Lithium value chain–past, present, and future

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November 18, 2024

Introduction

The electric vehicle stock has increased strongly from a few thousands in 2010 to 11.3 million in 2020, and 142 million electric vehicles are forecast to be on the road by 2030.

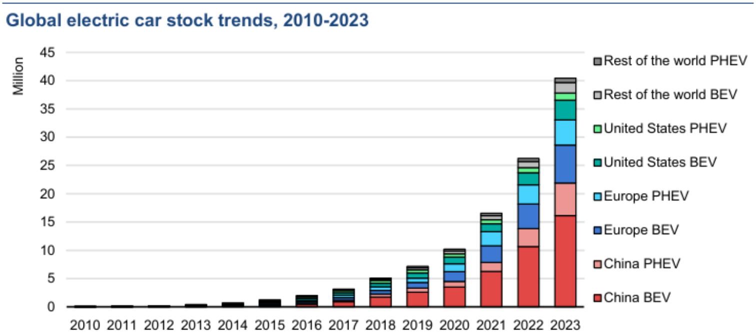

Figure: Electric vehicle growth trend. Source: IEA analysis

Lithium value chain

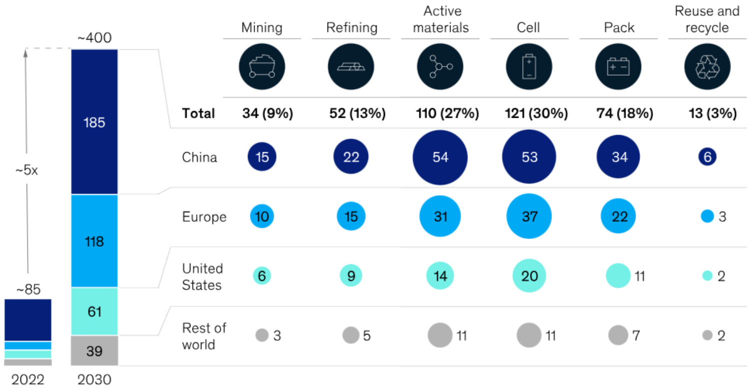

Figure: Source–(Fleischmann et al., 2023)

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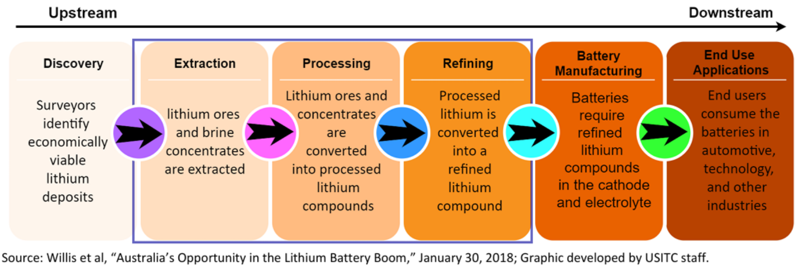

Figure: Source–(?)

What this presentation is about

- Questions I will answer:
  1. How the following processes happen: lithium mining, refinery, LIB manufacturing, and LIB recycling?
  2. How to model lithium supply and demand (not to very depth)?
  3. Which countries and firms are the main players?
  4. What is resource nationalism?
  5. Why resource rich country could make lithium a powerful weapon?
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- Example question I will not be able to answer:
    1. How to characterize off-path strategy under Markov Perfect Equilibrium?
    2. Should I go purchase Tianqi Lithium stock?

Contents

Methods for lithium extraction–hard rock (1/2)

Two major approaches for lithium extraction: **hard rock extraction** and **brine extraction**. Hard rock mining: mainly used in Australia. Three major approaches–traditional pyrometallurgy, pressure leaching, and bioleaching.

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3. Bioleaching: microorganisms to dissolve lithium without high energy costs. Too slow!

