Trade and Industrial Policy in Supply Chains: Directed Technological Change in Rare Earths

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Motivation

- Renewed interest in the effects of trade and industrial policy
  - Particularly in strategic sectors
  - Green transition and geopolitical tensions

⇒ Increased attention on *rare earth elements (REEs)* and other *critical minerals*

⇒ Impact of policies can be complex in an environment of global value chains and fast technological progress

Question:

What is the effect of industrial policy that limits global access to critical inputs?

This Paper

Measurement, Evidence, and Mechanism

1. Measurement: Use and innovation in REE-using sectors
   - Construct an input-output table that includes REEs
   - Measure downstream innovation related to REEs
2. Evidence on the impact of industrial policy in the context of GVCs
   - Exploit China's 2010 REE policy $\rightarrow$ adverse global REE supply shock
   - Expansion of innovation and exports in downstream industries outside of China
3. Mechanism: Directed technological change and comparative advantage
   - Build quantitative model of trade, IO linkages and directed technological change
   - Low substitutability of REEs $\Rightarrow$ REE-directed technological change
   - Calibrate the model to assess the welfare implications

Related Literature

- Quantitative trade: Eaton and Kortum (2002), Costinot and Rodríguez-Clare (2014), Caliendo and Parro (2015, 2022), Lashkaripour and Lugovskyy (2023)
- Directed technological change: Acemoglu (1998, 2002), Acemoglu et al. (2012), Aghion et al. (2016), Acemoglu et al. (2015), Kennedy (1964), Hanlon (2015), Popp (2002), Hassler et al. (2021), Blum (2010)
- Industrial policy: Harrison and Rodríguez-Clare (2010), Juhász et al. (2024), Criscuolo et al. (2019), Bartelme et al. (2025), Barwick et al. (2024), Kee and Xie (2025), Juhász et al. (2024), Liu (2019)
- Supply chain shocks / policy restrictions: Fajgelbaum and Khandelwal (2022), Grossman et al. (2024), Bown et al. (2023), Barattieri and Cacciatore (2023), Amiti et al. (2019), Fajgelbaum et al. (2020), Flaaen et al. (2020), Grossman et al. (2024), Alfaro and Chor (2023), Alfaro et al. (2025)

The Economics of Rare Earths

17 Elements (15 Lanthanides, Yttrium, Scandium): Not Rare in a Geological Sense

1. Key Inputs:
   - *"Faster, lighter, stronger":*
     Green transformation, medicine, military
   - *Often hard to substitute but relatively small total requirements*
   - *Permanent magnets:* electric motors, EVs, turbines; *catalysts:* energy efficiency, renewables
2. REEs susceptible to policy intervention
   - China is a quasi-monopolist in global REE supply
   - Supply inelastic in short run

▸ Details

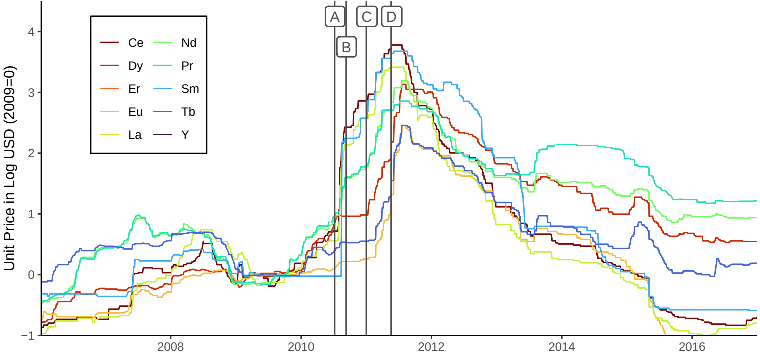
Chinese Industrial Policy on REEs

- Early 2000s: China emerged as the dominant player in global REE production
  - *"The Middle East has oil and China has rare earths."*, *Deng Xiaoping* in 1992
  - Market share in global REE mine production reached 98% in 2009
- Jul 2010: China cut export quota of REE by 72%
  (to reduce domestic price and combat illegal mining)
- Sep 2010: Chinese trawler collided with Japanese coast guard boats in disputed Senkaku-Diayou waters
  - China inofficially suspended REE exports to Japan
- Jan 2011: China raised export taxes on certain REE minerals
- May 2011: China introduced export quotas on REE ferroalloys
- Jan 2015: China eliminates quota following WTO ruling (2012 US-EU-Japan)

▸ REE Imports ▸ REE Mining

Chinese Industrial Policy on REEs

Unit Prices of Individual REEs



- *REE unit prices spiked by a factor of 10-45* and remained high for a few years
- Relevant episodes: A=Export quota cut by China; B=Senkaku-Diayou boat collision; C=Select export tariffs hike by China; D=New export quotas on ferro-alloys by China

Mapping REEs into an Input-Output Table

Data and Methodology

- Construct an extended IO table that incorporates individual REEs as inputs
  - U.S. BEA 2012 Use Table, United States Geological Survey (USGS), Asian Metal
- Supplying sectors: Map REE supply into *“Other Basic Inorganic Chemical Manufacturing”*
  - Split into 6 rows: 5 for the individual REEs + 1 large non-REE
  - REEs: lanthanum, cerium, praseodymium, neodymium, and dysprosium
- Using sectors: Match each REE application at ”general application” level: *Magnets, Alloys, Batteries, Catalysts (automobile), Catalysts (fluid-cracking)*
  - Split *”Other fabricated metals”* into magnet and non-magnet production
  - Convert usage from quantities into USD using REE unit prices

