Lithium and global value chain

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Contents

1 Introduction

Lithium, named after the Greek word “lithos” meaning “stone”, has the atomic number 3. Under standard conditions, lithium is the lightest metal and the least dense solid element. Lithium has a single valence electron making lithium easily released to form Li^+. Because of this, lithium is a good conductor of heat and electricity as well as a highly reactive element. All these properties makes lithium an ideal material for making portable energy storage device. (IEA, 2024) predicts that lithium based Cleantech demand will increase by roughly 30 times as of 2040 relative to the demand in 2021. Lithium, as an exhaustible resource, plays a pivotal role in the international competition in the clean technology war. This essay is dedicated for a critical review on the global value chain of lithium: which sector benefits the most and what are the concerns in the rapid development.

This paper is organized as the following: the second section discusses the lithium value chain from mining to recycling, the third section talks about the geopolitical concerns in the lithium mining process, the forth section presents the main research question this paper tries to answer along with the model and data used to address this question, the fifth section presents relevant results, and, finally, we reach to conclusion.

2 Lithium—from mining field to recycle factory

2.1 Mining

When discussing about any exhaustible resources, one needs to distinguish the difference between resources and reserves. Resources are generally defined as a geographical term of assured quantity available for exploitation, while reserves are the quantity that is extractable with current technical and socioeconomic conditions(Vikström, 2011). In the mining section, I will be focusing on only the reserves.

The lithium mining industry could be classified broadly into two categories: hard rock mining and brine mining. Continental brine is the largest resource (59%) for lithium occurrence, followed by hard rock (25%) (Swain, 2017). Figure 2 shows the distribution of lithium wealth over various countries. The mining method is determined by the geographical property of corresponding reserves (see table 1 for detailed country-specific mining description). Brine mining has relative costs advantage than hard rock mining: the hard rock mining ranges from \$4,000 to \$5,000 per ton of lithium carbonate equivalent[1] (vis-a-vis \$2,000 to \$3,500 per ton of LCE) (Flexer, Baspineiro, & Galli, 2018).

2.1.1 Hard rock mining

Australia is currently the world’s largest producer of lithium from minerals, mainly from spodumene[2]. Other potential sources for hard rock mining of lithium including petalite[3], lepidolite[4], zinnwaldite, etc. For more details, see table 2. Exploitation must generally be tailor-made for a certain mineral as they differ quite significantly in chemical composition, hardness and other properties (Wills & Finch, 2015).

Three methods are used for hard rock mining in general: traditional pyrometallurgy, pressure leaching, and bioleaching. Traditional pyrometallurgy, an established method, combines roasting and calcination with acid or alkaline treatments at high temperatures, yielding high lithium recovery rates but incurring significant energy costs and expenses, particularly with heat-sensitive minerals like spodumene. Pressure leaching, a technique applied to beta-spodumene in an alkaline medium, uses sodium chloride and calcium hydroxide under high pressure to facilitate lithium dissolution. This method’s efficiency depends on several factors, such as sodium chloride concentration, temperature, and particle size, with optimal extraction occurring under stoichiometrically controlled conditions(Gabra, Torma, & Olivier, 1975). However, increased pulp density beyond 30% may reduce efficiency due to diffusion limitations (Karavaiko, Krutsko, Melnikova, Avakyan, & Ostroushko, 1980).

Bioleaching, the most eco-friendly and energy-efficient of the three, employs microorganisms to dissolve lithium without high energy costs. This approach relies on organisms such as Penicillium purpurogenum,

[1] Abbreviation as LCE.

[2] Chemical composition of spodumene is a lithium aluminum inosilicate mineral with the chemical formula $LiAl(SiO_3)_2$.

[3] Chemical Composition of Petalite is $LiAlSi_4O_{10}$. It contains lithium, aluminum, and silica. The material is commonly used for glass manufacture due to its high iron content.

[4] Its composition–$K(Li, Al)_3(Si, Al)_4O_{10}(F, OH)_2$–includes potassium, lithium, aluminum, silicon, and sometimes fluorine. The material was earlier used as a lithium source but presently has lost its importance due to high fluorine content.

Aspergillus niger, and Rhodotorula rubra, which have shown promise in leaching lithium under specific media conditions, albeit at a slower rate due to kinetic limitations (Rezza, Salinas, Calvente, Benuzzi, & Tosetti, 1997). Each of these methods has unique limitations: pyrometallurgy requires substantial energy, pressure leaching demands precise control over reaction conditions, and bioleaching is constrained by the slow reaction kinetics inherent to biological processes. The most commonly used approach is traditional pyrometallurgy due t its efficiency, reliability, and scalability–despite its high energy costs and environmental impact.

2.1.2 Brine mining

In addition to hard rock mining, lithium could also be extracted from high concentration brine. Brine can be reachable directly from the surface or deep underground in saline expanses located in very dry regions–regions dry enough to have salt exist. High concentration lithium brine is mainly found mountain of high altitude. For instance, the Andes region and the south-western China. Chile, as one of the world's largest lithium producer, benefits strictly from accessible brine located at the large salt flat of Salar de Atacama(Vikström, Davidsson, & Höök, 2013).

The six primary methods for lithium extraction from brine include precipitation, chromatography, ion exchange, traditional liquid-liquid extraction, ionic liquid extraction, and membrane processes. Precipitation methods, as shown by (Pelly, 1978) and others, involve forming lithium aluminate to obtain high-purity lithium carbonate, although this process is highly sensitive to pH and temperature conditions. Chromatography, explored by (Rona & Schmuckler, 1973), separates lithium from magnesium ions using materials like polyacrylamide gel; while effective, it has high costs and is challenging to scale. Ion exchange methods (Bukowsky, Uhlemann, & Steinborn, 1991; Bukowsky & Uhlemann, 1993) offer high lithium selectivity but require handling and costly materials, making them less practical for industrial use. Traditional liquid-liquid extraction methods (Gabra et al., 1975) employ solvents, such as tributyl phosphate, which are effective in achieving high lithium recovery rates but raise environmental concerns due to the toxicity of these solvents. Ionic liquid extraction (Gao et al., 2015; Gao, Guo, Yu, Wang, & Deng, 2018) utilizes ionic liquids as both the solvent and co-extractant, offering high efficiency and selectivity. However, its higher cost makes it more suitable for specialized applications rather than large-scale production. Finally, membrane processes, including reverse osmosis and nanofiltration (Jiang, Wang, Wang, Feng, & Xu, 2014), offer efficient lithium recovery but are highly sensitive to the composition of brine and operational factors like pH and pressure. These methods collectively showcase a balance between high-purity yields and specific restrictions, with precipitation and traditional liquid-liquid extraction remaining widely used due to their effectiveness and scalability despite some cost or environmental limitations. More detailed brine extraction condition and methods see table 3.

2.1.3 Environmental problems

In brine mining, two distinct aquifers are exploited, brine and fresh water. Majority of lithium mining discussion is led by the discussion of water footprint (Bustos-Gallardo, Bridge, & Prieto, 2021). Excluding brine from the water footprint leads to a significant understatement of estimated environmental impact (Vera, Torres, Galli, Chagnes, & Flexer, 2023). Although the post-extraction brine is customarily re-injected into basin, the environmental impact is still pronounced through various channels. Firstly, re-injection can lead to interference with production wells (particularly in geothermal fields) and potentially disturb the stratigraphy in salar basins, which may alter the natural layer structures essential for ecosystem balance. In addition, the dissolution of active materials or solvent solubility issues can result in exogenous chemicals entering the salar, negatively impacting surrounding environments (Flexer et al., 2018).

Apart from the chemical pollution concern, the water usage is also challenging in brine extraction regulation. Freshwater usage is significant in many direct lithium extraction (DLE) technologies, with requirements far exceeding conventional evaporative methods. In some cases, DLE processes demand 500 m^3 of freshwater per tonne of lithium carbonate, which is over ten times the amount needed in traditional evaporative setups. This intensive water requirement poses substantial challenges in arid regions where salars are typically located. Moreover, the elution process from ion exchange resins often produces lithium solutions too dilute for direct crystallization, necessitating further concentration steps that can lead to more water loss or energy expenditure.

The last environmental concern is energy consumption. Energy needs in DLE are high, especially in processes requiring brine heating to improve lithium absorption. For example, heating brine to 80°C significantly enhances lithium capture efficiency but raises operational costs due to the vast brine volumes involved. In areas with high solar irradiation, solar energy could provide some relief, reducing dependence on non-renewable energy sources and lowering emissions. However, implementing solar solutions increases initial project costs and requires substantial infrastructure (Palagonia, Brogioli, & La Mantia, 2019, 2020).

2.2 Modeling lithium production

Voluminous mathematical models are applied for resource modeling: the Hubbert method; other curve-fitting methods such as exponential and Gaussian models; simulation models of resource discovery and extraction; and data-rich "bottom-up" models (Brandt, 2010). My lithium mining prediction strictly follows Hubbert Curve Model (HCM) (Hubbert, 1956, 1959), which is the most well-known model for nonrenewable resource. The model explicitly stating the following assumptions:

1. a finite availability of the resource;
2. a bell-shaped production curve where production rises, peaks, and then declines symmetrically;
3. a stable extraction technology and costs throughout the resource's lifecycle (which is surely violated)[5]
4. a constant economic and political policy that ensures continuous resource extraction (which is also likely to be violated due to resource war (Acemoglu, Golosov, Tsyvinski, & Yared, 2012; Yared, 2010)).

I consulted the data source from (British Geological Survey, n.d.) to perform the lithium production simulation. The functional form I use for prediction is:

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

where m is the extraction growth rate parameter, t_{peak} is the production peak parameter, and $Q_{\max}$ is the Ultimate Recoverable Resource (URR) [6]. The plot is constructed via setting the URR from 28 million tons to 63 million tons with 5 million tons as one step(U.S. Geological Survey, 2022). The production peak time ranges from 2021 to 2026. Notice that the production simulation focuses on the lithium mineral instead of the refined lithium for export. Different measurements induce significant differences among quantity estimate.

On the demand side, the estimation tends to vary. The main difficulties that prevent me from getting a direct parametric/semi-parametric/non-parametric modeling are:

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.
2. Substitution: a big demand shortage leads to a relative price advantage of some substitutive product that has been proven to be not economically viable (Dunn, Kamath, & Tarascon, 2011; Kushnir & Sandén, 2012).
3. Supply demand interaction: any geo-political uncertainty will be taken into the pricing which further affects the lithium production. The re-adjusted supply will affect the demand (R. Moores, Yang, & Belton, 2019; Sovacool, Ali, & Bazilian, 2021).
4. Recycle: accrued battery waste plus resource shortage incentivize $R\&D$ input in recycling (Harper, Sommerville, & Kendrick, 2019; Gaines, Reuter, & Andersson, 2020).

[5] One criticism arose when people using HCM modeling post OPEC crisis oil production: the model failed to take the massive expansion of reserve size, due to technology advancement, into account.

[6] The functional form of the production at time t could be reconstructed in alternative form and the predicted result will be modified.

. I consulted the paper (C. Xu et al., 2020) about the lithium demand modeling. The paper present lithium demand under different $R\&D$ path: NCM, NCA, and LFP. I stick to LFP to compare the lithium shortage in the future. This action is supported by the following reason. Firstly, the HCM is a conservative model in predicting the time specific global lithium prediction (the model fails to incorporate technology into prediction). Second, LFP is the growth path that involves the highest lithium consumption (C. Xu et al., 2020). With an understated supply and an overstated demand, I could draw the upper-bound of the lithium demand shortage. Figure 4 provides a detailed demonstration of the lithium shortage, which is elaborated over time. The first appearance of the shortage is roughly in 2026 then the supply and demand gap tends to be expanded. As of 2030, the demand-supply gap increases to 6823643.87 metric tons of lithium minerals. The demand, by that time, is roughly three times as high as the supply.

2.3 Assembling to Battery

The manufacturing process of lithium-ion batteries (LIBs) has its roots in protocols originally developed for consumer electronics. These protocols have been adapted and refined for large-scale applications such as electric vehicles (Ahmed, Nelson, Gallagher, & Dees, 2016). Despite differences in cell design—such as Panasonic's cylindrical cells [7], LG Chem's pouch cells [8], and CATL's prismatic cells [9]—the core manufacturing stages are largely uniform across manufacturers. These stages consist of electrode preparation, cell assembly, and electrochemical activation. A detailed LIB manufacturing procedure could be viewed at Figure 5.

