REE supply chains, as well as a desire to communicate the system dynamics methodology to orthodox resource economists, led to a further alteration of the Sterman and Pruyt structures. The following section describes our structural changes.

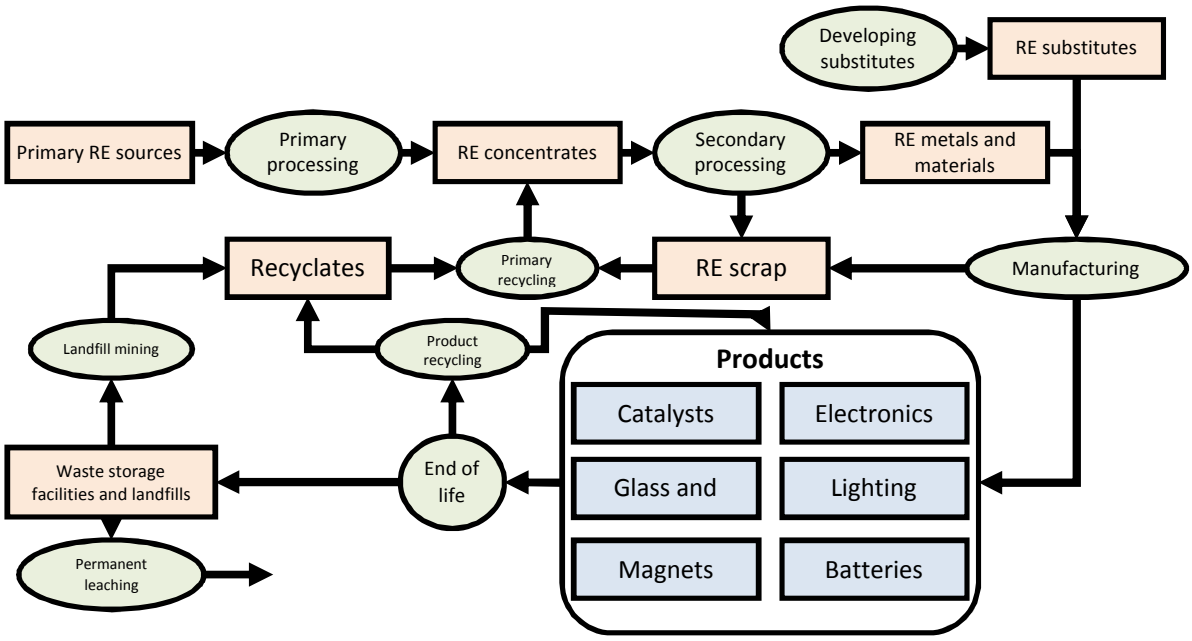

Figure 1. Stock and process diagram of the global rare earth supply chain, where ovals are processes and rectangles are stocks of material in different forms.

There are three independent suppliers of REE in the model: extraction and processing of mineral resources, recycling of end-of-life products, and substitution of alternative materials. The model treats them as independent entities that interact with the supply chain in different ways, resulting in subtle differences in structure to Figure 2. Each supplier has capacity and capacity expansion decisions, represented by different parameterizations of the left side of Figure 2.

Extraction is the most straightforward of the suppliers. It represents all mining and processing of ore into rare earth oxide throughout the world. This entity removes known extractable resource from the *Resources* stock and delivers it to the *Material Inventory* stock. Recent exploration of REE resources has led to speculations that the worldwide extractable resource represents more than a 100-year supply (Berger, 2009;

USGS, 2014). For this reason, exploration and discovery dynamics as described by Naill (1974) are not currently represented.

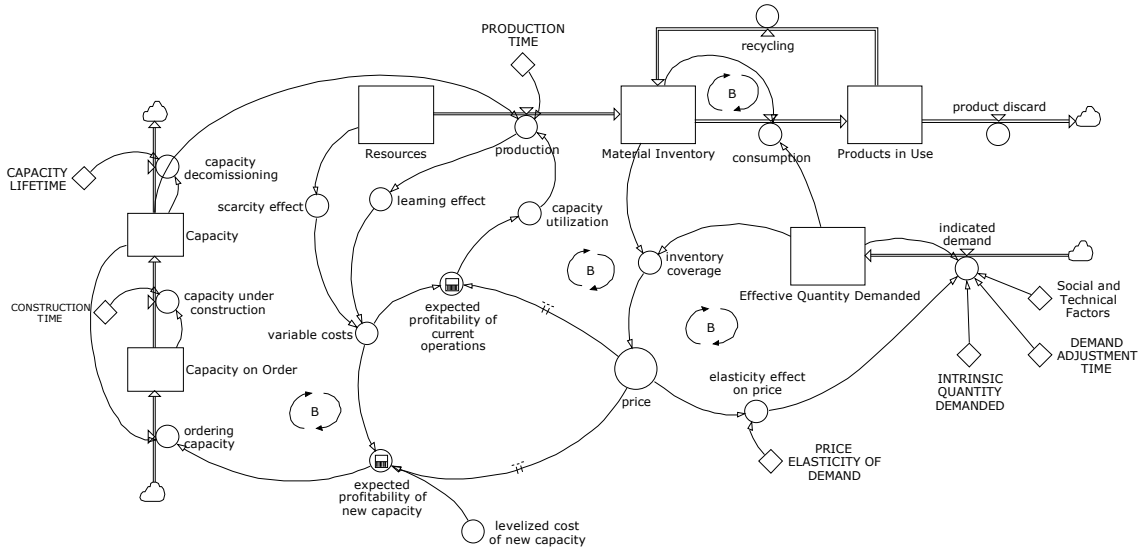

Figure 2. High-level structural diagram of feedback mechanisms in the generic SD commodity market model (Sterman, 2000).

