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Lithium: The Most Critical Mineral

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ABSTRACT

Lithium is a very critical mineral in today's economy. With a newfound interest in lithium for the growing market of batteries for electric vehicles, accessible lithium with traditional mining methods is not enough to keep up with this emerging demand. Traditional lithium mining techniques include hard-rock mining and solar evaporation from brine ponds, but new ways include extracting lithium from brine directly without additional process steps – termed Direct Lithium Extraction (DLE). This paper provides a history and overview of lithium materials as well as insight into the emerging techniques involved in DLE and how they affect the lithium supply chain and lithium battery market. Additionally, the various market players and how they approach the emergence of DLE technologies will be covered.

Introduction

The global market size of the lithium industry in 2022 was an estimated 7.49 billion USD (Lithium Market Size, Share & Growth Analysis Report, 2030). Around 130,000 metric tons of the mineral were produced all over the world across six continents ("Global Lithium Production 2022"). Lithium is a critical mineral in several industries, such as medicine, portable electronics, and automobiles; its applications are crucial to everyday life. With multiple different lithium compounds that are industrially relevant and the variety of products that it can be incorporated in, the lithium industry continues to have tremendous growth potential beyond what it has already experienced.

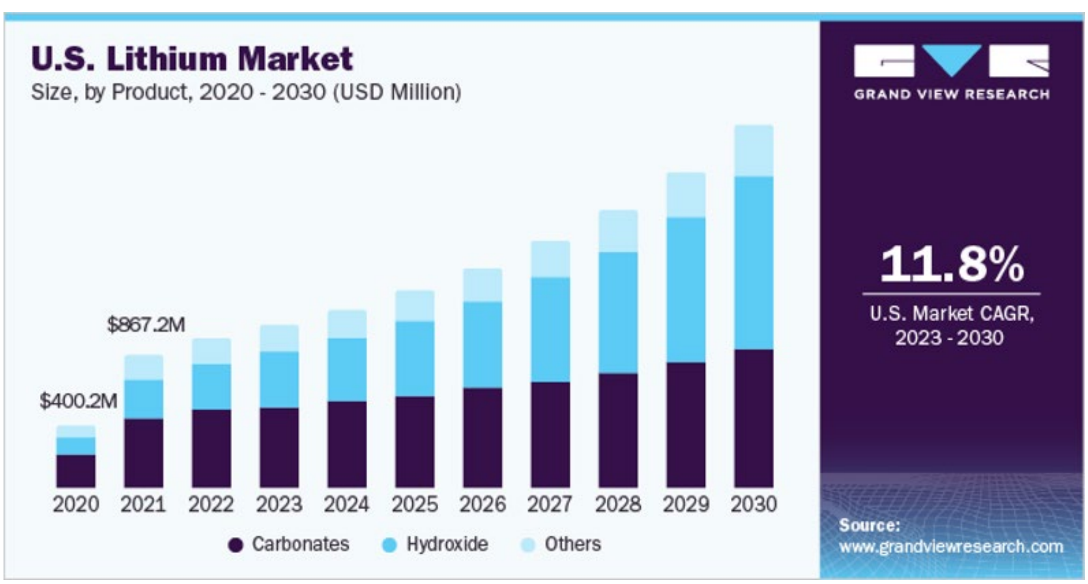

Figure 1. Chart depicting the increasing trend of the U.S. Lithium Market from 2020-2030. Reprinted from (Lithium Market Size, Share & Growth Analysis Report, 2030).

With the rise of the electric vehicle (EV) sector in the automobile industry, the need for more lithium-based batteries has grown exponentially. This necessity is the majority of the reason lithium has taken off over the past few years and why it is still on the rise and nowhere close to slowing down. Figure 1 shows that by 2030, the size of the lithium market will be roughly double what it was in 2023. It also highlights that all forms of lithium are projected to increase in sales, making it a very versatile industry. Figure 2 corroborates this fact as there are seven primary industries that lithium is used in.

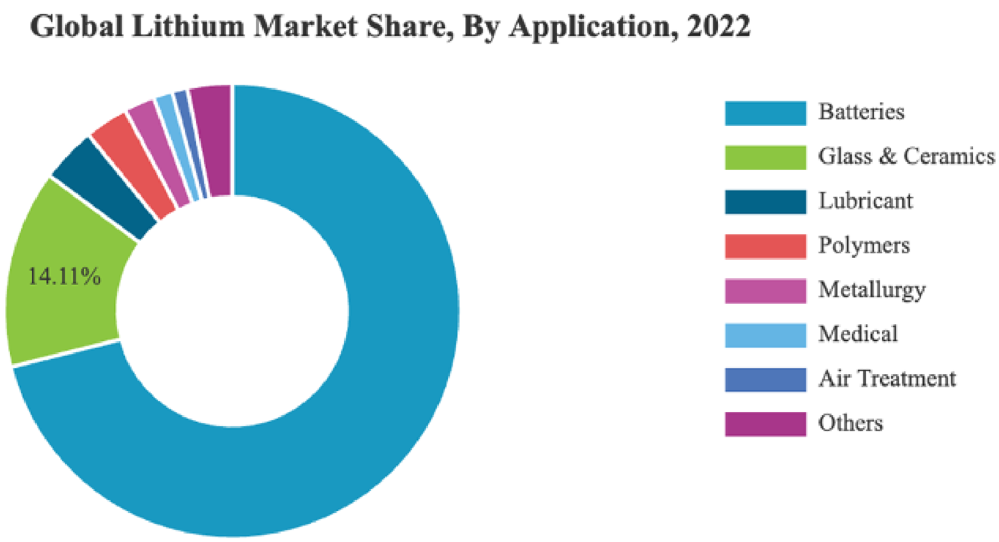

Figure 2. Different uses of lithium by application in 2022. Reprinted from (Lithium Market Size, Share, Value | Forecast Analysis [2030]).

While the current primary use of lithium is in batteries, it has a few other applications that are important to everyday life. Its presence in glass raises the melt rate of the glass and the melt temperature. Lithium also lowers the viscosity of glass and ceramics, allowing the coating of the ceramics to be easier ("Lithium"). Lithium is also used in grease where it improves the temperature stability of the grease, allowing lithium grease to be used in high-temperature applications. Additionally, medical lithium (lithium carbonate) is used as a mood-stabilizing drug to treat bipolar disorder and other mental ailments (Australia).

