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

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SUERF-ECB Workshop, September 16, 2025

Motivation

- Renewed interest in the effects of trade and industrial policy
  - Particularly in strategic sectors

$\Rightarrow$ Increased attention on *rare earth elements (REEs)* and other *critical minerals*

- In an environment of global value chains (GVCs) and fast technological progress

$\Rightarrow$ Impact of industrial policies can be complex and hard to predict

Question:

What is the effect of trade / industrial policy in critical resource inputs on global supply chains, production, welfare?

This Paper

Measurement, Evidence, and Mechanism

1. Measurement: Use and innovation in REE-using sectors
   - Construct an input-output table that includes REEs
   - Measure innovation in downstream sectors related to REEs
2. Evidence on the impact of industrial policy in the context of GVCs
   - Exploit China's 2010 REE policy as an adverse global supply shock
   - Innovation, productivity, exports in *downstream sectors* outside of China *expanded*
3. Mechanism: Directed technological change in downstream sectors
   - Build a quantitative model of trade, IO linkages and directed technological change
   - Low substitutability $\Rightarrow$ global price shock triggered REE-directed technological change
   - Calibrate the model to assess the impact of endogenous technologies

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
     - *Permanent magnets:* electric motors, EVs, turbines; *catalysts:* energy efficiency, renewables
   - *Often hard to substitute but relatively small total requirements*
2. REE supply susceptible to policy intervention
   - China is a quasi-monopolist in global REE supply
   - Supply inelastic in short run

▸ Details

Preview of findings: Global impact of Chinese policy regarding REEs

- Policy that targeted growth of China's downstream sectors inadvertently triggered growth in downstream sectors abroad: innovation, productivity, output

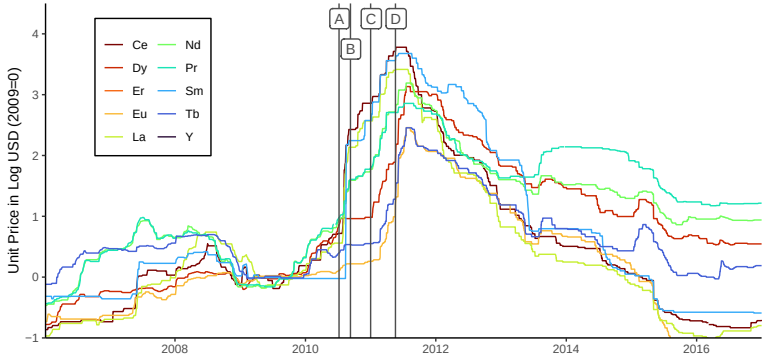
Chinese Industrial Policy on REEs

- Early 2000s: China emerged as the dominant player in the global production of REEs
  - *"The Middle East has oil and China has rare earths."*, *Deng Xiaoping* in 1992
  - Abundant reserves, low labor costs, weak enforcement of environmental regulations
  - 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)

$\Rightarrow$ Raised concerns regarding the reliability of REE supply ▸ REE Imports ▸ REE Mining

Chinese Industrial Policy on REEs

A First Look: REE Prices



- *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

Construct an extended IO table that incorporates individual REEs as inputs

1. U.S. Bureau of Economic Analyses: 2012 Use Table
   - Describes state of technologies around the time of Chinese REE trade-policy dispute
   - Disaggregated (405 sectors)
2. United States Geological Survey (USGS)
   - Describing downstream technological applications of REE
3. Asian Metal
   - Price data series for individual REEs to calculate input values
4. BCC industry reports on REEs
   - Industry reports further describing downstream technological applications
   - Unit values of REEs

Mapping REEs into an Input-Output Table

Methodology

- Using sectors: Match each REE application at "general application" level: *Magnets, Alloys, Batteries, Catalysts (automobile), Catalysts (fluid-cracking)*
  - Split sector code *"Other fabricated metals"* into magnet and non-magnet production
  - Convert usage from quantities into USD using unit prices at the REE level
- Supplying sectors: Map REE supply into sector code *"Other Basic Inorganic Chemical Manufacturing"*
  - Split this code into 6 rows: 5 for the individual REE and one for remaining non-REE production
  - Apply Leontief inverse to convert direct requirements into total requirements

