CHAPTER 1 COMMODITY SPECIAL FEATURE: ONLINE ANNEX 1.1

The Economics of Rare Earths: Global Impact of Shortages and Industrial Policies

Part I. Descriptive Statistics

Here we describe the data used in the descriptive statistics analysis.

Data for Figure 1.SF.2: Rare earth mining (in TREO equivalent), 1998-2024; by country

Country-level rare earth production data from 1998 to 2024 were sourced from the U.S. Geological Survey (USGS), Rare Earths Statistics and Information, reporting annual output in total rare earth oxide (TREO) equivalent, measured in metric tons of rare earth oxide (REO) content. Producing countries were grouped into China, United States, Australia, Myanmar, with all remaining producers aggregated into an "Others" category.

Figure 1. SF.3: China's Share of Rare Earth Supply Chains in 2024 and destination of its exports

- *Panel 1 & 2: Data on China's share of rare earth supply chain stages* for light rare earth elements (mining, oxide separation, metal refining) and heavy rare earth elements (mining, oxide separation, metal refining, and permanent magnets). Data were obtained from Bedford (2025).
- *Panel 3 & 4: Trade data on destination of China's exports of rare earth metals and compounds, and permanent magnets in 2024* were sourced from the World Integrated Trade Solution (WITS) database, maintained by the World Bank, drawing on UN Comtrade statistics.
- For panel 3, China's exports of rare earth metals and compounds, the analysis uses China's export data (quantities in kilograms) for 2024 under the following HS product codes: HS 280530 (rare earth metals), HS 284690 (rare earth compounds), and HS 284610 (cerium compounds). Export quantities were extracted at the partner-country level for each HS code. Quantities across all three HS codes were summed to construct total Chinese exports of rare earth metals and compounds in kilograms. Country shares were calculated as the ratio of each destination's aggregated export volume (kg) to total Chinese exports (kg) across the selected HS codes.
- For panel 4, China's exports of rare earth permanent magnets, the analysis uses China's export data (quantities in kilograms) for 2024 under HS 850511, corresponding to rare earth permanent magnets. Export quantities were extracted at the partner-country level. Country shares were calculated as the ratio of each destination's export volume (kg) to total Chinese exports (kg) of rare earth permanent magnets.

Figure 1. SF.4: China's exports of rare-earth permanent magnets and rare-earth magnet components intended for permanent magnet production.

- Monthly export data were sourced from the General Administration of Customs of China, covering exports of "permanent magnets or articles intended to be permanent magnets, of rare earth metals". The series corresponds to HS 2022 code 85051110. The figure plots the reported monthly export quantities (in tons) from January 2015 to December 2025.

Figure 1. SF.5: Value Added and Gross Output at Risk.

- Measures of value added and gross output at risk are constructed using sectoral reliance estimates from Nassar and others (2025) and the 2017 BEA 405-sector data. Rare earth dependence is first measured at the detailed BEA industry level as the share of gross output reliance on rare earth inputs. These reliance shares are then translated to OECD sectors using value-weighted aggregation based on gross output, so that dependence at the aggregated level reflects the economic importance of underlying industries. The resulting OECD-level reliance measures are multiplied by sectoral gross output or value added and normalized by total gross output or value added to obtain economy-wide indicators of exposure to rare earth supply disruptions.

Figure 1: SF.7 Aggregate stock market value of publicly listed firms in the rare earth industry

- Firm-level financial data were sourced from S&P Capital IQ Pro. The analysis covers the period from January 2025 to January 2026. The sample of firms was constructed using the Capital IQ Company Screening tool to identify publicly listed companies directly involved in the rare earth industry. Firms were identified through keyword searches ("Rare Earth," "Rare Earths," "Rare Earth Elements," "Rare Elements") applied to both business descriptions and long business descriptions.

- Firms with China as their primary geographic location were excluded to focus on non-Chinese rare earth producers and developers. Screening was restricted to public companies with operating status. The initial screening yielded 315 firms, each of which was manually reviewed by examining company websites, disclosed projects, and operational descriptions to confirm active involvement in rare earth extraction, processing, or project development. Firms with only tangential references to rare earths were excluded; the final sample includes 89 publicly listed firms actively engaged in rare earth production or development.