The recycling supplier uses its capacity to move REE from the *Products in Use* stock back to the *Material Inventory* stock. This entity represents the recycling of end-of-life product such as permanent magnets and not recycling of scrap that is present during processing and manufacturing of REE goods. Assuming that the recycler is unable or unwilling to incentivize discard of REE goods, they are limited to the amount of REE being discarded at any one time. This phenomenon is what's known as a resource recovery wall. The maximum amount recyclable also sends a signal to the recycling industry to limit capacity expansion only to the expected capacity needed for future REE good discard.

The substitution supplier does not use REE to meet demand, but a substitute material which creates the same ultimate utility in the final product. The substitution of SmCo magnets for NdFeB magnets is one such example. In the model, the substitute is not tracked in the REE supply chain, but instead by its own separate inventory stock. Otherwise, substitution has a similar structure to the other suppliers – making capacity investment decisions and responding to price with production decisions.

Scarcity, Learning by Researching, Learning by Doing

There are two feedback loops for each supplier that affect their operating costs. The first is a resource scarcity loop (Figure 3a), in which the declining existence of the raw resource contributes to increasing cost. The relationship is linear, such that at the beginning of the simulation, the cost is at its initial condition, and when zero resource remains, the cost to access deeper reserves is multiplied by the *Extraction Max Cost*

Fraction at Resource Limit. This assumes that when the resource stock becomes negative, it is simulating access to deeper reserves than were initially considered in the parameterization. The extraction sector is the only sector in our parameterization that uses this resource scarcity effect.

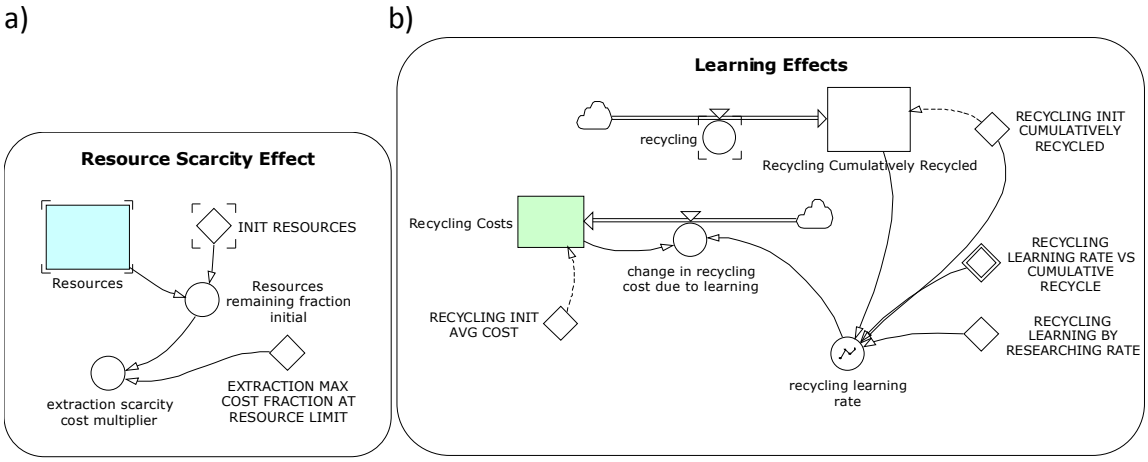

Figure 3. Model structure for the scarcity effect on production costs (a) and for two types of learning effects on production costs (b) – learning by researching and learning by doing.

The second loop that affects supplier costs is the learning loop (Figure 3b). This loop affects the rate of cost improvement for the sector. There are two components to the rate: one which is dependent on the production of that sector – learning by doing – and another which is dependent on an exogenously specified constant improvement – learning by researching. It is our hypothesis that CMI can influence the learning by researching rate, but will have less impact on the learning by doing relationship.

Capacity Expansion Decisions

In the generic SD model of commodity markets, the decision by a supplier to expand or contract capacity is determined by a relationship to expected long-term profitability. The expected long-term profitability is either a smoothed or forecasted function of the supplier's variable costs, the cost of new capacity, and the commodity price. Our interpretation of this method uses a forecasting function which takes as a parameter the suppliers' *planning time*, projecting the profitability function out to ½ *planning time* using a historical trend based on the previous ½ *planning time*. The long-term expected profitability is then used in a table function to set the supplier's desired growth rate. A growth rate of 1.2 would mean that the supplier is targeting a 20% capacity expansion over the next *planning time*. We refer to this method as pure profit-driven capacity expansion.

There is a potential inaccuracy in the profit-driven capacity expansion method when applying it to industries dominated by one supplier, especially when alternative suppliers may grow quickly if they become profitable. If an alternative supplier, such as a substitution sector in the REE case, determines that their long-term expected

profitability is high, they may target a high growth rate. However, a small supplier growing at 20% per year can remain a small supplier in comparison to the dominant supplier for quite some time. This long ramp-up period is not descriptive of industries in which suppliers are constantly hedging by exploring new means of supply, and can grow very quickly when profitable.

Our alternative capacity expansion method, which is herein referred to as relative utility capacity expansion, assumes that suppliers will use forecasts of quantity demanded in their decision, and compare the relative utility of all supply options to decide the type of capacity to invest in. The model uses the logit function from discrete choice theory to calculate the relative utility of investing in one type of supply capacity over another (Menard, 2002). This function and its structural implementation are shown with a shaping parameter β in Figure 4. The supplier uses the resultant relative utility, U_i, and targets expansion to capture that fraction of the quantity forecasted to be demanded after the *planning time*. If recycling's relative utility of capacity expansion is 0.6, then that industry will target expansion to capture 60% of the forecasted quantity demanded.