This report will investigate the history of lithium, its uses, and its criticality to current and future industrial and commercial uses that drastically affect the everyday lives of a wide range of consumers. Additionally, the methods with which lithium is extracted from the Earth and refined into useful products will be discussed – current techniques and resources as well as future methods in development and the natural resources they unlock, such as DLE technologies. Lastly, the effect of supply and demand on lithium industry economics and their interplay with the emergence of these new technologies and the lithium they can supply to the market will be discussed.

Fundamentals: Why is Lithium Important?

Lithium is a highly reactive, soft, silvery-white alkali metal. Because of its high reactivity, lithium as a metal does not occur naturally. However, it is found combined with other elements in igneous rocks and in the waters of mineral springs. Lithium is primarily recovered in mineral form as spodumene but is also found in other minerals such as amblygonite, lepidolite, and petalite. Lithium can be sold in many forms, the most commercially popular being lithium carbonate due to its wide availability and cost-effective benefits. This white, powdery substance creates lithium-ion batteries, ceramics and glass, adhesives and sealants, and medicine. The second most popular form of lithium is lithium hydroxide, which is an alternative to lithium carbonate but less widely used for batteries. Other forms of lithium include hydrides, nitrides, oxides, carbides, and phosphates, all useful but less available forms of lithium (MAT).

Rechargeable lithium-ion batteries are the primary reason behind the recent lithium demand increase worldwide. In the past, lithium was mined at much smaller amounts, which was enough for smaller batteries and other uses. However, with the increase in the electric vehicle market, larger lithium-ion batteries are in demand and require much more lithium. The average EV battery contains about 5,000 times the amount of lithium used in a smartphone battery, approximately 10kgs of lithium in an EV battery to just a couple of grams in a phone battery ("Are We in Danger of Running out of Lithium for Rechargeable Batteries?").

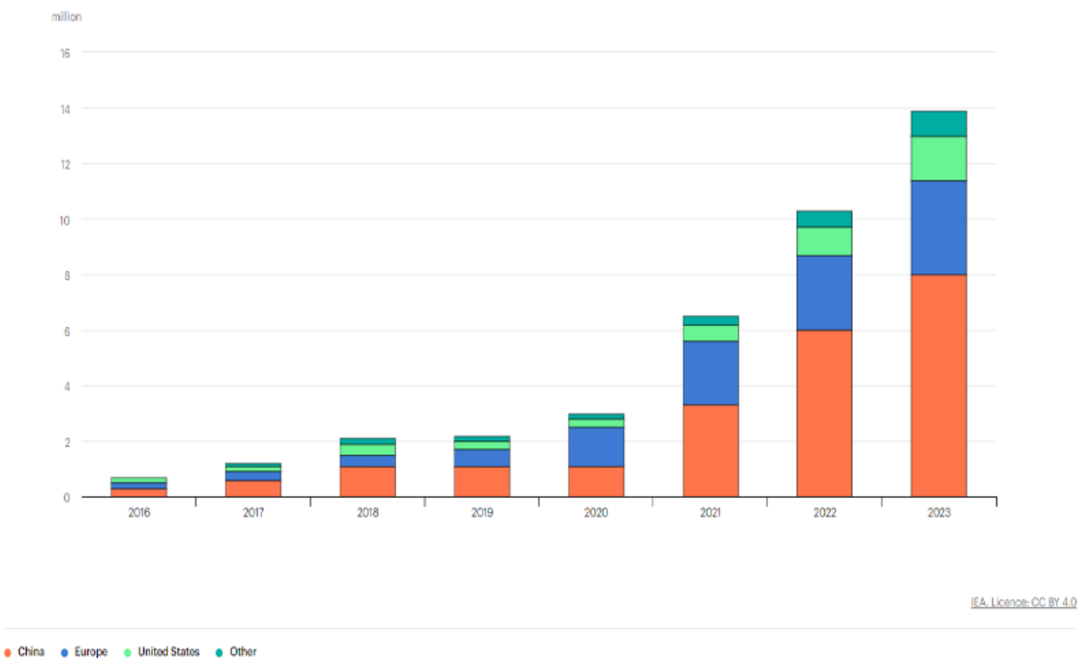

Figure 3. Graph showing the increasing trend of electric car sales from 2016-2023. Reprinted from ("Electric Vehicles").

Electric vehicle sales have seen exponential growth since 2006, as shown in Figure 3. Environmental concerns and public pressure have pushed motor companies into designing and producing fewer internal combustion engine ("ICE") cars, requiring access to more materials to enable renewable energy storage technologies for these alternative vehicles. Due to the higher demand for electric vehicles, the call for lithium batteries and more lithium mining has skyrocketed.

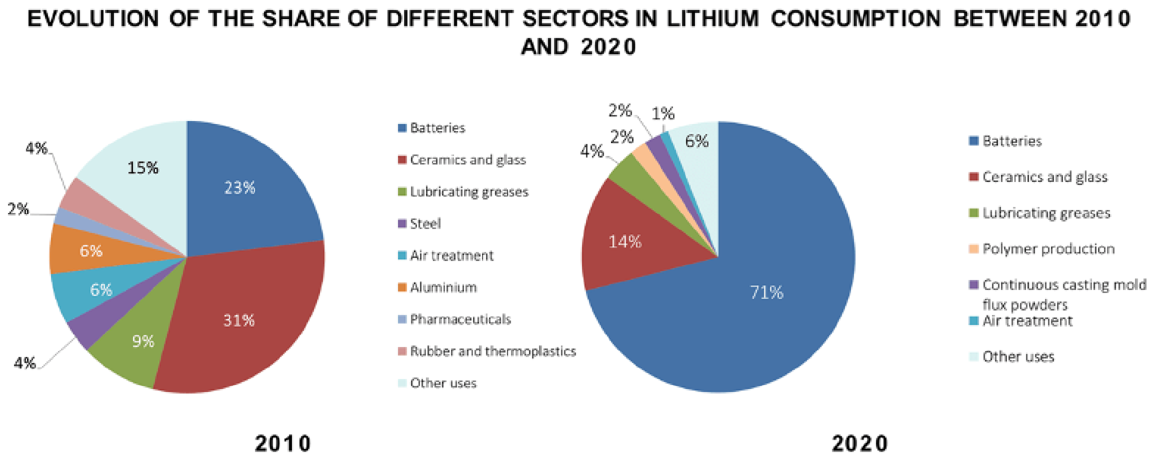

Figure 4. Pie charts showing the applications of Lithium in 2010 compared to in 2020. Reprinted from (Bogossian).