- For the final sample of firms, daily stock prices and market capitalization were collected from January 2025 onward. The figure plots the aggregate market capitalization of the identified rare earth firms over time. All estimates reflect IMF staff calculations based on S&P Capital IQ Pro data.

Part II. Small Open Economy Model with Production Networks and REEs Supply Constraints

The model in this Commodity Special Feature (CSF) is based on Bogmans, Cuadros Bloch, and others (forthcoming)– which extends the multi-sector dynamic small-open economy model of Silva and others (2024) and Gomez-Gonzalez and others (2025) – to incorporate supply constraints in the amount of REEs imported from abroad. The model is dynamic and features forward-looking households and cost-minimizing firms.

Households: The household maximizes its lifetime discounted utility of consumption subject to its budget constraint. The households earns labor income and accumulates foreign assets, denominated in units of the exportable commodity, at a given foreign interest rate.

Firms: In all sectors, firms produce with a mix of intermediate inputs, domestic and imported inputs, and a labor input. The imported input corresponds to REEs. The production function is a normalized CES with non-unitary elasticity of substitution among inputs.

REEs Supply Constraint

Total domestic demand for imported REEs is constrained by the following inequality:

$$\sum_{i=1}^{N+1} M_{i,M} \leq \overline{M}_M,$$

where $\overline{M}_M$ is the supply constraint on imported REEs from abroad. We assume the constraint is always binding by setting $\overline{M_M}$ smaller than the unconstrained equilibrium demand for REEs. The Lagrange multiplier associated with this constraint shows up as a wedge in the price of imported REEs. Hence, REEs inputs effectively cost $P_M(1+\tau_M)$, with $\overline{P_M}$ representing the global benchmark price of REEs.

Exogenous Processes

The commodity price in foreign currency ($P^*_{N+1,t}$), the exogenous productivity $Z_{i,t}$, and the constraint in REEs imports $\overline{M}_M$ are given by the three following exogenous processes:

$$\log P^*_{N+1,t} = \rho_{N+1} \log P^*_{N+1,t-1} + \varepsilon_{N+1,t}$$
$$\log Z_{i,t} = \rho_Z \log Z_{i,t-1} + \varepsilon_{i,t}$$
$$\log \overline{M}_{m,t} = (1-\rho_M) \log \widehat{M}_M + \rho_M \log \overline{M}_{M,t-1} + \varepsilon_{M,t} ,$$

with $\widehat{M}_M$ representing the long-run mean of the supply constraint.

Data for Calibration

The baseline data to construct the cross-country reliance on REEs is based on the 2017 U.S. Input–Output tables from the Bureau of Economic Analysis (BEA), which provide a 405 sector representation of production, intermediate use, and final demand. These data are augmented to explicitly account for rare earth elements (as raw materials) and magnets usage (embedded rare earth), which do not exist as standalone sectors in the original BEA classification. Information on rare earth requirements by element and application is drawn from Alonso et al. (2022) where tons usage per rare earth element (Lanthanum, Cerium, Praseodymium, Neodymium, Samarium, Europium, Gadolinium, Terbium, Dysprosium and Yttrium) is provided, while growth rates used to align quantities to the 2017 benchmark year follow Nkiawete and Vander Wal (2025).

Sectoral allocation of rare earth use and intermediate demand is guided by Nassar et al. (2025). After constructing rare earth and magnet sectors, NAICS industries are translated into OECD classifications and aggregated to obtain a synthetic U.S. OECD Input–Output matrix. Our key assumption to construct the REEs augmented OECD-IO table for other countries is that foreign sectors (e.g., electronics) use the same share of REEs in production as their U.S. counterpart. Hence, the main differences across countries are given by the size and linkages with the rest of the economy of the domestic sectors using REEs in their production.