In the electrode preparation stage, active materials, conductive additives, and binders are combined into a slurry. For cathode production, N-methyl pyrrolidone (NMP)[10] is used as a solvent to dissolve the binder, polyvinylidene fluoride (PVDF)[11]. However, NMP is toxic and subject to strict environmental regulations, making solvent recovery processes essential to minimize emissions. In contrast, anode slurry uses water as a solvent, which is less harmful and can be vented directly. Electrode coating follows immediately the electrode preparation stage: aluminum foil for cathodes and copper foil for anodes. Coated electrodes are left for calendaring, which is a process that enhances the key physical properties such as density and conductivity.

The cell assembly stage takes place in a controlled dry room, where prepared electrodes and separators are layered, wound, or stacked to create the cell's internal structure. Most manufacturers use ultrasonic welding to join current collectors. Minor particular design could not be fulfilled by ultrasonic welding and is accomplished by additional steps. The cell is then filled with electrolyte and sealed within an enclosure, which varies based on manufacturer preferences. This stage presents challenges in ensuring the reliability of welding techniques and the consistency of the cell enclosure, both of which are critical for safety and performance.

The final step is the electrochemical activation stage. Cells are charged and discharged at low rates to form a stable solid-electrolyte interface (SEI), which prevents unwanted reactions and extends cell life. Gases produced during SEI formation are vented for safety, and the cells go through an aging process to fully stabilize the electrolyte and SEI layers before sealing (T. Li, Zhang, Shi, & Zhang, 2019; Wood, Li, & An, 2019). SEI formation is essential for battery performance, especially to prevent lithium dendrite growth, which could pose safety risks during fast charging.

In summary, the LIB manufacturing process follows a standardized workflow well-established by standard cell manufacture. Ultrasonic welding is commonly used for assembly. Controlling NMP emissions, stabilizing the SEI layer, and managing welding and electrolyte protocols are essential for ensuring performance and safety.

In terms of costs allocation, one could consult Table 4 for details. Majority lithium manufacturing costs happen at formation/aging (32.61%), coating/drying (14.96%), and enclosing (12.45%). The remaining steps have no more than 10% of the total manufacturing costs. On the energy aspects, Drying/solvent recovery (46.84%) and Dry room (29.37%) take a significant share of the energy consumption. The intensive energy consumption is majorly induced by heating–which facilitates the drying process.

[7] Cylindrical cells are shaped like a cylinder and are one of the oldest and most standardized battery designs. Cylindrical cells are with high durability but low energy density

[8] Pouch cells have a flexible, laminated (soft) packaging rather than a rigid casing, allowing them to be lighter and thinner. This type of battery has high energy density and more portable than cylindrical cells. However, it is less stable and easy to swell.

[9] Prismatic cells have a rectangular, hard case that allows for a more efficient packing structure in battery packs. It has high energy density but is very bulky.

[10] With chemical formula C_5H_9NO, NMP is an organic compound miscible with water and most organic compound.

[11] With chemical formula $-(C_2H_2F_2)_n-$, PVDF holds active materials and conductive agents on current collector.

2.4 Recycling

By 2040, around 14 million waste lithium-ion batteries (LIBs) are projected to be generated each year. With current technology, LIBs are expected to grow in demand at an annual rate of 14%. This increase highlights two main challenges: managing the large volume of waste LIBs and securing raw materials for future battery production.

Efforts in LIB recycling have mainly focused on recovering valuable cathode materials, as they contain critical raw materials. However, recycling anode materials and electrolytes has not received as much attention (a detailed material description for manufacturing different component of lithium battery could be find at table 5). The recycling process for lithium-ion batteries (LIBs) is a critical component of addressing the growing demand for battery materials and reducing environmental impact. As electric vehicle and energy storage battery demand surges, recycling LIBs has become essential to recovering valuable materials and managing waste. Current LIB recycling strategies can be grouped into several primary methods: pretreatment, pyrometallurgy, hydrometallurgy, biometallurgy, and solvometallurgy. Each method has distinct advantages, limitations, and environmental implications.

The initial step in LIB recycling is pretreatment. This process includes discharging, disassembly, and sorting. The process mainly aims at safely separating the battery casing from valuable internal components such as aluminum, copper, separators, and black mass[12] (Kim et al., 2021). Pretreatment can be done manually, where battery shells are carefully removed, or mechanically, where automated equipment crushes and sieves the battery materials. Mechanical processing is preferred for large-scale operations due to cost-effectiveness and efficiency: (Widijatmoko, Fu, Wang, & Hall, 2020) found that mechanical pretreatment yields a higher recovery of black mass, which is essential for subsequent recycling stages.

Pyrometallurgy is the most mature and widely used LIB recycling method. This high-temperature technique includes pyrolysis, metal reduction, and gas incineration to extract metals from spent batteries. During the pyrometallurgical process, organic components of LIBs are decomposed thermally. Metals such as cobalt, nickel, and copper are recovered as alloys (J. Li, Li, Yang, & Jiao, 2023)[13]. However, lithium and aluminum are often lost in the slag due to their high reactivity and are challenging to recover. The main advantages of pyrometallurgy are its short process flow and ease of operation, but it is also associated with high energy consumption, environmental pollution, and relatively low product purity (Yang, Luo, Yu, & Chen, 2023). This method is suitable for large volumes, but the inability to recover lithium remains a significant drawback.

In contrast, hydrometallurgy is considered a promising alternative due to its lower energy requirements and ability to recover individual metals with high purity. This method uses chemical leaching agents (such as sulfuric or hydrochloric acid [14]) to dissolve metal ions from the battery material (Fan et al., 2021). Acid leaching is commonly used for extracting metals like lithium, cobalt, nickel, and manganese. The dissolved metals can then be purified through solvent extraction or chemical precipitation (Zeng et al., 2021). While hydrometallurgy offers a higher degree of metal separation and purity than pyrometallurgy, it generates significant amounts of wastewater that need treatment to prevent environmental contamination (Kumari, Jha, Lee, & Singh, 2016).

Biometallurgy leverages microorganisms, such as Aspergillus niger (a haploid filamentous fungus), to extract metals from LIBs (Bahaloo-Horeh & Mousavi, 2017). These microorganisms produce organic acids that dissolve metals from the battery materials in a mild, low-energy process. Bioleaching is cost-effective and environmentally friendly, as it does not require harsh chemicals or high temperatures. However, this method is relatively slow, limiting its scalability for industrial applications (Esmaeili, Rastegar, Beigzadeh, & Gu, 2020). As noted by (Moazzam et al., 2021), biometallurgy holds promise but requires further research to improve reaction rates and make it more viable for large-scale battery recycling.

Solvometallurgy is a recent advancement in LIB recycling that aims to address some of the limitations of hydrometallurgy. Unlike water-based leaching systems, solvometallurgy uses ionic liquids and deep eutectic solvents (DESs)[15] to dissolve metals. DESs are biodegradable, less toxic, and produce minimal wastewater, offering a more environmentally sustainable alternative. (He et al., 2023; Chen et al., 2020) have shown that

[12] a mixture containing valuable metals like lithium, cobalt, nickel, and manganese

[13] Umicore (one big enterprise participating LIB recycling) uses this method to obtain $Co - Ni - Cu - Fe$ alloy first, then utilize hydrometallurgy to obtain high-purity single metals and compounds.

[14] Sulfuric acid is a diprotic acid composed of hydrogen, sulfur, and oxygen, while hydrochloric acid is a monoprotic acid composed of hydrogen and chlorine. Sulfuric acid is more acidic and corrosive than hydrochloric acid due to its ability to donate two protons.

[15] DES is a unique class of solvents characterized by a combination of hydrogen bond donors (HBDs) and hydrogen bond acceptors (HBAs), which form a eutectic mixture with a melting point lower than that of either component.

solvometallurgy achieves high recovery rates of metals like cobalt, nickel, and lithium with reduced secondary pollution compared to traditional methods. However, this method is still under development and has not yet been adopted at an industrial scale.

Overall, each recycling method has its own set of trade-offs. Pyrometallurgy, while effective for large volumes, struggles with lithium recovery, energy consumption and pollution concerns. Hydrometallurgy offers high purity but produces substantial wastewater. Biometallurgy, at relatively early stage of application, provides a low-energy, environmentally friendly option, but is limited by slow processing times. Solvometallurgy presents a promising, sustainable approach, yet requires further refinement and testing for broader application.

Although the cathode recycling remains the mainstream of LIB recycling industry, the focus on anode recycling has grown[16]. Anodes in lithium-ion batteries (LIBs) are primarily made from materials like natural or artificial graphite, carbonaceous substances, and, in some cases, silicon. Of these, graphite is the most commonly used in commercial applications due to its excellent conductivity, stability, and low cost (Natarajan & Aravindan, 2020). Anode recycling typically involves pre-treatment, pyrolysis, hydrometallurgy, supercritical fluid techniques, and water treatment (to separate the active material, such as graphite, from copper or aluminum foil substrates). Common recycling methods include pyrometallurgical processing (not significantly different from cathode recycling), which can then be processed further with hydrometallurgy to recover valuable metals like lithium and cobalt. Mechanical methods, such as grinding and sieving, are also used to separate the graphite from the substrate before further processing (Zhang et al., 2019). Anode recycling could significantly reduce the need for virgin graphite and other raw materials, but challenges arise due to contamination of graphite particles during use, which can affect the quality of recycled materials.

Similarly, electrolyte recycling has gained traction. Traditional processes typically evaporate or burn electrolytes during thermal processing, but more recent techniques aim at recovering lithium from electrolyte. Initial recovery methods involved liquid extraction, while more recent approaches use sub- and super-critical media for higher recovery rates. Volatile organic solvent such as dimethyl carbonate (DMC) and diethyl carbonate (DEC) have been applied in the electrolyte recovery process and have been proved with high recovery rate (100% and 79.40% respectively) (R. Xu et al., 2023). Moreover, lithium left in the non-volatile materials could be recovered as lithium carbonate with recovery efficiency of 86.93% and purity of 92.45%. However, the chemical condition that the study requires is far more stringent than the economically profitable condition that industry could offer. Therefore, the electrolyte recycling is still at prototypical stage relative to cathode recycling.

In summary, as the demand for lithium-ion batteries grows, so does the need for efficient recycling technologies to reclaim valuable materials and mitigate environmental impact. Recycling LIBs not only helps conserve resources but also reduces the reliance on mining for primary materials. However, the LIB recycling industry places disproportionate attention at cathode recovery, due to economic viability, relative to anode and electrolyte. With advancements in technology and further research, recycling methods can be augmented and diversified, potentially leading to a more circular and sustainable LIB supply chain.

2.5 Decomposition the value chain by countries and firms

2.5.1 Upstream in LIB value chain

We now switch our attention back to the country-level resource composition. The lithium global value chain is characterized by its complexity, high entrance barrier, and oligopolistic structure. Majority of countries perform as passive compliers instead of active participants. Globally, lithium production is concentrated in a few key countries, with Australia, Chile, China, and Argentina dominating the supply chain. Based on (U.S. Geological Survey, 2024), in year 2024: Australia produces $86,000$ (47.7% of world production) metric tons of lithium product ($LiOH$ and $LiCO_3$); Chile, as the second largest supplier country, produces $44,000$ (24.4%) metric tons; China follows up immediately with $33,000$ (18.3%) tons. Argentina, though with only $9,600$ metric tons lithium products (dwarfed by the top 3 world suppliers), possesses $3,600,000$ metric tons of reserves. Bolivia is the country with the greatest potential: the country has 23 million tons of lithium reserves and the majority of the mines are awaiting for exploitation. USA is a rich source country that researchers pay significant attention to its manufacturing ability in the value chain but underestimates its lithium resource richness: 1,100,000 metric tons of lithium products are left unexploited. Unsurprisingly USA keeps its reserve

[16] Anode hasn't reached the same development level as cathode recycling yet

intact due to environmental policy, geopolitical consideration, and risk management (Sanchez-Lopez, 2023). A detailed lithium mine distribution across the world could be found at figure 6.

The Lithium Triangle—a triangular region consisting of Salar de Atacama in Chile, Salar de Uyuni in Bolivia, and Salar de Hombre Muerto in Argentina—possesses a comparative advantage in lithium extraction relative to the hard rock mining popular in Australia[17]. The region showcases diverse governance frameworks that shape lithium mining, its regulation, and associated socio-environmental transformations.