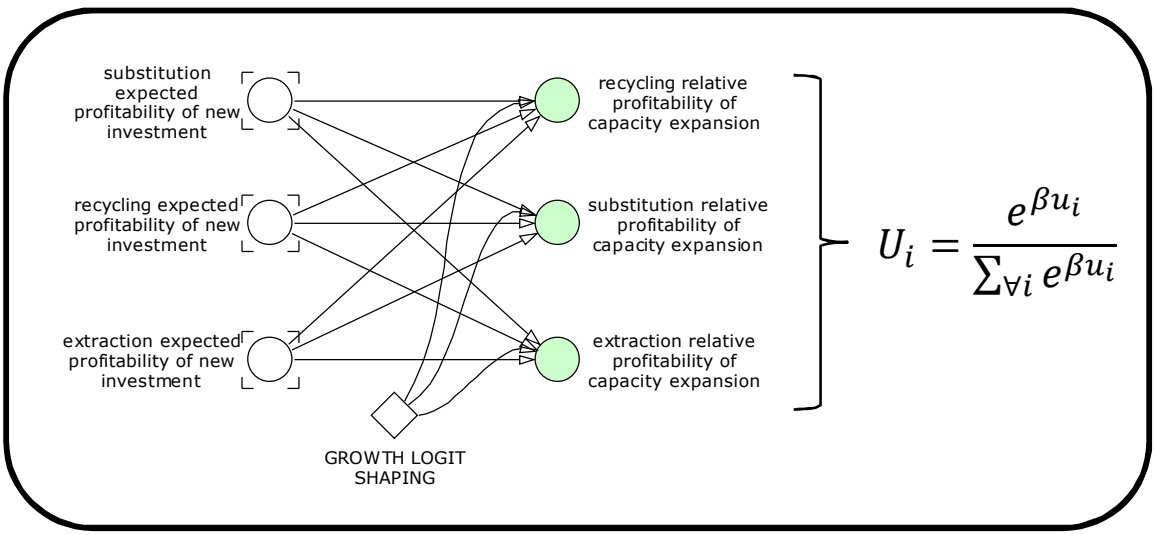

Figure 4. Calculation of relative utility of capacity expansion for each supplier (U_i) uses a multinomial logit function at right.

Market Clearing: Who Gets What and At What Price?

The generic SD commodity market model described by Sterman (2000) sets price based on a comparison of quantity in supply (e.g. inventory) to quantity demanded. This ratio is called inventory coverage, and can be expressed as the amount of time current inventory would last if no further production were available. The price responds to the inventory coverage as an exponential sensitivity: if the inventory coverage is less than the target coverage time, price goes up as a function using inventory coverage as the base and sensitivity as the exponent. This behavior may be approximately correct for a

spot market, in which a commodity must be placed into inventory before it can be sold. With REEs and many other commodities, the majority of transactions are contract-based, and the price is more responsive to the capacity of suppliers and demanders than to inventory.

Furthermore, in the generic SD commodity market model, the fractional response of quantity demanded to price is log-linear. As price increases above a nominal value, the quantity demanded decreases by a proportional percentage. This proportion is known as the price elasticity of demand and is constant in the generic SD approach. In a materials market such as the REE market, the demanders do not have a constant elasticity because they themselves are limited by capacity and storage constraints. They are consumers in the REE market, and suppliers in another market. For example, a magnet manufacturer has very little utility for material beyond that which he can process and/or store in a given period of time. If price continues to decrease past this point, the magnet manufacturer will likely still not purchase additional REE until he can expand capacity or invest in storage, both of which have explicit time constraints, and are modeled explicitly with our approach. The generic SD commodity market model does not reflect this condition.

Decisions about production are made using table function relationships to profitability in the generic SD commodity market model. This works well when inventories are tightly tied to prices. However, when relative capacities drive price, a simple relationship to profitability tends to misrepresent the more long-term contractual market. Assuming the contract-based market clears such that inventories are balanced, a co-dependent method that balances supply and demand using the relative cost-plus-margin of suppliers and the willingness to pay of consumers is appropriate.

Microeconomic theory describes the price that will clear a market in equilibrium. There are many complex and useful abstractions that can be made based on this theory that are not reflected in the generic SD commodity market model. On the other hand, a common criticism of orthodox economics approaches utilizing supply and demand theory is that they ignore or make implicit time lags that constrain the system. In reality, these time lags can lead to a dynamic equilibrium in which price is always “chasing” a value that clears the market but may never reach it.

The method utilized for simulating pricing and partitioning in this model and introduced by Jeffers et al. (2013) seeks to reconcile the stated differences between the system dynamics and more orthodox economic approaches. It does so by explicitly creating instantaneous supply and demand curves that are functions of endogenous model variables. Referencing Figure 5, the method draws incremental demand distributions centered about the variable costs plus margin of each supply or demand sector. These distributions have a spread that represents the heterogeneity within each sector. A highly regulated, single-process, single-source sector will have a very thin distribution, while a more variable, multi-process, diverse sector will have a wide distribution. A

useful interpretation for these curves is: given a change in price, how much more will the entity will be willing to buy/sell? The area under each curve is the current production capacity of that entity. The curves are dynamic, in that if production/consumption capacity changes the curve grows vertically about the delta quantity axis, and if costs change the curves move correspondingly about the price axis.

