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China's rare earth supply chain: illegal production, and response to new Cerium demand

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ABSTRACT:

As the demand for personal electronic devices, wind turbines, and electric vehicles increases, the world becomes more dependent on rare earth elements. Given the volatile, Chinese-concentrated supply chain, global attempts have been made to diversify supply of these materials. However, the overall effect of supply diversification on the entire supply chain, including increasing low-value rare earth demand, is not fully understood. This paper is the first attempt to shed some light on China's supply chain from both demand and supply perspectives, taking into account different Chinese policies such as mining quotas, separation quotas, export quotas, and resource taxes. We constructed a simulation model using Powersim Studio that analyzes production (both legal and illegal), production costs, Chinese and rest-of-world demand, and market dynamics. We also simulated new demand of an automotive aluminum-cerium alloy in the U.S. market starting from 2018. Results showed that market share of the illegal sector has grown since 2007 to 2015, ranging between 22% and 25% of China's rare earth supply, translating into 59–65% illegal heavy rare earths and 14–16% illegal light rare earths. There would be a shortage in certain light and heavy rare earths given three production quota scenarios and constant demand growth rate from 2015 to 2030. The new simulated Ce demand would require supply beyond that produced in China. Finally, we illustrated revenue streams for different ore compositions in China in 2015.

Key words: China's supply chain, rare earth, illegal production, system dynamics, simulation model

1. Introduction

Rare earth elements (REE) have become synonymous with technical innovation from their widespread use in applications such as mobile electronics, electric vehicles, and wind turbines. Since the 1990s, China has dominated global REE production [1]. Despite China's dominance, quantitative and systematic understanding of its supply chain is missing. REE reserves are unevenly distributed among China's northern and southern regions [2], complicating production management at the central and provincial government levels. Compounding the situation is the boom of illegal production, which has caused the global legal sector to operate at a loss [3, 4]. These factors, combined with sensitive demand behavior, have played a large role in recent global supply disruptions [5, 6].

Previous studies have estimated Chinese future production based on projected demand trends and rest-of-world (ROW) supply scenarios [7, 8]. Vertical REE supply chain models have also been developed but exclude demand, price, and government policy mechanisms [9, 10]. In-use stocks of each REE have been estimated based on manufacturing demand of different REE technologies, without indicating the source of mined material or the location of these inventory stocks [11, 12]. Furthermore, most studies have focused on production costs and supply from the legal sector [13, 14], whereas 40% of all traded REEs are illegal [15]. In this study, we define illegal production as REE production supported by the provincial government without central government production quotas (PQ)[1]. This includes provincial companies without PQ due to non-compliance with environmental regulations and/or artisanal miners. We assume there is no overproduction of the legal sector beyond the PQ.

REEs typically occur as rare earth oxide (REO) compounds and are categorized as light (LREO) and heavy (HREO). LREO naturally occur in larger quantities compared to the much scarcer HREO. The REE market is driven by demand for the more valuable and often scarcer REEs. This results in a surplus of certain REEs with lower

[1] While China eliminated its export quota in January, 2015 in line with a World Trade Organization ruling, production quotas are still in effect and drive legal production [16]

economic value. Research on this imbalance has suggested that increased demand for lower value REEs could improve the resilience of REE supply [17]. However, no research has been conducted to demonstrate this effect on the REE supply chain or specifically, the Chinese REE supply chain. In addition, REE revenue streams for varying ore compositions have not been estimated.

In this study, we have aimed to develop an in-depth understanding of the REE supply chain by estimating Chinese legal and illegal production. We constructed a simulation model in Powersim Studio 10, an icon-based software that applies System Dynamics methodology. This methodology is powerful for revealing the interplay of different REE supply chain factors and relevant policies, in the context of lacking data and high uncertainty. We considered eight REEs: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), europium (Eu), terbium (Tb), dysprosium (Dy), and yttrium (Y). These REEs accounted for greater than 90% of 2014 demand volume and value [5]. We estimated legal sector revenue streams for different REE ore deposits and the market share of illegal production. We also applied this model to test the effect of additional LREO demand on Chinese production. To model this effect, we considered U.S. demand of an automotive aluminum-cerium (Al-Ce) alloy with 12 wt% Ce [18].

2. Methodology

2.1 Model Overview

The building blocks of the model are stocks and flows. Stocks refer to accumulation of materials or resources, whereas flows control how materials/resources move among stocks (Appendix – Fig. 5). For example, REE legal inventory grows from production and shrinks from sales over time. This relationship is characterized by a first-order differential equation (Equation 1) solved by numerical integration.

$$\frac{dI}{dt} = P - S \tag{1}$$

Where I: inventory
t: time
P: production (depends on annual PQ)
S: shipments (depends on order backlog and inventory, calculated from other variables)

The model was comprised of four inter-linked sub-models (Fig. 1): (1) Production, (2) Demand, (3) Production Costs, and (4) Market. The model was simulated in months from 2007 to 2030 and tracked rare earth inventories in REO equivalent.

