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Global critical materials markets: An agent-based modeling approach

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ABSTRACT

As part of efforts to position the United States as a leader in clean energy technology production, the U. S. Department of Energy (DOE) issued two *Critical Materials Strategy* reports, which assessed 16 materials on the basis of their importance to clean energy development and their supply risk (DOE, 2010, 2011). To understand the implications for clean energy of disruptions in supplies of critical materials, it is important to understand supply chain dynamics from mining to final product production. As a case study of critical material supply chains, we focus on the supply of two rare earth metals, neodymium (Nd) and dysprosium (Dy), for permanent magnets used in wind turbines, electric vehicles and other applications. We introduce GCMat, a dynamic agent-based model that includes interacting agents at five supply chain stages consisting of mining, metal refining, magnet production, final product production and demand. Agents throughout the supply chain make pricing, production and inventory management decisions. Deposit developers choose which deposits to develop based on market conditions and detailed data on 57 rare earth deposits. Wind turbine and electric vehicle producers choose from a set of possible production technologies that require different amounts of rare earths. We ran the model under a baseline scenario and four alternative scenarios with different demand and production technology inputs. Model results from 2010 to 2013 fit well with historical data. Projections through 2025 show a number of possible future price, demand, and supply trajectories. For each scenario, we highlight reasons for turning points under market conditions, for differences between Nd and Dy markets, and for differences between scenarios. Because GCMat can model causal dynamics and provide fine-grain representation of agents and their decisions, it provides explanations for turning points under market conditions that are not otherwise available from other modeling approaches. Our baseline projections show very different behaviors for Nd and Dy prices. Nd prices continue to drop and remain low even at the end of our simulation period as new capacity comes online and leads to a market in which production capacity outpaces demand. Dy price movements, on the other hand, change directions several times with several key turning points related to inventory behaviors of particular agents in the supply chain and asymmetric supply and demand trends. Scenario analyses show the impact of stronger demand growth for rare earths, and in particular finds that Nd price impacts are significantly delayed as compared to Dy. This is explained by the substantial excess production capacity for Nd in the early simulation years that keeps prices down. Scenarios that explore the impact of reducing the Dy content of magnets show the intricate interdependencies of these two markets as price trends for both rare earths reverse directions – reducing the Dy content of magnets reduces Dy demand, which drives down Dy prices and translates into lower magnet prices. This in turn raises the demand for magnets and therefore the demand for Nd and eventually drives up the Nd price.

Introduction

As part of efforts to position the United States as a leader in clean energy technology production, the U. S. Department of Energy (DOE) issued two *Critical Material Strategy* reports, which assessed 16 metals on the basis of their importance to clean energy development and their supply risk (DOE, 2010, 2011). DOE identified five critical materials: dysprosium (Dy), neodymium (Nd), yttrium (Y), europium (Eu), and terbium (Tb). These critical materials are five of a set of 17 elements known as rare earths, which consist of the lanthanides in the periodic table plus yttrium and scandium. Rare earths are reasonably abundant in the Earth's

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crust but are rarely found in high concentrations. Separating them from one another is difficult and requires extensive processing to produce separated oxides. Five rare earth elements are commonly referred to as light (lanthanum cerium, neodymium, praseodymium, and samarium), with the remainder referred to as heavy rare earth elements. Rare earths are used in a wide variety of applications, including polishes, catalysts, lasers, fluorescent lights, capacitors, and powerful permanent magnets (used in electric vehicle motors, wind turbines, and consumer electronics). Rare earths are of particular concern because of their importance to clean energy technologies, as well as the potential for supply disruptions.

To understand the implications of rare earth supply disruptions for clean energy, it is important to understand the dynamics across the supply chain, from rare earth oxide extraction to end use application. In this paper, we focus on the use of Nd and Dy in permanent magnets used in wind turbines and electric vehicles. Nd and Dy are two of the critical materials identified by DOE, as measured both by their supply vulnerability and their importance for clean energy (DOE, 2010, 2011). Most Nd and Dy are used in neodymium iron boron (NdFeB) permanent magnets, which are the most powerful class of permanent magnet and have seen a steadily increasing share of the permanent magnet market since they were introduced in the 1980s (Dent, 2012). Nd is one of the core materials of these magnets, making up about 30% of a magnet's weight, while smaller amounts of Dy are added to allow magnets to perform at higher temperatures.

