



Energy Transition and Rare Earth Resource Constraints: Market Dynamics in an Asymmetric Duopoly Model

December, 2023

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Overview:

Our study analyzes the anticipated end of the Chinese monopoly in the rare earth elements (REEs) market, and we explore the transition towards a potential new duopoly between China and the rest of the world (ROW), using game theory.

Methodology:

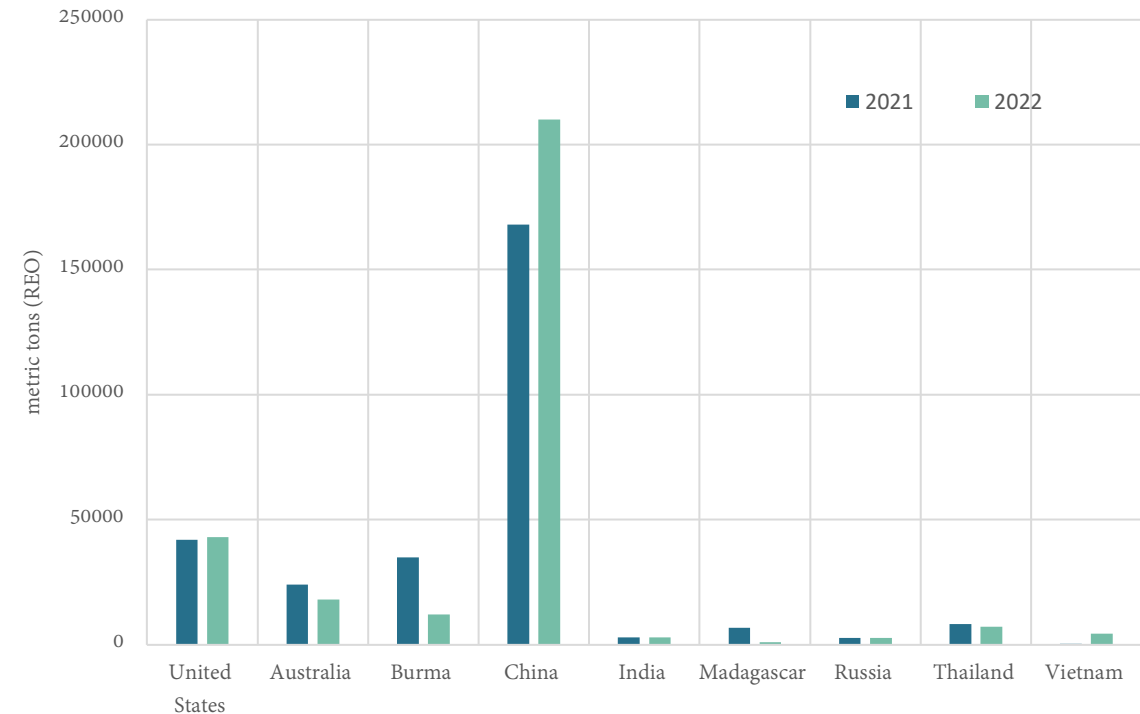
We present a numerical solution to a non-cooperative, differential game between China and the ROW using the NMPC technique while examining the effect of policymakers' levels of myopia.

Scenarios:

1. China is assumed to have a dominant position with lower marginal costs compared to the ROW while ROW enjoys a support policy.
2. The marginal extraction cost of the ROW decreases due to technological advancements.
3. The no supporting policy scenario.

Results:

Overall, the results emphasize the significance of considering the long-term implications of the market transformation and ensuring that both suppliers, China and the ROW, benefit from it.