▸ Table

Empirics

Goal

- Estimate the differential effect of China's REE policy on downstream manufacturing sectors: *i.* outside of China, *ii.* in China

Sample

- 50 largest economies in the world, manufacturing industries (4-digit SIC)
- 2002 to 2018

Outcomes

- Directed technological change: Patents on REE-related technologies
- Growth in exports

REE intensity of industries

- Based on our constructed IO table and an index of REE complementarity based on chemical and geological properties

Empirical Strategy

- DiD: *Compare change in economic activity before/after the REE supply shock between more/less REE-intensive industries*

$$y_{rst} = \beta REE\ Sensitivity_s \times post_t + \gamma \Delta_{rst} + \eta_{rs} + \eta_{rt} + \epsilon_{rst}$$

- Measure of *REE Sensitivity$_s$*:

$$REE\ Sensitivity_s = \sum_e tr_{es} \times compl_e$$

  - Rely on geological literature for estimates of element e complementarity ($compl_e$)
  - Index of complementarity from Graedel et al. (2015) ▸ Details
  - Ranges from 0 (perfect substitute available) to 100 (e cannot be substituted)

Measuring Directed Technological Change

Patents in REE-Intensive Manufacturing Sectors

- Google Patent Research Data:
  Granted patents that mention REEs or keywords in their title or abstract (>30,000)
  - Countries allocated based on patent assignee
  - Years allocated based on grant date (robust to using application dates)
  - Regions *EUR, USA, CHN, RUS, KOR, JPN, AUS, ROW*

- Use an LLM for further classification ▸ Details
  - Assign individual patents to a 4-digit SIC using sector
  - Identify technologies that *"enhance efficiency of REE use or help to substitute REEs"* ($\approx$ 60%)

Measuring Directed Technological Change

Example #1: GM Magnet Powder Coating Process Using Less Dysprosium

(12) **United States Patent**
Wang

(10) **Patent No.: US 8,480,815 B2**
(45) **Date of Patent: Jul. 9, 2013**

(54) **METHOD OF MAKING ND-FE-B SINTERED MAGNETS WITH DY OR TB**

(75) Inventor: **Yucong Wang**, West Bloomfield, MI (US)

(73) Assignee: **GM Global Technology Operations LLC**, Detroit, MI (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 58 days.

(21) Appl. No.: **13/007,203**

(22) Filed: **Jan. 14, 2011**

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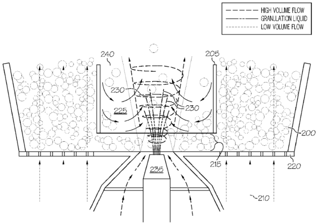
Japanese Office Action with a due date of Apr. 21, 2013 pertaining to JP Application No. 2011-245644.

3

DETAILED DESCRIPTION OF THE INVENTION

Magnets made using the present process use much less Dy or Tb than those made using the conventional methods while obtaining similar magnetic properties. In the present process, the Dy or Tb coated Nd—Fe—B powders are used to make the magnet, which results in a non-uniform distribution of Dy or Tb in the magnet, which can be seen and measured using a scanning electron microscope with a microprobe. This enables the present process to use much less Dy or Tb for the similar magnetic properties. For example, the amount of Dy and/or Tb can be reduced by about 20% or more compared to conventional processes, or about 30% or more, or about 40% or more, or about 50% or more, or about 60% or more, or about 70% or more, or about 80% or more, or about 90% or more. By non-uniform distribution, we mean that Dy and/or Tb are distributed or concentrated at the interface of the

Assuming the weight of permanent magnet pieces is about 1-1.5 kg per electric motor, and a yield of the machined permanent magnet (PM) pieces of typically about 55-60%, 2-3 kg of PM per motor would be required, or 4-6 kg per vehicle (some hybrid vehicles may use one induction motor and one PM motor). Moreover, Dy is also widely used by other industries. The only RE mine in the United States does not have any significant amounts of Dy. Therefore, reducing the Dy or Tb usage in permanent magnets would have a very significant cost impact.



Measuring Directed Technological Change

Example #2: Toyota Catalyst for Exhaust Gas Purification without Cerium

(12) **United States Patent**
Miura et al.

(10) **Patent No.: US 9,387,464 B2**
(45) **Date of Patent: Jul. 12, 2016**

(54) **IRON OXIDE-ZIRCONIA COMPOSITE OXIDE AND METHOD FOR PRODUCING SAME, AND EXHAUST GAS PURIFICATION CATALYST**

(71) Applicants: **Masahide Miura**, Toyota (JP); **Atsushi Tanaka**, Toyota (JP); **Takahiro Suzuki**, Toyota (JP); **Tadashi Suzuki**, Seto (JP); **Toshitaka Tanabe**, Nagakute (JP); **Naoki Takahashi**, Nagoya (JP)

(72) Inventors: **Masahide Miura**, Toyota (JP); **Atsushi Tanaka**, Toyota (JP); **Takahiro Suzuki**, Toyota (JP); **Tadashi Suzuki**, Seto (JP); **Toshitaka Tanabe**, Nagakute (JP); **Naoki Takahashi**, Nagoya (JP)

(73) Assignee: **TOYOTA JIDOSHA KABUSHIKI KAISHA**, Toyota-shi, Aichi (JP)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/384,283**

(22) PCT Filed: **Apr. 26, 2013**

(2013.01); ***B01J 23/83*** (2013.01); ***B01J 35/002*** (2013.01);

(Continued)

(58) **Field of Classification Search**
CPC B01J 21/04; B01J 21/066; B01J 23/10; B01J 23/56; B01J 23/63; B01J 23/745; B01J 23/76; B01J 23/83; B01J 23/8906; B01J 23/894
USPC 502/302–304, 326, 327, 332–334, 336, 502/338, 339, 349, 355
See application file for complete search history.