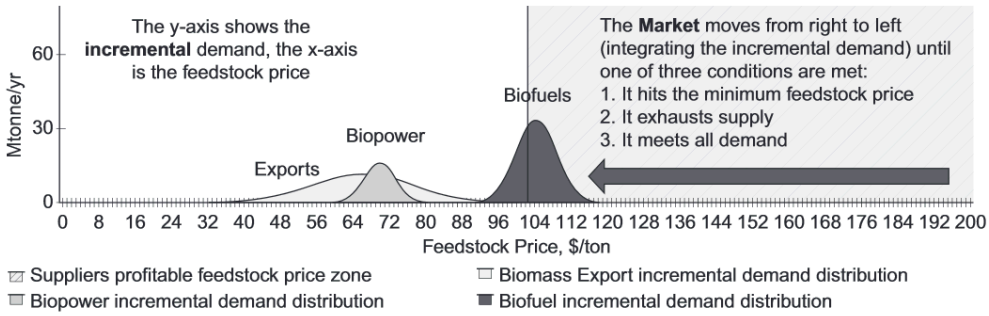

Figure 5. A description of incremental demand distributions by Jeffers et al. (2013), reproduced with permission from the authors. In the bioenergy case described here, the supplier is monopolistic and the purchasers are the biofuels, biopower, and export sectors.

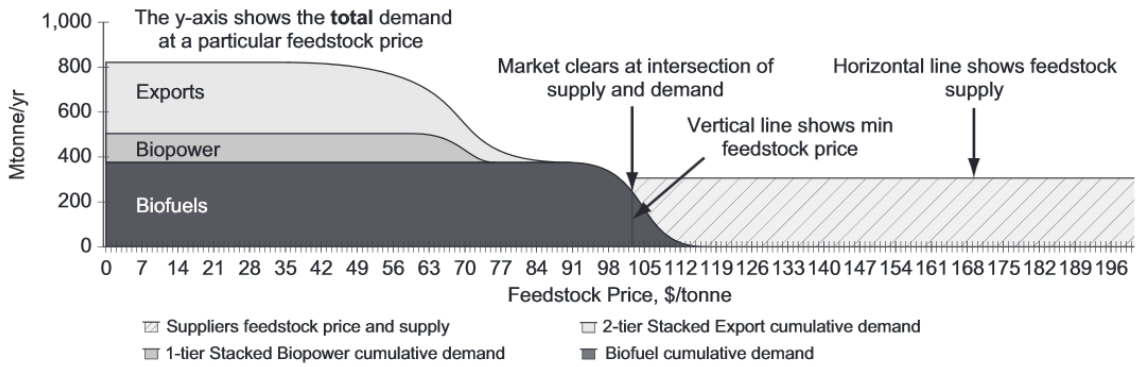

Figure 6. Instantaneous supply and demand curves that describe a market at a single point in time. The axes are descriptive for the progression of the method, however when communicating to an economist they should be inverted to follow convention.

To represent a market for the commodity, the method integrates supply distributions from left to right (low prices to high prices), and demand distributions from right to left, creating instantaneous supply and demand curves as illustrated in Figure 6. These curves are instantaneous in that they represent the quantity at a particular point in time that each sector is willing to purchase/sell at a particular price. The various suppliers and demanders are stacked (supplier on supplier, demander on demander) to create a representation of the full supply and demand currently on the market. The current price is the intersection between these stacked curves. Partitioning works by evaluating the individual, non-stacked curves at the current price. Supply and demand elasticities are endogenous and dynamic as the curves move due to various feedbacks and the intersection point changes.

3. Exploring an Export Restriction on Neodymium

A hypothetical neodymium market was created using the model and methods previously outlined to explore how the CMI strategy could contribute to the future balance of REE supply and demand in terms of achieving U.S. targets for clean energy technologies. The simulation covers a 50-year time period to investigate long-term shifts in supply competitiveness and price behavior. The primary exogenous input for the model is intrinsic demand through time, assumed to grow as shown Figure 7. The intrinsic demand growth represents an approximate doubling in neodymium oxide use by clean energy and other sectors over this time period. In the model, actual quantity demanded is allowed to differ from this curve dependent on price and method selection.

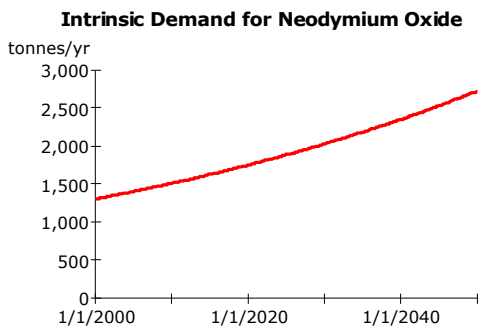

Figure 7. The driver for growth in actual demand is the exogenous input *intrinsic demand*.

The basic question we asked of the model is: assuming the growth in Figure 7, will Neodymium demand be met at a "reasonable" price? The definition of reasonable is left up to stakeholders, so it is the model's role to explore potential price differences. Additionally, we asked whether actions that CMI is taking now to research alternative supply, substitution, and recycling avenues can decrease the effect of another export restriction by China. These questions were explored using two scenarios for the exogenous Chinese withholding of capacity through time, illustrated in Figure 8Figure 8. Extraction capacity withheld from the market through time for the single restriction case (a) and the dual restriction case (b).. During the export restriction, 90% of global extraction capacity is withheld from the global market for three years. Furthermore, we explored whether the learning by researching effects assumed to be imparted by the CMI strategy have an effect on these events. Table 1 outlines the three scenarios that serve to contrast methods as well as explore these questions.