Lithium-ion batteries have enabled the wireless revolution owing to their light weight, ability to store a large amount of energy within a small volume, and reasonable charging times. Lithium is known to be the world's lightest metal and has a small ionic radius, allowing it to diffuse quickly during battery operation. This trait allows lithium-ion batteries to be useful in high-power applications. The first versions of batteries that incorporated lithium were dangerous as they incorporated lithium metal. Extra lithium ions are bundled up near the anode of the battery, causing dendrites that result in device failures and occasionally even fires (Battery Power Online | A Look Inside Your Battery). These batteries also were not safely rechargeable, making them not commercially viable. Over the years, scientists refined the concept and materials of the rechargeable lithium battery to safely enable the high-power and high-energy batteries that are used today – the primary and secondary lithium-ion batteries.

The Lithium battery is a primary cell battery, which means it cannot be recharged. The upside to these batteries is that their lone discharge cycle can be very long, much longer than a single discharge cycle of a rechargeable battery – on the order of years for a single discharge, however, they are not very powerful. These attributes make these batteries suitable for products like watches, calculators, pacemakers, etc. All devices that are impractical to recharge but do require long battery life. The fact that they cannot be recharged spiked an interest in companies to explore other possibilities. Along with the inefficiency, disposing of these batteries also caused a negative impact on the environment, leaving unnecessary waste.

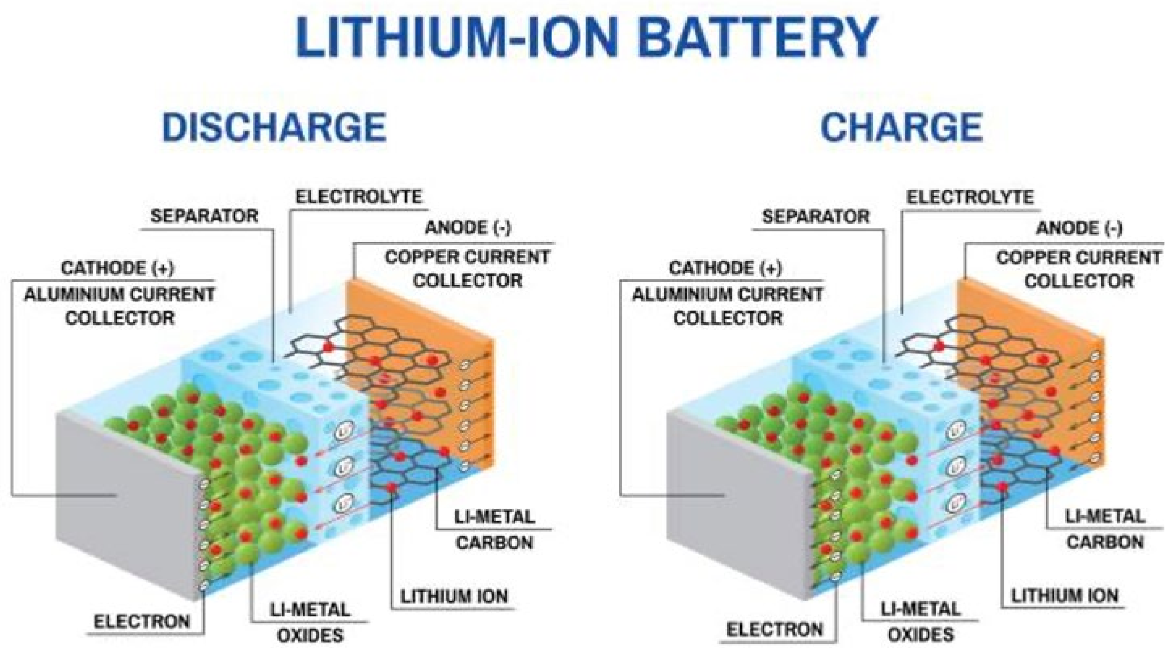

Figure 5. Shows layout of the Lithium-Ion battery, Reprinted from (How Does a Lithium-Ion Battery Work?).

The Lithium-ion battery is a secondary cell battery that can be recharged, unlike lithium batteries. A layout of the battery is shown in Figure 5. They are used in many essential electronics: laptops, phones, cameras, etc. These batteries can be wired together (i.e., many thousands of cells) into larger battery packs that are used in electric vehicles. Lithium-ion batteries are better than other rechargeable batteries because they can be charged many times before they decay and lose efficiency. They are much safer, more powerful, last longer, and lighter than rechargeable batteries. While lithium-ion cells do seem to be far superior to regular lithium cells, lithium cells do have some benefits. One benefit is that a single charge in lithium batteries can last much longer than lithium-ion batteries, they are present in devices that don't have to be replaced for more than 15 years (Darden).

Technology

There are around 88 million tons of lithium on Earth, only about ¼ of which is currently accessible ("Does the World Have Enough Lithium for Batteries?"). However, as lithium extraction technology improves, the amount of extractable lithium will increase by allowing previously unavailable lithium resources to be unlocked. Most of this lithium is found in igneous rocks and underground lithium brines. Currently, the world's biggest lithium producers are Chile, Argentina, and Bolivia; together, they are known as the "Lithium triangle." The Lithium Triangle holds over 75% of the lithium supply on Earth ("The Lithium Triangle"). Australia and China are also prominent lithium producers, as shown in Figure 6. In the Lithium Triangle, salt flats are an abundant source of lithium, which accounts for 75% of the lithium supply, but due to a lack of infrastructure and extraction capabilities, their output is severely cut back. On the other hand, Australia and China largely extract their lithium from mines by hard-rock mining.