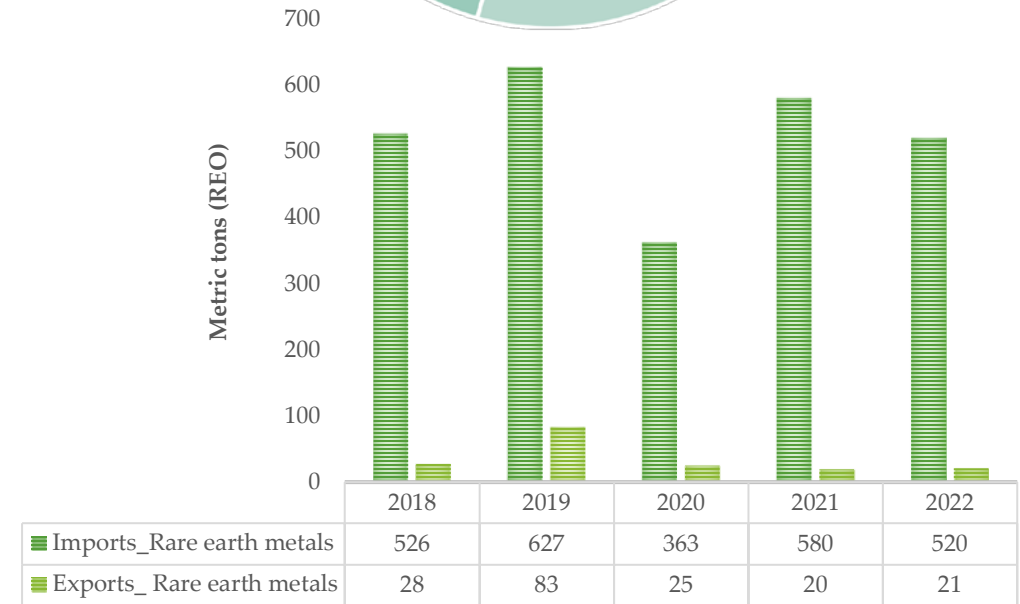
World REEs mine production. Source of data: US Geological Survey, 2023.

Rare Earth Elements (REEs) are vital materials utilized in various high-tech consumer goods and clean energy technologies, such as

- wind turbines,
- electric cars,
- solar photovoltaics,
- nuclear industries,
- critical military equipment.

- China dominates the global supply chain for rare earth elements, posing a strategic vulnerability for countries like the United States, which heavily rely on imports for various industries.
- Countries are taking steps to reduce their dependence on China for rare earths to address this issue
- The U.S. government has initiated plans to build a domestic supply chain for rare earth magnets, including constructing processing facilities and partnerships
- Australia, the U.S., and Japan, as allies with a stake in rare earth elements, could collaborate to build a clean and secure supply chain.

World REEs reserves.
Source of data: US Geological Survey, 2023



Imports & Export of Rare earth metals (United States.) Source of data: US Geological Survey, 2023

The model

- Our research explores various aspects of the potential duopoly between China and the rest of the world (ROW) in the REEs market.
- NMPC computes finite-horizon optimal trajectories in order to find the infinite-horizon optimal trajectory.
- The players' problems involve then the repetitive solution of an optimal control problem at each sampling instant in a receding time horizon fashion, but, in each instant of time, policymakers only implement the initial control action. A policy equilibrium consistent with this kind of optimization is introduced.
- We use the theoretical model of natural resource extraction by Groot *et al.* (2003) extended to a duopoly case where China holds a leading position due to lower marginal cost.
- Our analysis considers the rarity of REEs related to the difficulty of discovery and refinement, not their scarcity in the Earth's crust. This limited access to resources is captured in our model through the stock of available resources (Greiner *et al.*, 2012).

- Formally, the discovered reserves of REEs evolve as follows:

$$(1) \quad \dot{s}_t = f(s_t, s^0) - e_t^W \quad s_0 = \bar{s} \text{ for } t \in \mathbb{R}_0^+$$

- We assume that increases in REE are linear, i.e., $f(s_t, s^0) = \theta(\bar{s} - s_t - s^z)$ where $s^z \geq 0$ represents the value of the available resource below which no new deposits are discovered (Greiner *et al.*, 2012)

- we assume a linear function of supply:

$$(2) \quad p_t = \bar{p} - e_t^W$$

where \bar{p} represents the choke price, i.e., a price above which demand for the resource (e_t^W) will be zero.