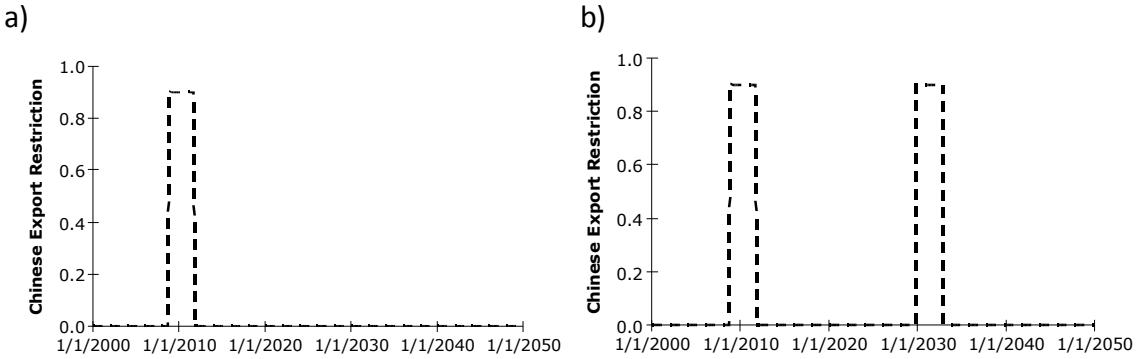

Figure 8. Extraction capacity withheld from the market through time for the single restriction case (a) and the dual restriction case (b).

Table 1. Selection of export restriction and learning parameters for three scenarios.

Scenario	Export Restriction	Extraction learning by researching	Recycling learning by researching	Substitution learning by researching
Single Restriction, no effect of CMI	Figure 8(a)	0.01 %/yr	0 %/yr	0 %/yr
Dual Restriction, no effect of CMI	Figure 8(b)	0.01 %/yr	0 %/yr	0 %/yr
Dual Restriction, CMI lowers costs	Figure 8(b)	0.05 %/yr	0.3 %/yr	0.3 %/yr

Scenario 1: Single Restriction, no effect of CMI

Results of variable costs through time for the three supply sectors (Figure 9) are nearly identical in this scenario using the two alternative methods discussed herein. The extraction sector is learning by doing, which lowers costs until 2013, at which point a resource scarcity effect begins to dominate and increases extraction costs at a rate proportional to extraction volume. Because learning by researching is off, the recycling and substitution sectors do not experience decreased costs until they begin to climb their respective learning by doing curves around 2030.

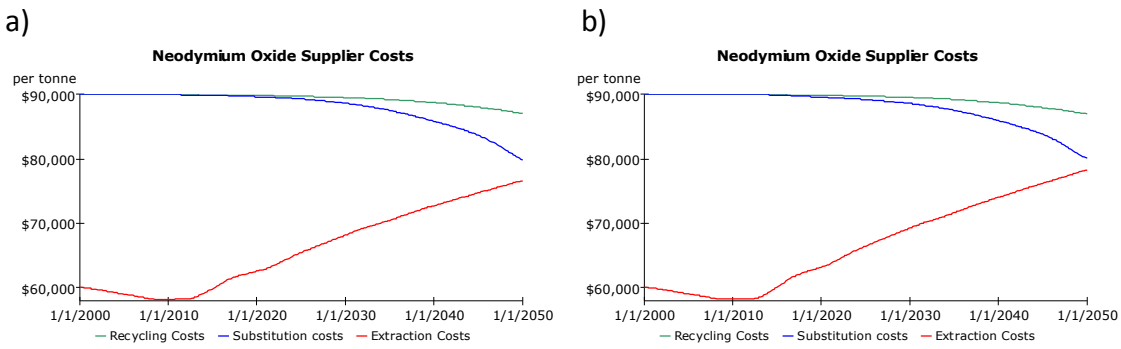

Figure 9. Model results of production costs for each sector through time using the two alternative methods. The impact of scarcity eventually increases the cost of extraction, while learning by doing effects ultimately decrease the cost of recycling and substitution.

In contrast to costs, price results are quite different for the two methods, as illustrated in Figure 10. Both methods exhibit a large price spike starting in 2009, which can be calibrated using different parameters in the two methods. The generic SD commodity market method (Figure 10a) reaches a high price quickly, at which point price elasticity of demand effects begin to decrease quantity demanded, increasing inventory coverage, which lowers price, and this loop begins to seek a new price equilibrium. The dynamic supply and demand method (Figure 10b) steadily increases price as the consumer of REE passes more and more of its cost increases on to its own customers – the consumers of permanent magnets. These magnet customers respond with their own elasticity, but the effect is second-order and relatively weak. The REE consumer also begins to decrease their capacity, but at a very slow rate because even at these high Neodymium Oxide prices, they are still nearly breaking even because Neodymium is only a portion of their total costs.

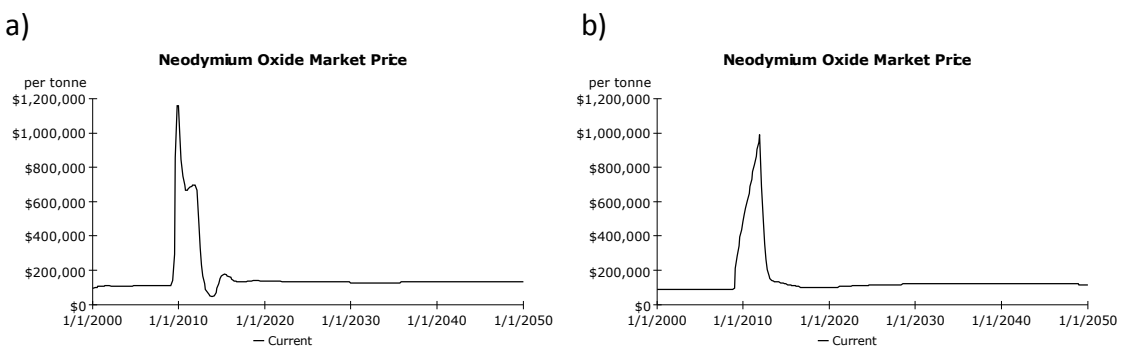

Figure 10. Model results of price for the single restriction scenario using the generic SD commodity market method (a) and the dynamic supply and demand method (b).

