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Lithium in the Green Energy Transition: The Quest for Both Sustainability and Security

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Abstract: Considering the quest to meet both sustainable development and energy security goals, we explore the ramifications of explosive growth in the global demand for lithium to meet the needs for batteries in plug-in electric vehicles and grid-scale energy storage. We find that heavy dependence on lithium will create energy security risks because China has a dominant position in the lithium supply chain and both Europe and North America seek to curtail reliance on China throughout their supply chains. We also find that efforts to expand lithium mining have been much less successful in Chile, the United States, and Europe than in Australia. Local communities resist licensing of new lithium mines due to a variety of environmental, social, and economic concerns. There are alternative technologies that may make lithium mining more sustainable such as direct lithium extraction, but the timing of commercialization of this process is uncertain. Progress is also being made in battery recycling and in alternative battery designs that do not use lithium. Such advances are unlikely to attenuate the global rate of growth in lithium demand prior to 2030. We conclude that tradeoffs between sustainability and energy security are real, especially in the next decade.

Keywords: lithium; energy security; sustainability; EVs; LIB; battery; lithium-ion

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1. Introduction

Sustainable development (SD) and energy security (ES) are well-recognized concepts. Beginning with the 1987 report of the Bruntland Commission, SD was defined as an obligation to meet the current needs of society without compromising the ability of future generations to do the same. It is now the "overarching paradigm of the United Nations", recognized in official frameworks on climate change, biodiversity, disaster risk reduction, and sustainable consumption and production [1]. The concept of ES is often associated with the international oil trade and originated with the oil instability concerns of the 1956 Suez crisis. It is now defined as the "uninterrupted availability of energy sources at an affordable price" and is the central challenge of the International Energy Agency [2]. The sponsors of this journal pose a provocative question: Is the pursuit of ES compatible with the pursuit of SD (or the more general term sustainability)?

In this article, we explore the ES and SD ramifications of the increased use of lithium in the global energy transition. Lithium is a crucial raw material in the production of lithium-ion batteries (LIBs), an energy storage technology crucial to electrified transport systems and utility-scale energy storage systems for renewable electricity [3–5]. The startup Tesla, with its business lines in electric vehicles (EVs) and grid-scale energy storage, exemplifies the view that LIBs can contribute to SD and ES by reducing reliance on fossil fuels for transport and power production.

Concerns about sustainability relative to electricity generation and the energy transition to carbon-free sources of power are incentivizing numerous public policies at multiple levels of government. Of prominence on national and supranational levels is the suit of Executive Orders issued by several recent US administrations designed to enhance the energy security of the nation by enhancing the mineral supplies and at the same time promote sustainable development [6–8]. The EU, in a similar manner, has proposed policies within their Circular Economy Action Plan to promote competitive sustainability and are necessary for green transport, clean energy, and to achieve climate neutrality by 2050. The proposal addresses the social, economic, and environmental issues related to all types of batteries [9].

This article analyzes three broad claims related to lithium dependence for EVs and grid-scale storage batteries. First, we evaluate whether an expansion of worldwide mining and processing of lithium will be necessary to facilitate the energy transition. Second, we explore the challenges of accessing lithium in several regions of the world by illustrating some of the sustainability and security risks of lithium mining and processing. Finally, we explore some technological strategies that might attenuate the sustainability and security risks of lithium mining/processing and their barriers to implementation.

The article provides both a narrow and broad intellectual contribution. In a targeted way, we draw attention to some of the downsides of lithium mining and processing, such as concerns that lithium mining is not sustainable and thus will trigger organized opposition by environmental groups and communities located near development projects. More broadly, we illustrate with the lithium example that there will be tradeoffs between SD and ES required in the energy transition, and that creative strategies are both feasible and necessary to lessen the negative aspects of these tradeoffs. We draw from—and build upon—a fledgling literature on lithium that is rarely framed in the context of SD and ES [10].