Fig. 1. Model inputs, key results, components and their interactions

2.2 Production Sub-Model

We considered production of five provinces, which accounted for over 93% of China's production from 2007 to 2015 [19]. While legal production took place in all provinces, illegal activity only occurred in two southern provinces. We modeled detailed extraction and separation processes for each considered REE. We defined extraction as the production of mixed REO concentrates from ore by mining, beneficiation, chemical treatment, and similar processes. We defined separation as the production of individual REO from such concentrates. To model the maximum impact of the illegal sector, we did not consider different oxide purity requirements for different demand applications. Legal sector extraction recovery rates were 21.6% for Bayan Obo, 38.75% for Shandong, 40.98% for Sichuan, 70% for Jiangxi, and 63.75% for Guangdong [2, 20]. Recovery rate of illegal production was assumed to be 10% lower because their processes are less efficient than the legal sector's. Each province's supply chain contribution was tracked assuming a representative ore composition for each province [2, 21-24]. LREO and HREO inventories were tracked separately for each province, as well as before and after May 2015. Due to lacking mine inventory data, all 2007 inventories were initialized at zero mt.

Since PQs constrain the legal sector, their production decisions were not modeled based on prices. The illegal sector was responsive to prices but had constrained capacity to avoid being exposed. We assumed maximum illegal production capacity to be twice as much as the initial illegal capacity of 20,000 mt REO in 2007. This initial capacity is based on USGS estimates of actual production against production quotas [25] and 69% deposit share of Guangdong and Jiangxi in 7 southern provinces [24].

2.3 Demand Sub-Model

We compiled Chinese 2007 to 2015 demand from several sources [5, 26, 27]. Based on China's demand share, we inferred ROW (U.S., Japan and Asia, and Europe) demand. We classified demand into five categories: (1) magnets, (2) catalysts, (3) lighting phosphors, (4) metallurgy, and (5) glass, polishing, and ceramics. From 2015 to 2030, we assumed one annual growth rate for each category: 8% for magnets, 4% for catalysts, 5% for lighting phosphors, 4% for metallurgy, and 6% for glass, polishing, and ceramics [26, 28]. Demand for each REE was estimated for all categories using Du and Graedel's method [12]. Ce demand for the Al-Ce alloy was added to U.S. demand with two adoption rates (Appendix – Table I).

2.4 Production Costs Sub-Model

We considered two main production costs: extraction and separation. While all REOs had the same extraction cost, HREO had higher separation costs. We calculated provincial level costs, then applied the corresponding resource tax on prices, given a profit margin of 5% for extraction and 7% for separation (see Equations 2–4). A value-added tax (VAT) of 17% was included in concentrate price.

$$REO\ concentrate\ price = extraction\ cost + \ extraction\ profit\ margin + resource\ tax + 17\%\ VAT \quad (2)$$

$$Initial\ domestic\ REO\ price = REO\ concentrate\ price + separation\ costs + separation\ profit\ margin \quad (3)$$

$$Initial\ FOB\ REO\ price = initial\ domestic\ REO\ price + export\ tariff\ (when\ applicable) \quad (4)$$

These prices were the basis for calculating domestic prices and free on board (FOB) prices. Producers and consumers compared historical prices with new prices, creating fluctuating price behavior based on demand elasticity (0.3 for HREOs and 0.5 for LREOs) [29] (Fig. 1).

Tax rates before May 2015 were applied for ore [30]. Tax rates after May, 2015 were applied for sales of concentrates produced from that point forward [31]. Tracking this inventory separately identified when the new resource tax would be applied for each REO. In this model, rare earths were sold as separated REOs, skipping the stage of selling concentrates. Therefore, we only captured a portion of the new resource tax, as we were unclear from the new policy how it would be applied for sales of separate REOs.

2.5 Market Sub-Model

Before 2015, we incorporated export quotas to control exported quantity. Between 2010 and 2012, two primary mechanisms affected prices. First, middlemen conducted speculative stockpiling when they observed increased prices. As prices dropped, they rapidly sold their stock to prevent further loss [32]. Second, a panicking effect occurred when suppliers created a supply risk condition (e.g. incident between China and Japan, or tightened export quota). Consumers paid higher prices to get the same quantity while suppliers preferred to sell at higher prices. The panicking effect lasted longer, with larger magnitude, in China's export market than in its domestic market.

3. Results and Discussion

3.1 How large is the Illegal Sector?

The illegal sector plays a significant role in China's REE supply chain, especially in providing HREO. During 2015, for the eight elements considered, the illegal sector contributed 22% to the total market share and 59% to HREO market share. Illegal HREO share was highest in 2009/2010 at 65%. We came to this conclusion by quantifying legal and illegal REO production. Our calculation of 2015 legal production showed similar results to Chen's estimate [33]. For the 2015 REO PQ of 105,000 mt, the eight considered rare earths constituted 95.2% in our analysis and 96.3% in his analysis. Our estimate showed a lower La share (23% versus 27.91%) and a higher Y share (7.7% versus 4.59%). 2015 illegal production for two southern provinces was 33,820 mt (33.9% Y, 17.29% Nd, 15.97% La, 5.32% Dy, 5.15% Ce, and 5.29% remaining REOs). This result agreed with other estimates of total illegal production of 40,000 – 50,000 mt REO when only considering the two largest REO-producing southern provinces: Jiangxi and Guangdong [34, 35]. Given the varying mineral types and additional southern provinces [36, 37], the HREO illegal production share could be as high as 80%.