The NdFeB magnet supply chain consists of multiple steps, including mining and initial processing of rare earths into concentrates, separation into oxides, refining into metals, production of alloys and powders, and production of magnets (Shih et al., 2012). Often, more than one of these steps is done by the same vertically integrated company. There has been a trend toward increasing levels of vertical integration. Some companies, such as Molycorp and Great Western Minerals, have focused on obtaining capabilities at each stage of the mine-to-magnet supply chain.

China is a major player throughout the NdFeB magnet supply chain. In 2011, 97% of the world's rare earth production occurred in China (Morrison and Tang, 2012). This dominance has diminished slightly with the initiation of new production from Mountain Pass mine in the United States and Mount Weld in Australia; the latest estimates from the United States Geological Survey (USGS) are that 89% of 2013 world production occurred in China (USGS, 2014). However, there is still very little production of heavy rare earths such as Dy from outside of China. China has also become the leading player in the production of NdFeB magnets, with an estimated 79% of market share in 2012 (Benecki, 2013). Most of the remaining production is concentrated in Japan. China has also increased its share of wind turbine production, with four of the top 10 wind turbine producers now located in China.

The permanent magnet supply chain provides a rich opportunity to explore interactions among the different markets that are not immediately obvious. Markets for wind turbines and electric vehicles are connected because of their use of rare earth permanent magnets. Nd and Dy oxide markets are also closely connected because they are produced together in the same mines and used together in permanent magnets. Demand for rare earths is also strongly dependent on technological developments that can make demand highly uncertain and difficult to predict. All these supply and demand interconnections among the different rare earths can generate interesting market dynamics that are not well understood.

Rare earth markets have also been volatile in recent years. Prices for most rare earths increased more than tenfold from 2009 to 2011, followed by a significant drop in prices that continued through 2013. This price spike and associated market disruptions highlighted the need for an improved capability to anticipate and respond to future market developments. It also highlighted the need for an improved understanding of how rare earth market developments impact the development of clean energy technologies, and how clean energy technology developments impact rare earth markets.

The rare earth permanent magnet supply chain presents an opportunity for using systems-level modeling to explore recent and possible future market dynamics and the effect of market conditions. Such modeling is largely absent in the existing literature, although there is a wide body of literature devoted to understanding different aspects of rare earth supply chains. Studies have explored the industrial structure, geographical concentration, and market power in the supply chain (DOE, 2010, 2011; Humphries, 2013; Shih et al., 2012) and analyzed the causes of the recent spikes in rare earth prices (Massari and Ruberti, 2013). Many studies have also projected demand or supply for Nd, Dy, and other rare earths and, in some cases, compared independent demand and supply projections to identify potential gaps between them (Alonso et al., 2012; DOE, 2010, 2011; Hatch, 2011; Hykawy et al., 2010; Kingsnorth, 2013; Shaw and Chegwidden, 2012). While these independent projections provide useful insights, a number of questions remain unanswered:

- How will markets adjust to accommodate any supply shortages that are identified?
- What will the impact on prices be?
- How will technological developments be affected and can they help to alleviate these shortages?
- How will the development of new deposits respond to changing market conditions?
- How do market structures and behaviors throughout the supply chain influence the outcomes?

This paper addresses some of the gaps in the existing literature. We conducted a quantitative, model-based, forward-looking analysis of the key complexities of Nd and Dy supply chains and markets. The analysis was conducted by using the Global Critical Materials (GCMat) model. GCMat is a newly developed, dynamic model of rare earth global supply chains that captures the relevant system complexities and includes the entire value chains—from mining to magnet production to end use applications.

The remainder of the paper is structured as follows: *Methodology* documents the GCMat model design, including the structure of the model and key assumptions. Full details regarding the model assumptions are provided in the online Supplemental materials. *Baseline scenario assumptions and setup* describes the inputs used in the baseline scenario and the efforts that were made to calibrate and validate our model. *Results* presents model results and discusses insights gained from the simulation runs. Here, we demonstrate how the model can contribute to a better understanding of important historical developments and explore market outcomes under alternative future scenarios. Finally, *Conclusions* offers conclusions and directions for future research.

Methodology

Background

Modeling resource and commodity markets has a long history. Approaches include econometric, equation-based models that focus on the short term, with structural relationships derived from historical data (Labys, 1978); partial equilibrium models of commodity and energy markets that include explicit detail on the underlying determinants of supply and demand; and alternative market structures, such as imperfect competition (Takayama and