2. Research Gaps in the Lithium Socio-Environmental Literature

A rapidly growing scientific literature explores the increased use of lithium to meet societal needs. Major areas of study have been focused on the promising applications of lithium [11,12], drivers of demand for lithium and lithium price volatility [13–15], the global demand and supply dynamics [16], production trends [17], security issues in the supply chain [18], and the socio-environmental impacts of lithium extraction and processing [19]. In this investigation, we complement this research by exploring the socio-environmental impacts of lithium development, especially as they relate to local community acceptance/support of the processes of lithium extraction and processing.

The socio-environmental impacts of lithium extraction/processing include ramifications for workers, local communities, and ecosystems, with those impacts serving as inputs to environmental lifecycle analysis (LCA) and social-lifecycle analysis (S-LCA) [20,21]. A classic illustration is the impact of lithium extraction in the Atacama Desert of northern Chile, as consumption of scarce water for mining threatens the subsistence of indigenous communities and ecosystems [22]. A review of environmental lifecycle analyses of lithium-ion batteries (LIBs) found that LCAs of LIBs tend to focus more on greenhouse gas emissions than the other environmental impacts of LIB production (e.g., toxicity, worker/community exposures, and ecosystem impacts throughout the supply chain) [23].

A recent review identified 395 scientific articles related to lithium development [10]. Using a bibliometric approach, the authors found that some themes in the literature are better developed than others. The authors concluded that relatively “neglected thematic areas” include water scarcity/quality and socio-environmental impacts, especially in research that was conducted by scientists located in the communities where lithium development occurs or is proposed. In a similar study [16], researchers examined 88 studies of 43 critical elements and determined that in many of the examined studies, the social and environmental implications induced by demand growth are not quantified, nor does the literature adequately address the implications of technical utilization innovations such as recycling and reuse in advanced manufacturing processes.

In this paper, we seek to address some of the aspects missing in the literature surrounding this mineral commodity by linking socio-environmental concerns to public acceptance of lithium mining and processing. In broad terms, our paper concerns the need for "sustainable governance" of scarce metals around the world [24].

3. Projected Global Expansion of Lithium Mining and Processing

3.1. Expansion of Lithium Mining

Pure lithium is a soft silvery white metal. It is absent in its native state because of its high reactivity; it is only present in salts and other compounds. Lithium occurs naturally in felsic igneous rocks in the form of other lithium-rich mica (lepidolite) or as a silicate mineral in pegmatites (spodumene). Because of its high solubility and its incompatibility in most minerals, it also occurs in terrestrial brines and seawater.

Lithium in a refined form is used in the cathodes of lithium-ion battery (LIB) cells. As recently as 2010, global demand for lithium was predominantly in the form of lithium carbonate used in glass, ceramics, and consumer electronics. Since 2010, the use of lithium for automotive-grade LIBs for electric vehicles has dominated global growth in the demand for lithium [25]. Cathode makers require either lithium carbonate (19% lithium content) or lithium hydroxide (29% lithium content). As cathode makers shift to low-cobalt or lithium—iron—phosphate LIB cells, they prefer lithium hydroxide rather than lithium carbonate as a feedstock, which in return favors hard rock-mined lithium versus brine as a source [26–28]. Figure 1 provides an overview of the various end products in which lithium is used and the pathways in which the different types of feedstocks interact. Of particular note is the process of creating the lithium form desired for cathode manufacturing in LIB. This is the chemical process of transforming lithium carbonate to a hydroxide using calcium hydroxide.