Calibration

The model is set to match each country's sectoral final consumption shares, IO shares, REEs imported shares in 2017. The discount rate, the persistence and volatility of shocks are from Silva and others (2024). The persistence and standard deviation of the REEs supply shock are set to 0.9 and 80%, respectively. The elasticities of substitution in production are set to two values: first a very small elasticity of substitution of 0.015, which reflects short-run constraints of substituting imported intermediates (see, for example, Bohem and others, 2019), in this case, REEs. Second, we use an elasticity of 0.8 which according to Alfaro and others (2025) describes longer time horizons (up to five years) in which firms can substitute REEs with other inputs of production. The model is solved using a first-order log-linear approximation around the non-stochastic steady state.

Discussion of results

The model has two key mechanisms of amplification. First, the strength of input-output linkages between domestic sectors and imported REEs. The disruption in the use of REEs affects sectors that locate upstream and downstream from the domestic REEs users. If the motor vehicles sector scales down, suppliers of the motor vehicles sector will observe a reduction in demand. On the other hand, the disruption creates misallocation of inputs such that the domestic price of motor vehicles increases, affecting the marginal cost of production of downstream sectors such as the transportation sector. The second mechanism of amplification operates through the degree of flexibility with which domestic sectors can substitute inputs of production. The direct impact reflects the (im)possibility of replacing rare earth elements with other materials or with primary factors such as labor or capital. Indirect effects arise through production networks, as firms adjust their use of non-REE but REE-intensive intermediate inputs. For example, a sector that relies heavily on transportation services may become indirectly exposed to REE supply disruptions, particularly if those services cannot be easily substituted in the short run.

Part III. Global Model of REE production with Industrial Policies (IPs)

This model draws from Bogmans, Cuadros Bloch, and others (forthcoming). The production of rare-earth elements (REEs) consists of two stages: mining and refining. We assume the world consists of J countries and in each country a representative miner and a representative refiner operate. Miners extract raw REEs from the earth's crust and sell them to refiners, who transform the raw material into a refined product for sale to consumers (e.g., magnet or catalyst producers) in the global market. The model rationalizes China's current dominant position in both stages through country-specific cost differences, which are calibrated using project-level data (Online Annex Figure SF.1.1.1) and which can be offset by industrial policies such as investment subsidies or price floors.[1]

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[1] The model takes China's competitiveness in the REE industry as given. This competitiveness stems from multiple factors: an abundance of skilled labor including engineers, chemists, and metallurgists; a large intellectual property portfolio spanning the entire REE value chain; geologically superior deposits; a history of state support; and more lenient environmental regulations.

Miners – Each representative miner j operates in a competitive fashion and extracts a non-exhaustible endowment of natural resource $x_{j,t}$. Following Kellogg (2024) and Anderson et al. (2018), REE extraction follows an exponential decline at a rate $\eta_j > 0$, assumed to be equal for all countries.[2]

Letting $i_{j,t}^{x}$ denote the rate of investment in new extraction capacity, the extraction's law of motion is

$$x_{j,t} = (1 - \eta_j)x_{j,t-1} + i_{j,t}^{x} \tag{1}$$

Miners incur two sources of costs: investment in capacity costs (CAPEX), and extraction costs (OPEX). Taking as given price sequences, miners in country j solve the problem:

$$\max_{x_{j,t}, i_{j,t}^{x}} \sum_{t=0}^{\infty} \beta_j^t \left(p_t^x x_{j,t} - c_j^{ix}(i_{j,t}^{x}) - c_j^{x}(x_{j,t}) \right)$$

subject to (1). We denote with $\beta_j, c_j^{ix}(\cdot), c_j^{x}(\cdot)$, respectively, the discount factor, miners' CAPEX and miners' OPEX. We also denote with p_t^x the international price of raw REEs.

OPEX costs are linear while CAPEX are linear-quadratic, such that the marginal miners' CAPEX and the marginal miners' OPEX are given by:

$$\frac{\partial c_j^{ix}}{\partial i_{j,t}^{x}} = \alpha_j^{ix} + \gamma_j^{ix}\left(x_{j,t} - (1 - \eta_j)x_{j,t-1}\right)$$

$$\frac{\partial c_j^{x}}{\partial x_{j,t}} = \alpha_j^{x}$$

where $\alpha_j^{ix}, \gamma_j^{ix}, \alpha_j^{x}$ are country-specific and time invariant parameters. See Bogmans, Cuadros Bloch, and others (forthcoming) for further details on the miners' optimality condition.