In Chile, lithium has been a state-declared strategic resource since 1979. Lithium minerals are identified as reserved resources for the state under Decree No. 2886[18] and are excluded from concessional mining regimes. Minor exceptions happen among entities holding mining rights (pertenencias mineras) before 1979 (Poveda Bonilla et al., 2020). Chile's governance framework is based on centralized state management, but the Mining Code of 1983 introduced provisions allowing private entities to exploit non-concessional lithium resources through three mechanisms: direct exploitation by state companies, administrative concessions, and special contracts of operations[19].

As a result, two private companies, Albemarle (US) and Sociedad Química y Minera de Chile (SQM), have been extracting lithium for over 25 years. Both operate in concession areas managed by the Chilean Production Development Corporation (CORFO) in the Atacama salt flat. Albemarle[20] operates under a contract valid until 2043. The company is exploring Direct Lithium Extraction (DLE) technology to enhance production efficiency, with plans for expansion by 2028. SQM holds a contract in the same region until 2030. In 2018, China's Tianqi Lithium Corporation acquired a 24% stake in the company for $4.1 billion. This action highlights China's strategic interest in lithium resources. Both Albemarle and SQM companies play vital roles in the global lithium supply chain, contributing significantly to lithium carbonate and hydroxide production for electric vehicle batteries and other technologies.

In recent years, lithium governance has become a topic of intense public debate in Chile. In 2014, the National Commission of Lithium (CNL) was established to develop a national lithium policy[21](Sanchez-Lopez, 2023). Key CNL recommendations include: (1) promoting direct state participation through entities like CODELCO[22], ENAMI[23], and CORFO[24], while encouraging public-private partnerships (PPP); (2) revising contracts with Albemarle and SQM; and (3) recognizing the rights of local communities to benefit from and receive compensation for lithium exploitation in their territories. Starting in 2016, the renegotiation of contracts with Albemarle and SQM introduced significant changes to governance, emphasizing benefit redistribution to local governments and communities(Poveda Bonilla et al., 2020). Moreover, recent government proposals to nationalize Chile's lithium industry could further reshape these companies' operations and contracts, underlining the evolving governance landscape in the region.

Argentina, in contrast, does not consider lithium a national strategic resource, except in Jujuy province[25] (Slipak & Urrutia Reveco, 2020). Its federal governance delegates mining regulation to provinces, fostering a hybrid model of private and public-private partnerships. Over the past decade, Argentina has been the most dynamic player in lithium expansion, with more than 38 projects at different prefeasibility or feasibility stages(?, ?). The regulatory framework is based on the National Constitution, the Mining Code, and the Law for Mining Activity, with provinces retaining the authority to define concessions and regulate mining activities within their jurisdictions(Slipak & Urrutia Reveco, 2020).

Key projects include Salar de Olaroz, a public-private partnership in Jujuy province operated by Sales de Jujuy S.A.(a joint venture involving Orocobre Limited), Toyota Tsusho Corporation, and Jujuy Energía y Minería Sociedad del Estado (JEMSE, a company owned by the Jujuy provincial government). Another significant site is Salar del Hombre Muerto in Catamarca province, operated by the private company Minera del Altiplano S.A., owned by Livent (formerly FMC Corporation, an American chemical manufacturing company). These examples highlight Argentina's mixed approach, combining private investments with public-private partnerships,

[17] China extracts lithium from salars on Tibet plateau (as demonstrated in figure 6), which is another important brine reserve in the world.

[18] The code was established by Ministerio de Minería in 1979.

[19] In spanish is "contratos especiales de operación" (CEOL)

[20] The company produced approximately 39,000 metric tons of lithium metal worldwide in 2023 (Statistica).

[21] The reformation was declared by Ministerio de Minería in 2015.

[22] Copper State company

[23] Empresa Nacional Minera is a Chilean state-owned mining company.

[24] Chilean Production Development Corporation.

[25] A province at northern western part of Argentina. The province is part of the core area of Lithium Triangle.

particularly in provinces like Jujuy, where lithium has been declared strategic.

Meanwhile, Bolivia views lithium as a strategic resource under strict state control, managed by Yacimientos del Litio Boliviano (YLB). Despite significant investments exceeding $1 billion, Bolivia's production remains minimal, achieving only 666 tons between 2017 and 2019 (Sanchez-Lopez, 2021). The minimal lithium output was as a result of stringent state control and lack of foreign investment and technology: partnerships are limited to industrialization phases, with the state retaining at least 55% of net profits. The Bolivian government is actively seeking changes: it collaborates with Xinjiang TBEA Group Co Ltd (a Chinese lithium mining consortium) in a 2.3$ billion lithium project with the Chinese firm holding 49% stake in 2019. However, the project is not yet clear about the industrialization and technology involved and transferred.

To sum up, three major lithium suppliers exhibit different delegation strategy: Chilean government emphasizes on the state-ownership and declares on the sole ownership of the minerals; Argentinean government shows more diversity in mining partnership; Bolivian government seeks to preserve longer-value chain domestically but the evolution process is particularly slow albeit the nation holds the largest reserve in the world. The mining strategy summary is presented in table 7. The table shows the evolution of mining policy in three countries plus the $R\&D$ progress. table 8[26] presents Lithium Triangle countries (plus Mexico, a country with minor lithium mineral but actively seek for nationalization of the resource) lithium mineral export share by different product categories in 2023. The table shows that all three countries in Lithium Triangle exports majorly crude materials (unrefined $LiCO_3$): Argentina and Bolivia solely rely on $LiCO_3$ but Chile exports about 16% of its mineral in $LiOH$. Mexico, as a country joining the mining industry recently, exports modest lithium related product and is mostly characterized by downstream product.

China's influence spans all three countries in the Lithium Triangle through its dual role as the world's largest lithium market and a major investor. It dominates the lithium carbonate market, creating high dependence for Bolivia and Argentina, while Chile benefits from a more diversified export portfolio. Chinese companies have strategically leveraged investments and partnerships to secure resources, including projects with Ganfeng Lithium in Argentina, infrastructure development in Bolivia, and Tianqi Lithium's acquisition of a 24% stake in SQM. These strategies highlight varying degrees of dependence: Bolivia remains heavily reliant on China[27], Argentina experiences growing Chinese involvement alongside other foreign players[28], and Chile maintains relatively lower dependence due to competition from U.S. firms[29]. Together, these dynamics underscore the complex interplay of governance, market forces, and China's rising power in the Lithium Triangle.

2.5.2 Downstream in LIB value chain

The downstream LIB value chain reveals significant disparities in value generation–it highlights China's dominant role in both manufacturing and geopolitics. Upstream activities like mining and refining contribute only 2% of the value ($3.8 billion), while downstream processes–including electrochemistry, battery cell production, and assembly–generate 46%. The final stage of EV manufacturing accounts for 54% of the total value, showcasing the concentration of profits in the latter stages(Trade, Commission, et al., 2018). This disparity underscores the strategic importance of controlling downstream processes(Heredia, Martinez, & Surraco Urtubey, 2020).

Central to downstream operations are Gigafactories—large-scale battery manufacturing plants, pioneered by Tesla, which are now critical for meeting global demand and attracting foreign direct investment (FDI)(Cooke, 2020). These facilities are measured in gigawatt-hours (GWh) of capacity, and their distribution reflects stark

[26] The table is computed using (Nations, n.d.) data.

[27] The geological similarity between China's lithium mining industry and that of the Lithium Triangle presents a unique opportunity for Chinese consortia to actively participate in resource extraction in the region. In Bolivia, a $1 billion agreement was signed in January 2023 between the Bolivian government and a Chinese consortium led by Contemporary Amperex Technology Co. Ltd (CATL), alongside BRUNP and CMOC (collectively forming the CBC). This partnership aims to develop lithium extraction plants in the Uyuni and Oruro salt flats, which hold the largest lithium reserves globally. This agreement marks a significant step for Bolivia, which has struggled to fully capitalize on its lithium potential due to political and infrastructural challenges.

[28] In Argentina, Chinese firms like Ganfeng Lithium have established a strong presence. Ganfeng holds a majority stake in Minera Exar, the operator of the Cauchari-Olaroz project, one of Argentina's largest lithium ventures. Additionally, companies such as Tibet Summit Resources have pledged over $2 billion in projects in Salta province, further consolidating China's influence in Argentina's lithium sector.

[29] In Chile, Chinese companies have formed crucial alliances with local lithium producers. Tsingshan Holding Group has invested in lithium production in Antofagasta, securing preferential deals with SQM, one of Chile's leading lithium producers. Meanwhile, BYD, a major Chinese corporation, has partnered with the Chilean government to enhance lithium extraction efforts. These collaborations underscore the depth of Chinese involvement in Chile's lithium industry and its growing role across the Lithium Triangle.

regional imbalances. Asia, led by China, accounted for 71% of global Gigafactory capacity in 2021, with China alone contributing 69%. Europe and the U.S., while expanding capacity, remain far behind. For example, CATL, a leading Chinese company, held 22% of the world's 500 GWh capacity in 2021 and is expanding operations in Europe and potentially the U.S.(S. Moores, 2021). This concentration of production has geopolitical implications, as Gigafactories are seen as both economic assets and "geopolitical hot potatoes" due to their strategic importance(S. Moores, 2021).

Innovation in battery technology also underscores the shifting balance of power. From 2014 to 2018, Japan led battery patenting activity (41%), followed by South Korea, Germany, the U.S., and China(EPO, 2020). Since 2018, China has rapidly caught up, now contributing patents at rates comparable to the U.S. and Europe. However, Japan's leadership in battery patents has not translated into market dominance; its EV market represented just 2% of the global share in 2019(Global, 2021). In contrast, China has aligned its technological advancements with its industrial policies to dominate EV production and renewable energy technologies(Kalantzakos, 2020).

These developments have major geopolitical implications. First, the concentration of manufacturing capacity in Asia creates trade imbalances and supply risks for net-importing regions like Europe and the U.S.(Månberger & Johansson, 2019; Overland, 2019). The competition for control over the LIB value chain is no longer limited to raw material access but extends to technology, patents, and production capacity. Scholars argue that the energy transition's geopolitics resemble those of fossil fuels, as both prioritize securing resources and technological dominance(Freeman, 2018). China's ability to integrate renewable energy goals with its industrial strategy has placed it at the forefront of this transition.

Second, this concentration of economic benefits in major industrial nations poses challenges for lithium-rich countries like Bolivia and Argentina, which seek to industrialize their lithium reserves. Despite vast resources, these countries remain locked in lower-value stages of the supply chain, as downstream processes are dominated by established industrial players(Kalantzakos, 2020). For instance, Bolivia has struggled to capitalize on its reserves due to political and infrastructural barriers, while Argentina has seen significant foreign investment but limited progress in value-added industries.

Third, China's dominance in batteries illustrates its broader challenge to traditional industrial powers like the U.S., the EU, and Japan. China not only controls significant portions of the LIB value chain but also dominates the production of critical raw materials, including 66% of global graphite, 68% of silicon, and 7% of lithium(Lebedeva, Di Persio, & Boon-Brett, 2016). Additionally, its influence extends to resource-rich countries like the Democratic Republic of Congo, which supplies most of the world's cobalt. This integration of raw material control with manufacturing and technological leadership has positioned China as a pivotal player in the energy transition.

Ultimately, lithium exemplifies the shifting dynamics of energy geopolitics. While traditional energy geopolitics focused on controlling fossil fuels, the low-carbon transition emphasizes securing access to technology, patents, and critical materials. China's dominance in the LIB value chain reflects this shift, driven by its expansive industrial policies, renewable energy goals, and concentrated control over strategic resources. These factors underscore the critical role of lithium in the reconfiguration of global energy geopolitics.

2.6 Why downstream firms want vertical integration?

Vertical integration has emerged as a crucial strategy in the mining sector, particularly in the lithium industry, as companies seek to secure supply chains, capture higher margins, and mitigate the risks associated with market volatility. By controlling upstream resources, companies can reduce exposure to unpredictable price fluctuations and supply shortages, stabilizing their downstream operations. For instance, ArcelorMittal's integration into iron ore and coal production helped insulate its steel operations during volatile market periods. Similarly, in the lithium sector, battery manufacturers have integrated upstream to address rising demand for batteries and electric vehicles (EVs) while navigating the challenges of price spikes and supply mismatches.