Methods for lithium extraction–hard rock (2/2)

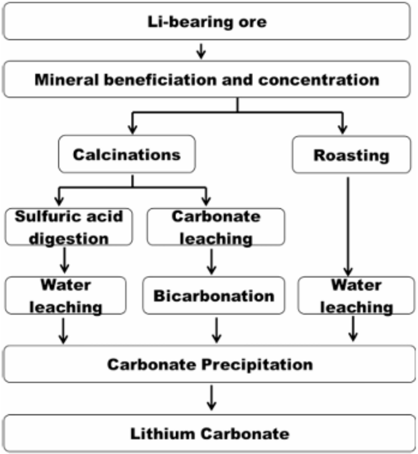

Figure: Source–(Swain, 2017)

Methods for lithium extraction–brine (1/3)

- **Brine extraction**: 6 primary methods involved: precipitation, chromatography, ion exchange, traditional liquid-liquid extraction, ionic liquid extraction, and membrane processes.
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- **Brine extraction** (continued):
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    6. **Membrane process:** Uses reverse osmosis and nanofiltration. This method offers efficient lithium recovery but is highly sensitive to brine composition and operational factors like pH and pressure.

Methods for lithium extraction–brine (3/3)

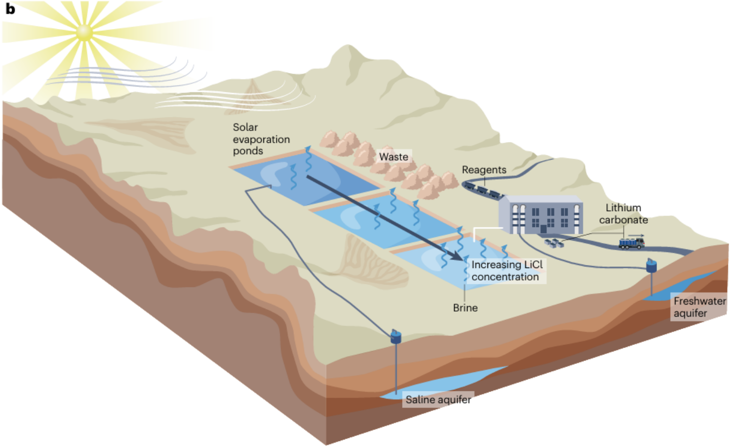

Figure: Source–(Vera et al., 2023)

Environmental problem

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It is hard to balance production costs with externality!

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- The functional form I use for prediction is:

$$q(t) = \frac{Q_{\max} \cdot m \cdot e^{-m \cdot (t - t_{\text{peak}})}}{\left(1 + e^{-m \cdot (t - t_{\text{peak}})}\right)^2}, \tag{1}$$

Modeling lithium mineral production (2/2)

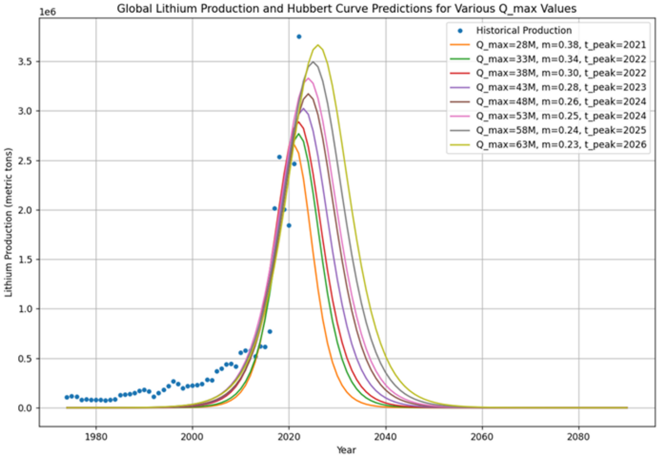

Figure: Lithium production via HCM. Data source: (British Geological Survey).

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Issues with demand modeling:

1. **Technology growth factor:** it is hard to weight different technology bundles that may lead to one bundle of factors economically dominates another one. Cobalt manganese oxide (NCM), lithium nickel cobalt aluminum oxide (NCA), and lithium iron phosphate (LFP) each have different lithium composition. A minor factor advantage in any of the path above may lead to a significant *R&D* input that pushes the lithium production onto the corresponding path.

