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Simulating producer responses to selected chinese rare earth policies

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A B S T R A C T

This study explores the effects of Chinese rare earth stockpiling, environmental taxation, and improvements in recovery rates on rare earth markets. It uses a Stackelberg model with a leading producer (legal Chinese producers) and two sequential followers (illegal Chinese producers and the Mount Weld mine in Australia), each producing multiple rare earths. The model is parameterized for the production and prices of separated rare earth oxides (REOs) from ore. Counterfactuals involving Chinese policies are compared to the no-policy, business-as-usual (BAU) scenario. The five counterfactuals are: (1) further Chinese State Reserve Bureau (SRB) stockpiling of neodymium, (2) further SRB stockpiling of dysprosium, (3) an environmental tax on the production of legal Chinese rare earths, (4) increased recovery rates of neodymium at legal Chinese operations, and (5) increased recovery rates of dysprosium also at legal Chinese operations. The BAU scenario and five counterfactuals are run with (a) four different levels of reference illegal Chinese production and (b) with and without the Chinese production quota, yielding 48 total outcomes ($6 \times 4 \times 2$). The first finding is that any SRB stockpile purchase increases the price of the stockpiled REO and increases legal Chinese ore production. However, given co-production, increased ore production involves more production of all REOs, and the prices of non-stockpiled REOs decrease. Thus if the stockpiled REO represents a large (small) portion of illegal Chinese and Mount Weld revenue, then illegal Chinese producers and the Mount Weld mine will increase (decrease) their production. An environmental tax decreases legal Chinese production, increases production by illegal Chinese producers and Mount Weld, and increases prices of all REOs. Increased legal Chinese recovery rates lead to increased legal Chinese production, decreased production by illegal Chinese producers and Mount Weld, and decreased REO prices. Increased levels of reference illegal Chinese production (a) exacerbate the policy-driven production increases or dampen production reductions of illegal producers and (b) conversely, for legal Chinese producers, reduce policy-driven production increases and further increase production reductions.

1. Introduction

This study asks, “What influence could Chinese rare earth stockpiling, an environmental tax on rare earth production in China, or increased rare earth recovery rates have on global rare earth oxide markets?” Mined rare earth materials, which are further processed into rare earth oxides[1] (REOs), are subject to supply risk because of the geographic concentration of production in China and the resulting fragility of rare earth markets as illustrated by the dramatic price increases in 2010 and 2011 in which certain rare earths’ prices increased by over 1000%. Since several consumer electronics and renewable energy technologies depend on rare earths, the potential repercussions of these actions are a salient issue on many agendas.

Although rare earth prices in 2017 are much lower than their peaks in 2011, rare earth users remain vulnerable to the consequences of potential Chinese policy. Five policy areas are of special interest. First, the Chinese State Reserve Bureau (SRB) began a rare earth stockpiling program in 2013. The first stockpile purchase was in mid-2013 and the SRB paid a 10% premium for the stockpiled rare earths. In late-2014 it was reported that the government had built storage for more than 40 thousand tons of REOs and the SRB may purchase up to 100 thousand tons, primarily focusing on medium to heavy rare earths (McLeod, 2014; Burns, 2014). Second, a revised resource tax is now in effect and in response to the extensive environmental consequences of REO production (Shira, 2016; Ge et al., 2016). Third and since the 1960s, an ongoing effort by multiple research institutions has been to increase recovery rates of REOs from ore. One particular initiative is that the Chinese Rare Earth Development Plan for the 2009–2016 period set a non-specific goal of an increased recovery rate for Baotou Iron and Steel and Rare Earths Corporation (Tse, 2011). In addition, specific goals of

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[1] Following industry practice, rare earth oxides are used to represent all forms of rare-earth intermediate products after the separation stage but before conversion to alloys and metal; in addition to oxides, manufacturers use specialized intermediate products such as carbonates, chlorides, and various other chemical forms.

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the 2016–2020 Chinese Rare Earth Development Plan are to increase light rare earth ore recovery by 5%, increase comprehensive utilization of ion adsorption clays by 10%, and increase the recycling rate of rare earth smelting and separation by 2% (Chinese National Development and Reform Commission, 2017). The Chinese government has also invested in and encouraged development of more efficient recovery equipment (Embassy of the People's Republic of China in the United States of America, 2012). Fourth, since 2012 the Chinese government has set an annual production quota for rare earth producers and in 2016 the Chinese government set the production quota at 105 thousand tons per year. At the time this analysis was conducted, the annual production quota was expected to either remain constant or increase to 140 thousand tons by 2020 (Adamas Intelligence, 2015b; Burns, 2014); the quota has since been raised[2] to 140 thousand tons per year starting in 2019 (Chinese National Development and Reform Commission, 2017). Finally, as of 2017 the Chinese government has been actively attempting to reduce and eliminate the illegal Chinese rare earth production that has persisted for more than a decade. This is furthered by the goals stated in the 2016–2020 Chinese Rare Earth Development Plan in which it is indicated that from 2011 to 2016, 113 cases of illegal prospecting and mining were investigated and rectified.