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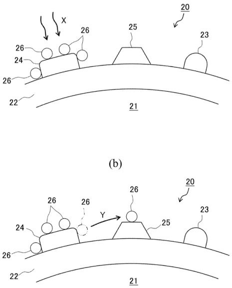
FIG. 38

(a)



(57) **ABSTRACT**

A composite oxide with a high oxygen storage capacity is provided without using cerium. The composite oxide is an iron oxide-zirconia composite oxide containing iron, zirconium, and a rare-earth element. The total content of Fe_2O_3, ZrO_2, and an oxide of the rare-earth element is not less than 90 mass %, the content of an iron oxide in terms of Fe_2O_3 is 10 to 90 mass %, and the absolute value of the covariance COV (Fe, Zr+X) of the composite oxide, which has been baked in the atmosphere at a temperature of greater than or equal to 900° C. for 5 hours or more, is not greater than 20.

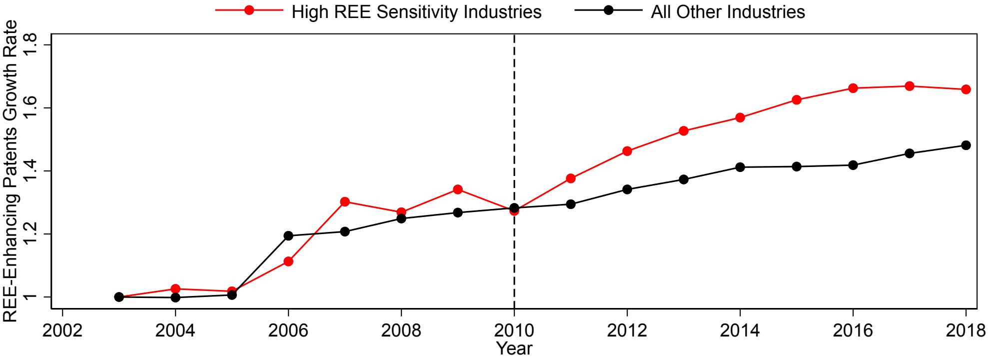
ite oxide obtained by causing an iron oxide to be supported on a support containing ceria.

Cerium contained in such composite oxides is expensive, and a problem has emerged that cerium is now difficult to obtain stably due to the deterioration of the procurement environment in recent years. Thus, suppressing the amount of cerium used is considered.

However, it is recognized by one of ordinary skill in the art that when the content of cerium is reduced in a composite

Trends in REE-Related Innovation Outside of China

Event Study

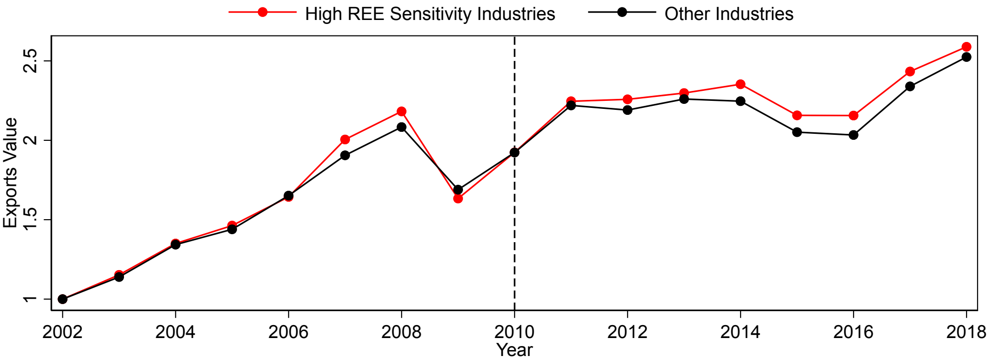


Rare-Earth Enhancing Patents in Manufacturing Industries

	PPLM: REE-Enhancing Patents					
	NONCHN (1)	USA (2)	EUR (3)	JPN (4)	ALL (5)	CHN (6)
REE Sens. × Post	15.46*** (4.943)	17.91** (7.227)	18.43*** (6.026)	25.65** (11.05)	14.36*** (5.155)	2.886 (19.35)
Observations	5,561	1,200	1,140	972	7,606	2,045
Clusters	387	81	74	66	531	144
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Region × Ind F.E.	Yes	Yes	Yes	Yes	Yes	Yes
Region × Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes

Trends in Manufacturing Exports Outside of China

Event Study



Export Growth in Manufacturing Industries

	Annualized Growth: Exports Value					
	NONCHN	USA	EUR	JPN	ALL	CHN
	(1)	(2)	(3)	(4)	(5)	(6)
RE Sens. × Post	0.880***	0.155	0.639*	1.685**	0.812***	-0.804
	(0.254)	(0.770)	(0.340)	(0.803)	(0.245)	(0.800)
Observations	271,740	6,048	107,895	5,979	277,723	5,983
Clusters	17,249	378	6,754	375	17,623	374
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country x Ind F.E.	Yes	Yes	Yes	Yes	Yes	Yes
Country x Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes

Backdrop: Empirical Findings

Directed technological change

- Increased patenting in affected mft. industries outside of China
- 1 standard-deviation increase in REE sensitivity $\rightarrow$ +7.4% REE-related patents
- Patents focused on REE-efficiency-enhancing technologies
- No significant growth of patenting within REE-intensive Chinese industries

Exports

- Higher export growth in REE-intensive industries outside of China
- No higher export growth within respective industries in China