Another interesting difference in the price behavior of the two methods occurs after the conclusion of the export restriction period. With the generic SD commodity market model, price dips below its nominal equilibrium value as the sudden glut of capacity increases inventory coverage. With the dynamic supply and demand method, price falls to a value above the eventual equilibrium. This is because the REE consumer has a lag in setting its price to the end consumer, and it had been passing increased costs on to

these consumers during the export restriction. Therefore, this intermediate consumer has a higher willingness to pay for a couple of years after the export restriction's conclusion.

The flow of material from alternative sources – shown in Figure 11 – also exhibits differing behavior between the methods tested. At the beginning of the simulation, extraction makes up nearly 100% of the supply with both methods. During the restriction period, recycling and substitution grow and begin producing because they are suddenly profitable. However, for four years after the restriction, behavior differs. Demand capacity has a different meaning in the two methods. For the generic SD method, it is directly related to the quantity of REE ordered. For the dynamic supply and demand method, it is the current capacity of the demand entity – e.g. the horizontal line at the top of the demand curve in Figure 6. After the export restriction is over, material flow is very high for a short period to make up inventory shortfalls in the generic SD method, and it then dips after inventories rebound. In the dynamic supply and demand method, however, supply flows are much more stable because price and demand capacity are also more stable.

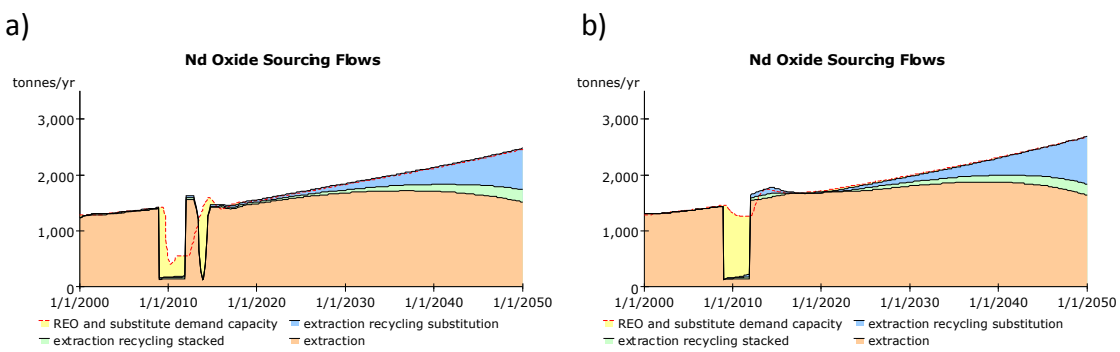

Figure 11. A comparison of material flows and demand capacity for the single restriction scenario using the generic SD commodity market method (a) and the dynamic supply and demand method (b).

Figure 12 shows behavior of production capacities for the three supply sectors. Since cost dynamics are virtually the same for the two methods, most of the difference in capacity behavior comes from the differences in price using the two methods. Namely, the extraction sector downsizes with the generic SD method during the price dip after the export restriction event. Because there is no price dip using the dynamic supply and demand method, capacities retain their oversupply condition.

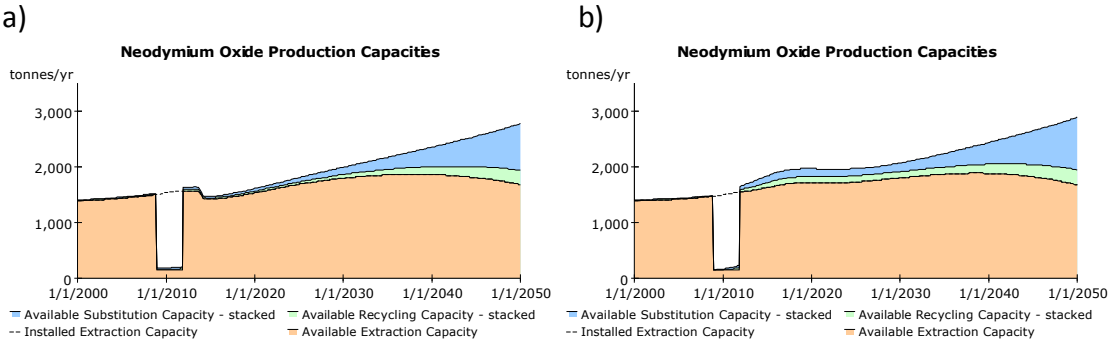

Figure 12. Comparison of supply capacity for the single restriction scenario using the generic SD commodity market method (a) and the dynamic supply and demand method (b).

Scenario 2: Two Restrictions, no effect of CMI

The second scenario explores the condition in which research improvements from CMI do not exist, and there is a second export restriction placed in 2030 that mimics the first – e.g. 90% of extraction capacity withheld from the market for three years. Market price using the two methods is illustrated in Figure 13. With both methods, the second price spike has a lower magnitude and similar shape to the first perturbation.