The Mount Weld (Australia) and Mountain Pass (United States) mines began to produce rare earths following the 2010–2011 price spike; however, the Mountain Pass mine ceased production in 2015 due to financial and technological difficulties. Although rare earth production outside of China has increased, the production of certain rare earths remains concentrated in China. In a simplified sense, the supply of the light rare earths (LREEs[3]) will be more geographically diverse if Mount Weld produces at planned capacity than the supply of heavy rare earths (HREEs[45]) whose production is expected to primarily remain from ion adsorption clays in southern China with a large portion from illegal Chinese producers (Adamas Intelligence, 2015b). As of early 2017, the Mountain Pass and Mount Weld mines have been the only two new major sources of supply since 2010, with only Mount Weld being in production in early 2017 (Adamas Intelligence, 2015b). Although a small number of the well-explored known deposits outside of China could come into production in the future, no new major sources of supply are imminent (Humphries, 2013; Adamas Intelligence, 2015b).

Recent research has partially but not entirely evaluated these policies and market developments outside of China. Related to the coproduction aspect of our model, Nieto and Zhang (2013) demonstrate that byproducts of rare earths significantly influence the more prominent, primary products. Using a generalized Weng model to forecast production quantities, Wang et al. (2013) recommend that the Chinese government pursue environmental and resource exhaustion taxes for their rare earth industry. A detailed assessment of rare earth markets indicates that rare earths face a near-term supply risk due to lack of substitutes, concentrated production, and growing demand (Massari and Ruberti, 2013). Han et al. (2016) have evaluated the implications of the Chinese government's vertical integration efforts and assert that the Chinese government should seek vertical integration. Ge et al. (2016), using a dynamic computable general equilibrium model, forecast that the technological improvements of substitution and recycling rare earths will decrease mining activities in China by 2025. Past research has not incorporated the potential Chinese market power on an international scale and has not portrayed production concentration among a small set of producers. Our research adds to the current literature by providing a theoretical framework for coproduction in a Stackelberg game, applying the model to REO markets to represent potential Chinese market power, and evaluating this selected set of potential Chinese policies.

In this work, the influence of Chinese policies is evaluated while considering the market power of legal Chinese producers. This is accomplished through developing and then calibrating a Stackelberg game of coproduction with three actors: legal Chinese producers, illegal Chinese producers, and the Mount Weld mine in Australia. Stackelberg games have been used in several analyses focusing on non-renewable resource extraction, for a review see Wan and Boyce (2014). The Stackelberg setup allows us to demonstrate a leader with two followers in the context of rare earth markets. A Stackelberg game is a strategic game where the leader moves first through choosing its production quantity with knowledge of its competitors' responses. The leader-follower relationship in a game is appropriate when either the leader is committed to an action, the leader was a monopolist before new entrants, or if the leader holds excess production capacity. The Chinese government production quota symbolizes a commitment to a production decision. Also, when Mount Weld began producing in relatively small quantities in 2011, China was an incumbent monopoly in the rare earth markets. Furthermore, in 2016 China used less than half of its rare earth production and refinement capacity (Adamas Intelligence, 2015b).

Although there are numerous mines and processors within China, the Chinese government imposes policy on a national level, making it reasonable to model legal Chinese production as a single actor from the perspective of non-Chinese users and producers. The Chinese government has demonstrated its ability to impact rare earth markets, exert its control on producers through production quotas, and is pursuing consolidation of firms which should further its domestic production control. An important difference between this Stackelberg game and other Stackelberg games is that the one presented here incorporates coproduction of multiple products (rare earths) from a single production variable (ore) while calibrating costs to forecasted levels of production. Finally, Mount Weld's concentrate is currently processed in Malaysia; although these geographical intricacies are not explicitly represented in the model, additional costs are captured through the cost calibration.

This paper is structured as follows. First, the conceptual Stackelberg model is presented. Second, the data sources, assumptions, and calibration method used to parameterize the model are covered. Third, we present the results from counterfactuals for each actor as well as variations in the assumed illegal Chinese production rate. Finally, we discuss the implications of this work. Appendices A, B, and C contain the Stackelberg game's derivations, the full set of production results, and confidence intervals from sensitivity analysis by scenario, respectively.

2. Model

The primary considerations of modeling rare earth markets are

[2] We recognize that the 2016–2020 Rare Earth Development Plan has updated the production quota to 140 thousand tonnes starting in 2019. The primary source of data for our model is Adamas (2016b) which based its forecasts on the 105 thousand tonne production quota. Since the model incorporates and calibrates to the market data for illegal Chinese producers, Mount Weld, and REO prices and not just legal Chinese production, it would be inconsistent to assume this change in the context of presently-available data. Increasing the production to 140 thousand tonnes and its calibration would lead to the following differences relative to the current setup: 1) the *calibrated* costs of producing ore for legal Chinese producers would be lower but higher for other actors, similar to when assumed illegal Chinese production is increased and illegal Chinese production costs decrease and other actors costs increase 2) the legal Chinese production increases in response to stockpiling or increased recovery rates would be relatively greater with greater assume market share; similarly, the environmental tax would result in less of a relative decrease 3) illegal Chinese and Mount Weld production responses to policy would increase less or decrease more and 4) Increased assumed illegal production would have less of an effect on legal Chinese producers (given increased market share) but more of an effect on Mount Weld (given decreased market share). The general conclusions remain true regardless of the quota level or exogenous production data.

[3] Lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, and gadolinium.

[4] Yttrium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium.

[5] Although analyses differ in their classification of LREEs and HREEs, the classification of LREEs and HREEs is based on the 4f shell electron's spin direction. Starting with terbium, additional spinning electrons rotate counter-clockwise as opposed to clockwise which designates an element as an HREE (InvestorIntel Rare Earth Handbook, 2013).