This approach also allows companies to capitalize on higher margins available in adjacent stages of the value chain. For example, converting spodumene, a lithium concentrate priced at $600 per tonne, into lithium carbonate or hydroxide, which fetches $10,000 per tonne, enables lithium miners to significantly boost profitability. Vertical integration broadens market access, reduces reliance on dominant refiners like Albemarle, Tianqi, Ganfeng, and SQM, and enhances overall resilience. Moreover, integration can stimulate demand for specific commodities. Brazil's CBMM, for instance, developed new applications for niobium-alloyed steels, doubling global demand for niobium in the 2000s and ensuring a balanced supply-demand dynamic.

However, vertical integration introduces significant risks and challenges. While it reduces macro-level earnings volatility, operational complexities such as variations in mineral grades, processing throughput, and machine utilization can disrupt efficiency and strain upstream operations, particularly during periods of low pricing. Expanding into new business segments also risks distracting management from core operations, especially during acquisition and integration phases, when senior leadership must allocate significant time and resources to managing new entities. This can lead to inefficiencies and reduced focus on existing operations.

Internal conflicts, such as transfer pricing disputes and performance management issues, may arise between upstream and downstream units. Ensuring transparency and implementing external benchmarks are essential to maintaining alignment and resolving such challenges. Sovereign risk is another consideration, particularly when operating in countries with beneficiation policies that require local manufacturing. These policies can increase compliance costs and operational complexity, further complicating integrated operations.

Vertically integrated companies also face operational risks, as disruptions in owned upstream facilities can directly impact downstream production. Unlike non-integrated firms that can rely on third-party suppliers during disruptions, vertically integrated entities have fewer alternatives. Additionally, upstream customers may perceive integration as a conflict of interest, potentially prompting them to shift purchases to independent suppliers. As markets mature, the original rationale for vertical integration may weaken, making it difficult to unwind integrated operations without significant losses.

To manage these risks and maximize value, companies must adopt a clear and strategic approach to vertical integration. This includes defining operating models and investment horizons to ensure that integration delivers superior returns. A robust framework for managing internal risks, aligning systems and processes, and ensuring transparency is essential. Due diligence must identify and secure strategic benefits, such as improved margins and market access, which should be integrated into post-merger plans to capture long-term value.

Ultimately, while vertical integration offers substantial benefits in securing supply chains, improving profitability, and responding to growing market demands, it requires careful management of operational and strategic challenges. In the rapidly evolving lithium and battery markets, a well-executed integration strategy can provide significant competitive advantages, but it demands a balanced approach to risk management and long-term planning.

2.7 Why upstream countries do not like vertical integration?

Resource-rich countries often resist vertical integration by manufacturing nations in the lithium industry because it perpetuates economic inequalities and undermines their aspirations for industrial development (Heredia et al., 2020)[30]. When manufacturing countries dominate downstream activities such as refining lithium or producing batteries, resource-rich nations are left to focus on the lower-margin extraction of raw materials like lithium carbonate or spodumene. This limits their ability to capture the full economic benefits of their natural resources. High-value processes create more skilled jobs and generate significantly greater revenue, but these benefits accrue to manufacturing nations, leaving resource-rich countries dependent on volatile raw material prices. This dependency exposes them to market fluctuations and restricts their ability to achieve stable economic growth.

The environmental and social implications also fuel resistance. Extraction activities can cause significant ecological damage (see environmental problem section) and disrupt local communities (Lertzman & Vredenburg, 2005), yet the benefits often flow out of the host country. Local populations bear the environmental costs without seeing equivalent investments in infrastructure, employment, or social services. This exacerbates existing inequalities and fosters public opposition to foreign-led projects.

Geopolitically, vertical integration reduces the leverage of resource-rich countries by shifting control over critical supply chains and technological advancements to manufacturing nations. Foreign firms dominate negotiations by bringing advanced technology and capital, which limits the ability of resource-rich countries to foster their own downstream industries or secure favorable terms. This dependence delays the development of local expertise and industrialization efforts, leaving resource-rich nations in a subordinate position within the global value chain.

Finally, vertical integration by foreign firms is often perceived as a threat to national sovereignty in countries like Bolivia and Chile, where lithium is regarded as a strategic asset critical to economic futures. This

[30]One radical example is Bolivia: as a country with the most abundant lithium reserve, Bolivia is the country exploiting lithium the slowest in the Lithium Triangle. Bolivian government, prior to 2018, was seeking a complete industrialization in the lithium industry to secure the entire value chain within its national border. The attempt failed due to insufficient technology and investment.

tension between retaining sovereignty and relying on foreign expertise further fuels skepticism of foreign-led vertical integration, reinforcing concerns that these arrangements disproportionately benefit external actors while perpetuating domestic economic inequalities.

3 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 (Koch & Perreault, 2019; Bremmer & Johnston, 2009).

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.

The Sonora Lithium Project in Mexico is one of the largest lithium deposits in the world, with an estimated 8.8 million tons of lithium carbonate equivalent (LCE) resources. The project spans over 10,000 hectares in the northeastern part of Sonora State, Mexico. Initially developed by Bacanora Lithium (a UK-based mining company), the project ownership was fully transferred to Ganfeng Lithium in 2021 while keeping Bacanora Lithium as the project operator. In 2022, the AMLO government canceled nine mining concessions held by the Chinese company Ganfeng Lithium, which had acquired a controlling interest in the Sonora Lithium Project by purchasing Bacanora Lithium in 2021. Despite Ganfeng's significant investments, the Mexican government stated that the company had failed to meet minimum investment requirements between 2017 and 2021, leading to the cancellation of its concessions. Ganfeng has since disputed this and filed for arbitration, claiming that the cancellation is unjustified. The nationalization has raised concerns about Mexico's capacity to efficiently exploit its lithium resources, as the deposits in Sonora are found in clay, which is more challenging and costly to process compared to traditional lithium brine extraction. Despite this, the government is determined to retain control over its lithium resources, viewing it as crucial for the future of renewable energy and electric vehicle production.

In Chile, similarly, 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. Boric's vision is for public-private partnerships in which the state would hold a majority stake, much like Codelco[31], Chile's state-owned copper company. The government aims to ensure that lithium extraction and profits are controlled for the long-term benefit of the country, particularly in the global shift toward electric vehicles (EVs) and renewable energy storage.

Bolivia and Argentina, as the other two members in the lithium triangle, have not yet taken the nationalization campaign: Bolivia is at the very early stage of resource extraction, albeit its massive lithium reserve; on the other hand, Argentina is under Milei administration which, as a government, emphesizes on the liberalism and efficiency. However, the vicissitude politics in South America hinges potential advent of left-wing populism (Rodrik, 2021) and foreshadows the ownership complexity in the two countries left.

3.1 Historical perspective

The War of the Pacific (1879–1884), fought between Chile, Bolivia, and Peru, is widely regarded as a resource-driven conflict, primarily over control of the valuable guano (bird excrement), nitrates, and saltpeter deposits in the Atacama Desert. These resources, particularly nitrates, became highly valuable in the 19th century due to their use in fertilizers and explosives. 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.

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.

[31] It was formed in 1976 from foreign-owned copper companies that were nationalised in 1971.

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.

Similar incidence: Cedar war in ancient Lebanon. Phoenicians used these trees for building ships and the Egyptians used them for the ceremonial purpose and the extensive exploitation lead to rapid dwindling of the resource. (Koelsch, 2019) provides evidence that a main objective of the Phoenician invasion of Cyprus in the eleventh century B.C. was scarcity of the trees and an attempt to conserve the timber from the mountains.

Cedar as a crucial resource securing thalassocracy, counter-intuitively, is an exhaustible resource that takes too much time to replenish. These properties determined that cedar was as a natural resource with inelastic demand.

3.2 Resource war theory

There are generally two classes of models for geopolitical condition related exhaustible resource modeling: location analysis (Caselli, Morelli, & Rohner, 2015) and stochastic game approach (Acemoglu et al., 2012; Yared, 2010). Common assumptions in both analysis are: two entities, no entanglement in defining war and peace, and invading country bear military costs in trade of resource extraction. We restrict our focus on (Acemoglu et al., 2012) approach as it is more pertinent to our context.

The setup sketch of the stochastic game is as the following: a as resource-poor country and S as resource-rich country. S with initial allocation e_0 of resource and extract x_t in period t in trade of consumption goods c_{St}. Country A chooses armament m_t which induces a cost of $\ell(m_t)$ procured via lump-sum tax. The armament increases the share of resource obtained if A invades S. A and S play infinitely repeated game under competitive equilibrium case (many firms in S as price takers) or under monopoly equilibrium with the following timing:

1. A chooses armament
2. S chooses resource extraction to A and A consumes a share of extracted resource at market clearing price if A does not attack S
3. A decides attack or not
4. Extraction and consumption plan take place.

Under monopolistic environment we have the following timing:

1. A chooses armament
2. S proposes a take-it-or-leave-it offer consisting: extraction plan and consumption goods transfer
3. A chooses if accepting offer or not. If not, A chooses to attack or not
4. Extraction and consumption take place.

Key elements here are: elasticity of demand, initial endowment, and military capture share. Under competitive environment, the Markov Perfect Competitive Equilibrium (MPCE) says when with inelastic demand and sufficiently large military capture, the war will happen at finite time and the extraction plan is at maximum. In addition, if the endowment is not richer than the max extraction plan, the war will happen. Heuristically speaking: due to inelastic demand, spending on the resource (since competitive pricing $p_t = u'(x_t)$) and incentives to declare war increase over time. If, by spending the necessary resources, country A can capture a sufficient fraction of the remaining endowment of the resource, then it will necessarily find it optimal to declare war at some point.

Alternatively, under the monopoly environment, country S could regulate its production plan and transfer contract so it could always avoid warfare. The regulation of extraction follows: if elastic demand, the capacity constraint of extraction is binding for some finite number of periods and for the remaining period, the extraction plan increases at a minimum rate satisfying: $\beta u'(x_{t+1}) > u'(x_t)$, where β is the discount rate and $u(\cdot)$ is the utility function of country A with resource input. Similarly, with inelastic demand, the capacity constraint is never binding and the extraction decreases at the rate of $\beta u'(x_{t+1}) < u'(x_t)$ for all periods.

3.3 Theory-fact isomorphism

The resource nationalism story in Mexico and Chile seem to be derailed from the resource war theory introduced in section 2. However, if we view the foreign company as the resource-rich country and the entity takes nationalization action as the resource-poor country, the analysis becomes more pertinent to the well-established framework.

The country government plays a repeated game with the foreign company with the following timing:

1. The government chooses regulation intensity which translates to a cost of potential investment and technology diffusion
2. The foreign company propose a contract consisting of tax submitted to government (as a share of extracted material) and extraction plan
3. Government decides whether or not nationalize the mine
4. Extraction and consumption take place

Notice that here the context more relevant is competitive environment as the firms are all price takers. One crucial question is: can we conclude the demand for lithium is inelastic? Evidence shows that there are many substitutive materials to lithium for battery making, however, they seldom outperform lithium. Sodium-ion battery has lower energy capacity and magnesium-ion battery lacks magnesium-ion-compatible material for electrolytes and cathodes. The elasticity of lithium demand is not constant over time but is inelastic for the current period.

Following the MPCE result, the theory generates the following prediction. Firstly, large resource endowment likely to avoid nationalisation. Second, the costs of suspended technology diffusion and potential foreign investment decreases over time. If the government could capture a sufficiently large share of resource (in our case is likely to be 1, as the foreign company is unlikely to destroy all unexploited lithium), then the nationalization will happen.

4 Main research question

The stochastic game approach explains under what condition nationalization happens. We are particularly interested in the impact of nationalization on major manufacturer price change, stock market performance, and supply chain shift–particularly in China. Classical trade theory (Autor, Dorn, & Hanson, 2013, 2016) applies here. Firstly, we define the trade penetration from resource-rich country in China at time t as the following:

$$IMP_{ct}^{country} = \frac{IM_{ct}^{country}}{D_{2021} + IM_{2021} - EX_{2021}}, \tag{2}$$

where the import penetration of resource-rich country at time t in China is approximated by the import in product category c at time t divided by the sum of domestic demand plus the net export at the last pre-period, which is 2021 here. To capture the regional differentials, I construct the following variable:

$$PP_{pt} = \sum_{c} \frac{x_{pc,2021}}{x_{p,2021}} IMP_{ct}^{country} \tag{3}$$

where the fraction $\frac{x_{pc,2021}}{x_{p,2021}}$ captures the product category specific share of the product in province p. The reason we fix the year 2021 is to place the time as the most recent pre-period before the resource nationalism.