In turn, country j's supply of raw REEs, denoted with $R_{j,t}^{s}$ is equal to $x_{j,t}$ and global supply of raw REEs is:

$$R_t^s = \sum_{j=1}^{J} R_{j,t}^{s} = \sum_{j=1}^{J} x_{j,t}$$

Refiners – Each representative refiner j operates in a competitive fashion and purchases raw REEs $z_{j,t}$ from the global market at the price p_t^x. Refining raw REEs requires investment in refining capacity $\mathrm{y}_{\mathrm{j,t}}$, with exponential decline rate δ_j, and a law of motion given by:

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[2] Kellogg (2024) applies his model to a *tapped* resource (oil, gas) whereas rare earths are a *mined* resource, such that in our context x is best interpreted as total mine production capacity rather than an exhaustible resource.

$$y_{j,t} = (1-\delta_j)y_{j,t-1} + i^y_{j,t} \tag{2}$$

Refining technology is linear in its input and satisfies the equation $y_{j,t} = z_{j,t}$, hence refining is constrained by refining capacity. Similarly to miners, refiners take as given final good prices, input prices and subsidy sequences and solve the following problem:

$$\max_{y_{j,t}, i^y_{j,t}} \sum_{t=0}^{\infty} \beta_j^t \left(p_t^y f_{j,t} y_{j,t} - p_t^x z_{j,t} - \left(1 - s^{iy}_{j,t}\right) c_j^{iy}\left(i^y_{j,t}\right) - c_j^y\left(y_{j,t}\right)\right)$$

subject to (2). We denote with $c_j^{iy}(\cdot), c_j^y(\cdot)$, respectively, the cost of investment in refining capacity (refiners' CAPEX), and the cost of refining (refiners' OPEX) in country j. We also denote with p_t^y the international price of refined REEs (i.e. the final good) and with $s^{iy}_{j,t}$ the refiners' CAPEX subsidy, which is country-specific. In addition, $\mathrm{f}_{\mathrm{j,t}} \geq 1$ represents a country-specific price floor that refiners receive. We further assume that the functional forms of marginal refiners' CAPEX and the marginal refiners' OPEX are given by:

$$\frac{\partial c_j^{iy}}{\partial i^y_{j,t}} = \alpha_j^{iy} + \gamma_j^{iy}\left(y_{j,t} - (1-\delta_j)y_{j,t-1}\right)$$

$$\frac{\partial \mathrm{c}_{\mathrm{j}}^{\mathrm{y}}}{\partial \mathrm{y}_{\mathrm{j,t}}} = \alpha_{\mathrm{j}}^{\mathrm{y}}$$

where $\alpha_j^{iy}, \gamma_j^{iy}, \alpha_j^y$ are country-specific and time invariant parameters. See Bogmans, Cuadros Bloch, and others (forthcoming) for further details on the refiners' optimality condition.

In turn, country j's demand of raw REEs, denoted with $R^d_{j,t}$ is equal to $y_{j,t}$ and the global demand of raw REEs is:

$$R_t^d = \sum_{j=1}^{J} R^d_{j,t} = \sum_{j=1}^{J} y_{j,t}$$

The equilibrium price of raw REEs p_t^x is such that $R_t^d = R_t^s$. Country j's demand for refined REEs is exogenously given by:

$$q_{j,t} = a_{j,t}\left(p_t^y\right)^{\epsilon}$$

where $q_{j,t}$ denotes the quantity demand by country j, $a_{j,t}$ represents a country-specific final demand shifter and ϵ is the elasticity of demand with respect to its price, assumed to be common across countries. Then, global demand for refined REEs is $Q_t = \sum_{j=1}^{J} q_{j,t}$. Consequently, the equilibrium price level for refined REEs products is such that the global market clears, i.e. $Q_t = Y_t = \sum_j y_{j,t}$.