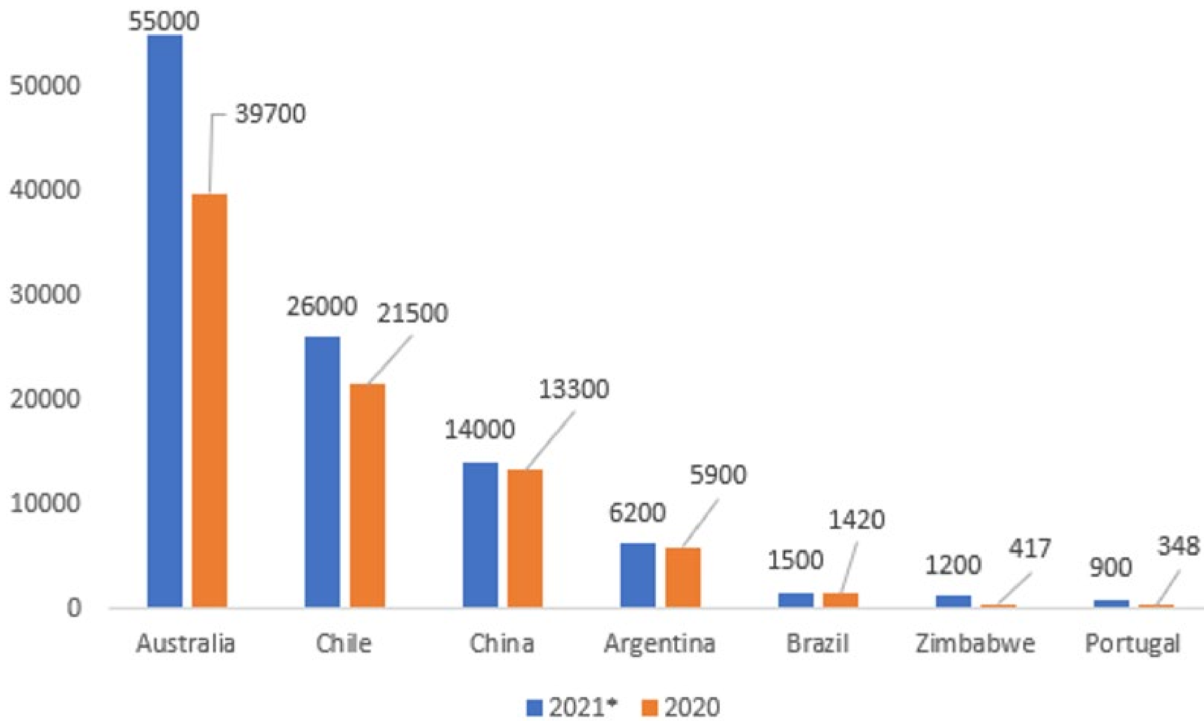

Figure 6. Chart showing the amount of Lithium produced by countries in 2020 and 2021. Reprinted from ("The World's Largest Lithium Producing Countries in 2021 – Report").

Hard-rock mining is one of the first ways of extracting lithium from natural resources. Pegmatites, which are coarse rocks composed of crystals that come in various sizes formed during the crystallization of magma, contain the mineral spodumene. Spodumene is a mineral prevalent in pegmatites, which are igneous rocks. Lithium spodumene and other minerals can produce both lithium carbonate and lithium hydroxide ("Where Lithium Comes from Does Make A Difference?"). Lithium-Cesium-Tantalum ("LCT") Pegmatites are responsible for 25% of the world's Lithium production, most prevalent in Australia, China, and Canada (Bogossian).

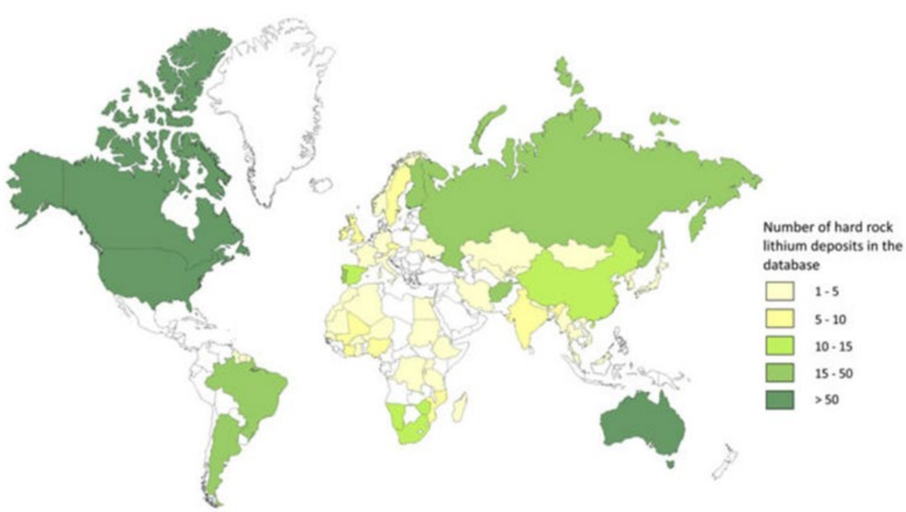

Figure 7. Global distribution of hard rock lithium mining. Reprinted from (Bogossian).

When mining hard rock deposits, open-pit mining methods are used. A global sense of where this method is used is shown in Figure 7. When the minerals like spodumene are extracted, they are crushed, milled, roasted, purified, dried, and separated. The method is shown in Figure 8. They have a concentration of around 5-7% lithium superoxide (LiO2) when they are packaged and sent to be chemically processed into lithium carbonate. This extraction method is usually more expensive than other forms due to its need for skilled workers and expensive equipment. However, it does result in higher quality lithium, which has a higher lithium content (Mangrove's Technology for Hard Rock Lithium Processing).

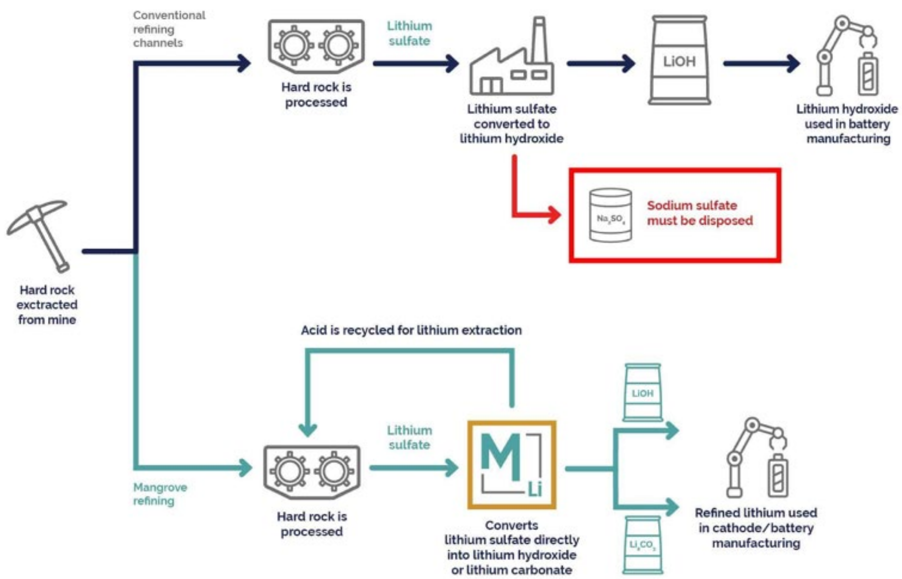

Figure 8. Process of Hard-Rock Lithium Mining. Reprinted from (Mangrove's Technology for Hard Rock Lithium Processing).