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4. **Recycle:** accrued battery waste plus resource shortage incentivize *R&D* input in recycling (Harper et al., 2019; Gaines et al., 2020).

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- I performed calibration using the early period to compute the conversion rate from lithium mineral to LCE. The conversion rate is $\alpha = 71198651.09897064 \times 10^{-6}$.

Modeling lithium mineral demand (3/3)

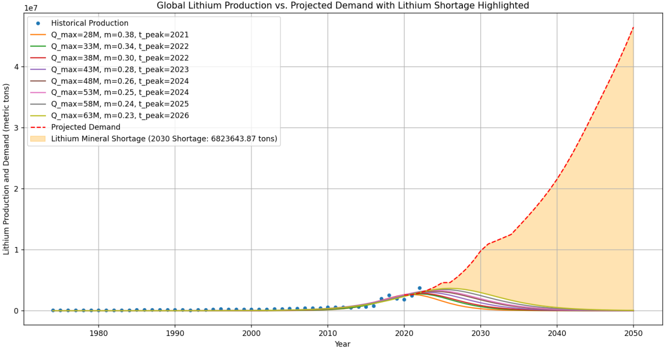

Figure: Data source–(Xu et al., 2020) and (British Geological Survey)

Compared with other modeling

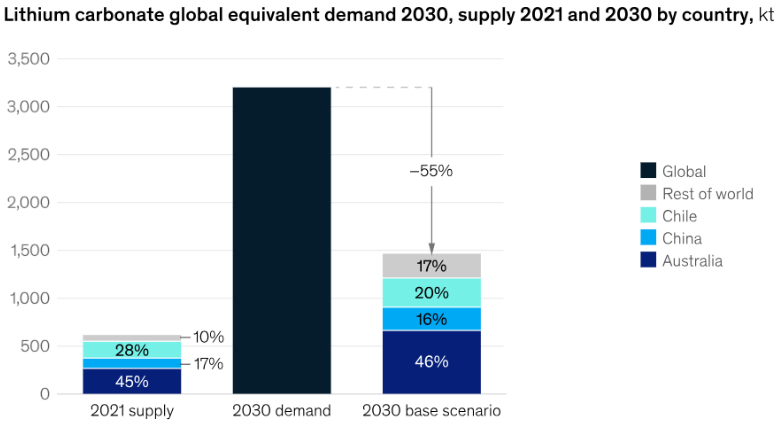

Figure: Source–(Fleischmann et al., 2023)

Lithium battery production–illustration

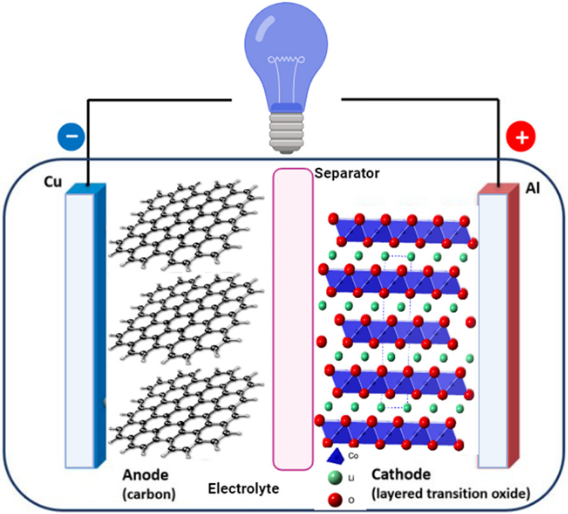

Figure: Source–(Zanoletti et al., 2024)

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  - **Prismatic (e.g., CATL):** Efficient packing, high density, bulkier than other forms.

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  - Gas venting and cell aging to stabilize SEI and electrolyte.