Projected illegal market share highly depends on the PQ. When the legal sector cannot satisfy demand, the illegal sector can pick up remaining demand. We ran three PQ growth scenarios: (1) no growth (NG), (2) modest growth (MG), and (3) high growth (HG). NG kept a constant PQ from 2015 to 2030. Over the same period, MG and HG assumed an annual PQ growth rate of 3% and 5%, respectively. Results showed that in 2030, HREO illegal market share reached 66%, 55%, 46% in NG, MG, and HG, respectively (Fig. 2). Total illegal market share was 28%, 19%, and 14% in each corresponding scenario (Appendix – Figure 6).

Fig. 2. HREO illegal market share of total Chinese HREO production from 2010 to 2030
*Including legal and illegal of eight considered REOs

3.2 Will China Be Able to Meet Its Own Demand?

In the model, as China tightened its PQ, the unmet demand of certain REOs increased. We define unmet demand as percent of global demand unsatisfied by Chinese supply annually. LREO unmet demand was more common than HREO unmet demand since the illegal sector mostly supplied HREOs. With NG, La, Ce, Pr, and Nd unmet demand kept rising from 2015 until 2030, reaching 59%, 54%, 80%, and 75%, respectively. By 2030, Eu and Tb unmet demand reached 53% and 72%, respectively. Dy unmet demand began in 2020 and reached 44% in 2030. For HG, 2030 unmet demand of La, Ce, Pr, and Nd lowered to 41%, 30%, 72%, and 67%, respectively. For Eu, Tb, and Dy, 2030 unmet demand also decreased to 38%, 68%, and 37%, respectively.

In NG, if China prioritized its entire inventory for domestic demand, China's unmet demand for La, Ce, Pr and Nd would grow to 14%, 17%, 75%, and 69% by 2030, respectively. China's unmet demand for Eu, Tb, and Dy grew to 43%, 66% and 32% by 2030, respectively. In brief, among eight analyzed REOs, only ROW demand of Y was satisfied by Chinese supply. China would not meet its demand for the remaining seven REOs in NG. In HG, China met its La and Ce demand until 2030, and partially satisfied Dy demand before 2024. Overall for HG, unmet Chinese demand in 2030 was 65%, 58%, 25%, 61%, and 23% for Pr, Nd, Eu, Tb, and Dy, respectively. ROW demand of Y was always satisfied while Pr, Nd, Eu, and Tb demand was 100% unmet since 2016. Unmet ROW demand for La and Ce reached 79% and 66% in 2030, respectively. Dy demand was met until 2019. Unmet Dy demand then grew from 24% in 2020 up to 100% in 2023.

These different PQ scenarios showed unbalanced unmet demand for different REOs for two reasons. First, we assumed a uniform PQ growth rate for all provinces. Second, the ore composition used for Jiangxi and Guangdong had high Y content, leading to abundant Y supply. Although our model assumes constant PQ growth rate, simulating dynamic growth is also possible.

3.3 Mining Revenue Streams and Additional Cerium Demand

We analyzed revenue streams for five provinces to gain a better understanding of how (1) PQ, (2) ore composition, and (3) prices affect mine economy. We did not consider factors affecting sales since we believed each province already had a stable customer base. For each mine, we converted annual revenue to percent of total revenue for each REO (See Fig. 3 for 2015 revenue streams). This conversion allowed us to compare across mines, which suggested how mines could react to increased/decreased demand of certain REO. For Bayan Obo's bastnaesite deposit, Nd, Pr,

and Ce accounted for 49.5%, 23.3%, and 14.1% of revenue, respectively. Shandong gained 41.3% revenue from Nd, 23.6% from Pr, and 17.8% from Ce. Sichuan revenue streams showed a similar trend to Bayan Obo regarding the top three REOs, but Sichuan's Eu share was larger at 8.8%. For Guangdong's xenotime, Dy, Tb, and Y were top contributors with 39.8%, 34.6%, and 13.6%, respectively. Jiangxi's clay received most revenue from Tb, Dy, and Y with 37.2%, 32.9%, and 15.6%, respectively.

Fig. 3. Simulated contribution of REE to mine revenue (R) and ore composition (O) in 2015

Since revenue streams depend on three aforementioned variables for a given mine, the contribution of each REO changes when the quota and prices change. Results showed that in 2011, the year of the price spike, revenue from Ce surpassed Nd in Shandong (32.1% vs. 28.0%). In Sichuan, Ce revenue was almost as significant as Nd revenue (27.7% vs. 28.3%). This result suggested that Shandong and/or Sichuan would benefit the most from increased Ce demand.