Robustness

- *i.* Alternative country-industry specific measure on REE sensitivity, *ii.* Impact on country-industry productivity growth, *iii.* HS-code level exports, *iv.* Earnings calls: REE-related discussions

Quantitative Model

Goal

- Tractable quantitative model to study the GE impact of the Chinese REE policy

Sketch

- Directed technological change in a quantitative GE model of trade with 2 production factors
- Factor market for labor is national (non-tradable factor)
- Factor market for REEs is international, *CHN* sole supplier (tradable factor)
- Value added of each tradable good Y_{is} is produced with two input bundles: Y_{Ris} made of REEs and Y_{Lis} made of equipped labor
- Input bundles are endogenous to research effort

→ Comparative advantage shaped by HO forces + DTC + IO propagation

Production of Tradable Goods

Country-Industry-Level Goods Y_{is}

- Used to build final-consumption good or in input-materials bundle
- Combine REEs and equipped labor with materials
- Key parameters:
  - γ_s is the REE intensity of industry s
  - ε_s is the e.o.s. between REE inputs equipped and labor

$$VA_{is} = \left[\gamma_s Y_{Ris}^{\frac{\varepsilon_s - 1}{\varepsilon_s}} + (1 - \gamma_s) Y_{Lis}^{\frac{\varepsilon_s - 1}{\varepsilon_s}}\right]^{\frac{\varepsilon_s}{\varepsilon_s - 1}}$$

$$Y_{is} = \Psi_{is} VA_{is}^{\phi_{is}} \prod_{s'}^{S} M_{iss'}^{\phi_{iss'}}$$

Intermediate firms

- Monopolistic competition + hold a patent for their variety
- Static profit maximization
- Use linear technologies: $y_{Ris}(a) = r_{is}(a)$ and $y_{Lis}(a) = l_{is}(a)$
- Maximize profits given factor prices w_{Ri} and w_{Li}

Free entry

- Determines measures A_{Ris} and A_{Lis} (state of technology in country i, sector s)

Input bundles

$$Y_{Ris} = \underbrace{A_{Ris}{}^{\delta}}_{\text{innovation externality}} \underbrace{\left[\int_0^{A_{Ris}} y_{Ris}(a)^{\frac{\mu-1}{\mu}} da\right]^{\frac{\mu}{\mu-1}}}_{\text{CES aggregate}} \qquad Y_{Lis} = \underbrace{A_{Lis}{}^{\delta}}_{\text{innovation externality}} \underbrace{\left[\int_0^{A_{Lis}} y_{Lis}(a)^{\frac{\mu-1}{\mu}} da\right]^{\frac{\mu}{\mu-1}}}_{\text{CES aggregate}}$$

Impact of an REE Export Tax on Comparative Advantage

- Consider the introduction of an REE export tax $\tau_X > 1$ by *CHN*
  - $w_{Rj}/w_{Lj} \uparrow$ outside of *CHN* and $w_{Rj}/w_{Lj} \downarrow$ within *CHN*
- Direction of technological change $\frac{A_{Rjs}}{A_{Ljs}}$ depends on elasticity ε_s
  - Iff $\varepsilon_s < 1$ then $w_{Rj}/w_{Lj} \uparrow \Rightarrow \frac{A_{Rjs}}{A_{Ljs}} \uparrow$
- Price of industry-s goods produced in country j for country i

$$P_{ijs} = d_{ijs}\Bigg[\gamma_s^{\varepsilon_s} {A_{Rjs}}^{\delta(\varepsilon_s-1)+\frac{\varepsilon_s-1}{\mu-1}} \left(\frac{\mu}{\mu-1}\right)^{1-\varepsilon_s} {w_{Rj}}^{1-\varepsilon_s} + (1-\gamma_s)^{\varepsilon_s} {A_{Ljs}}^{\delta(\varepsilon_s-1)+\frac{\varepsilon_s-1}{\mu-1}} \left(\frac{\mu}{\mu-1}\right)^{1-\varepsilon_s} {w_{Lj}}^{1-\varepsilon_s}\Bigg]^{\frac{\phi_{is}}{1-\varepsilon_s}} \prod_{s'} P_{js'}^{\phi_{jss'}}$$

- Whether P_{ijs} rises or falls depends on how strong the technological response is relative to the change in factor prices + IO spillovers

Quantification

Taking the Model to the Data

Baseline economy before China's REE policy in 2009

- 12 manufacturing sectors, agriculture and services
- 5 regions: CHN, EU, JPN, U.S., ROW
- Match aggregate GDP, consumption expenditure shares, IO linkages, value-added shares, trade shares, labor endowments, relative technology bias

Elasticities

- Trade elast. $\sigma = 6.0$, final demand elast. $\rho = 1.36$, scale elast. patents: $\mu = 6.5$
- Structural estimation of ε_s and γ_s, industry-specific
- Calibrate externality δ to match the empirical response of patents

Quantification

Estimation of the REE Elasticity of Substitution ε_s and REE Intensity γ_s

- Identify ε_s from relation between *relative factor prices* and *direction of innovation* (via patents)

$$\log\left(\frac{A_{Ris}}{A_{Lis}}\right) = \beta_s \log\left(\frac{w_{Ri}}{w_{Li}}\right) + \alpha_s + u_{is}, \text{ where } \beta_s \equiv \frac{(1-\varepsilon_s)(\mu-1)}{\kappa_s}$$