Mapping REEs into an Input-Output Table

Sectors 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

Empirics

Broad idea

- Estimate the effect of the negative Chinese REE supply shock on downstream manufacturing sectors: *i.* Outside of China, *ii.* In China

Outcomes

- Directed technological change:
  - Patents on REE-related technologies
    (from the Google Research Patent Database classified using an L.L.M.)
  - TFP growth
    (from UNIDO INDTSTAT, OECD STAN, Japanese Manufacturing Census, NBER CES)
- Growth in exports (from UN Comtrade)

REE intensity of sectors

- Based on our constructed IO table and an index of REE complementarity

Sample

- 50 largest economies (or 8 regions), manufacturing sectors (4-digit SIC), 2002 to 2018

Measuring Directed Technological Change

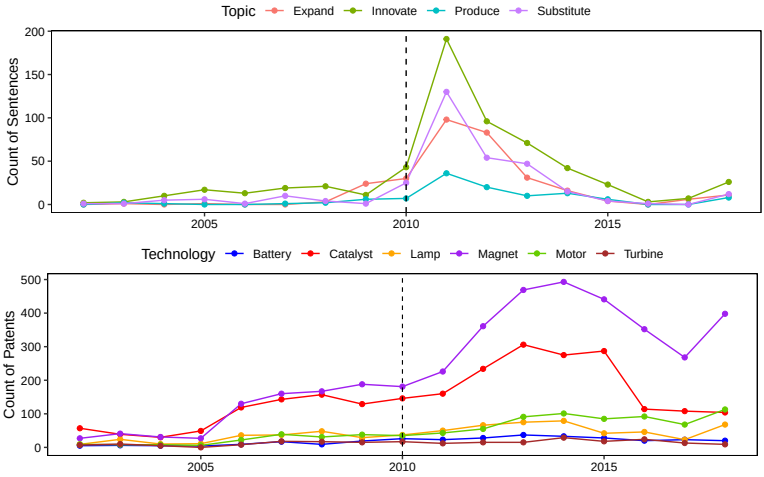
Patents in REE-Intensive Manufacturing Sectors

- 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 GPT4 L.L.M. for further classification (via OpenAI API) ▸ Details ▸ Examples
  - Assign individual patents to a 4-digit SIC using sector
    Advantages of using LLM compared to technology class concordances:
    1. Specific to subset of REE patents
    2. Uses text information of each individual patent to assign sector
  - Identify technologies that *"enhance efficiency of REE use or help to substitute REEs"* ($\approx$ **60%**)
  - Further: draw large random sample of unrelated patents (L.L.M. sector-allocated), scaled by region's total stock of manufacturing patents

A First Look: REE-Biased Technological Change

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



Empirical Strategy

- DiD: *How does economic activity change differently before/after the REE supply shock in sectors that are more/less sensitive to the supply shock?*

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

  - Outcome y_{rst} for 4-digit manufacturing sector s, region r (or country c) during year t
  - $REE\ Sensitivity_s$: treatment intensity
  - $post_t$: treatment dummy (1 for years $\geq$ 2010)
  - Δ_{rst}: controls, η_{rs}: region $\times$ sector FE, η_{rt}: region $\times$ year FE

- 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 **?** ▸ Details
  - Ranges from 0 (perfect substitute available) to 100 (e cannot be substituted)