Following the previous discussion regarding unmet demand, we considered demand of an automotive Al-Ce alloy with 12 wt% Ce. In parallel with the three PQ scenarios, we simulated two alloy adoption scenarios with both targeting U.S. light-duty vehicles: (1) low adoption (LA) and (2) high adoption (HA) (Appendix – Table I). In LA/MG after prioritizing China's demand, unmet ROW demand for Ce increased from 32% in 2018 to 68% in 2030. For HA/MG, unmet demand rose to 83% in 2030. For LA/HG unmet demand rose to 20% in 2030, whereas in HA/HG, unmet demand increased to 56% by 2030 (Fig. 4).

Fig. 4. Unmet ROW Ce demand assuming 2 different Al-Ce adoption scenarios

Market dynamics will change accordingly when the new Ce demand is recognized. Since it is difficult to project market behavior, we ran two prices scenarios: (1) business as usual (BAU) and (2) reactive to prices. Both scenarios showed that in LA, annual average Ce price slightly increased in 2018 and peaked in 2021 whereas in HA, price peaked in 2024/2025. Price went back to equilibrium 2 years after the peak in LA. In HA, price dropped to equilibrium in 2027 and kept oscillating until reaching equilibrium in 2029. We did not attempt to forecast prices because different market factors and policies between 2018 and 2030 would impact prices on a weekly basis. Rather, we tried to gain an understanding of long-term price trends. Price peak for HA in the reactive scenario was 1.7 times higher than price peak in BAU. In reality, this value could vary depending on market drivers. In brief, LA caused price fluctuations for 6 years before reaching equilibrium again. In HA, the oscillation was more severe and lasted 10 – 12 years.

3.4 Interpreting China's New Resource Tax

The new resource tax gave the impression that REO prices would increase. Since then, prices have dropped, potentially due to illegal production [3, 4]. Our model showed that price would drop even without the illegal sector since tax dropped 37% – 88% by switching from old to new taxes, depending on the province. The new resource tax highly depends on extraction cost, without considering profit margin. Several sources have estimated extraction costs as high as 70% of total production cost [13, 38]. However, it is well-known in the rare earth industry that separation is the most costly process [39]. REO producer Lynas has reported that extraction costs contributed only 25% to total cost, while refining and processing contributed 66% [24]. In this paper, depending on the REO and ore composition, our extraction costs ranged from 26 – 60% of total cost, where the less abundant HREOs costed more to separate [40]. The old tax on ore seemed low per ore weight but significant per concentrate weight, especially for southern provinces with low REE ore content. Therefore, the new tax on concentrate sales did not significantly contribute to price. We also found the new resource tax not straightforward. It is intended for concentrate sales, suggesting that producers who can extract, separate, and sell REO directly could circumvent this tax. Concentrate sales mostly occur among a few producers, while most transactions occur with REO sales.

4. Conclusion

In this paper, we have provided insight into China's REE supply chain under government policy impacts. Illegal production plays a significant role, accounting for 59% of 2015 HREO market share. Illegal market share changes in

response to the PQ, where it will continue to grow if PQs do not keep pace with future demand. From a resource protection standpoint, illegal production degrades resources more quickly, leading to diminished production. We will investigate this effect in more depth in future studies. We illustrated different PQ scenarios that showed unbalanced supply given different growth rates of 5 demand categories. Finally, additional Ce demand from U.S. automobile alloys caused Ce price to rise and fall within 6 to 12 years after introduction, depending on the Al-Ce alloy's adoption rate.

We have over-projected demand from 2015 to 2030 to demonstrate worst case scenarios. With the development of new recycling and substitution technologies over the next 15 years, we will update the model to gain a deeper understanding of the REE supply chain. The model should be expanded to include more international ore compositions to better understand co-production with implications to ROW supply.