- Constant $\alpha_s \equiv \frac{\varepsilon_s(\mu-1)}{\kappa_s} \log\left(\frac{\gamma_s}{1-\gamma_s}\right)$, residual $u_{is} \equiv \frac{\mu-1}{\kappa_s} \log\left(\frac{f_{Li}}{f_{Ri}}\right)$ and $\kappa_s \equiv \mu - \varepsilon_s + \delta(\mu-1)(1-\varepsilon_s)$
- Calibration of γ_s based on ε_s and TRs from our IO table

$$\frac{P_{Ris} Y_{Ris}}{P_{VAis} VA_{is}} = \frac{1}{1 + \left(\frac{1-\gamma_s}{\gamma_s}\right)^{\varepsilon_s} \left(\frac{P_{Lis}}{P_{Ris}}\right)^{1-\varepsilon_s}}$$

Quantification

Estimates of ε_s and γ_s

Manufacturing Industry	ε_s	γ_s
Transport equipment	0.774	0.00097
Basic metals and fabricated metal	0.828	0.00125
Rubber and plastics	0.841	0.00010
Mining, petroleum, and coal products	0.884	0.00047
Computer and electronic products	0.931	0.00031
Chemicals and chemical products	0.936	0.00001
Other non-metallic mineral products	0.945	0.00005
Machinery	0.991	0.00047
Food, beverages, and tobacco	1.177	0.00005
Wood and paper products	1.186	0.00003
Furniture and misc. manufacturing	1.306	0.00002
Textiles and textile products	1.389	0.00004

Quantification

Impact of China's REE Policy

China's REE policy

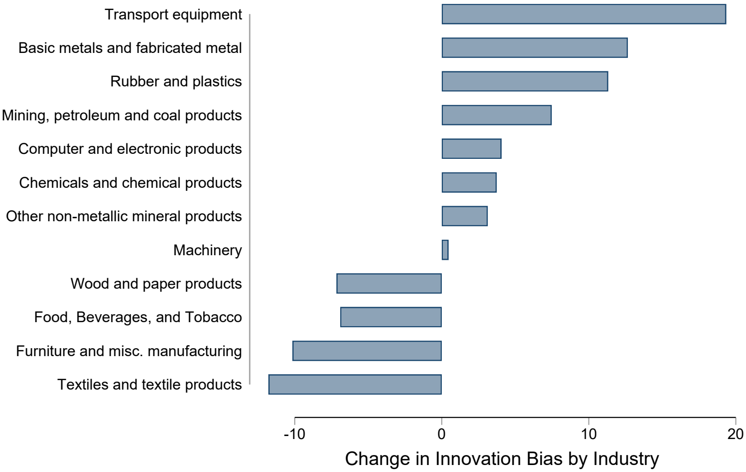
- Evaluate the GE impact of China's REE policy
- China's REE policy: tax $\tau_X > 1$ on *CHN* exports of REEs
- Export-tax equivalent of $\tau_X = 3$
  - Inferred from the average wedge between the *Free on Board* and the *Ex Works* REE prices, measured in RMB between 2010 and 2012

Consider two model variants

- Endogenous technologies with DTC
- Fixed exogenous technologies without DTC

Impact of China's REE Policy

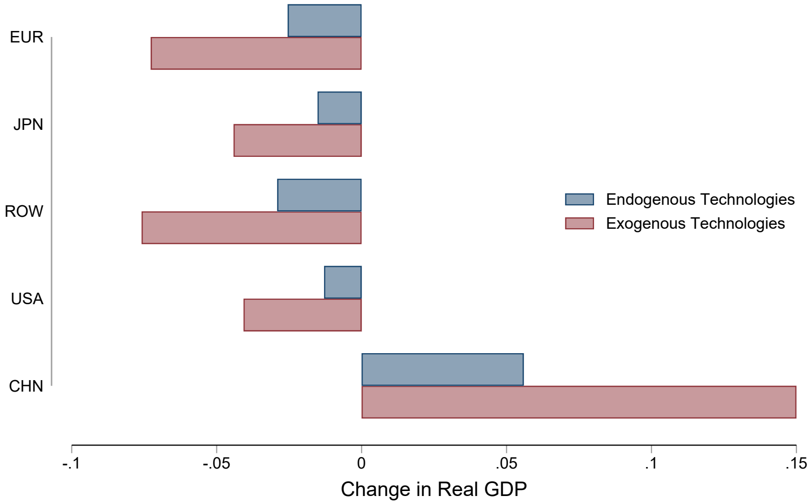
Effect on Directed Technological Change $\frac{A_{Ris}}{A_{Lis}}$



- Export Growth
- Revenue Growth

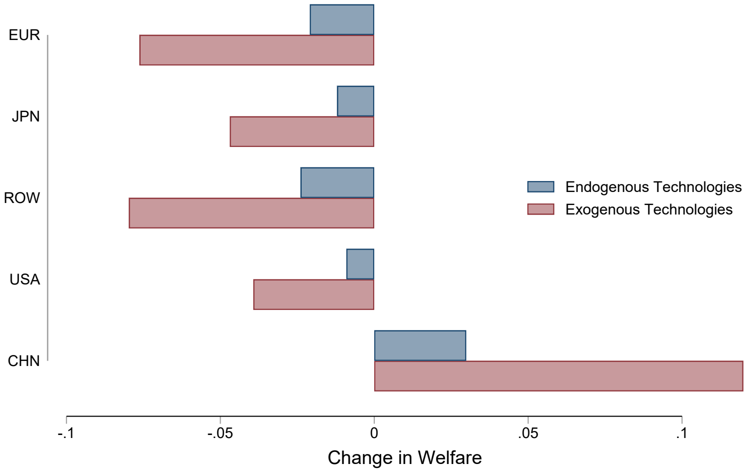
Impact of China's REE Policy

Effect on Real GDP



Impact of China's REE Policy

Effect on Welfare



Conclusion

- Have studied Chinese industrial policy regarding REEs
  - Negative REE supply shock in the rest of the world (*Rare-Earth Crisis*)
- Finding: REE-intensive industries downstream responded more expansionary
- Mechanism: Policy-induced supply shock triggered directed technological change
- Some policy implications:
  - Impact of the policy was cushioned compared to exogenous technology
  - Sanctions on exports of critical inputs may backfire
    (e.g. U.S. restrictions on exports of AI chips to China)