This variable structure allows me to investigate the impact of country-specific shock on the provincial price-level in China.

4.1 Data

To fulfill the research question requirement, I consulted the following data source:

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). A detailed description of products included in the dataset could be consulted in table 7.

Firm stock market performance: I use Alpha Vantage API (application programming interface)[32] and FMP API to construct a dataset consisting of the Chinese firms that play an important role in the whole manufacturing process. I record, at firm-level, the stock price plus main characteristics of the firm performance[33]. These indicators helps me to understand how the supply shock in the source country affect the actual performance of firms at downstream in the value chain.

The firms I select into lithium industry are the firms listed in lithium battery sector in Tonghuashun (a financial application commonly used for traders in China). A detailed table recording all stocks selected could be found at table 8.

Lithium trade penetration to other major manufacturing countries: I consult the (Nations, n.d.) to build a dataset on lithium related product import. The dataset records product types at country level. The main purpose of the data here is to isolate the supply shock from demand-related factors. Coinciding with the massive scale of nationalization, Chinese government expanded its subsidy towards the electric vehicle which pushes up the demand side of lithium in the global value chain. The subsidy is a solid concern as it affects both import penetration and lithium upstream product price. To solve this issue, I apply the same method as (Autor et al., 2013, 2016; Medina, 2024) to instrument the import penetration of country c in China on the import penetration of country c in USA, Korea, Japan, and Sweden.

Covariates: The study also needs provincial level covariates. The data is extracted from China Census Bureau.

Lithium demand in 2021: I directly access the data through state council, the lithium demand (excluding EV sale) is 150 billion yuan in 2021.

4.2 Empirical method

I propose the following equation for the estimation:

$$Y_{pt} = \alpha + \beta PP_{pt} + X_{pt}\Lambda + \epsilon_{pt} \tag{4}$$

where PP_{pt} is the provincial import-weighted trade penetration, X_{pt} are province-level covariates that potentially affects outcome variable and provincial penetration, and Y_{pt} is the outcome variable at province p and time t (at monthly level). The outcome variable could be: the exported price index of lithium related product, the share of lithium imported from other source countries unaffected by resource nationalization, and the downstream firm performance. The firm statistics are weighted by firm size at province level.

Due to the endogeneity problem described in the data section, I use the trade penetration of country c in USA, Sweden, Japan, and Korea as instrument for the import penetration of country c in China. Since I study the resource nationalization, $c \in \{Chile,\ Mexico\}$.

4.3 Threat to inference

Since most of the lithium crude materials are shipped from south America to the major manufacturing countries, the registration of Lithium import could be severely overestimating the province with ports. If this argument holds, the province-level import decomposition biases downward the import penetration among province not along the coastal line but with large lithium manufacturing industry (vice versa upward bias for provinces with ports but no lithium manufacturing port). To address this concern, I plot the main crude material ($LiCO_3$ and $LiOH$) provincial import registration ratio in figure 8. The figure shows three points: firstly, the majority of lithium import registration happens in Sichuan province which is not a province along the shoreline; Second, both import and export are concentrated at one province[34]; Third, the provinces taking most mineral import are not exactly the provinces exporting Lithium batteries. This indicates the import is not severely biased by the transportation restriction. The entrance has already taken into account the location of industry.

[32]This is widely used method to access semi-open source data. Usually subject to a free rate limit, API allows researchers to access data that not available for direct web-scraping.

[33]Statistics including: ROA (Return on Assets), ROE (Return on Equity), Gross Profit Margin, and Operating Margin.

[34]Import mostly happen in Sichuan province and export of processed material mostly happen in Guangdong province.

5 Results

6 Conclusion

This paper investigates the complexities of the global lithium value chain, with a particular focus on lithium-ion battery (LIB) production, value generation disparities, governance models in resource-rich countries, and the theoretical underpinnings of resource nationalism. It also examines the impact of nationalization on global trade dynamics and supply chains, especially in the context of China's pivotal role.

Lithium-ion battery production is the cornerstone of the lithium value chain, with standardized processes across manufacturers despite differences in cell designs, such as cylindrical, pouch, and prismatic cells (Ahmed et al., 2016). The production process includes three key stages: electrode preparation, cell assembly, and electrochemical activation. Challenges such as solvent recovery, stabilization of the solid electrolyte interface (SEI), and energy-intensive drying dominate the manufacturing landscape. Costs are concentrated in formation and aging (32.61%) and coating and drying (14.96%), while energy consumption is highest in drying and solvent recovery (46.84%) and maintaining dry rooms (29.37%) (T. Li et al., 2019; Wood et al., 2019). This process efficiency is crucial to the growing demand for LIBs, particularly for electric vehicles (EVs) and renewable energy storage.

The LIB value chain reveals significant disparities in value generation. Upstream activities like mining contribute only 2% of the total value ($3.8 billion), whereas downstream processes, including battery cell production and EV manufacturing, account for 46% and 54%, respectively (Trade et al., 2018). This highlights the strategic importance of controlling downstream processes, where China dominates with 69% of global Gigafactory capacity as of 2021. Supported by extensive industrial policies and rapid advancements in battery technology, China has become a leader in EV production and renewable energy technologies. However, resource-rich countries like Bolivia and Argentina remain confined to low-margin extraction activities, struggling to industrialize their resources and move up the value chain (Kalantzakos, 2020; S. Moores, 2021).

The governance models in the Lithium Triangle (Chile, Bolivia, and Argentina) and beyond shape the dynamics of resource management and nationalization efforts. Chile, the second-largest global producer of lithium, manages its resources under a centralized framework, leveraging public-private partnerships and entities like CORFO. Argentina adopts a hybrid model that grants provincial authorities discretion over mining regulations, while Bolivia enforces strict state control but lags in production due to technological and investment constraints. Mexico, outside the Lithium Triangle, has nationalized its lithium industry through LitioMx, limiting foreign involvement. Resource nationalism, characterized by nationalization and restrictive policies, aims to maximize domestic benefits but often disrupts global supply chains (Koch & Perreault, 2019; Heredia et al., 2020).

Using stochastic game theory, this paper models the conditions under which resource nationalism occurs and its broader implications. In this framework, nationalization can be seen as a strategic move by governments to secure a larger share of resource rents. The paper defines trade penetration in China as a measure of the import share of lithium-related products, weighted by regional and category-specific production shares. Data sources include Chinese customs records, firm-level stock market performance via Alpha Vantage and FMP APIs, and lithium trade data from major manufacturing countries (Autor et al., 2013, 2016). The analysis addresses endogeneity by instrumenting trade penetration in China with data from the U.S., Japan, Korea, and Sweden, isolating the effects of resource nationalism on provincial price indices, firm performance, and supply chain adjustments. Preliminary results suggest significant shifts in trade flows and downstream manufacturing outcomes in response to nationalization policies (Sanchez-Lopez, 2023).

In conclusion, this paper highlights the critical interplay between LIB production, value distribution, governance strategies, and resource nationalism. It emphasizes China's dominant role in downstream manufacturing and the challenges faced by resource-rich countries in advancing up the value chain. By integrating theoretical insights and empirical methods, the study sheds light on the evolving geopolitics of lithium, demonstrating its central role in the global energy transition and the complexities of securing equitable participation in the value chain.

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7 Appendix–Figures

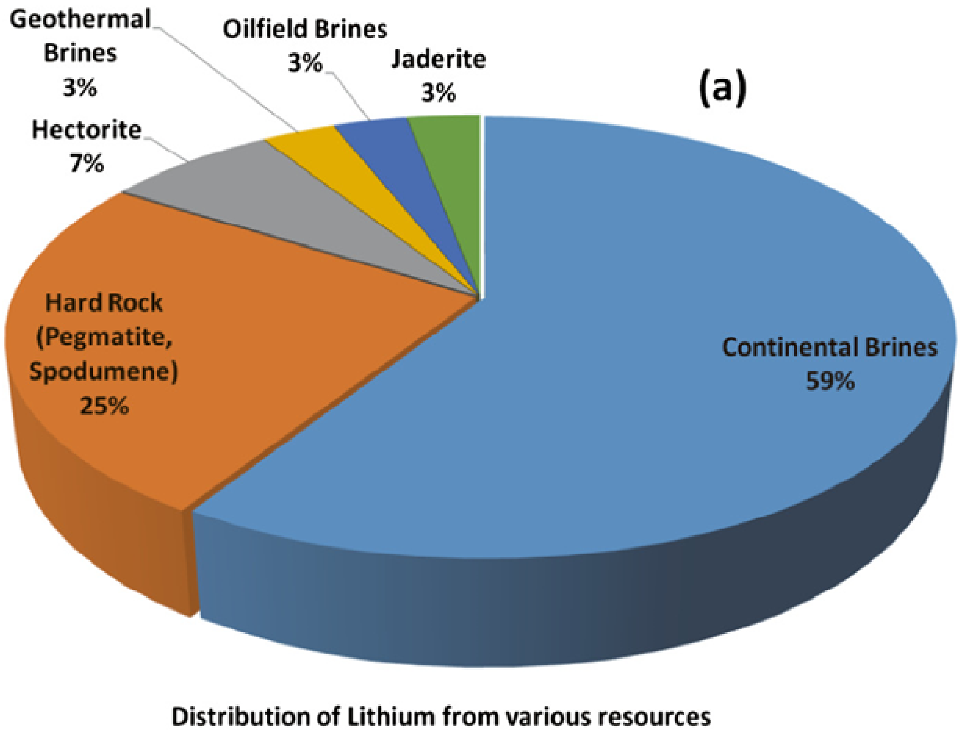

Figure 1: Lithium composition by country (Swain, 2017).

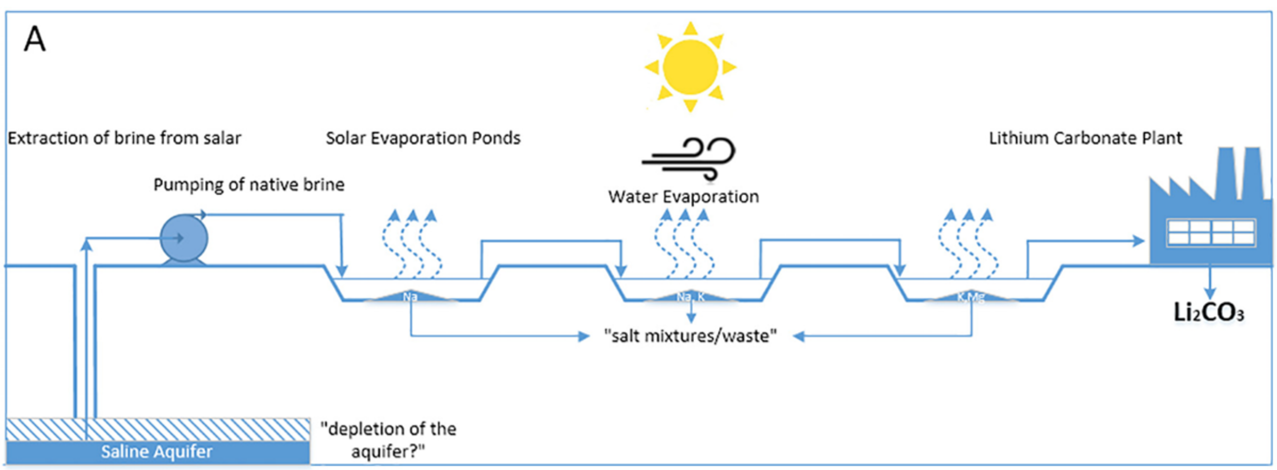

Figure 2: Brine extraction (Flexer et al., 2018)