Lithium-Ion Battery (LIB) Manufacturing Process (3/3)

Costs and Energy Allocation:

- **Cost Allocation (top 3):** Formation/aging (32.61%), coating/drying (14.96%), enclosing (12.45%).
- **Energy Usage (top 2):** Drying/solvent recovery (46.84%), dry room (29.37%).

Lithium battery production

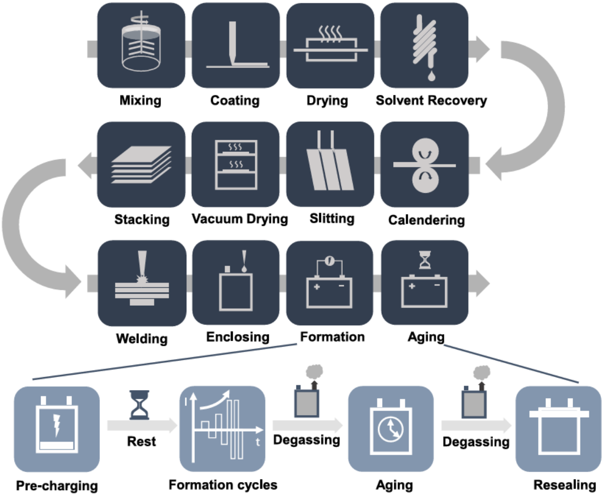
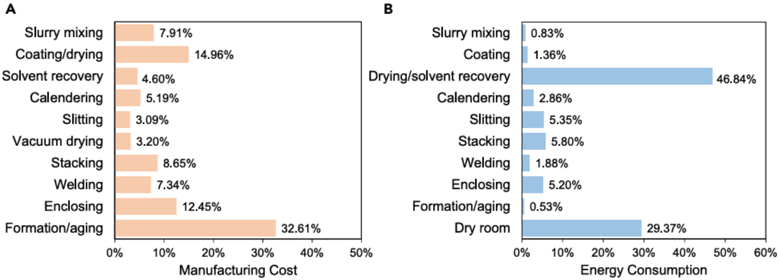


Figure: Source–(Liu et al., 2021)

Costs and energy consumption



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  4. **Biometallurgy:** uses microorganisms produce organic acids that dissolve metals from the battery materials in a mild, low-energy process. Same problem as above, too slow!

Lithium recycle (1/3)

- Industry level: lithium recycling happens only on cathode. The recycling methods are described as the following:
  1. **Pretreatment:** the process includes discharging, disassembly, and sorting. Mechanical processing is preferred for large-scale operations due to cost-effectiveness and efficiency.
  2. **Pyrometallurgy:** decomposes organic components and recovers metals (cobalt, nickel, and copper) as alloys. Lithium and aluminum are often lost in the slag. High energy consumption, environmental pollution, and relatively low product purity!
  3. **Hydrometallurgy:** uses chemical leaching agents to dissolve metal ions from the battery material. Hydrometallurgy offers a higher degree of metal separation and purity than pyrometallurgy, it generates significant amounts of wastewater.
  4. **Biometallurgy:** uses microorganisms produce organic acids that dissolve metals from the battery materials in a mild, low-energy process. Same problem as above, too slow!
  5. **Solvometallurgy:** uses ionic liquids and deep eutectic solvents (DESs) to dissolve metals. It has high recovery rates of metals like cobalt, nickel, and lithium, but too expensive to be applied in industry!

Lithium recycle (2/3)

Table: Direct comparison of main LIB recycling technologies and pollution characteristics.

	Pyrometallurgy	**Hydrometallurgy**	**Biometallurgy**	**Solvometallurgy (Ionic Liquid)**	**Solvometallurgy (DES)**
Advantages	Short process flow, low equipment requirements, strong operability	Low energy consumption, great versatility, high product purity, high recovery efficiency	Complete metal recovery, simplicity, cost-effectiveness, low energy consumption, mild conditions	Nonflammable, low volatility, tunable	Nonflammable, low recovery cost, green process, cheap and easy preparation, low toxicity
Disadvantages	High energy consumption, poor metal purity, difficulty in lithium recovery	Need to dispose of large amount of acid and toxic wastewater, long recovery process	Long processes and low kinetics, vulnerability to pollution	Expensive	Difficulty to scale-up, low cathode/DES ratio
Applied at industrial level	Yes	Yes	No	No	No
Main source of pollution	Emission of polluting gases and production of slags	Release of toxic gases (e.g. NO_x, SO_x, Cl_2)	-	-	-

Note: source–(Zanoletti et al., 2024).