Downstream Innovation: Patents in REE Technologies

PPML: Stock of REE-Related Patents

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

- Controls Δ_{rst}: log of all (non-REE) patents in ***rst***, cap. and lab. intens. ***s*** × post, ***rs*** subsidy share (GTA) × post, ***rst*** demand control (lagged growth rate of weighted log real GDP of the top importer countries for each ***rs***)
- Robustness: country-sector REE Sens.: $\sum_e tr_{es}$ × country-level REE price spikes ▸ Table ; $\sum_e tr_{es}$ x pre-shock import shares of REE in country ***i*** sourced from China ▸ Table
- Event-Study Graph: ▸ Figure

Downstream Innovation: Productivity Growth

TFP Growth (Midpoint) Based on UNIDO INDSTAT, NBER CES Manufacturing, Japanese Annual Manufacturing Census

	Annualized Growth: Total Factor Productivity					
	NONCHN	ALL	USA	EUR	JPN	CHN
	(1)	(2)	(3)	(4)	(5)	(6)
REE Sens. × Post	0.498*	0.466*	0.479*	0.555**	1.029***	-2.142***
	(0.260)	(0.259)	(0.281)	(0.242)	(0.370)	(0.742)
Observations	183,818	186,770	6,323	88,055	5,679	2,952
Clusters	14,981	15,350	452	6,306	414	369
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

- Controls Δ_{cst}: cap. and lab. intens. $\boldsymbol{s}$ × post, $\boldsymbol{cs}$ subsidy share (GTA) × post, $\boldsymbol{cst}$ demand control (lagged growth rate of weighted log real GDP of the top 10 importer countries for each country-sector) ▸ TFP construction
- Robustness: labor productivity ▸ Table
- Robustness: country-sector REE Sens.: $\sum_e \boldsymbol{tr_{es}}$ × country-level REE price spikes ▸ Table ; $\sum_e \boldsymbol{tr_{es}}$ x pre-shock import shares of REE in country $\boldsymbol{i}$ sourced from China ▸ Table
- Event-Study Graph: ▸ Figure

Downstream Exports

Export Growth (Midpoint) Based on UN Comtrade

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

- Controls Δ_{cst}: cap. and lab. intens. s × post, cs subsidy share (GTA) × post, cst demand control (lagged growth rate of weighted log real GDP of the top 10 importer countries for each country-sector)
- Magnitude: NONCHN: 1 Std. increase in REE Sens. ↑ ⇒ export growth by around 0.3 p.p.
- Event-Study Graph: ▸ Figure

Downstream Exports: Comparison to Chinese Sectors

Export Growth Difference to Same Sector in China (Differences in Midpoint Growth Rates)

	Differences in Annualized Export Growth to China				
	NONCHN	ALL	USA	EUR	JPN
	(7)	(8)	(9)	(10)	(11)
REE Sens. × Post	3.516***	3.351***	3.251***	3.562***	2.832*
	(0.495)	(0.476)	(0.936)	(0.698)	(1.471)
Observations	270,342	276,325	5,987	107,321	5,951
Clusters	17,159	17,533	375	6,722	374
Controls	Yes	Yes	Yes	Yes	Yes
Country × Ind F.E.	Yes	Yes	Yes	Yes	Yes
Country × Year F.E.	Yes	Yes	Yes	Yes	Yes

- Controls Δ_{cst}: cap. and lab. intens. s × post, cs subsidy share (GTA) × post, cst demand control (lagged growth rate of weighted log real GDP of the top 10 importer countries for each country-sector)
- Robustness: country-sector REE Sens.: $\sum_e tr_{es}$ × country-level REE price spikes ▸ Table ; $\sum_e tr_{es}$ x pre-shock import shares of REE in country i sourced from China ▸ Table

Taking stock: Empirical Findings

Patents and Productivity

- Increased patenting in downstream affected sectors, focused on REEs and efficiency-enhancing technologies, but not significantly within China
- Greater productivity growth in affected sectors compared to less affected ones, with no significant increase in China

Exports

- Higher export growth in downstream sectors impacted by the Chinese REE supply shock
- Both, relative to less affected domestic sectors and to the same sectors in China