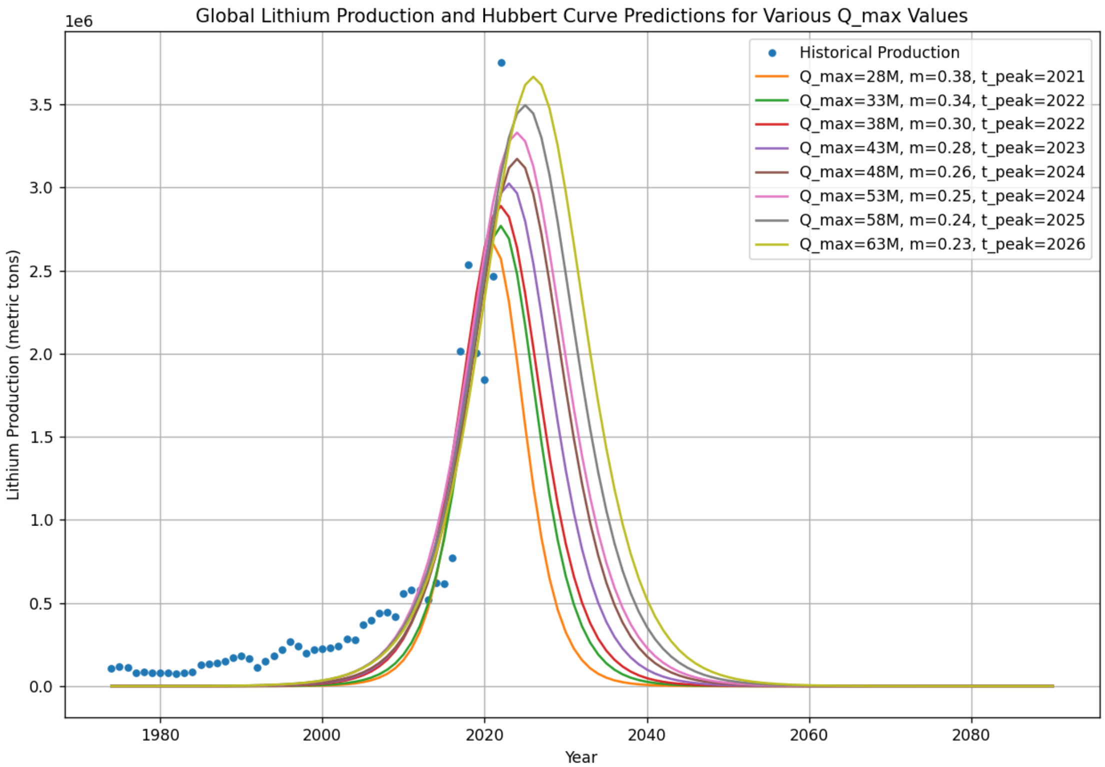

Figure 3: Lithium production simulation

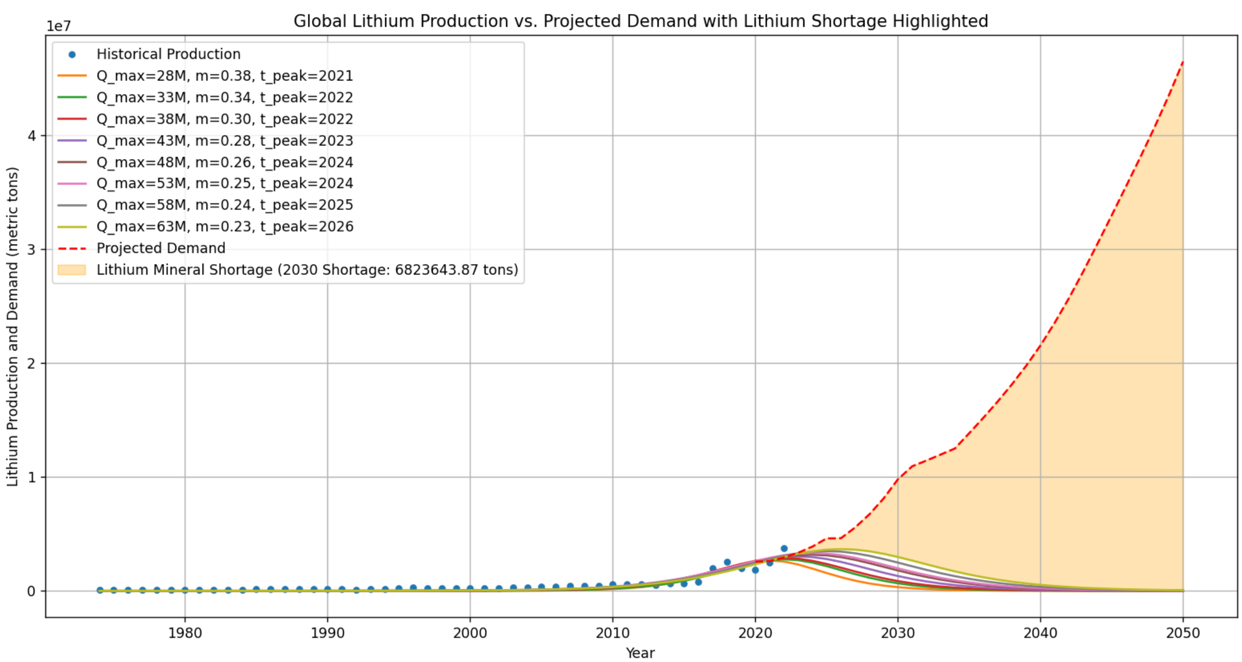

Figure 4: Lithium shortage prediction

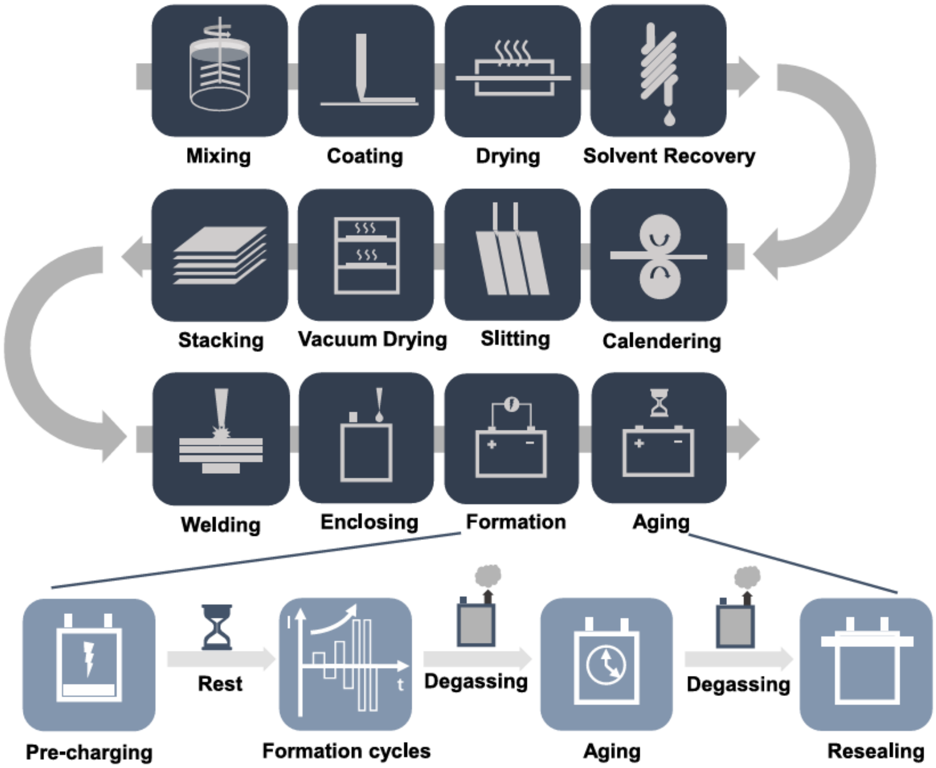

Figure 5: Lithium ion battery manufacture. Source–(Liu et al., 2021)

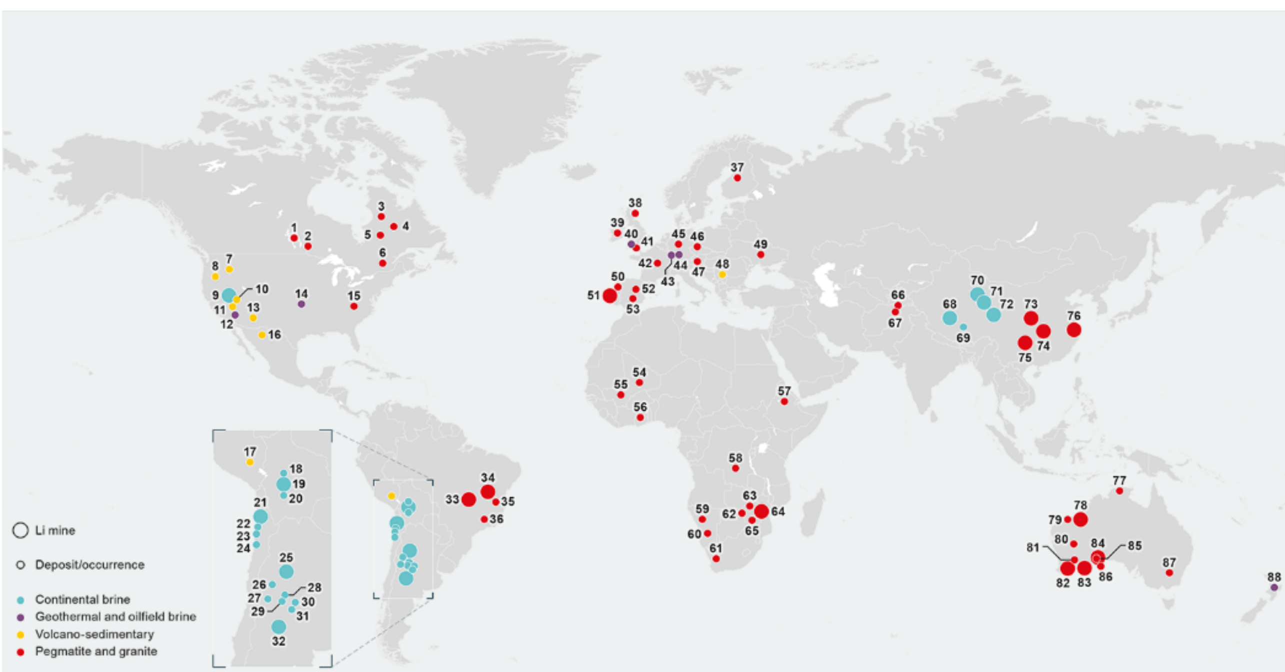

Figure 6: Source–(British Geological Survey, n.d.)

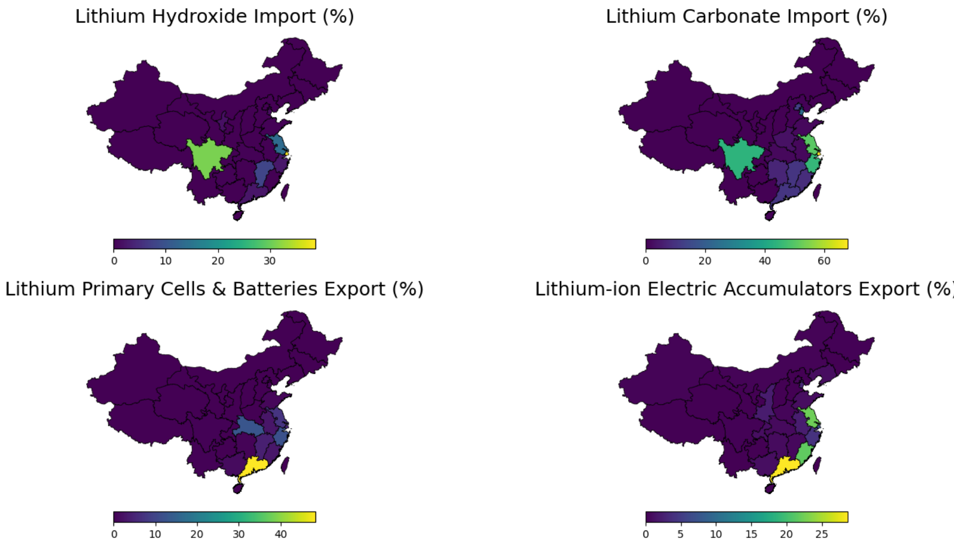

Figure 7: Lithium related product share (import and export) by province)