- Given the strategies of the other firm, both players aim to maximize their discounted profits at each point in time $t = \mathbb{R}_0^+$
- The market leader (China) maximizes the following optimization problem:

$$(3) \quad \begin{aligned} & \max_{e_t^C} \int_t^{t+T} e^{-rt} (\bar{p} - e_t^W - m^C) e_t^C dt \\ \text{s.t} \quad & \dot{s}_t = \theta(s^0 - s_t - s^Z) - e_t^W, \quad e_t^W = e_t^C + e_t^R \end{aligned}$$

- To ensure that China and the Rest of the World have sufficient incentives to extract, we assume their marginal extraction costs are lower than the choke price.

- Similarly, the follower seeks to maximize its profits, its optimization problem is formulated in each instant of time $t = \mathbb{R}_0^+$.

$$(4) \quad \max_{e_t^R} \int_t^{t+T} e^{-rt} (\bar{p}(1 + z_R) - e_t^W - m^R) e_t^R dt$$

$$\text{s.t.} \quad \dot{s}_t = \theta(s^0 - s_t - s^Z) - e_t^W, \quad p_t = \bar{p} - e_t^W, \quad e_t^W = e_t^C + e_t^R$$

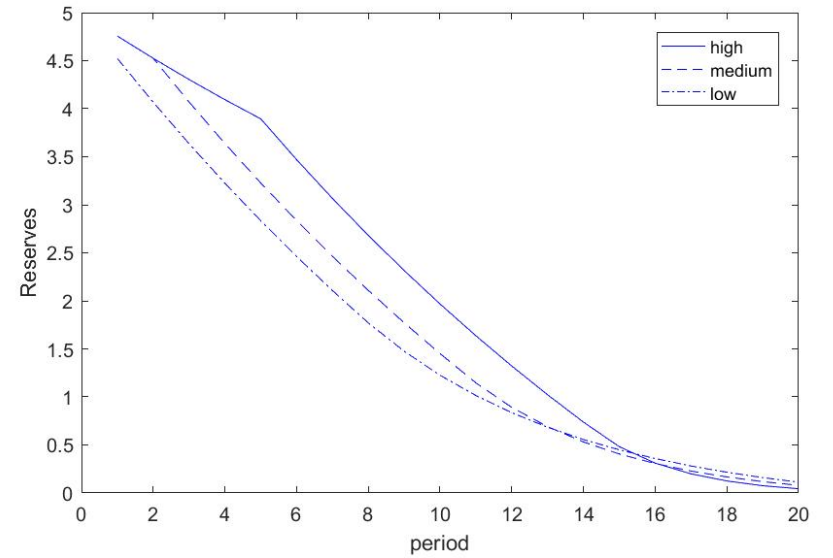
- Where z_R is a subsidy to support the production in the rest of the world.
- Our optimization problem, considers e_t^C and e_t^R as control variables and s_t as the state variable representing the stock of discovered resources.

Duopoly market scenario

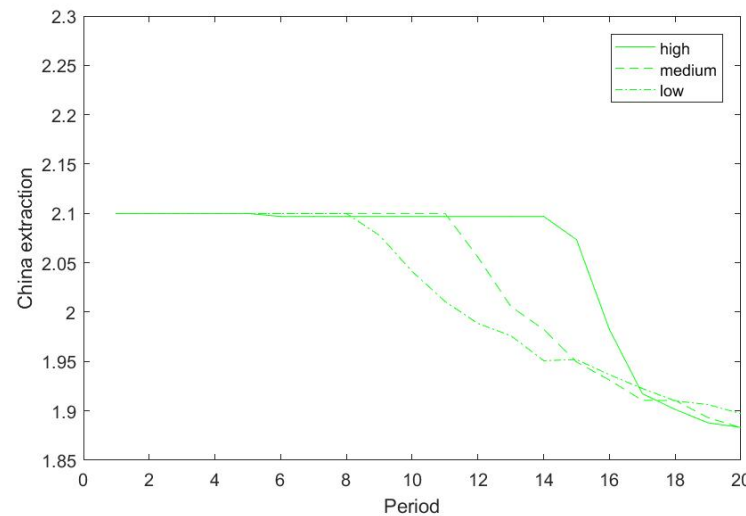
- In the first scenario, we assume that the rest of the world's (ROW) marginal cost is significantly higher than China's, specifically three times higher, reflecting China's previous and continued dominance throughout the supply chain.
- Furthermore, we consider the existence of a support policy as the second assumption.