Lithium recycle (3/3)

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    2. **Electrolyte recycling:** still at early stage. Methods using organic solution could retract high share of lithium carbonate at high purity, but the condition is hard to mimic in industry (Xu et al., 2023)

National Level (1/3)

- **Major Lithium Producers:**
  - **Australia**: Leading producer with 86000 metric tons, accounting for 47.7% of global production. Key products include $LiOH$ and $LiCO_3$ (U.S. Geological Survey, 2024).

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- **Bolivia**: Holds the world's largest lithium reserves at 23 million metric tons, although most remain untapped.
- **United States**: Contains substantial lithium reserves of 1100000 metric tons, yet remains largely unexploited due to environmental regulations, geopolitical strategies, and risk management (Sanchez-Lopez, 2023).

National level (2/3)

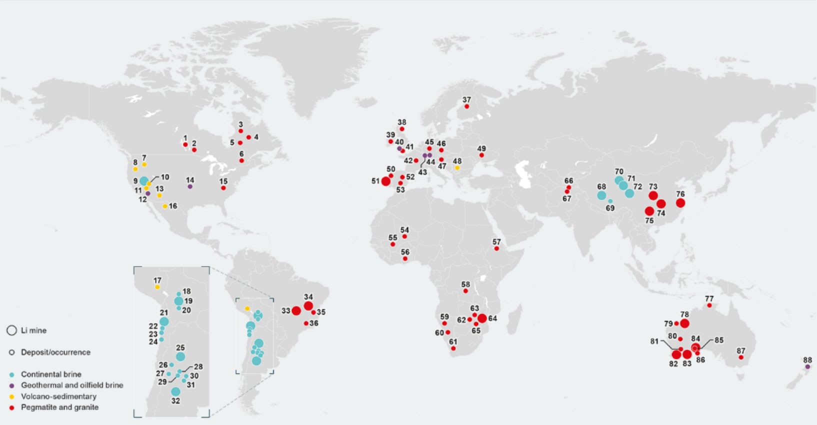

Figure: Source–(British Geological Survey)

National level (3/3)

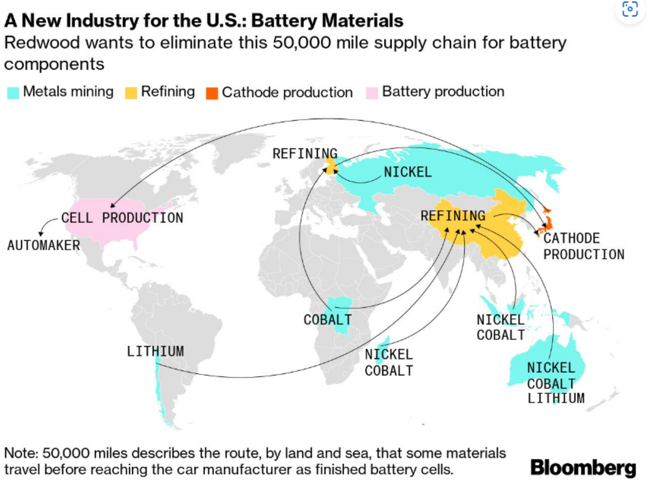

Figure: Source–Bloomberg

Disparities in the LIB Value Chain

- Upstream activities like mining and refining contribute only 2% of the value ($3.8 billion), while downstream processes generate 46%.
- The final stage of EV manufacturing accounts for 54% of the total value, highlighting the concentration of profits in later stagesTrade et al. (2018).
- Controlling downstream processes is strategically importantHeredia et al. (2020).