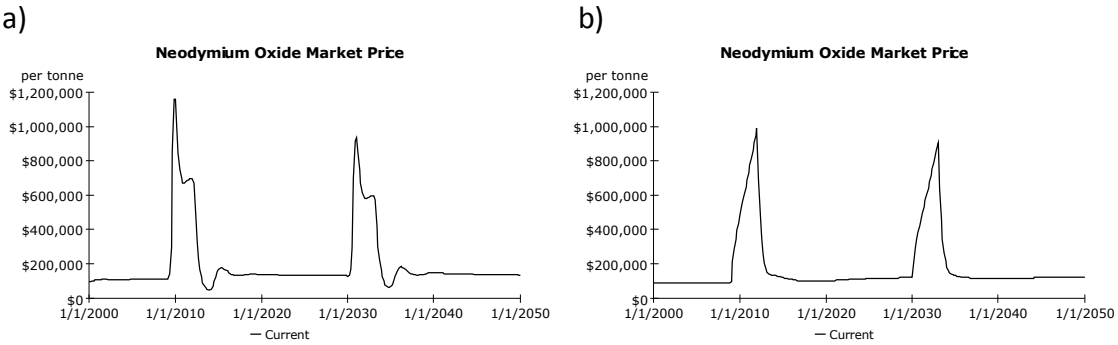

Figure 13. Price behavior for the dual restriction scenario using the generic SD commodity market method (a) and the dynamic supply and demand method (b).

Results of material source flows (Figure 14) illustrate why the price spike is lower in 2030 than in 2009. There is greater sourcing from the substitution and recycling suppliers in 2030 than in 2009 using both methods, allowing a greater fraction of demand to be satisfied by suppliers outside of China. The primary behavior modes are similar to the single-restriction scenario.

a) b)

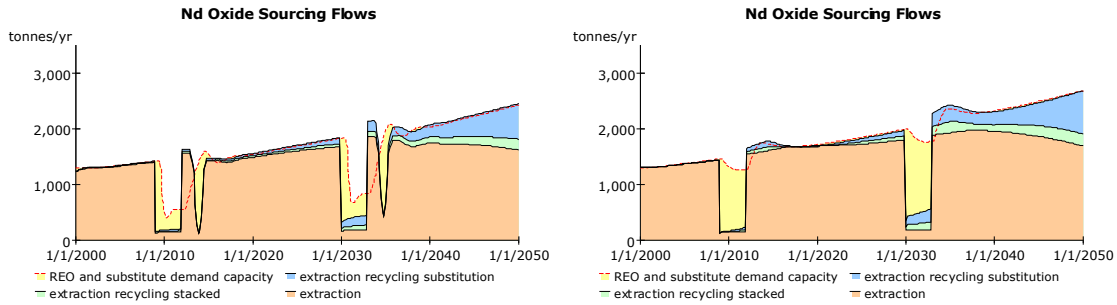

Figure 14. Comparison of material flows for the dual restriction scenario using the generic SD commodity market method (a) and the dynamic supply and demand method (b).

Production capacities using the two methods are illustrated in Figure 15. Without CMI influencing research-based learning, substitution holds 9% of capacity before the second export restriction event, and recycling holds 4%. Behavior is also similar in characteristic to the single-event case.

a) b)

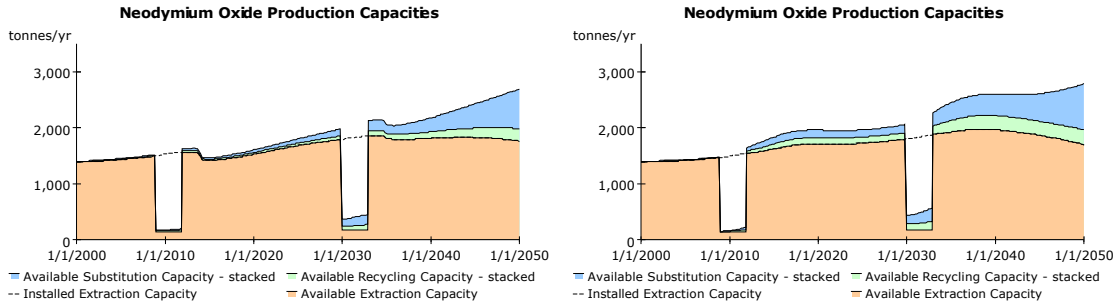

Figure 15. Comparison of supply capacity for the dual restriction scenario using the generic SD commodity market method (a) and the dynamic supply and demand method (b).

Scenario 3: Two Restrictions, CMI lowers costs

When the potential effect of learning by researching is included with the two-restriction scenario, cost competitiveness of the alternative source industries improves as illustrated in Figure 16. The addition of a 0.3% per year constant learning, which is independent of quantity produced, allows both alternative sectors to be at cost parity with the extraction sector by the end of the simulation.

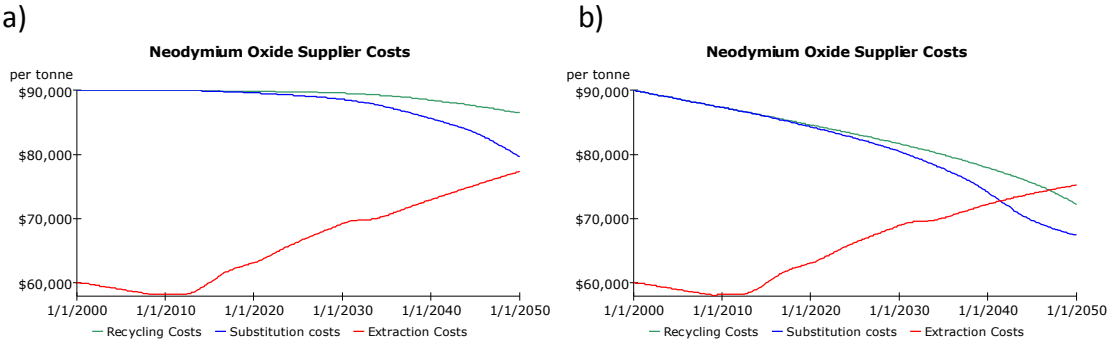

Figure 16. Results of supplier costs by sector for the dual restriction scenario without CMI research impacts (a) and with CMI research impacts (b). Both graphs simulated using the dynamics supply and demand method.