Results:

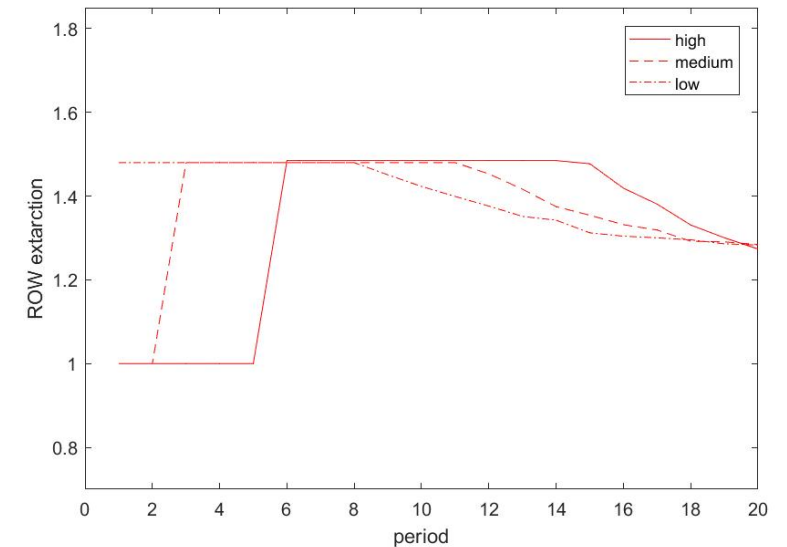
- ROW can maintain its presence in the REE market and even increase its extractions.
- its marginal cost remains higher compared to China, making it unlikely for the ROW to obtain China's dominant position.



Stock of discovered reservation: The case of the high marginal cost of ROW



China Extractions: The case of the high marginal cost of ROW



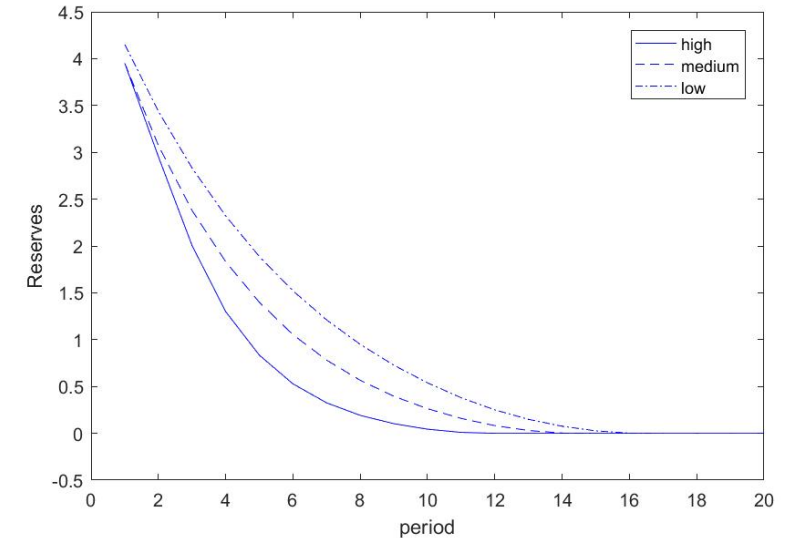
ROW Extractions: The case of the high marginal cost of ROW