Gigafactories:

- Large-scale battery manufacturing plants, pioneered by Tesla, are crucial for meeting global demand and attracting foreign direct investment (FDI)Cooke (2020).
- In 2021, Asia (led by China) accounted for 71% of global Gigafactory capacity, with China alone contributing 69%.
- CATL, a leading Chinese company, held 22% of the world's 500 GWh capacity in 2021 and is expanding operations globallyMoores (2021).
- Gigafactories are both economic assets and "geopolitical hot potatoes" Moores (2021).

Innovation, Geopolitics, and Challenges

Innovation in Battery Technology:

- From 2014 to 2018, Japan led battery patenting (41%), followed by South Korea, Germany, the U.S., and ChinaEPO (2020).
- Since 2018, China has rapidly caught up, aligning technological advancements with industrial policiesKalantzakos (2020).
- Japan's leadership in patents has not translated into market dominance (2% global EV share in 2019)Global (2021).

Geopolitical Implications:

- Concentrated manufacturing capacity in Asia creates trade imbalances and supply risks for Europe and the U.S.Månberger and Johansson (2019); Overland (2019).
- Lithium-rich countries like Bolivia and Argentina remain in lower-value supply chain stages, struggling to industrialize their reservesKalantzakos (2020).
- China controls significant portions of the LIB value chain, including:
  - 66% of global graphite
  - 68% of silicon
  - 7% of lithiumLebedeva et al. (2016)
- Integration of raw material control with manufacturing has made

Lithium price

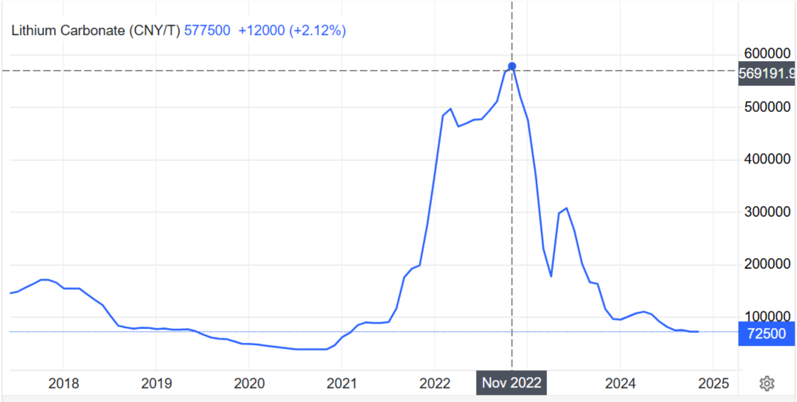

Figure: Source–Trading Economics

Stock market performance

(a) Albemarle

(b) SQM

(c) Tianqi

(d) Ganfeng

Resource nationalism

- Resource nationalism refers to the efforts by governments to assert control over natural resources located within their borders, often by restricting foreign involvement, renegotiating profit split, increasing taxes, or nationalizing industries. The goal is usually to maximize the country's benefit from the extraction and sale of these resources, which are considered national assets.

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- In 2022, Mexican President Andrés Manuel López Obrador declared lithium a strategic mineral and established a state-run company, LitioMx, to control lithium extraction in the Bacanora Lithium Project, aiming to limit foreign involvement in the burgeoning industry.

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- In Chile, President Gabriel Boric announced plans to create a state-owned lithium company and implement policies that would give the Chilean government majority control over all lithium extraction projects. This move would increase state participation in the industry, particularly for new projects or when renewing existing contracts with private companies such as SQM and Albemarle.

Historical lesson

The War of the Pacific (1879–1884), fought between Chile, Bolivia, and Peruis widely regarded as a resource-driven conflict, primarily over control of the valuable guano (bird excrement), nitrates, and saltpeter deposits in the Atacama Desert. The causes of the war is characterized as the following:

1. Gigantic resource wealth: in the pre-war period, nitrates accounted for 20% of Peru's government revenue and later, 48% of Chile's revenues after its victory.