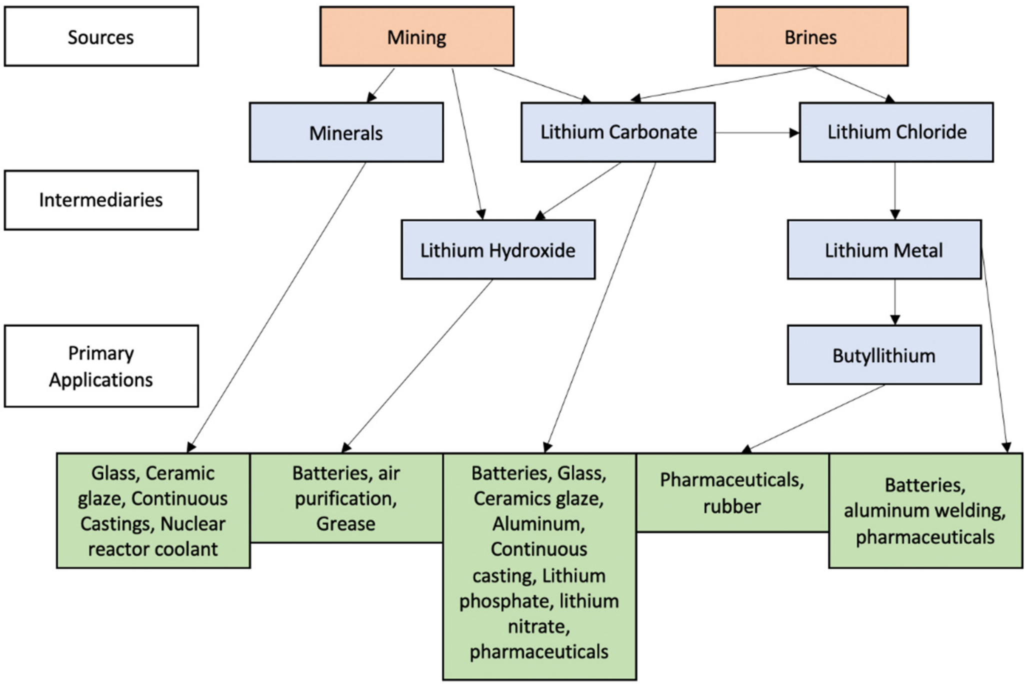

Figure 1. Process diagram showing lithium uses and pathways for converting primary resources to various applications [29].

The LIBs in consumer electronics (e.g., cell phones, laptops) contain only a few LIB cells, which require anywhere from 2 to 10 g of lithium. In contrast, a 75 kW battery for an all-electric passenger vehicle contains approximately 7 to 13 kg of lithium, or roughly 1000 times as much. For a grid-scale LIB storage system, the amount of required lithium is many times larger. A large facility such as one with a 50 MW/100 MWh capacity would require 12,000 to 14,000 kg of lithium depending on the type of LIBs used [30].

In 2020 the global demand for lithium (expressed as kilotons of lithium carbonate equivalent) was estimated at 429 kt. It is projected to grow to more than 1000 kt in 2030 under current policies and to more than 2500 kt if nations adopt policies to meet IEA's "sustainable development scenario" [31]. Figure 2 illustrates the estimated growth in lithium carbonate demand through the end of the decade. The largest single source of growth is the projected expansion in the global market for plug-in electric vehicles (PEVs). Grid-scale energy storage is not projected to grow explosively until after 2030 and thus exerts little influence on the 2030 forecast [32].