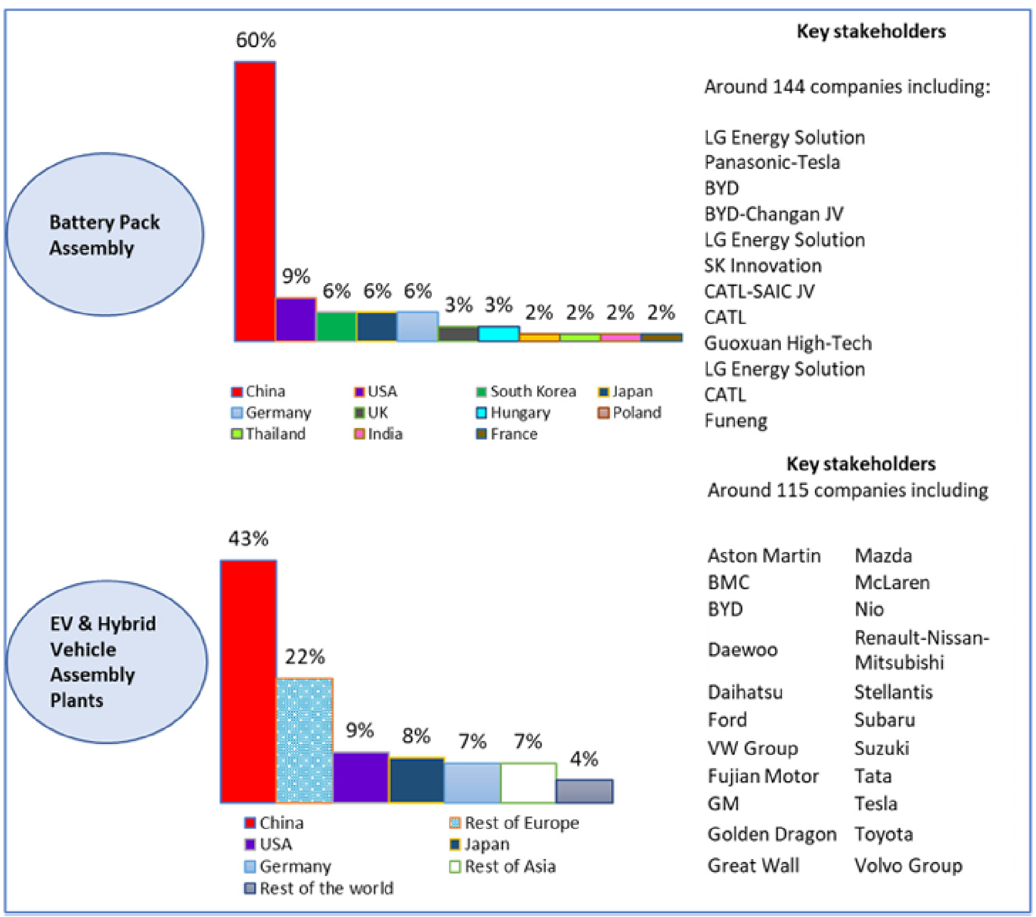

Figure 8: Source–(Sanchez-Lopez, 2023)

8 Appendix–Tables

Table 1: Lithium Minerals and Brine: World Production, by Country or Locality

	2018			2019			2020			2021		
Country or locality	**Gross weight**	**Lithium content**	**LCE**	**Gross weight**	**Lithium content**	**LCE**	**Gross weight**	**Lithium content**	**LCE**	**Gross weight**	**Lithium content**	**LCE**
Argentina, subsurface brine:												
Lithium carbonate	29,707	5,585	29,707	29,994	5,639	29,994	26,911	5,059	26,911	28,520	5,362	28,520
Lithium chloride	5,005	816	4,284	4,284	698	3,717	4,836	788	4,196	3,230	575	3,230
Australia, spodumene	1,965,910	54,731	291,335	1,587,980	44,858	238,135	1,427,380	40,723	211,527	1,955,670	55,281	294,261
Brazil, concentrate	41,000	1,141	6,076	33,700	938	4,994	57,500	1,601	8,521	60,000	1,670	8,890
Canada, spodumene	9,000	192	1,020	9,000	192	1,020	–	–	–	18,500	5	5
Chile, subsurface brine:												
Lithium carbonate	87,029	16,841	87,029	100,787	18,948	100,787	114,260	21,481	114,260	150,348	28,265	150,348
Lithium chloride	3,826	624	3,320	3,826	624	3,320	1,636	267	1,636	–	–	–
Lithium hydroxide	6,468	1,067	6,581	9,934	1,639	8,725	9,030	1,490	7,931	10,653	1,765	10,653
China, lithium carbonate equivalent	37,800	7,170	37,800	57,500	10,900	57,500	60,600	13,273	70,600	75,000	13,700	70,000
Namibia, lepidolite	30,000	258	–	–	–	–	–	–	–	–	–	–
Portugal, lepidolite	76,818	1,152	4,134	50,000	750	2,000	23,185	385	1,851	25,000	375	2,000
United States, lithium	W	W	W	W	W	W	W	W	W	W	W	W
Zimbabwe, petalite, lepidolite	80,000	1,210	6,430	20,859	477	2,221	–	–	–	51,600	1,036	5,511
Total	2,470,000	91,800	489,000	1,950,000	84,400	446,000	1,460,000	82,700	400,000	2,360,000	106,100	566,000

Note: Data source–USGS 2022.

Table 2: Lithium Minerals and Their Properties

Name	**Formula**	**Li content [%]**	**Hardness [Moh grades]**	**Density [g/cm^3]**
Amblygonite	$(Li,Na)AlPO_4(F,OH)$	3.44	5.5–6	3.0–3.1
Eucyptite	$LiAlSiO_4$	5.51	6.5	2.6–2.7
Hectorite	$Na_{0.3}(Mg,Li)_3Si_4O_{10}(OH)_2$	0.53	1–2	2.5
Jadarite	$LiNa_3SiB_3O_7(OH)$	3.16	4–5	2.5
Lepidolite	$KLi_2Al(Al,Si)_3O_{10}(F,OH)_2$	3.58	2.5–3	2.8–2.9
Petalite	$LiAlSi_4O_{10}$	2.09	6–6.5	2.4–2.5
Spodumene	$LiAlSi_2O_6$	3.73	6.5–7	3.1–3.2
Zinnwaldite	$KLiFe^{2+}Al(AlSi_3)O_{10}(F,OH)_2$	1.59	3.5–4	2.9–3.0

Note: source–(Vikström et al., 2013).

Table 3: Recovery of lithium from brine by various processes

Resources	**Process**	**Reagent**	**Mechanism**
End brine and Dead Sea brine	Precipitation	Lithium aluminate	Precipitation
Dead Sea brine	Precipitation	Lithium aluminate	Precipitation
Dead Sea brine	Precipitation	Lithium aluminate	Precipitation
Salar de Uyuni, Bolivia, Dead Sea brine	Precipitation	Lithium aluminate	Precipitation
Dead Sea brine	Gel permeation chromatography	Polyacrylamidegel, Bio-Gel P-2 and Blue Dextran 2000	Column chromatography
From other alkali metal	Reversed phase chromatography	Polytetrafluoroethylene tributyl phosphate (TBP), dibenzoylmethane (DBM) and trioctylphosphine oxide (TOPO)	Column chromatography
Seawater, hydrothermal water	Column chromatography	Titanium (IV) antimonate cation exchanger (TiSbA)	Column chromatography
Synthetic brine	Chelating resins	MC50 resin, TP207 resin, Y80-N Chemie AG	Ion exchange
Brine of natural gas wells	Inorganic ion exchanger	H_2TiO_3 ion exchanger	Ion exchange
Salt Lake brine	Inorganic ion exchanger	H_2TiO_3 ion exchanger	Ion exchange
Synthetic brine	Liquid-liquid extraction	n-Butanol	Liquid-liquid extraction
Synthetic brine	Liquid-liquid extraction	2-Ethyle-1,3-hexanediol, isoamyle alcohol, di-isopropyl ether, diethyl ether	Liquid-liquid extraction
Brine	Liquid-liquid extraction	Tributyl phosphate (TBP)	Liquid-liquid extraction
Brine	Liquid-liquid extraction	Heptofluorodimethyloctunedione, peniafluorodimeihylhepiunedione, trifluorodimethylhexanedione, dibenzoylmethane, and tetramethylheptonedione	Liquid-liquid extraction
Salt Lake brine	Ionic liquid liquid-liquid extraction	-Butyl-3-methylimidazolium bis[(trifluoromethyl)-sulfonyl]-imide, 1-ethyl-3-methyl-imidazolium bis[(trifluoromethyl)-sulfonyl]-imide, and 1-butyl-3-methylimidazolium hexafluorophosphate	Liquid-liquid extraction
Brine	Ionic liquid liquid-liquid extraction	1-Alkyl-3-methylimidazolium-based ionic liquids (ILs), with the alkyl chain lengths were 4-butyl (C_4), 5-pentyl (C_5), 6-hexyl (C_6), 7-heptyl (C_7), 8-octyl (C_8) or 9-nonyl (C_9)	Liquid-liquid extraction
Salt Lake brine	Ionic liquid liquid-liquid extraction	1-Octyl-3-methyl-imidazolium hexafluorophosphate, and tributyl phosphate (TBP)	Liquid-liquid extraction
Salt Lake brine	Ionic liquid liquid-liquid extraction	Bis(trifluoromethylsulfonyl) imide in TBP	Liquid-liquid extraction
Brine	Electro-electrodialysis	Bipolar membranes	Membrane electrolysis
Salt Lake brine	Membrane electrolysis	Bipolar membranes	Membrane electrolysis
Dead Sea brine	Solvent impregnated membrane	Solvent-polymeric membranes (2-ethylhexyl)-diphenyl phosphate	Membrane
Brine	Desalination	Nanofiltration membrane	Membrane
Salt Lake brine	Desalination	Nanofiltration (NF90 membrane XLE membrane)	Membrane

Note: source–(Swain, 2017).

Table 4: Cost, throughput, and energy consumption of LIB manufacturing processes

Manufacturing processes	**Cost per year/$***	**Percentage %**	**Throughput**	**Manufacturing processes**	**Energy consumption per cell/kWh**	**Percentage %**
Slurry mixing	7,396,000	7.91%	30 min–5 h	Slurry mixing	0.11	0.83%
Coating/drying	13,984,000	14.96%	35–80 m/min	Coating	0.18	1.36%
Solvent recovery	4,296,000	4.60%	NA	Drying/solvent recovery	6.22	46.84%
Calendering	4,849,000	5.19%	60–100 m/min	Calendering	0.38	2.86%
Slitting	2,891,000	3.09%	80–150 m/min	Slitting	0.71	5.35%
Vacuum drying	2,990,000	3.20%	12–30 h	Stacking	0.77	5.80%
Stacking	8,086,000	8.65%	NA	Welding	0.25	1.88%
Welding	6,864,000	7.34%	NA	Enclosing	0.69	5.20%
Enclosing	11,636,000	12.45%	Depend on the cell design	Formation/aging	0.07	0.53%
Formation/aging	30,482,750	32.61%	Up to 1.5–3 weeks	Dry room	3.9	29.37%

Note: source–(Liu et al., 2021).

Table 5: Comparative properties and performance characteristics of key battery metals.

Metal	Properties	Benefits	Limitations
Lithium	Core component of the electrolyte, low standard reduction potential (-3.05 V), high capacity (3860 mAh g^{-1}).	High energy density, lightweight, excellent electrochemical characteristics, facilitates high-capacity batteries.	Highly reactive; requires protection from air and water, needs secure and tamper-resistant sealing.
Nickel	High energy density, improves battery performance, commonly used in NMC cathodes with varying nickel content (33 % to 90 %).	Increases energy density and battery efficiency, extends driving range of EVs, lower cost compared to some alternatives.	Stability issues at high temperatures, higher cost than some other metals.
Manganese	Provides high-rate capability, improves safety, reduces risk of thermal runaway, enhances structural stability.	Enhances safety and stability, good rate capability, extends battery lifespan by mitigating capacity fading.	Relatively low specific energy and specific strength.
Cobalt	Enhances thermal stability, improves low-temperature performance, increases energy density, and optimizes rate performance.	Improves thermal stability and low-temperature performance, increases energy density and rate performance.	High cost, environmental and ethical concerns related to mining.
Aluminium	Provides stability in NCA chemistries, contributes to long service life, maintains good specific power strength.	Increases structural stability and battery life, comparable specific energy to NMC, lightweight and cost-effective.	Typically used in small quantities (5%-10%), limited to specific applications.

Note: source–(Koech, Mwandila, Mulolani, & Mwaanga, 2024).

Table 6: 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, Carena, Ferrara, & Bontempi, 2024).