Numerical Algorithm – Firstly, given the model parameters, we begin by computing the deterministic steady state of the economy in which no IPs is implemented. We determine the optimal steady state values of mining and refining capacities for each country given an initial guess of the final good price and for a grid of intermediate good prices p^x. We construct the aggregate demand and supply functions for each point of the grid and compute the equilibrium price such that the excess supply of raw REEs is nil. We then recover the final good price, update the guess, and repeat until convergence. Secondly, we solve for the model dynamics in a similar fashion, using the open-loop equilibrium approach, i.e. one in which the paths of all policies are determined at time $t = 0$. We construct a guess for the final good price $\{p_t^{0,y}\}_{t=0}^T$ and the state variables $\{x_{j,t}^0\}_{j,t}$ and $\{y_{j,t}^0\}_{j,t}$ and start from the initial conditions $\{x_{j,-1}, y_{j,-1}\}_{j=1}^J$. We solve forward the difference equations associated with the problem for each point of the intermediate good price grid and compute, for each t, the equilibrium price. We then compute and update the guess of the final good price and the guesses of the state variables until convergence is achieved.

Data and Calibration – The industrial policy model is calibrated with data from multiples sources. On the demand side, the short-run price elasticity of demand for refined REE is based on an unweighted average of elasticity estimates for magnet REEs (Nd, Pr, Dy, Tb) from Shojaeddini et al. (2024). China accounts for 50% of refined REE consumption in the base year, based on the 2020 estimate from Shao et al. (2026). The remaining 50% is distributed across other countries based on their shares of Chinese REE exports in 2019 (also from Shao et al., 2026). For example, if country i received 10% of Chinese REE exports, it is assigned 5% (= 0.10 × 0.50) of global consumption. Demand growth rates are equated to primary supply growth rates from the IEA’s Global Critical Minerals Outlook (IEA, 2025), which suggests a growth of 4.7% for the period 2025-2029, 1.42% for the period 2030-2034, and 0% thereafter. Global refining production levels are also taken from IEA (2025), while global mining production levels are drawn from the United States Geological Survey (U.S.G.S.) Rare Earth Summary (2024). Our estimates for mining and oxide separation costs in China are based on the premise that between 2006-2010, China held a near-monopoly in REEs, and its industry was not yet consolidated, characterized by many competing firms. We therefore take average prices during that period (in real terms) as a proxy for China's costs. For ex-China countries, cost estimates are based on an evaluation of 21 ex-China REE projects (mining and mining-plus-refining). The project-level data suggests ex-China projects are on average substantially less competitive than Chinese projects, but there is limited evidence for a strong cost ranking among ex-China countries. We therefore assume that cost parameters are identical across all ex-China countries. Finally, given the estimated α parameters, we calibrate the γ parameters by targeting the initial refining and mining shares.

Policy Experiments – We conduct two sets of four different policy experiments, and we focus our attention on the effect of the policies on the U.S. economy. In the first set of policy experiments we analyze the effects of industrial policies (IPs) that allow the U.S. to attain a 25% self-sufficiency rate by 2035.[3] In the second set of policies we replicate the experiments for a 50% independence target. Within each set, we consider “unilateral” IPs and “coordinated among importers” IPs using as instruments subsidies to investment in capacity and price floors for refiners. Uncoordinated IPs are policies implemented unilaterally by the U.S., while coordinated IPs are policies implemented, equally, by all importer countries. The U.S. fiscal costs of the IPs are computed in terms of domestic usage of refined REEs (i.e. the final product) under the baseline calibration, and are given by:

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[3] We define self-sufficiency as the quantity of refined REEs that the U.S. does not import from China, the market leader in REEs, in terms of U.S. consumption of refined REEs (i.e. the final product). Values close to 0 indicate that all U.S. consumption of refined REEs is imported from China, while values close to 1 indicate that all U.S. consumption is either produced domestically or imported from other net importing countries.

$$\mathrm{FiscalCost}^{\mathrm{subsidy}}_{\mathrm{U.S.,t}} = \frac{\mathrm{s}^{\mathrm{iy}}_{\mathrm{U.S.,t}}\mathrm{c}^{\mathrm{iy}}_{\mathrm{U.S.}}\left(\mathrm{i}^{\mathrm{y}}_{\mathrm{U.S.}}\right)}{\mathrm{p}^{\mathrm{y}}_{\mathrm{t}}\mathrm{q}_{\mathrm{U.S.,t}}}$$

$$\mathrm{FiscalCost}^{floor}_{U.S.,t} = \frac{\mathrm{p}^{\mathrm{y}}_{\mathrm{t}}\left(\mathrm{f}^{\mathrm{y}}_{\mathrm{U.S.,t}} - 1\right)\mathrm{y}_{\mathrm{U.S.,t}}}{p^{y}_{t} q_{U.S.,t}}$$

where the first equation represents the fiscal cost of subsidies to investment costs, while the second equation represents the fiscal cost of price floors, which we denote as $f^{y}_{U.S.,t}$.