A Quantitative Trade Model of Directed Technological Change

Goal

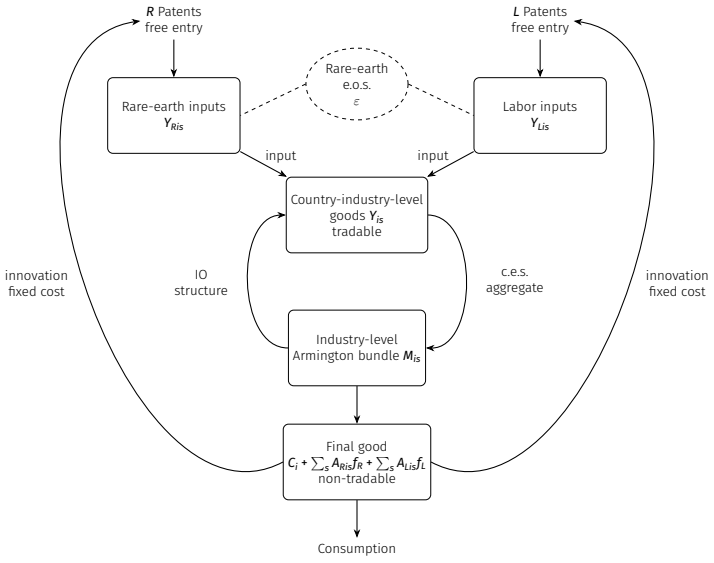
- Build a tractable quantitative model that allows to study the general-equilibrium impact of the Chinese REE policy on downstream sectors abroad

Model Sketch

- Directed technological change (**?**) meets a quantitative GE model of trade (**?**, **?**)
- Value added of each tradable good Y_{is} (e.g. "Japanese EVs") is produced under perfect competition with two input bundles:
  Y_{Ris} made of REE and Y_{Lis} made of labor
- Each of these bundles is produced with an endogenous measure of imperfectly substitutable input varieties (i.e. patents) A_{Ris} and A_{Lis}, endogenous to research effort

Quantitative Trade Model with Directed Technological Change

Model Layout



Factor Prices, Direction of Technological Change, Tradable Sectors

Consider an export tax of REE and that REE and labor are complements ($\varepsilon_s < 1$): Relative price of REE ↑ outside China.

Direction of the technology bias:

- Relative factor demand for REE falls $r_{is}/l_{is} \downarrow$
- Relative expenditure on REE bundle increases $P_{Ris}Y_{Ris}/P_{Lis}Y_{Lis} \uparrow$
- Technologies shift towards REE $A_{Ris}/A_{Lis} \uparrow$

Sectoral revenue, exports and prices:

- A reduction in unit costs lowers prices, increases sectoral revenues and exports
- Technology effect: Unit costs decrease more in high γ_s sectors when technology bias shifts towards REE
- Factor-cost effect (Heckscher-Ohlin): Unit costs increase more in high γ_s sectors when w_{Rj} increases
- Iff technology effect dominates factor-cost effect:
  revenues of REE-intensive sectors increase relative to other sectors

Calibrating the Model

World Input Output Database (WIOD)

- Consider year before the REE shock (2009)
- 12 manufacturing sectors, agriculture and services
- 5 regions: CHN, EU, JPN, U.S., ROW
- Fit data on final expenditure shares, IO linkages, trade imbalances, value-added shares, bilateral trade shares

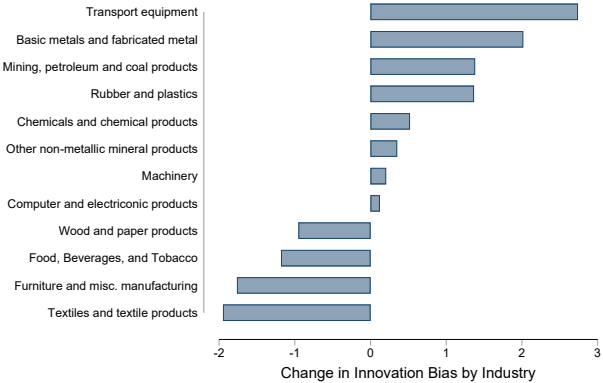
Can structurally identify e.o.s. between REE an labor $\varepsilon_{\mathbf{s}}$ from relation between *relative factor prices* and *direction of innovation* (via patents) using the model.