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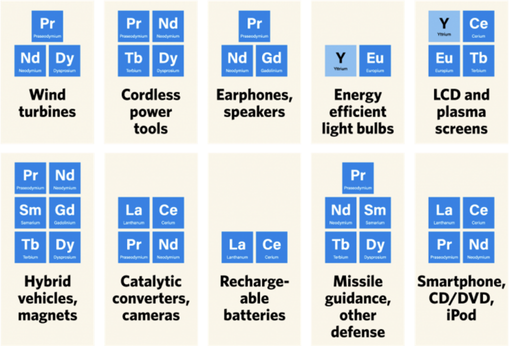
Background: Rare Earth Elements

Broad and Diverse Applications

REEs have applications across a wide range of critical sectors



Examples of REE applications. Source: Stratfor (2019)

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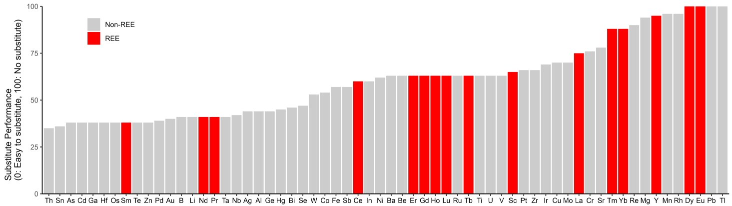
Background: Rare Earth Elements

Small Quantity Required But Difficult to Substitute

- REE inputs are often needed only in small quantities in terms of material weight (e.g., as magnets, additives to alloys, glass, fertilizer, etc.)
- They are often virtually irreplaceable due to their unique properties
  - **Example:** REE permanent magnets (using Nd and Pr) can be replaced with ferrite magnets, but for EV motors it would make them 30% heavier (Adamas Intelligence, 2023)



Substitute performance of elements. Source: Graedel et al. (2015)

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Background: Rare Earth Elements

Relatively Inelastic Supply

Despite not actually being rare, due to two reasons:

- Nature as byproducts: REE are only mined as byproducts to other elements, with very few exceptions
  - E.g. lanthanum, La (1838; Greek for ”lying hidden” in cerium), Ce; Dysprosium, Dy (1886, 1950; dysprositos, Greek for ”hard to get”)
- Highly toxic processing: In 2002, the only US REE facility closed due to toxic waste spill
- Few major facilities outside China

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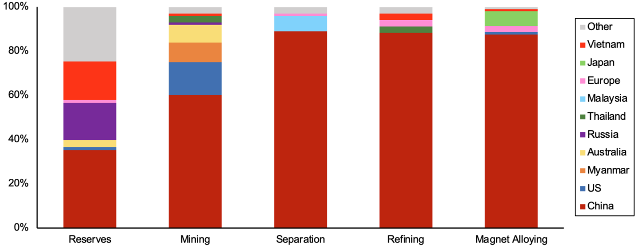
Background: Rare Earth Elements

Highly Concentrated Market Share in Mining and Processing

China controls 90% + of post-mining processing

- REE: among the highest concentrations across mineral resources (Nassar et al., 2020)



Country shares of REE across value chain.. Source: USGS (2022), Daigle and DeCarlo (2021)

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Mapping REEs into an Input-Output Table

Industries with High REE Total Requirements

Table: REE Total Requirements (10^{-3} USD of REE per 1 USD of SIC Final Demand)

No	SIC	Description	All	Ce	La	Nd	Pr	Dy
1	3691	Storage Batteries	6.93	0.00	6.93	0.00	0.00	0.00
2	3499	Fabricated Metal Products, NEC	5.91	0.00	0.00	4.06	0.18	1.66
3	3625	Relays and Industrial Controls	0.58	0.00	0.00	0.40	0.02	0.16
4	3511	Turbines and Turbine Generator Sets	0.53	0.00	0.00	0.36	0.02	0.15
5	3292	Asbestos Products	0.47	0.01	0.00	0.32	0.01	0.13
6	3714	Motor Vehicle Parts and Accessories	0.41	0.09	0.00	0.22	0.01	0.09
7	3519	Internal Combustion Engines, NEC	0.39	0.19	0.00	0.14	0.01	0.06
8	3585	Refrigeration and Heating Equipment	0.37	0.18	0.00	0.13	0.01	0.05

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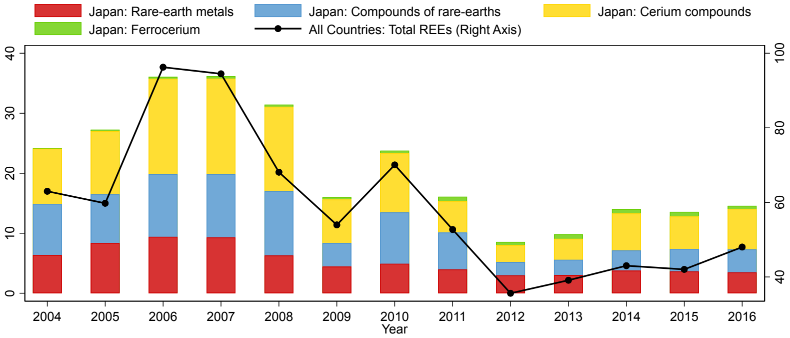
Import of REEs from China

Import Quantities (HS Codes Related to REEs)

Figure: Annual REE Imports From China, Quantity (1K Metric Tons)



Notes: The figure plots yearly import quantities of REEs (HS Codes 280530, 284610, 284690, 60690) from China by all countries (line) and Japan (bar) using data from UN Comtrade.