For each country $j \in 1, \ldots, J$ and each period $t \in 0, \ldots, T$ we construct the matrix of net import flows M_t that collects the net flow of imports of refined REEs from country j to country i. We first construct the world's export share of each country as:

$$\mathrm{xs}_{j,t} = \frac{max\left(y_{j,t} - q_{j,t}, 0\right)}{\sum_i max\left(y_{i,t} - q_{i,t}, 0\right)}$$

Given that goods are homogenous across countries, we then assign each country's net imports in proportion to each net exporter's share of world's exports as follows:

$$m_{ij,t} = max\left(q_{i,t} - y_{i,t}, 0\right) \cdot xs_{j,t}$$

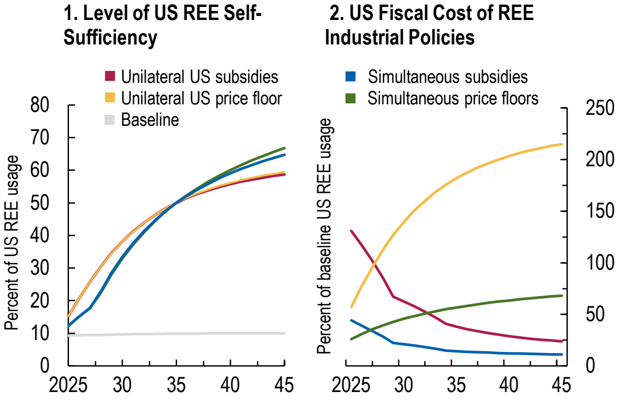
where m_{ij} is the generic element of the matrix of net import flows. For each country $\mathrm{j} \neq \mathrm{China}$ we define the degree of self-sufficiency as the share of country j consumption that is produced either domestically or imported from any other country $\mathrm{i} \neq \mathrm{j}, \mathrm{China}$. Specifically, we computed self-sufficiency as:

$$\sigma_{i,t} = 1 - \frac{m_{iCH,t}}{q_{i,t}}$$

where $m_{iCH,t}$ represents country i's imports from China.

Online Annex Figure 1.1.1 reports the results of the public intervention necessary to achieve the 50% target by 2035. Compared to the 25% target, achieving the 50% self-sufficiency target is significantly more costly in terms of fiscal resources, particularly in the case of price floors. As before, coordination yields higher self-sufficiency levels in the long run, as global production increases, depressing price levels and compressing profit margins of Chinese producers. The U.S. can improve self-sufficiency employing an uncoordinated investment subsidy of 93.8%, an uncoordinated price floor of 5.64, a coordinated investment subsidy of 92% or a coordinated price

Online Annex Figure 1.1.1. Effectiveness and Fiscal Cost of Alternative Industrial Policies to Achieve 50 percent of REE Self-Sufficiency in the US



Source: IMF staff calculations.
Note: Investment subsidy to US refiners only implemented with a 90.6 percent subsidy; investment subsidy to refiners outside of China only implemented with a 89.4 percent subsidy; price floor subsidy to US refiners only implemented with a price floor 4.82 times the period market price; price floor subsidy to refiners outside China only implemented with a price floor 3.23 times the period market price. Baseline scenario assumes a 4.7 percent global demand growth in 2025–2029, a 1.42 percent global demand growth in 2030–2034. REE= rare earth element.

floor of 3.37. Unlike the 25% target, for higher levels of self-sufficiency coordinated investment subsidies rates (price floors) are lower than uncoordinated policy rates undertaken by the U.S, highlighting the importance of coordinated efforts in achieving ambitious targets.

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