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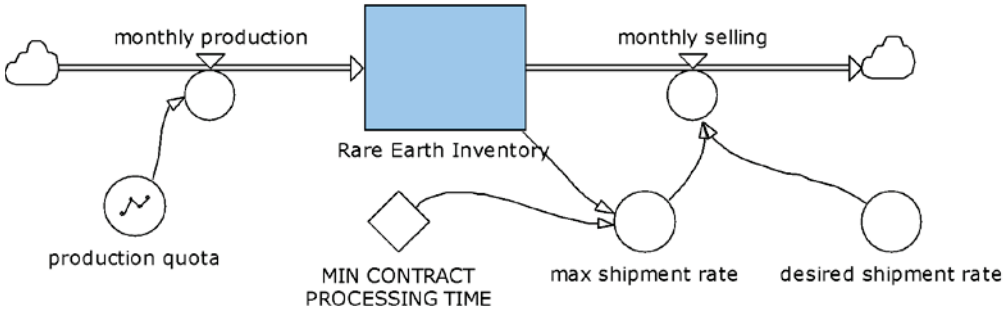
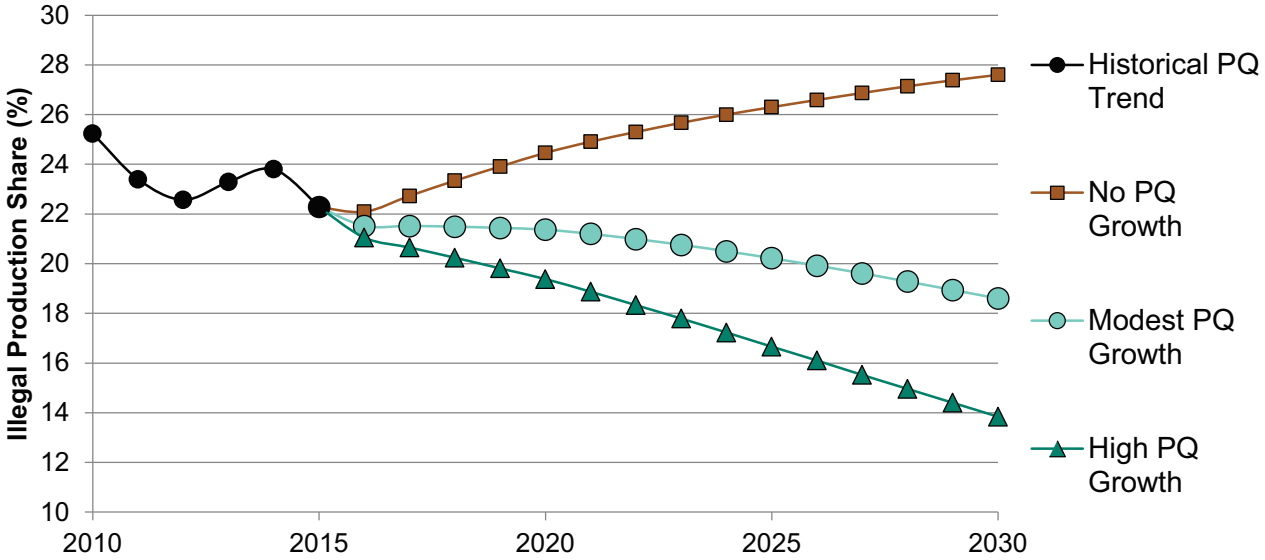
Appendix



Appendix - Fig. 5. An example of stocks and flows using Powersim Studio



Appendix – Fig. 6. Total Chinese illegal production (LREO and HREO) market share against total Chinese production (legal and illegal) of eight considered REOs

Appendix – Table I. Data for LA and HA scenarios[*, a]

Year	Total Aluminum Alloys in Sold Light Vehicles[**, b] (kt Al)	LA Quantity Alloy Demand (kt Al-Ce alloy)	LA Quantity of Ce Demand (kt Ce)	HA Quantity Alloy Demand (kt Al-Ce alloy)	HA Quantity of Ce Demand (kt Ce)
2018	357	2	0.2	2	0.2
2019	360	4	0.5	4	0.5
2020	363	8	1.0	8	1.0
2021	366	16	1.9	16	1.9
2022	369	32	3.8	32	3.8
2023	372	32	3.9	64	7.7

Year	Total Aluminum Alloys in Sold Light Vehicles**, b (kt Al)	LA Quantity Alloy Demand (kt Al-Ce alloy)	LA Quantity of Ce Demand (kt Ce)	HA Quantity Alloy Demand (kt Al-Ce alloy)	HA Quantity of Ce Demand (kt Ce)
2024	375	33	3.9	128	15.4
2025	378	33	3.9	256	30.7
2026	381	33	4.0	381	45.7
2027	384	33	4.0	384	46.0
2028	387	34	4.0	387	46.4
2029	390	34	4.1	390	46.8
2030	393	34	4.1	393	47.2

*The different between low adoption (LA) and high adoption (HA) scenarios was production capacity growth. LA assumed Al-Ce alloy production doubling each year from 2018 until 2022, after which it grew consistent with domestic vehicle sales. HA assumed Al-Ce alloy production would double until reaching 100% market share of the targeted applications in U.S. light-duty vehicles, after which it also grew consistent with domestic vehicle sales.
**The considered Al-Ce alloy targeted cylinder block and cylinder head applications in U.S. light-duty vehicles because these applications already often use aluminum alloys. Quantity of Al-Ce consumed depended on the different adoption trend and light-duty vehicle sales.
a *The Past, Present and Future of Aluminum in North American Light Vehicles* (Ducker Worldwide, 2012)
b *The U.S. Automotive Market and Industry in 2025* (Center for Automotive Research, 2011)