Table 7: Governance Indicators of Bolivia, Chile, and Argentina

Indicator	Chile	Bolivia	Argentina
Role of the state in lithium mining	Centralized decision making	Centralized decision making. Direct participation and control in extraction and industrialization of lithium.	Decentralized decision making. No direct participation except through public–private partnerships.
Mining framework	Exploitation rights in three forms: State companies, administrative concessions, and special contracts of operation (CEOL). Royalty lithium: Variable (from 6.8% to 40% of the sale price) paid to CORFO. Contracts with SQM and Albemarle.	State control in all the mining activities of the salt flats. Royalty of 3% to be transferred to the Departmental Government, not the municipalities.	Hybrid framework: Provincial governments are the owners of mineral resources and are in charge of mining management, concession regimes, and royalty distribution.
Industrial policy of lithium	• Two main research initiatives (public and public–private partnerships, mostly by Li companies). • Cathode materials and batteries. • 2015: National Commission of Lithium: New guidelines for public policy. • 2017: Compulsory quota of 25% of Albemarle production for supporting local industry (Proyecto de Inversión de Productores Especializados de Litio en Chile). • 2018: CODELCO (Copper State Company) was given a special contract for lithium operations. • 2019: Creation of the Technical Institute of Solar Energy, Low Emissions Mining, and Advanced Materials of Lithium and Other Minerals. • 2020: Private-driven industrialization policy: Chilean company Nanotec (production of nanoparticles of Li).	• 2010: Pilot plants of potassium chloride and lithium carbonate (extractive phase). • 2018: Industrial scale plant of potassium chloride. • 2019: Construction of the industrial plant of lithium carbonate. • Cathode materials and batteries. • Industrialization of lithium-ion batteries and cathode materials (public–private partnership) • 2013: Pilot plant of lithium-ion batteries. • 2017: Pilot plant of cathodic materials (LMO, NMC, LFP). • 2018: YLB signed a joint venture with a German company for an industrial complex of lithium hydroxide (contract rescinded by Morales government due to local protests). • 2019: Joint venture with Chinese consortium Xinjiang TBEA Group-Baocheng for exploring and extracting resources from Coipasa and Pastos Grandes salt flats (unclear how industrialization will take place).	• Two research centers (public funds). • Cathode materials and batteries: • Innovation: YTEC/INIFTA/Laboratorio de Energías Sustentables de Córdoba (public funds). • Two private companies (Probattery and Plaka) (assembly of batteries). • 2019: Public–Private partnership (Jujuy Litio SA) (between Y-TEC, Italian FIB-FAAM & JEMSE) to install a lithium cells and batteries plant.

Note: Source–(Sanchez-Lopez, 2023). CORFO = Chilean Production Development Corporation; LMO = lithium manganese oxide; NMC = lithium nickel manganese cobalt oxide.

Table 8: Export Product Share by Country, 2023

Product	**Argentina**	**Bolivia**	**Chile**	**Mexico**
Carbonates; Lithium Carbonate	0.999438	0.996511	0.842691	0.000000
Electric Accumulators; Lithium-Ion	0.000562	0.003277	0.000165	0.951165
Cells and Batteries; Primary (Other)	0.000000	0.000024	0.000259	0.001398
Cells and Batteries; Primary, Lithium	0.000000	0.000025	0.000040	0.046049
Electric Accumulators; Other	0.000000	0.000162	0.000043	0.001315
Lithium Oxide and Hydroxide	0.000000	0.000000	0.156803	0.000000
Carbonates; N.E.C.	0.000000	0.000000	0.000000	0.000072

HS Code	**Product Description**
28051910	Strontium and barium
28252010	Lithium oxide
28252090	Other lithium oxides
28269020	Lithium carbonates
28273910	Lithium chlorides
28369100	Lithium carbonates
28416910	Lithium molybdates
28429030	Lithium chromates
28429040	Lithium dichromates
28429060	Lithium permanganates
28453000	Phosphides, whether or not chemically defined, excluding ferrophosphorus
29043300	1,2,3,4,5,6-Hexachlorocyclohexane (HCH), including lindane
85065000	Primary cells and primary batteries of lithium
85076000	Lithium-ion accumulators

Table 9: Product descriptions by HS code

Index	Stock Symbol	Company Name
1	835237.SS	Likai Technology
2	833523.SS	Derui Lithium
3	873152.SS	Tianhong Lithium
4	300530.SZ	Leading Science & Technology
5	688772.SS	Zhuhai CosMX Battery
6	002245.SZ	Shandong Xiangcheng Science & Technology
7	300207.SZ	Sunwoda Electronic
8	002324.SZ	Pretech
9	600241.SS	Times Electric Vehicle
10	300750.SZ	Contemporary Amperex Technology (CATL)
11	688567.SS	Yibin Tianyi Lithium Industry
12	301327.SZ	Huabao New Energy
13	301217.SZ	Tongguan Copper
14	000049.SZ	Desay Battery
15	301210.SZ	Jinyang New Materials
16	301121.SZ	Zijian Electronics
17	002850.SZ	Keda Clean Energy
18	300953.SZ	Zhengyu Technology
19	688063.SS	Pylon Technologies
20	600478.SS	Keliyuan
21	001283.SZ	Haopeng Technology
22	688345.SS	Baolv Microelectronics
23	300014.SZ	Eve Energy
24	301150.SZ	Zhongyin Technology
25	688388.SS	Jiayuan Technology
26	600110.SS	Nord Co., Ltd.
27	301587.SZ	Zhongrui Shares
28	600152.SS	Weifu High-Technology
29	301511.SZ	Defu Technology
30	300068.SZ	Nandu Power
31	300438.SZ	Penghui Energy

Table 10: List of Firms with Stock Symbols and Names

Table 11: 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}

Table 12: Import and Export Shares of Lithium Products by Province (%)

Province	Lithium Hydroxide Import (%)	Lithium Carbonate Import (%)	Lithium Primary Cells & Batteries Export (%)	Lithium-ion Electric Accumulators Export (%)
Anhui Province	0.00	1.41	2.70	2.29
Beijing	0.00	12.51	0.50	0.37
Chongqing	0.00	0.00	0.06	1.03
Fujian Province	0.06	8.70	3.02	21.63
Gansu Province	0.00	0.00	0.00	0.00
Guangdong Province	2.26	10.58	48.36	28.61
Guangxi Zhuang Autonomous Region	0.00	0.00	1.51	1.08
Guizhou Province	0.30	0.19	0.03	0.06
Hainan Province	0.00	0.29	0.01	0.06
Hebei Province	0.00	0.30	0.08	0.07
Heilongjiang Province	0.00	0.00	0.02	0.17
Henan Province	0.03	3.10	0.11	0.40
Hubei Province	0.26	1.43	12.71	0.77
Hunan Province	0.14	7.11	0.51	0.83
Inner Mongolia Autonomous Region	0.00	0.00	0.00	0.32
Jiangsu Province	13.39	50.56	7.19	22.34
Jiangxi Province	7.93	10.43	4.24	0.62
Jilin Province	0.00	0.00	0.01	0.00
Liaoning Province	0.00	0.02	0.11	1.00
Ningxia Hui Autonomous Region	1.61	0.06	0.00	0.01
Qinghai Province	0.00	0.00	0.00	0.00
Shaanxi Province	0.00	0.05	0.02	2.22
Shandong Province	0.20	1.55	0.88	0.97
Shanghai Province	38.74	67.78	4.85	7.34
Shanxi Province	0.00	0.00	0.02	0.05
Sichuan Province	30.90	43.72	0.25	0.12
Tianjin	1.18	23.30	0.52	3.24
Tibet Autonomous Region	0.00	0.00	0.00	0.00
Xinjiang Uygur Autonomous Region	0.00	0.01	0.12	0.26
Yunnan Province	0.08	0.01	0.25	0.05
Zhejiang Province	2.31	45.12	11.91	4.06
Total	**100.00**	**100.00**	**100.00**	**100.00**

Table 13: Summary Statistics of Lithium Trade: Import and Export (in CNY Yuan)

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

Table 14: 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.

9 Appendix–Simulation code

```
import numpy as np
import matplotlib.pyplot as plt
from scipy.optimize import minimize

# Historical data: global lithium production from 1974 to 2022
years = np.arange(1974, 2023)
production = [
    105656, 117741, 110172, 78448, 86354, 81277, 78128, 79090, 77412, 80603,
    87206, 127039, 132846, 137007, 152442, 170720, 184498, 164212, 113334,
    148449, 182948, 219895, 267604, 240310, 197322, 221443, 222822, 230725,
    242453, 285452, 279929, 370550, 395121, 442179, 442290, 417648, 559204,
    577624, 576536, 521503, 623071, 617336, 770818, 2015673, 2533449,
        2004446,
    1843731, 2463673, 3752727
]

# Projected demand data (scaled by factor 71198651.09897064)
demand_data = [
    0.03603618097, 0.036716, 0.041133, 0.046928, 0.054564, 0.064651,
        0.06486,
    0.078185, 0.094372, 0.114008, 0.137608, 0.15365458385, 0.16070732985,
    0.1681150962, 0.17561744299, 0.19447800438, 0.21362152854, 0.2336031043,
    0.2548365278, 0.277753, 0.302734, 0.330804, 0.361182, 0.393987,
        0.428315,
    0.463437, 0.499042, 0.534844, 0.571939, 0.611074, 0.652979
]
demand_years = np.arange(2020, 2051)
demand_scaled = np.array(demand_data) * 71198651.09897064

# Define the range for Q_max values (28 million to 63 million with steps of
    5 million)
Q_max_values = np.arange(28e6, 64e6, 5e6)

# Hubbert curve model function
def hubbert_curve(t, Q_max, m, t_peak):
    exp_component = np.exp(-m * (t - t_peak))
    return (Q_max * m * exp_component) / ((1 + exp_component) ** 2)

# Objective function to minimize: Mean Squared Error (MSE)
def mse_loss(params, Q_max):
    m, t_peak = params
    predicted = hubbert_curve(years, Q_max, m, t_peak)
    return np.mean((production - predicted) ** 2)

# Initial guesses for parameters: m and t_peak
initial_params = [0.1, 2000]  # Initial guess for m and t_peak

# Set bounds for m and t_peak
bounds = [(0.01, 5), (1974, 2091)]

# Prepare to plot all the curves
```

```
plt.figure(figsize=(12, 8))
plt.plot(years, production, 'o', label='Historical Production', markersize
    =4)

# Loop over each Q_max value and plot the Hubbert curve for each
for Q_max in Q_max_values:
    # Minimize the MSE to find the best m and t_peak for the current Q_max
    result = minimize(mse_loss, initial_params, args=(Q_max,), bounds=bounds
        , method='L-BFGS-B')

    # Get the optimized parameters for m and t_peak
    m_opt, t_peak_opt = result.x
    t_peak_opt = int(round(t_peak_opt))  # Round t_peak to the nearest
        integer

    # Generate the optimized Hubbert curve for visualization
    years_extended = np.arange(1974, 2051)
    predicted_production = hubbert_curve(years_extended, Q_max, m_opt,
        t_peak_opt)

    # Plot the Hubbert curve for the current Q_max
    plt.plot(years_extended, predicted_production, '-', label=f'Q_max={Q_max
        /1e6:.0f}M, m={m_opt:.2f}, t_peak={t_peak_opt}')

# Plot the projected demand
plt.plot(demand_years, demand_scaled, '--', color='red', label='Projected
    Demand')

# Calculate and display the shortage area and exact figure for the year 2030
predicted_production_max = hubbert_curve(demand_years, 63e6, m_opt,
    t_peak_opt)
year_2030_index = np.where(demand_years == 2030)[0][0]
shortage_2030 = demand_scaled[year_2030_index] - predicted_production_max[
    year_2030_index]

# Shade the area for lithium mineral shortage and update the legend
plt.fill_between(demand_years, demand_scaled, predicted_production_max,
                 where=(demand_scaled > predicted_production_max),
                 interpolate=True, color='orange', alpha=0.3,
                 label=f'Lithium Mineral Shortage (2030 Shortage: {
                     shortage_2030:.2f} tons)')

# Finalize the plot
plt.xlabel('Year')
plt.ylabel('Lithium Production and Demand (metric tons)')
plt.title('Global Lithium Production vs. Projected Demand with Lithium
    Shortage Highlighted')
plt.legend()
plt.grid()
plt.show()
```