Price results using both methods are compared to the case without the impact of CMI in Figure 17. In both cases, learning by researching decreases the magnitude of the second price spike. However, with the generic SD commodity market method, the price reduction is much greater than results using the dynamic supply and demand method. In the dynamic supply and demand case, the reduction in the price spike is not as pronounced because the market is operating in a region that is highly inelastic – that is the market has weeded out consumers that have alternatives during the price spike, and therefore is mostly selling to customers that are willing to pass most of the additional cost onto their consumers.

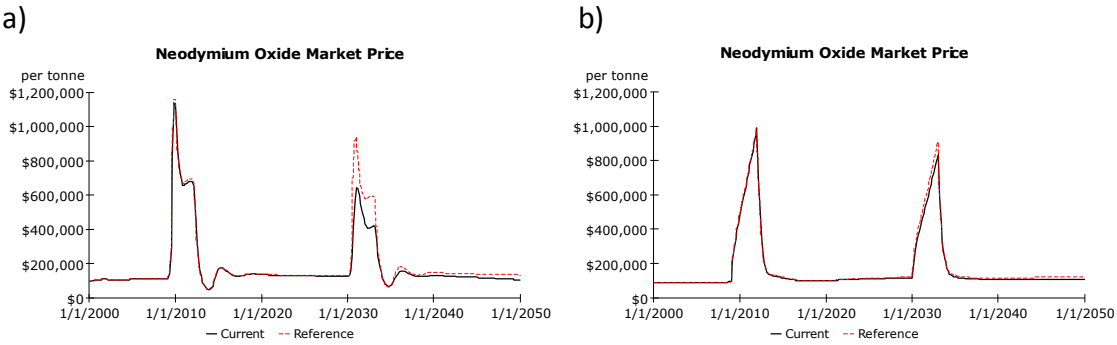

Figure 17. Comparison of neodymium oxide price without CMI impact (red) and with CMI impact (black) using the generic SD commodity market method (a) and the dynamic supply and demand method (b).

Sourcing flows comparing the case with and without CMI research impacts in Figure 18 (both graphs are using the dynamic supply and demand method) suggests that research has a significant long-term impact on the types of technologies that ultimately make up the global REE portfolio. Just before the second export restriction in 2030, substitution supplies 11% of global flow and recycling supplies 7% in the case with CMI research compared to 9% and 4% without CMI effects. However, it is after the second disruption that the differences are more apparent. This highlights the point that research sometimes pays off nonlinearly, and that it can take a long time to reach the payoff.

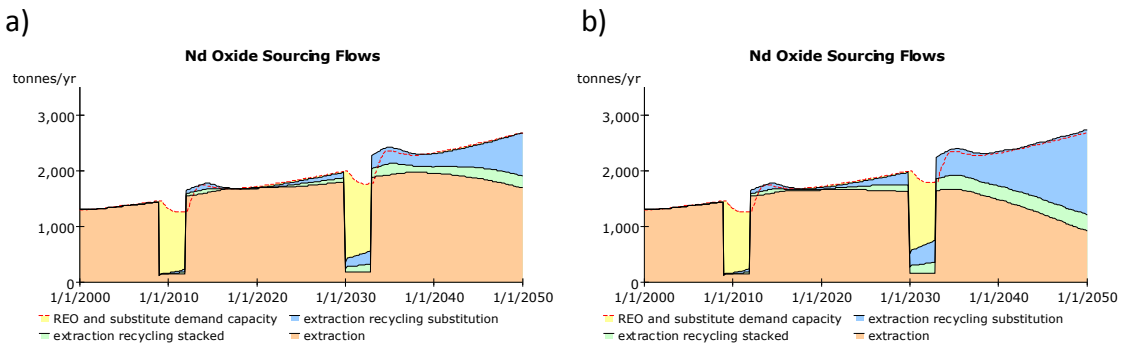

Figure 18. Comparison of material flows for the dual restriction scenario using dynamic supply and demand method without the impact of CMI research (a) and with the impact of CMI research (b).

4. Conclusions

This paper applies system dynamics to global critical material supply chains in order to understand the potential influence of three strategies to address the uncertainty in future supply given the current dominance of a single source country. In particular, we developed a hypothetical scenario for neodymium oxide, exploring the impact of an export restriction in the future similar to the restriction that began in 2009. Additionally, the goal of the paper is to explore a new method for simulating materials markets as an alternative to the generic system dynamics method for doing so, especially those that have multiple unique suppliers or consumers. This method is intended to appeal to both system dynamicists and orthodox economists.

The results of analyzing the market suggest that learning by researching at the rates assumed leads to some improvement in material price during the second export restriction in 2030. However, much of the additional sourcing from recycling and substitution occurs after the 2030 in our analysis, suggesting that learning by researching can lead to very nonlinear cost progression. This is because learning by doing can take over only once there is sufficient production capacity in the system. This type of information may be helpful for US DOE when setting expectations for payoffs from research.

The analysis of methods found that both approaches are able to reflect the large price spike for neodymium oxide from the previous export restriction. However, the methods differ strongly in the behavioral characteristics of the price spike. The dynamic supply and demand method tends to result in a more damped behavior with fewer oscillations, however further exploration of parameter sensitivity would help to firm this assertion. Perhaps more importantly, the dynamic supply and demand method creates explicit instantaneous supply and demand curves that can be communicated to and further analyzed by economists. We are eager to continue this experiment of mixing SD with orthodox economics.

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