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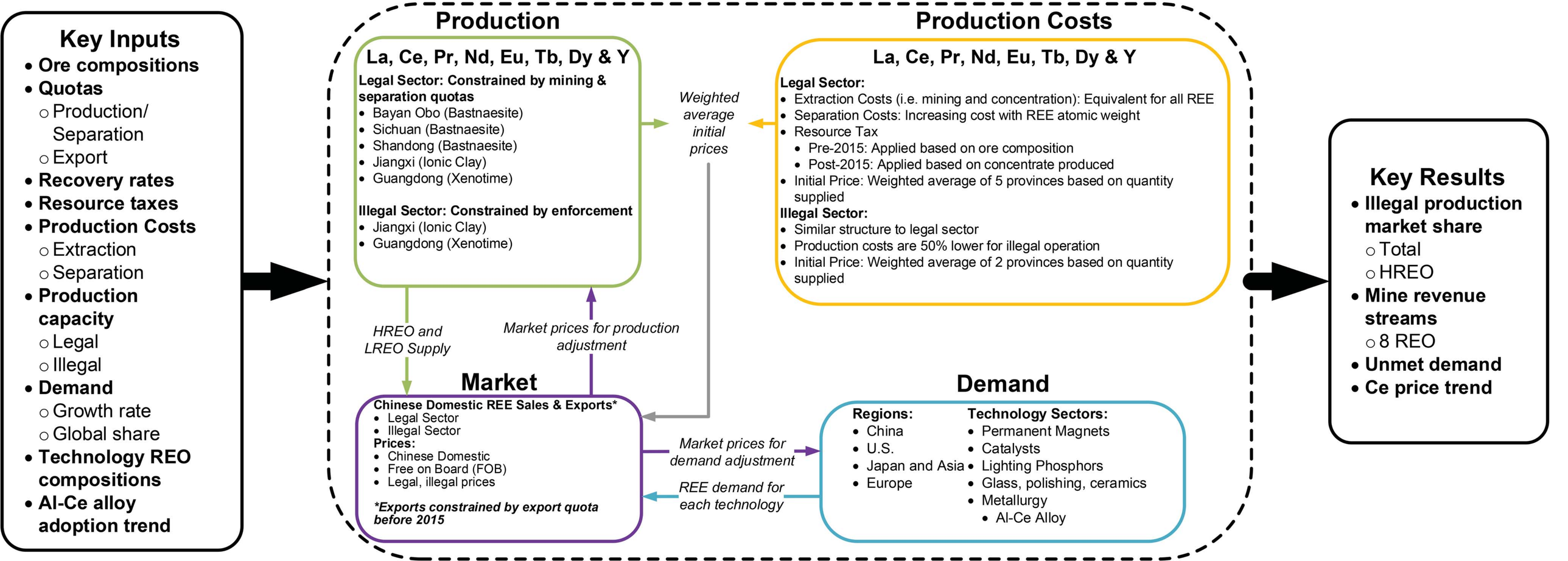