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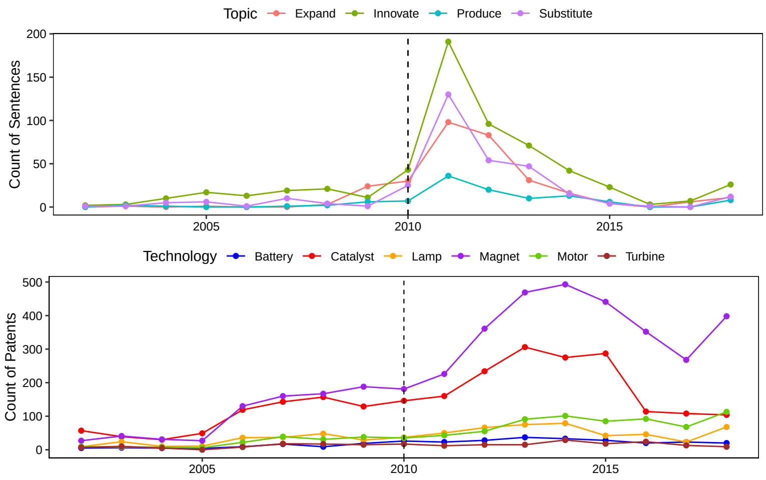
REE-Biased Technological Change

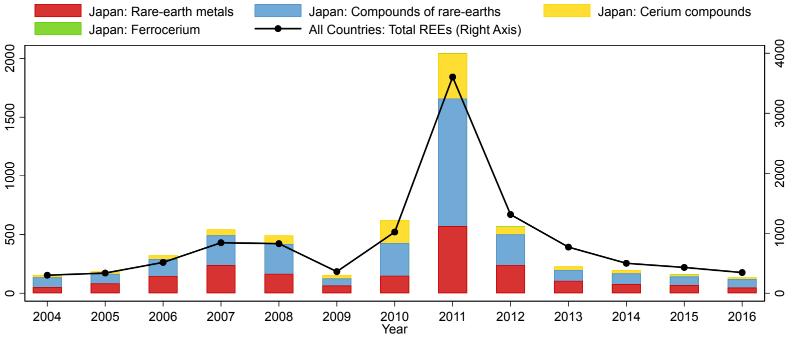
REE-Related Sentences in Corporate Earnings Calls and REE-Related Patent Grants



Import of REEs from China

Import Values (HS Codes Related to REEs)

Figure: Annual REE Imports From China, Value (USD Million)



Notes: The figure plots yearly import values of REEs (HS Codes 280530, 284610, 284690, 60690) from China by all countries (line) and Japan (bar) using data from UN Comtrade.

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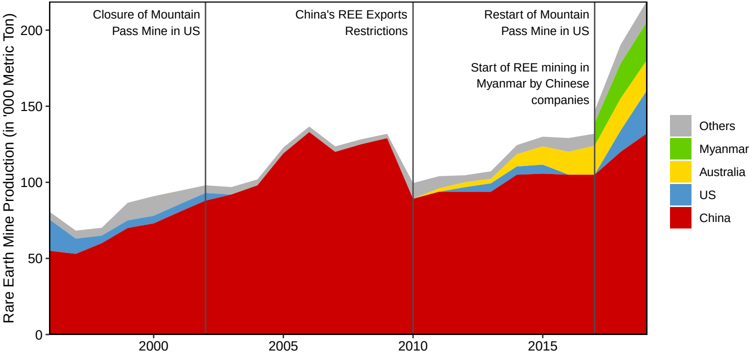
Geographical Concentration in REE Mining

Delayed Increase in Mining Abroad



Country shares of REE Mine Production. Source: USGS.

- Australia and US increased mining very slowly after the trade dispute
- Processing remains concentrated in China (processing in Canada started 2024)

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Using GPT 4 to Classify Patents

- Source: universe of granted patents related to REE from Google Patent Research database
  - Identify patents as broadly REE-related when title or abstract contains certain keywords

- GPT4 Turbo LLM: Used for two purposes
  1. Link patents to SIC 4-digit sectors based on text description
  2. Identify patents that describe technologies improving the usage of REE or helping to substitute away from their usage

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Using GPT 4 to Classify Patents

Patent Keywords

- Cerium: cerium, ceo2
- Dysprosium: dysprosium, dy2o3
- Erbium: erbium, er2o3
- Gadolinium: gadolinium, gd2o3
- Holmium: holmium, ho2o3
- Lanthanum: lanthanum, la2o3
- Lutetium: lutetium, lu2o3
- Neodymium: neodymium, nd2o3, ndfeb, rare(-)earth (element) magnet, nib magnet, neo magnet, nd2fe14b, prnd
- Praseodymium: praseodymium, pr2o3, rare(-)earth (element) magnet, nib magnet, neo magnet, nd2fe14b, prnd
- Scandium: scandium, sc2o3
- Samarium: samarium, sm2o3, smco, rare(-)earth (element) magnet
- Terbium: terbium, tb4o7
- Yttrium: yttrium, y2o3
- Ytterbium: ytterbium, yb2o3
- Europium: europium, eu2o3