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2. Inelastic demand: (Mathew, 1970) argues that in Britain (one of the key importers) the demand elasticity for nitrates was low; despite higher prices, British farmers did not want to substitute to other fertilizers.
3. Competitive market equilibrium: firms are as price takers and induces externality when each extra unit is produced. Attempts for monopolization failed due the conflict among major European banking groups.

Historical lesson

Figure: Source: Janitoalevic

Model setup

Basic analysis

Simple implication

Theory-fact isomorphism

Research question

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Research question: How will the upstream resource nationalization affect downstream production and price?

Data description

- **Chinese customs data:** I accessed the monthly Chinese customs data from 2019 January until 2024 September. The data set decomposes lithium related product by country, product type, trade code, and by time. The dataset I constructed consists of import (a total number of 36,557 records) and export (a total number of 61,007 records).
- **Firm stock market performance:** I use Alpha Vantage API and FMP API to construct a dataset consisting of the Chinese firms that play an important role in the whole manufacturing process.
- **Lithium trade penetration to other major manufacturing countries:** I consult the Nations (n.d.) to build a dataset on lithium related product import.
- **Province level covariates:** The data is extracted from China Census Bureau.
- **Demand in 2021:** Non-EV demand would represent approximately 150 billion Yuan.

Empirical method

$$Y_{pt} = \alpha + \beta PP_{pt} + X_{pt}\Lambda + \epsilon_{pt} \tag{2}$$

- $PP_{pt} = \sum_c \frac{x_{pc,2021}}{x_{p,2021}} IMP_{tc}^{country} = \sum_c \frac{x_{pc,2021}}{x_{p,2021}} \frac{IM_{tc}^{country}}{D_{2021}+IM_{2021}-EX_{2021}}$.
- IM_t^c = import from country c to China at time t; D_{2021} = the total lithium demand in China in 2021; EX_{2021} = total export to China in 2021.
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- Many ways of decomposing the full penetration to region/industry/ethnic group specific–by relative import, employment, population density

Empirical method–How could it be wrong?

$$Y_{pt} = \alpha + \beta PP_{pt} + X_{pt}\Lambda + \epsilon_{pt} \tag{3}$$

- For instance, policy interventions (EV subsidy) may affect PP_{pt} and Y_{pt}, as high subsidy gives enterprise incentive to invest in the subsidy-rich province and pushes up the product price (although payment made by consumer may be lower).

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- Placebo test on pre-trends (i.e. run zero-first stage test on monthly data 2019-2020).

Data description

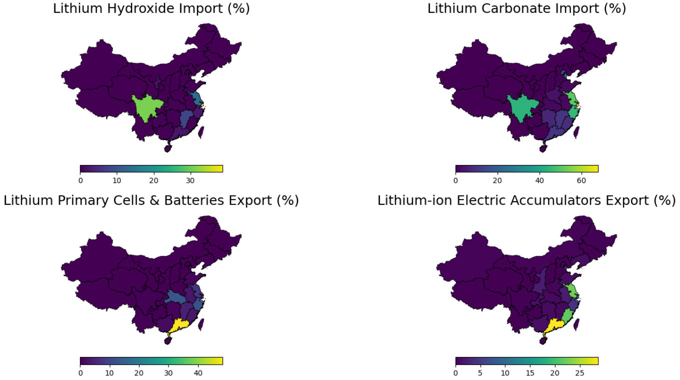

Figure: 01/2021 - 09/2024 Lithium related product share (import and export) by province)

Summary stats (in RMB)