A second method of lithium extraction is brine evaporation. Underground lithium-rich brines found in places such as the Lithium Triangle are pumped into ponds on the surface and evaporated. The evaporation process forms heaps of salt, which are further processed to separate the lithium salts from the rest of the mixture. This extraction method is a much cheaper way of producing lithium compounds because it doesn't require the heavy machinery and skilled labor used in hard rock mining but yields a product with lower lithium content. It also takes over a year to evaporate these brines, and as the salt left behind decays, it harms the surface (Lithium Brine Extraction Technology). The process also risks contaminating local water sources and releasing excess toxic metals into the environment. Figure 9 shows the unnatural heaps of salt on the flats.

Figure 9. Salt evaporated from lithium brines in the salt flats of the Lithium Triangle. Reprinted from ("The Lithium Triangle").

The most recent method of producing lithium is through a process called DLE. This extraction method is superior to other methods because it is cost-effective, better for the environment, and can access more untapped lithium brine deposits than traditional practices. The three main types of DLE are solvent extraction, absorbent extraction, and membrane extraction (An Introduction to Direct Lithium Extraction (DLE) | Darcy Partners).

Solvent extraction is capturing and transforming lithium into lithium chloride or Lithium-ion from the brine; it works as a new substitute to the brine evaporation process. A solvent molecule is used to capture Li+ or LiCl ions, that solvent is later separated, and the lithium is released into a concentrated solution. This process is faster, cheaper than the alternative, and more efficient as a smaller percentage of lithium is lost. Along with its economic advantages, it also has environmental ones; once finished, the brine used to extract the lithium can be returned to where it came from, reducing the area of evaporation ponds and resulting in less surface destruction. The biggest benefit of this process over the other methods of DLE is that it is a stand-alone process, there are other additional steps for other DLE technologies. However, there have been no suitable solvents to capture the ions for this method found yet ("Lithium Overview - Lithium Solvent Extraction").

The second type of DLE, absorbent extraction, has a lengthy process to reach the result. First, lithium chloride (LiCl) is collected and then washed multiple times with a diluted LiCl solution to remove alternate ions and a second time to obtain the lithium chloride. With absorbent extraction, the process is not significantly impacted by weather conditions and is the most successfully proven method for DLE. However, the equipment for this process can be expensive, and the process still needs to be perfected. Materials used for lithium absorption are still under research, and the questionability of their long-term stability and degradation grow concerns about the costs needed to constantly replace them (Global Metals & Mining Direct Lithium Extraction: A Potential Game Changing Technology).

The final type of DLE technology is ion-exchange membranes. Absorbents in the membranes soak up Li+ ions and discharge all other excess ions. This method reduces energy consumption because the adsorption capacity of the membrane is higher than other methods. This method is positive because it is environmentally

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friendly and very energy efficient, but due to its recent upcoming, it has very little research and not enough proof of its working (Li et al.).

New DLE technology is still rising, being tested and used by companies to extract lithium faster, cheaper, and more effectively. It can access more lithium reserves that are not amenable to current hard rock mining and brine evaporation techniques, and take up less space and be easier on the environment. DLE methods also usually yield greater than 90% lithium extraction efficiency. Figure 10 below summarizes the pros and cons of each lithium extraction method and highlights that the new DLE method is superior to older ways.

LITHIUM EXTRACTION METHODS
TECHNOLOGY COMPARISON

	DIRECT LITHIUM EXTRACTION (DEL)	LITHIUM BRINE EXTRACTION IN EVAPORATION PONDS	MINING HARDROCK (MINERAL ORE)
Production times	Hours to days	Months to years	NA
Land area requirement	Low	High	High
Weather dependance?	No	Yes	Yes
Water consumption	Low	High	High
Energy Consumption	++	+	++++
Lithium recovery rates / contained	70-99%	~50%	6% – 7% Li2O in ~80% spodumene
GHG impact (Scope 1 emissions)	Low	Low	High
Dominant Process	Adsorption | Ion Exchange | Solvent Extraction	Staged atmospheric evaporation	Heating, cooling, crushing and roasting
Costs	$$	$	$$$

Proprietary and confidential

Figure 10. Comparison of competing lithium extraction technology. Reprinted from (Mangrove's Technology for Hard Rock Lithium Processing).

Economics of Lithium Mining and Processing

The demand for lithium over the last few years has grown exponentially and only continues to grow. The root of this growth is the rise of the electric vehicle market and the need for lithium carbonate and hydroxide in batteries, as shown in Figure 11. Tesla suggests they would need 16 times the amount of lithium carbonate produced currently, 1000 kilotons of lithium, per year by 2030 to meet their projected EV demand. The charts below show the projected increase in demand for EVs and lithium through 2030 (Australia's Potential in the Lithium Mining Market | McKinsey).