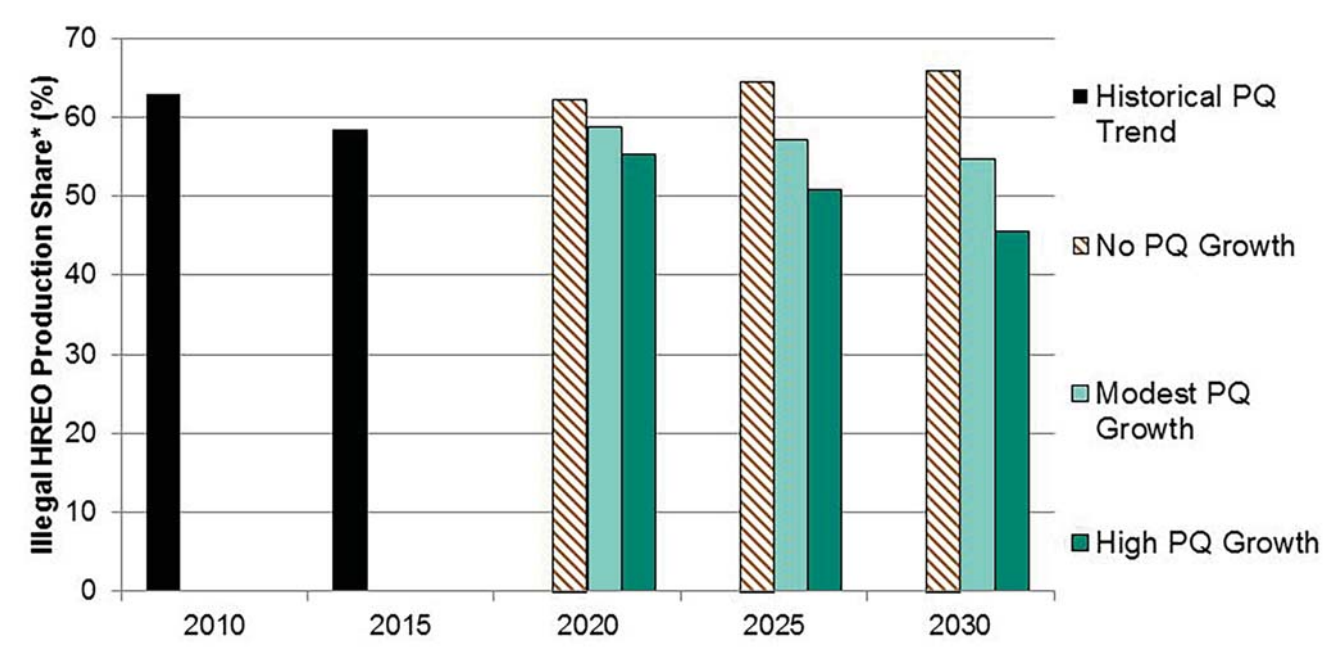
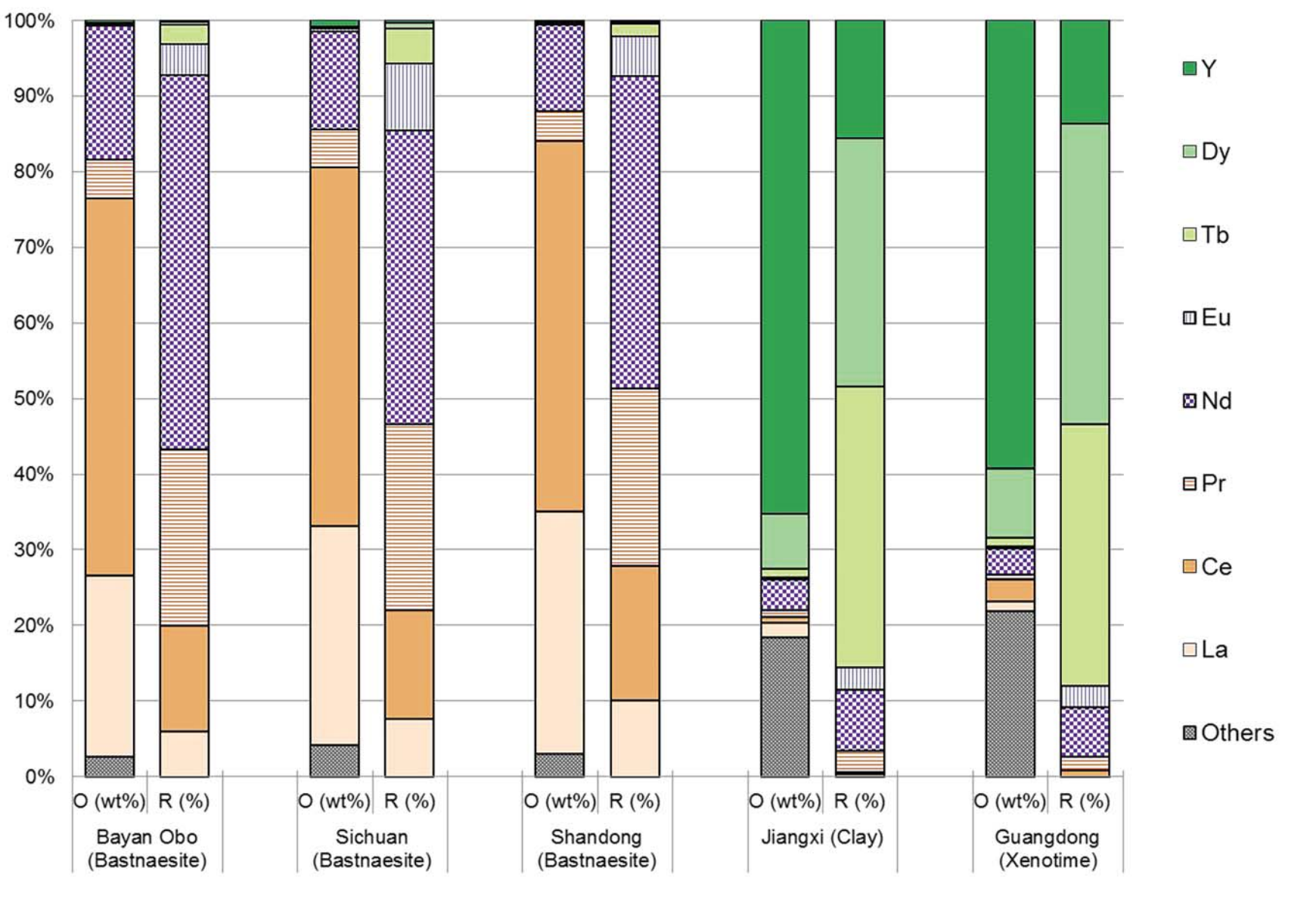
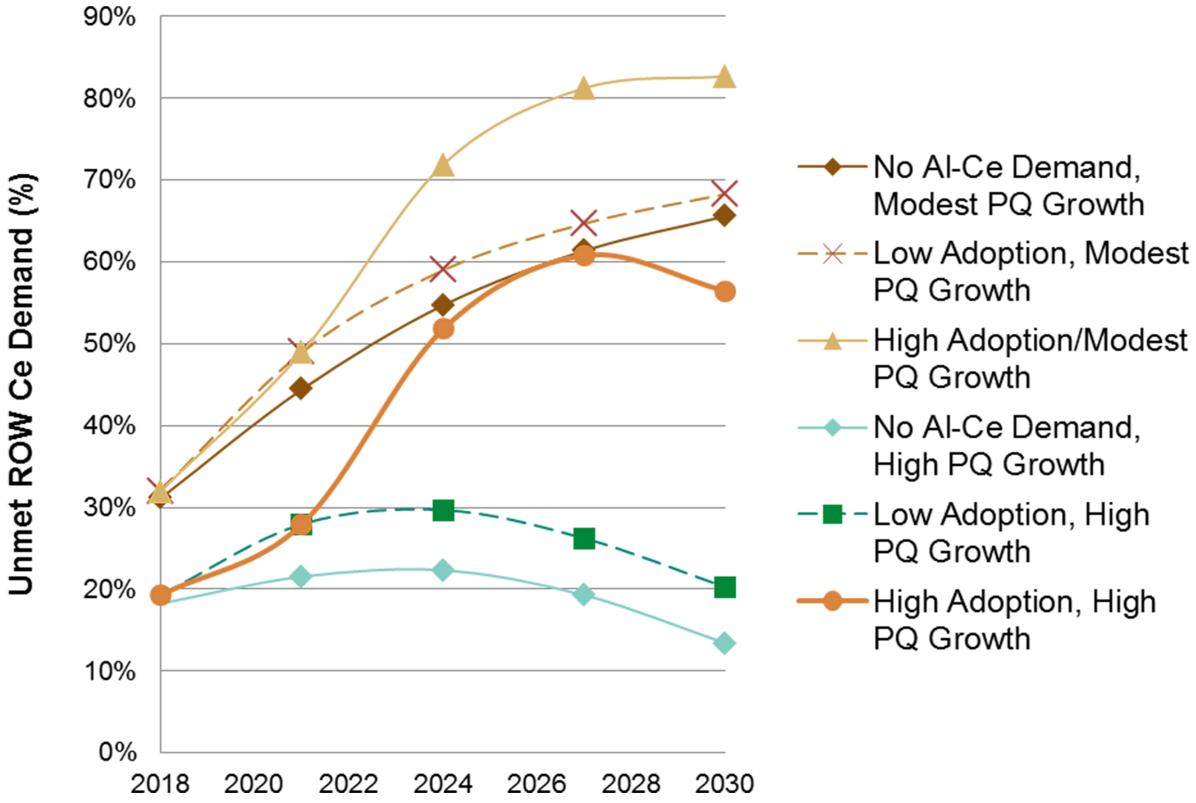