Estimates of ε_s and γ_s

WIOD Manufacturing Industry	ε_s	γ_s
Transport equipment	0.75	0.0071
Basic metals and fabricated metal	0.80	0.0074
Mining, petroleum and coal products	0.86	0.0021
Rubber and plastics	0.86	0.0005
Chemicals and chemical products	0.94	0.0004
Other non-metallic mineral products	0.96	0.0001
Machinery	0.98	0.0006
Computer and electronic products	0.99	0.0003
Wood and paper products	1.12	0.0003
Food, beverages and tobacco	1.16	0.0000
Furniture and misc. manufacturing	1.25	0.0000
Textiles and textile products	1.28	0.0000

Effects of the Chinese REE Export Tax

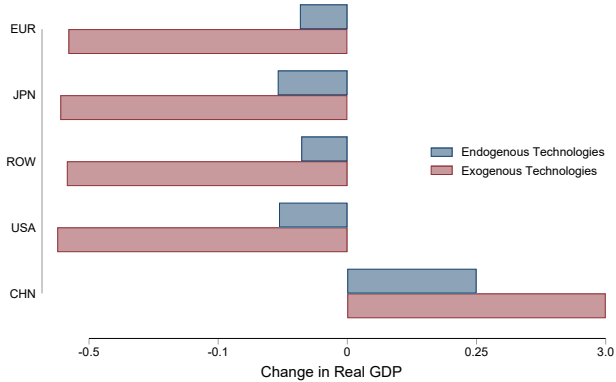
Directed Technological Change



Notes: The figure plots relative changes in A_{Ris}/A_{Lis} outside of China (measured in % change from the baseline economy) in response to the introduction of the Chinese REE export tax. Regions are weighted according to real GDP in the baseline economy.

Effects of the Chinese REE Export Tax

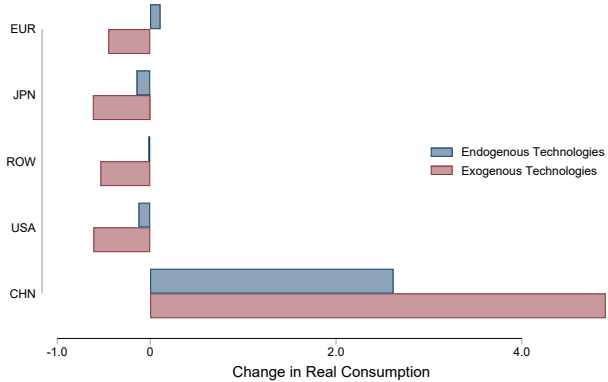
Real GDP



Notes: The figure plots relative changes in real GDP (measured in % change from the baseline economy) in response to the introduction of the Chinese REE export tax.

Effects of the Chinese REE Export Tax

Welfare



Notes: The figure plots relative changes in real consumption (measured in % change from the baseline economy) in response to the introduction of the Chinese REE export tax.

Conclusion

- Have studied Chinese industrial policy regarding REEs
  - Negative REE supply shock in the rest of the world (*Rare-Earth Crisis*)
- Shock was more expansionary in downstream sectors that were affected more strongly
- Channel: Negative supply shock triggered directed technological change
- Policy implications:
  - Impact of the policy was cushioned compared to exogenous technology
  - Self-imposed reduction in imports of complementary inputs (via input tariff) may promote domestic downstream sectors
  - Sanctions on exports of complementary inputs may backfire and trigger innovation and growth in downstream sectors (e.g. U.S. restrictions on exports of AI chips to China)