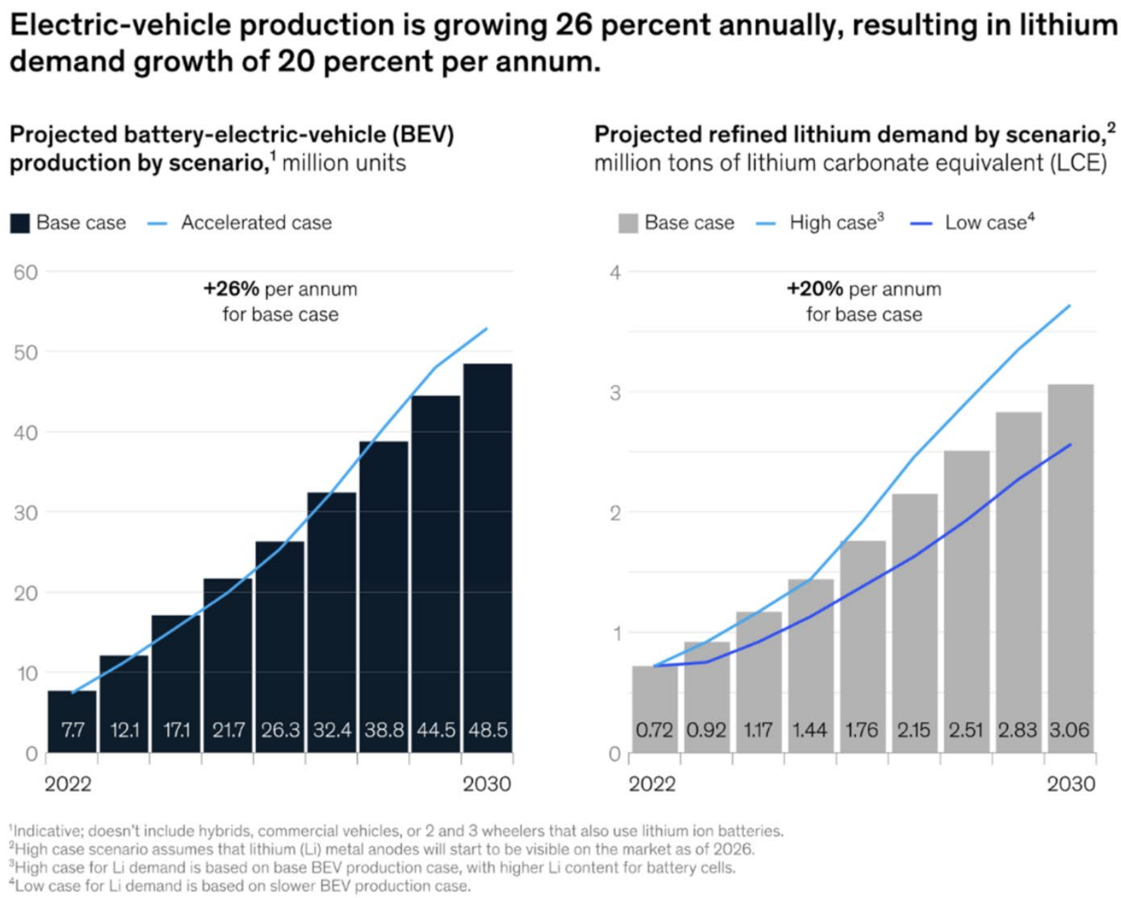

Figure 11. Projected EV and lithium demand growth through 2030. Reprinted from (Australia's Potential in the Lithium Mining Market | McKinsey).

Currently, much of this demand is being met by Australia, currently producing 335,000 tons of lithium carbonate, they are projected to produce an expected 470,000 tons of lithium carbonate equivalent by 2024, per Figure 12. Their predicted increase in exports and their value is shown in the figure below. Out of 26 million tons of lithium reserves worldwide, Australia has the second most, 6.2 million tons. It is the world's largest spodumene producer, the base material for lithium carbonate and hydroxide. Australia's reserves are highly amenable to current high throughput industrially available extraction methods, giving them the largest exports in the world. The world's largest lithium reserves are in Chile, which has 9.3 million tons of reserves, mostly made up of lithium brines at salt flats. However, the lack of proper funding and structure, as well as low production rates of brine evaporation ponds, limit their capabilities to produce and export at the same rate as Australia. These troubles in producing adequate lithium for export apply to all South American countries with large lithium reserves, like Argentina and Bolivia, who, along with Chile, make up the Lithium Triangle ("Capturing the Value of the Global Lithium Supply Chain").

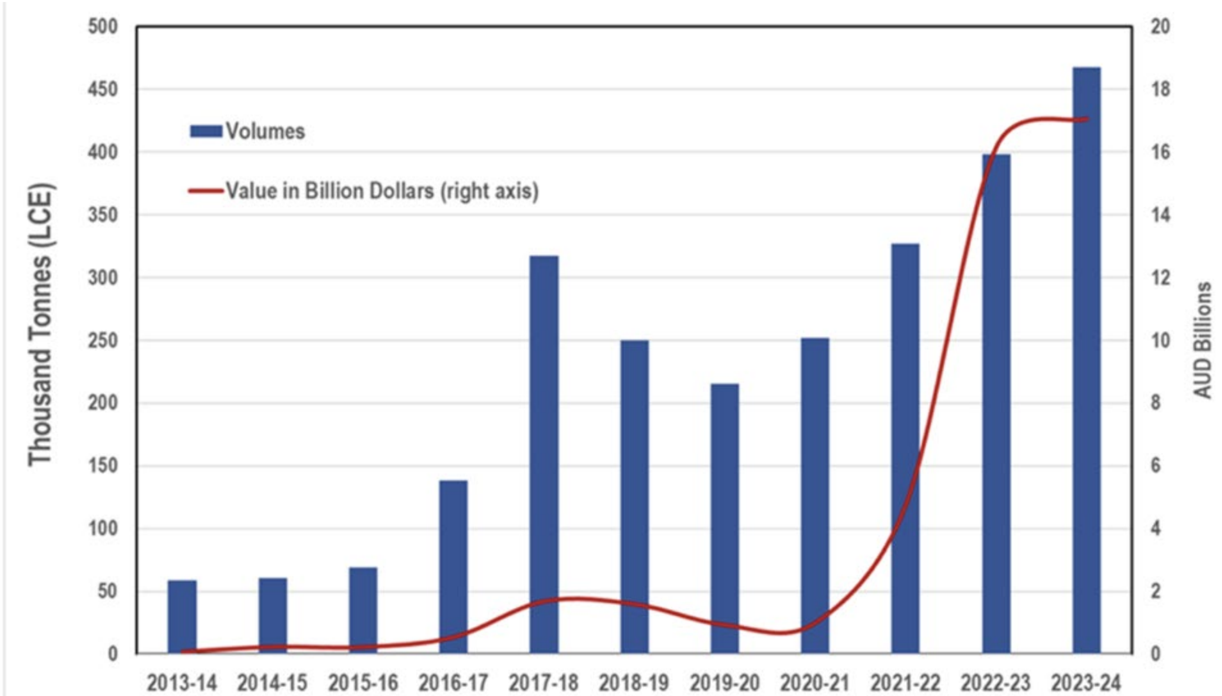

Figure 12. Predicted exports of LCE from Australia through 2024 and the value of those exports. Reprinted from ("Capturing the Value of the Global Lithium Supply Chain").