Key Inputs
Ore compositions
Quotas
Production/ Separation
Export
Recovery rates
Resource taxes
Production Costs
Extraction
Separation
Production capacity
Legal
Illegal
Demand
Growth rate
Global share
Technology REO compositions
Al-Ce alloy adoption trend
Production
La, Ce, Pr, Nd, Eu, Tb, Dy & Y
Legal Sector: Constrained by mining & separation quotas
Bayan Obo (Bastnaesite)
Sichuan (Bastnaesite)
Shandong (Bastnaesite)
Jiangxi (Ionic Clay)
Guangdong (Xenotime)
Illegal Sector: Constrained by enforcement
Jiangxi (Ionic Clay)
Guangdong (Xenotime)
Weighted average initial prices
Production Costs
La, Ce, Pr, Nd, Eu, Tb, Dy & Y
Legal Sector:
Extraction Costs (i.e. mining and concentration): Equivalent for all REE
Separation Costs: Increasing cost with REE atomic weight
Resource Tax
Pre-2015: Applied based on ore composition
Post-2015: Applied based on concentrate produced
Initial Price: Weighted average of 5 provinces based on quantity supplied
Illegal Sector:
Similar structure to legal sector
Production costs are 50% lower for illegal operation
Initial Price: Weighted average of 2 provinces based on quantity supplied
HREO and LREO Supply
Market prices for production adjustment
Market
Chinese Domestic REE Sales & Exports*
Legal Sector
Illegal Sector
Prices:
Chinese Domestic
Free on Board (FOB)
Legal, illegal prices
*Exports constrained by export quota before 2015
Market prices for demand adjustment
REE demand for each technology
Demand
Regions:
China
U.S.
Japan and Asia
Europe
Technology Sectors:
Permanent Magnets
Catalysts
Lighting Phosphors
Glass, polishing, ceramics
Metallurgy
Al-Ce Alloy
Key Results
Illegal production market share
Total
HREO
Mine revenue streams
8 REO
Unmet demand
Ce price trend


Illegal HREO Production Share* (%)
70
60
50
40
30
20
10
0
2010
2015
2020
2025
2030
Historical PQ Trend
No PQ Growth
Modest PQ Growth
High PQ Growth


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
O (wt%)
R (%)
Bayan Obo (Bastnaesite)
Sichuan (Bastnaesite)
Shandong (Bastnaesite)
Jiangxi (Clay)
Guangdong (Xenotime)
Y
Dy
Tb
Eu
Nd
Pr
Ce
La
Others


Unmet ROW Ce Demand (%)
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
2018
2020
2022
2024
2026
2028
2030
No Al-Ce Demand, Modest PQ Growth
Low Adoption, Modest PQ Growth
High Adoption/Modest PQ Growth
No Al-Ce Demand, High PQ Growth
Low Adoption, High PQ Growth
High Adoption, High PQ Growth