Panel A: Import						Panel B: Export				
Commodity	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
Lithium	224	794,409.6	2,612,620	176	24,300,000	391	5,255,659	7,188,171	44	63,000,000
Lithium Iron Phosphate	196	809,847.1	1,296,698	170	9,879,130	520	526,394.5	1,312,929	6	9,026,640
Lithium Carbonate	1,371	81,300,000	446,000,000	15	11,400,000,000	827	7,156,669	28,200,000	6	376,000,000
Lithium Chloride	607	741,900.3	2,271,543	7	20,800,000	382	377,905.9	1,089,251	7	15,400,000
Lithium Enriched in Lithium-6	5	17,459.6	3,954.5	12,615	22,755	–	–	–	–	–
Lithium Hexafluorophosphate	161	2,684,438	4,866,950	20	31,000,000	552	7,095,791	9,427,186	11	59,900,000
Lithium Hydroxide	452	5,911,896	18,500,000	36	176,000,000	847	54,600,000	184,000,000	7	1,980,000,000
Lithium Manganate	101	915,832.7	1,325,719	126	10,100,000	233	543,795.1	1,800,999	70	13,700,000
Lithium Nickel Cobalt Aluminum Oxides	345	53,600,000	121,000,000	758	651,000,000	142	8,275,086	20,800,000	7	107,000,000
Lithium Nickel Cobalt Manganese Oxide	1,094	76,000,000	220,000,000	20	2,230,000,000	1,412	29,500,000	97,600,000	7	1,170,000,000
Lithium Oxide	85	72,807.1	334,249.6	99	2,935,759	59	1,701,989	3,797,940	7	18,100,000
Lithium Primary Cells & Batteries	12,631	696,479.9	1,923,192	2	27,200,000	12,798	610,870.2	1,957,702	0	56,500,000
Lithium-ion Electric Accumulators	18,773	6,624,487	26,000,000	6	624,000,000	40,830	13,900,000	88,100,000	2	3,710,000,000

Summary stats–trade penetration

Table: Lithium Import Penetration Summary

Variable	Obs	Mean	Std. Dev.	Min	Max
Panel A: Monthly Lithium Trade Penetration in China					
mex_pen	388	1.08×10^{-6}	2.44×10^{-6}	1.15×10^{-10}	0.0000264
chi_pen	486	0.0016991	0.0060186	5.26×10^{-10}	0.0935313
Panel B: Lithium Import Penetration by Country (from Mexico)					
USA	249	0.0001605	0.0000834	0.0000602	0.0003873
Japan	98	0.0000488	0.0000311	1.15×10^{-6}	0.0001448
Korea	103	0.0000388	0.0000259	8.41×10^{-6}	0.000105
Sweden	84	0.0003622	0.0004598	1.70×10^{-7}	0.0024563
Panel C: Lithium Import Penetration by Country (from Chile)					
USA	134	0.0001637	0.0001244	6.53×10^{-6}	0.0005268
Japan	106	0.0075517	0.0063659	0.0004869	0.0302904
Korea	101	0.0546896	0.0516539	0.0112835	0.1972923
Sweden	3	1.39×10^{-6}	2.15×10^{-6}	9.37×10^{-8}	3.87×10^{-6}

First Stage Results

Variable	Coefficient	Std. Err.	t	P>|t|	[95% CI]
Panel A: Chile (Year = 2022, 2023, 2024; Obs = 96)					
Penetration USA	4.322	10.872	0.40	0.692	[-17.271, 25.916]
Penetration Japan	0.266	0.198	1.34	0.183	[-0.128, 0.660]
Penetration Korea	-0.008	0.028	-0.30	0.768	[-0.063, 0.047]
_cons	0.001	0.003	0.23	0.822	[-0.006, 0.008]
Panel B: Mexico (Year = 2022, 2023, 2024; Obs = 64)					
Penetration USA	0.010	0.005	2.14	0.036	[0.001, 0.019]
Penetration Japan	-0.008	0.020	-0.43	0.669	[-0.048, 0.031]
Penetration Korea	-0.021	0.014	-1.52	0.134	[-0.048, 0.007]
_cons	-0.000	0.002	-0.09	0.932	[-0.003, 0.003]

Note: Trade penetration of Sweden is omitted due to insufficient observations. The dependent variable is trade penetration in China.

Main results

Takeaway

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