The lithium supply chain, from raw materials to automobiles, is broken into five main stages. The first stage is mining lithium, which involves any type of lithium production: hard rock mining, brine extraction, or any DLE technique. The second stage is refining and processing, where all non-lithium contents are removed, and the raw lithium compound is purified and refined. The next step is making battery materials, where the refined lithium combines with other critical minerals and elements to form the final compounds used in battery cells. The fourth stage is battery cell manufacturing, followed by the final stage of assembling the cells into battery packs. Despite being the main producer and exporter of lithium, Australia only profits from a tiny fraction- less than 1%- of the total gross revenue made throughout this chain. More than 99% of the gross revenue created throughout the battery supply chain is generated in the last three steps. The revenue breakdown throughout the different portions of the supply chain is visualized in Figure 13 ("Capturing the Value of the Global Lithium Supply Chain").

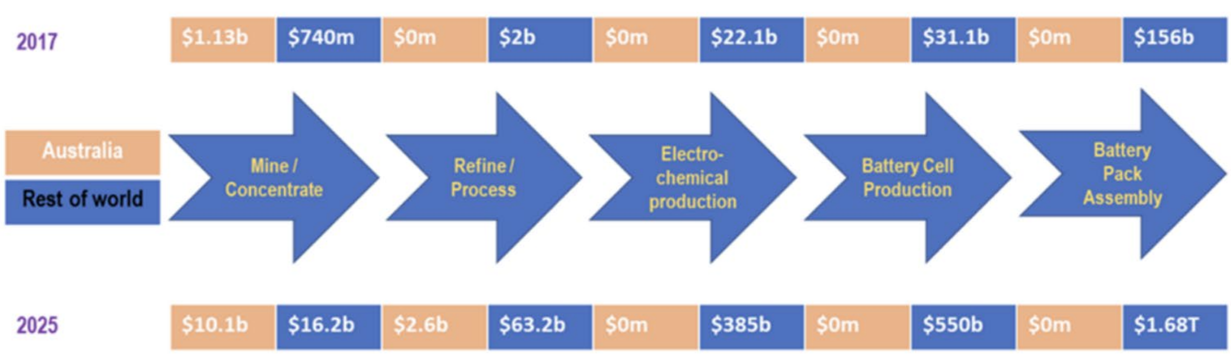

Figure 13. Cash flow of the lithium supply chain for Australia and the rest of the world. Reprinted from ("Capturing the Value of the Global Lithium Supply Chain").

Australia controls about 50% of the lithium mining in the world, but China largely controls the rest of the supply chain. China controls over 70% of the supply chain, specifically stages 2, 3, and 4. They have an overwhelming majority in lithium refining and electrochemical production and over 50% control in cell production. This allows their economy to benefit from the large revenue generation from the later stage supply chain steps. Figure 14 below shows the breakdown of the countries controlling the global supply chain ("Capturing the Value of the Global Lithium Supply Chain").

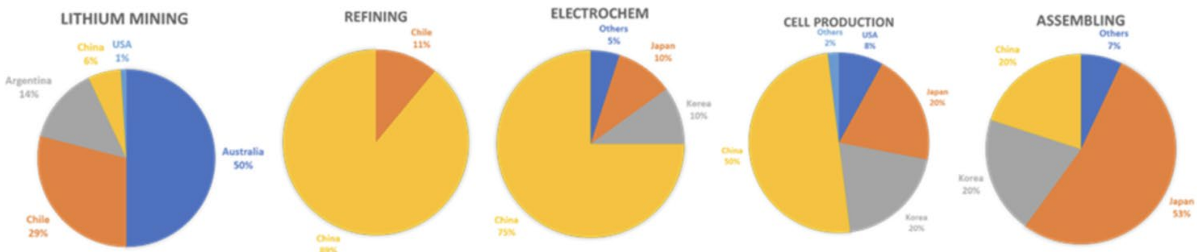

Figure 14. Percentages of lithium supply chain stages controlled by different countries. Reprinted from ("Capturing the Value of the Global Lithium Supply Chain").

The implementation of DLE technologies has the potential to significantly increase the supply of lithium from brine projects, nearly doubling lithium production on higher recoveries and improving project returns, with the bonus of offering environmental, sustainability, and governance ("ESG") benefits, while also dampening the projection on lithium price hikes as lithium battery production steepens. The superior lithium recovery rates achieved through DLE are highlighted in Figure 15, with DLE technology able to achieve up to 90% recovery compared to the average 40-60% achieved through traditional LCE methods.

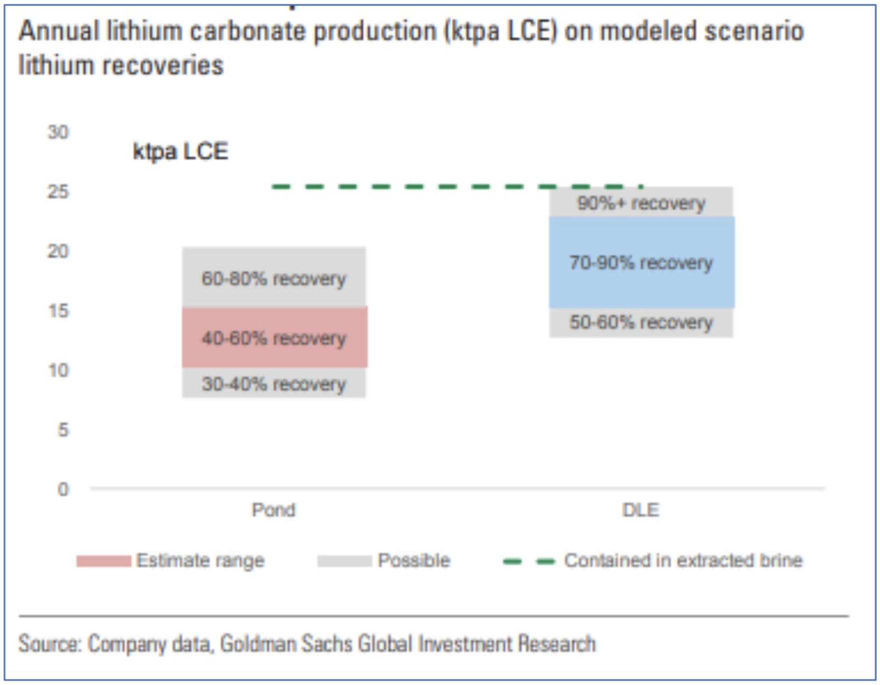

Figure 15. Recover rates of Lithium Carbonate Extraction. Reprinted from (Global Metals & Mining Direct Lithium Extraction a Potential Game Changing Technology).