ROW lower marginal cost

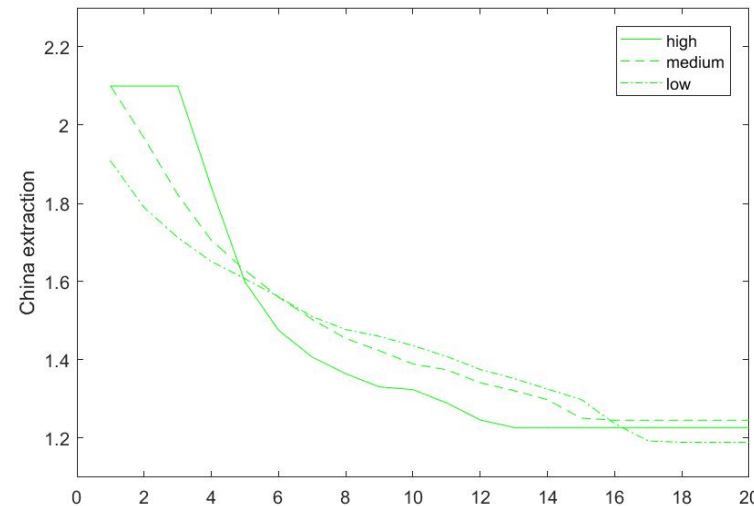
- Second scenario assesses a situation where the marginal extraction cost of ROW decreases, reaching a level 1.5 times higher than China's.
- This decrease can be attributed to factors such as companies having been in the market for many years or advancements in technology benefiting new competitors

Results:

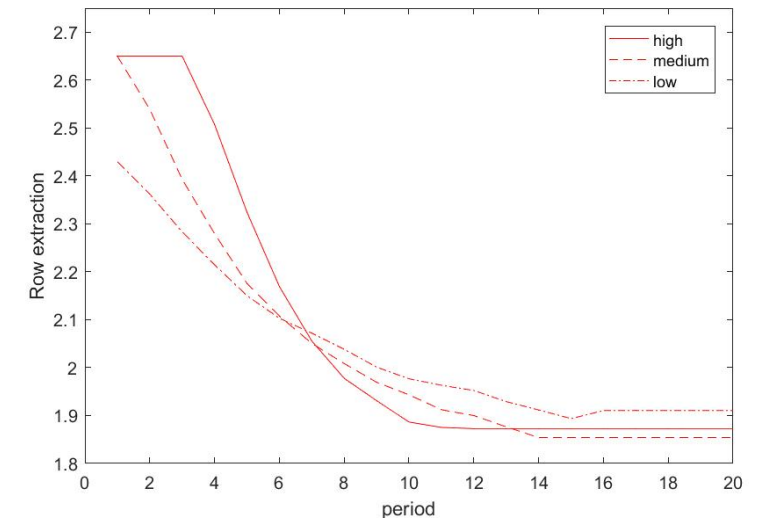
- In a scenario where China already has a high level of extraction and ROW, as the other oligopolist extracts even more, the stock of discovered resources will not last for an extended period.



Stock of discovered reservation: The case of the lower marginal cost of ROW



China Extractions: The case of the lower marginal cost of ROW



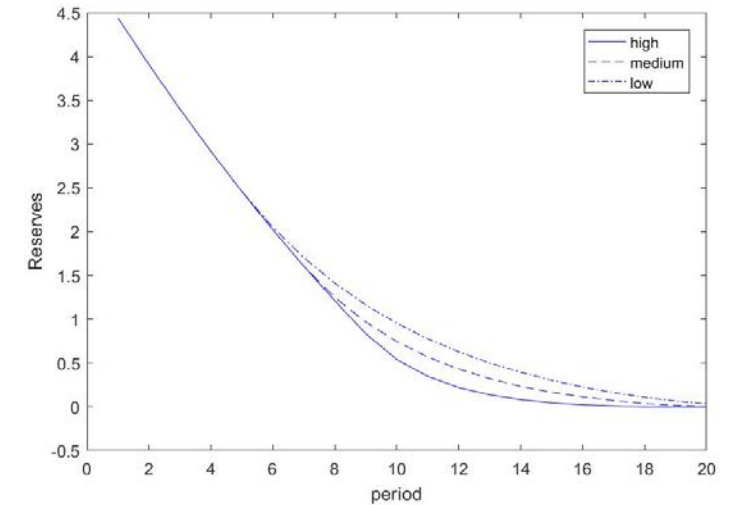
ROW Extractions: The case of the lower marginal cost of ROW