On the Element Index of Complementarity

Element-level substitute performance score by Graedel et al. (2015): "On the materials basis of modern society", PNAS

- List uses of each element, determine primary or "best" substitute for each use, then score its performance
- Assessment based on "the assimilation of research and expert opinion"
- Substitute performance pertains "physical" or "chemical" property rather than economic

Metal	Application	Application Details	Percentage into Application	Primary Substitute	Substitute Performance
Ce	Glass polishing	Used to polish precision optics	25% (47) (global)	iron oxide	adequate (81)
	Glass additives	Used as a decolorizer and dopant	19% (47) (global)	selenium	adequate (82)
	Automobile catalytic converters	Cerium oxide applied as an oxygen-exchange coating on the ceramic (83)	16% (47) (global)	lanthanum	adequate (47)
	Metallurgy, except batteries	Includes aluminum, magnesium, and iron alloys	14% (47) (global)	magnesium	adequate (81)
	Battery alloys	Used in nickel-metal hydride batteries using nickel and mischmetal	10% (47) (global)	lithium-ion batteries	good (48)
	Other	Includes use in arc welding and carbon arc lighting	16% (47) (global)	not applicable	not applicable

Example of substitute performance scoring for Cerium. Source: Graedel et al. (2015)

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Patents in Rare-Earth Intense Manufacturing Industries

Robustness Patents: OLS Results

	Linear: REE-Enhancing Patents					
	NONCHN (7)	USA (8)	EUR (9)	JPN (10)	ALL (11)	CHN (12)
REE Sens. × Post	12.04*** (4.386)	20.52** (9.132)	27.75*** (6.256)	15.19 (10.13)	7.334 (4.904)	-17.25 (19.73)
Observations	4,865	1,101	966	893	6,185	1,320
Clusters	382	81	73	66	522	140
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Region × Ind F.E.	Yes	Yes	Yes	Yes	Yes	Yes
Region × Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes

Patents in Rare-Earth Intense Manufacturing Industries

Robustness Patents: OLS Differences to China

	Linear: Percent Difference in REE-Enhancing Patents to China					
	NONCHN (13)	USA (14)	EUR (15)	JPN (16)		
REE Sens. × Post	50.98*** (18.07)	62.59 (54.68)	66.08** (31.95)	80.70** (32.90)		
Observations	3,633	738	728	655		
Clusters	363	74	69	64		
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Region × Ind F.E.	Yes	Yes	Yes	Yes	Yes	Yes
Region × Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes

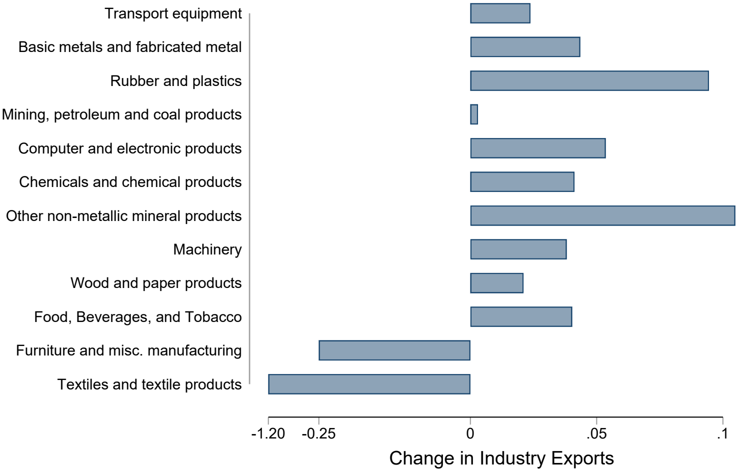
Downstream Export Growth

Robustness Exports: Differences to China

	Differences in Annualized Export Growth to China					
	NONCHN	USA	EUR	JPN		
	(7)	(8)	(9)	(10)		
RE Sens. × Post	3.548***	3.133***	3.540***	2.920**		
	(0.502)	(0.945)	(0.709)	(1.398)		
Observations	270,342	5,987	107,321	5,951		
Clusters	17,159	375	6,722	374		
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Country x Ind F.E.	Yes	Yes	Yes	Yes	Yes	Yes
Country x Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes

Impact of China's REE Policy

Effect on Exports



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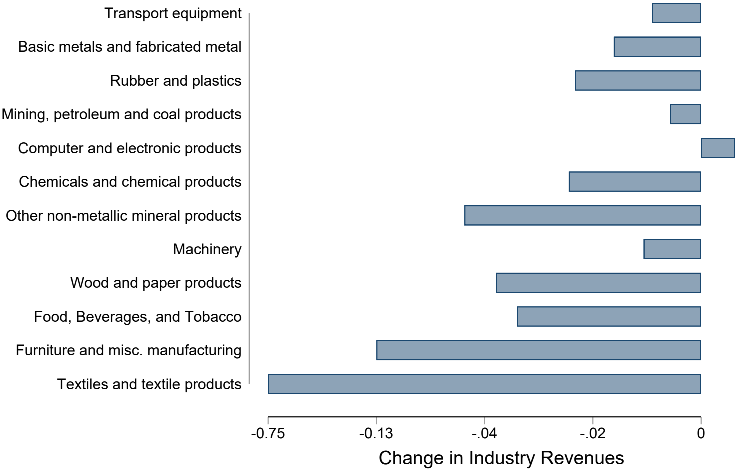
Impact of China's REE Policy

Effect on Revenues



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