Brine holds two-thirds of all lithium reserves globally, but only 40% of the available brine is currently used to produce lithium. With the implementation of new DLE technologies, untapped lithium brines can be reached, and already existing efforts can double their yield, putting an estimated 70-140,000 tons of more lithium into the supply chain, per Goldman Sachs ("Fast, Low-Cost Direct Lithium Extraction Could Avert a Supply Crisis").

The result of the Increase In production through DLE technologies Is a lower price point of lithium, which will help to lower the cost of the final EV product and work to make it affordable to the average consumer. The changes in the price point of lithium is shown in Figure 16. Lithium supply is getting closer to fulfilling the increasing demand because of the easier access and increasing production rates of lithium. A major increase in lithium supply has brought down its cost, resulting in a cheaper battery for EVs and other devices.

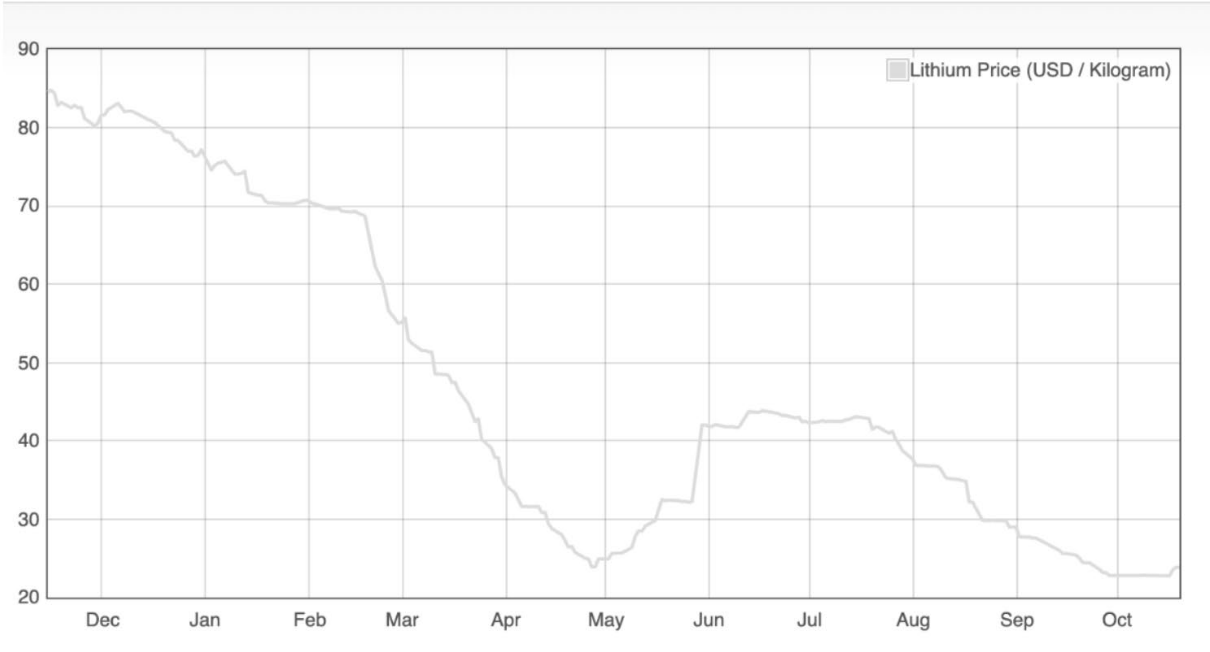

Figure 16. Lithium price (USD/Kilogram) in 2022. Reprinted from (Daily Metal Price: Lithium Price (USD / Kilogram) Chart for the Last Year).

There are a lot of companies in the lithium industry, both old and new. Large companies like Albemarle, SQM, and Gengfeng Lithium primarily operate out of the U.S., Argentina, and China, respectively, and dominate the market. These companies are the world's lithium producers and have used traditional lithium mining methods for decades. With new companies and technologies emerging, they are being pushed into investigating, innovating, and utilizing new DLE technologies to stay on top of the industry. Newer companies are focusing on technology development in hopes of partnering with lithium resources that cannot extract their lithium efficiently with traditional methods. Start-ups are starting to see an influx of capital as large companies across the supply chain are looking to secure their own lithium, evidence of this phenomenon can be seen in General Motors's investment into EnergyX, a privately owned DLE technology startup based in Austin, TX. Similarly, other companies like Standard Lithium have received significant investments to enhance technology development to unlock previously unavailable lithium resources. These large investments into startups within the lithium industry will force the major incumbents to evaluate how they will leverage emerging technology with their core business (Scheyder and Scheyder; "Standard Lithium Announces US$100 Million Direct Investment From Koch Strategic Platforms").

Conclusion

The onset of the electric vehicle market has created a boom in demand for lithium-ion batteries. Global lithium consumption has increased by 283% between 2010 and 2021 and shows no sign of slowing down (Bhutada). As lithium demand increases yearly, traditional brine evaporation and hard-rock mining methods no longer satisfy the emerging demand for lithium. New DLE methods that are less expensive and more efficient are on the rise and enable lithium resources that are not amenable to traditional mining techniques. Thus, new markets outside of South America, China, and Australia, each of which has seen a significant boost to their economy because of their ability to produce lithium for battery manufacturing, are getting closer to being unlocked by

DLE technology. Most notably, North America and Europe can enter the market by innovating and improving these DLE methods to the point where their own domestic resources can contribute to their demands. This trend has not gone unnoticed, as shown by the significant investment in U.S. and European-born startups in the lithium extraction space.

The price of lithium has become very volatile as the demand for EVs has skyrocketed since 2019, with lithium prices reaching record highs in early 2022 and keeping the price of consumer EVs out of reach for the average person. Long-term lithium carbonate prices are set to drop between 2025 and 2027, per Fastmarkets (Murray). This is due to the increased supply unlocked by DLE and additional traditional mining projects coming online. DLE technology is still in its infancy, with current methods improving and new technologies emerging daily. New materials, as well as their integration into specific DLE processes, are undergoing development to bring DLE to the forefront of the lithium extraction industry. Many of the world's reserves are still untouched, which allows DLE to quickly go to market and provide an advantage over incumbent technology. If DLE technologies are successful at unlocking new resources, electric vehicles will become much more affordable and common to see on roads.

Acknowledgments

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