No supporting policy

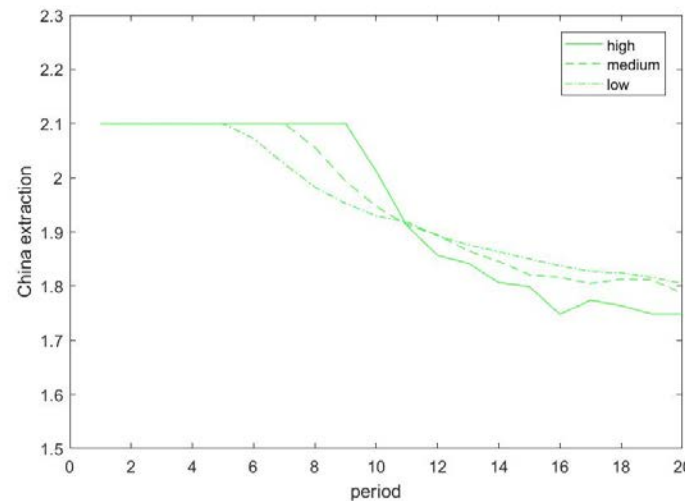
- In this section, we examine the impact of supporting policies on the market structure. In this context, we remove supporting policies, but keep the assumption of the lower marginal cost of ROW.
- China still maintains its dominant position and enjoys a lower marginal cost compared to the ROW.

Results:

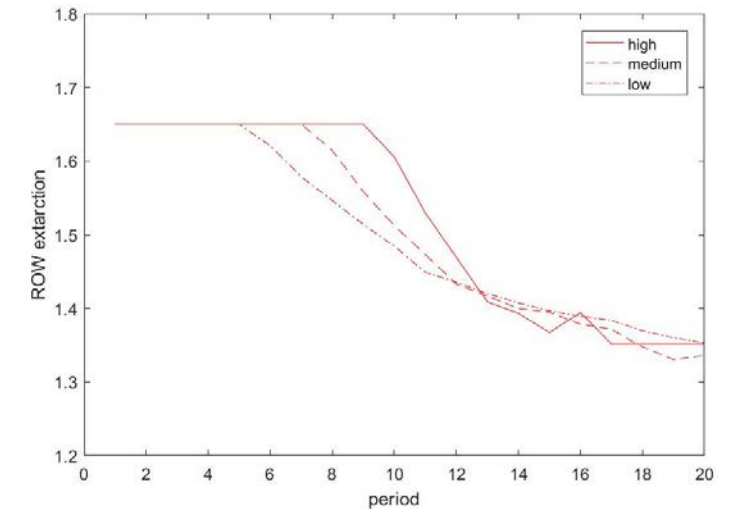
- Results highlight the importance of product pricing as a critical factor in maintaining the market structure.
- A lower marginal cost would benefit the ROW's market share, but only if it is accompanied by supporting policies, such as a higher choke price.



Stock of discovered reservation: without support



China Extraction: without support



ROW Extraction: without support

Conclusions

- The results indicated that support policies, such as implementing a higher choke price for ROW, could greatly improve ROW's market share in the duopoly market.
- However, in the absence of such support, a reduction in ROW's marginal costs would not significantly impact ROW's market share.
- The results emphasize the significance of considering the long-term implications of the market transformation and ensuring that both suppliers, China and the ROW, benefit from it.
- The study advises cautiously proceeding toward a duopoly market and thoroughly evaluating different supporting policies.