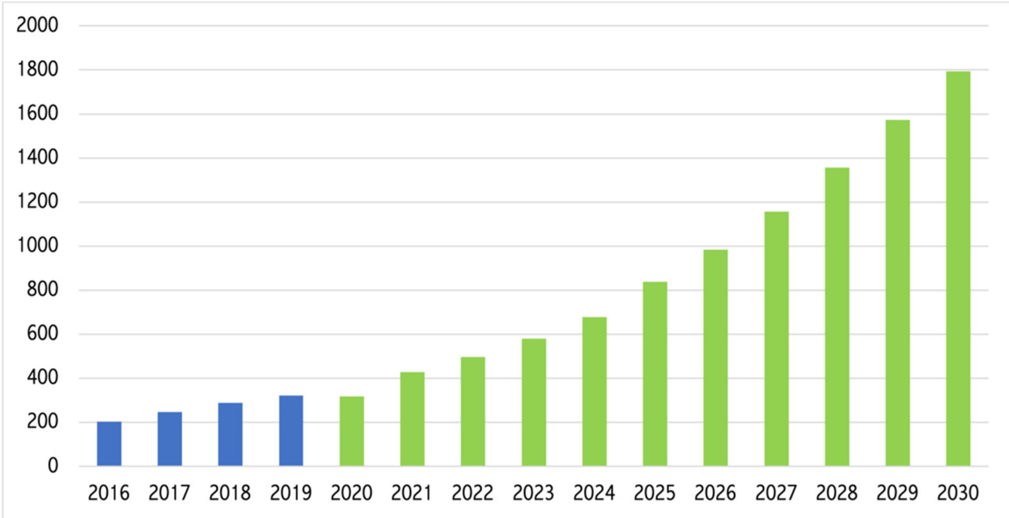

Figure 2. A modest forecast of lithium demand (in Kt of lithium carbonate equivalent) through 2030 in the absence of the IEA's sustainable development scenario. Demand is largely driven by electric-vehicle battery use [33].

The total amount of lithium resource in the world is enormous—possibly adequate to meet the overall requirements of the IEA's sustainable development scenario. Table 1 ranks countries in the world according to known lithium resources. However, as with most mineral resources, technically and economically recovering the reserve portion of the resource without inflicting ecological and social harm is a complex challenge [34]. The impacts of mining and processing of minerals are basically understood, but the geographically specific environmental and social impacts associated with a dramatic expansion in the mining and processing of lithium are poorly appreciated and rarely studied by scientists in the communities where mining and processing occurs. Of particular concern is the geographically restricted nature of the processing of the mined ores and concentrates into commercial products for cathode makers. At present, while several nations have the capacity to produce the less-desired lithium carbonate from brines (e.g., Chile), essentially all such processing of lithium hydroxide from hard rock-mined sources is done in one nation, China [35]. As discussed in their 2020 metanalysis of 88 critical mineral resources, Watari et al. found that the long-term demand projections, as well as various key dynamics that may significantly impact global supply and demand of these commodities, have been underemphasized [16].

Table 1. Global lithium resources and reserves (in metric tons) by country [36].

Country	Lithium Resources (Metric Tonnes)	Lithium Reserves (Metric Tonnes)
Portugal	270,000	60,000
Spain	300,000	n/a
Brazil	470,000	95,000
Zimbabwe	500,000	220,000
Mali	700,000	n/a
Peru	880,000	n/a
Serbia	1,200,000	n/a
Czechia	1,300,000	n/a
Mexico	1,700,000	n/a
Germany	2,700,000	n/a
Canada	2,900,000	530,000
Congo	3,000,000	n/a
China	5,100,000	1,500,000
Australia	6,400,000	4,700,000
United States	7,900,000	750,000
Chile	9,600,000	9,200,000
Argentina	19,300,000	1,900,000
Bolivia	21,000,000	n/a
World total	86,000,000	—

As noted by the USGS in their 2021 mineral commodity summary of the global resources and reserves for lithium, several nations are uniquely endowed with this mineral resource. While Table 1 shows those nations which are now producing some of their reserves, several countries have significant amounts of this natural resource, but for one or more reasons (technical, economic, or governance) have yet to produce this commodity. Of note are the resource values for the three nations in the "Lithium Triangle": Bolivia at 21.0 million tons (Mt), Argentina at 19.3 Mt, and Chile at 9.6 Mt relative to their current production [37]. In correspondence with this global geographical distribution of resources and reserves are a series of established and evolving mines or "production sites". Figure 3 shows the global distribution of both mineral and brine resources, shown in Mt of resources along with a recovery percentage, aggregated by economic area. The figure also shows the location of existing operations ("production site") where a portion of these resources are being mined as recoverable reserves. Planned projects are also shown, as well as hypothetical locations where some additional resources may become both economically and technically recoverable at some point in the future ("row resources") [38]. Based on the references in Grosjean et al. (2012), the project data presented on the map are assumed to be 2010 vintage. Several of these planned projects that appear on this map are discussed in more detail later in the paper. As the state of play for planned projects is a rapidly evolving and uncertain affair, this map does not have all the possible projects that have recently been announced, such as the Sonora Lithium project in Mexico. As discussed later in the paper, many of the newly proposed projects are joint interest ventures in which companies from different nations are planning to collaborate in the development of these projects.

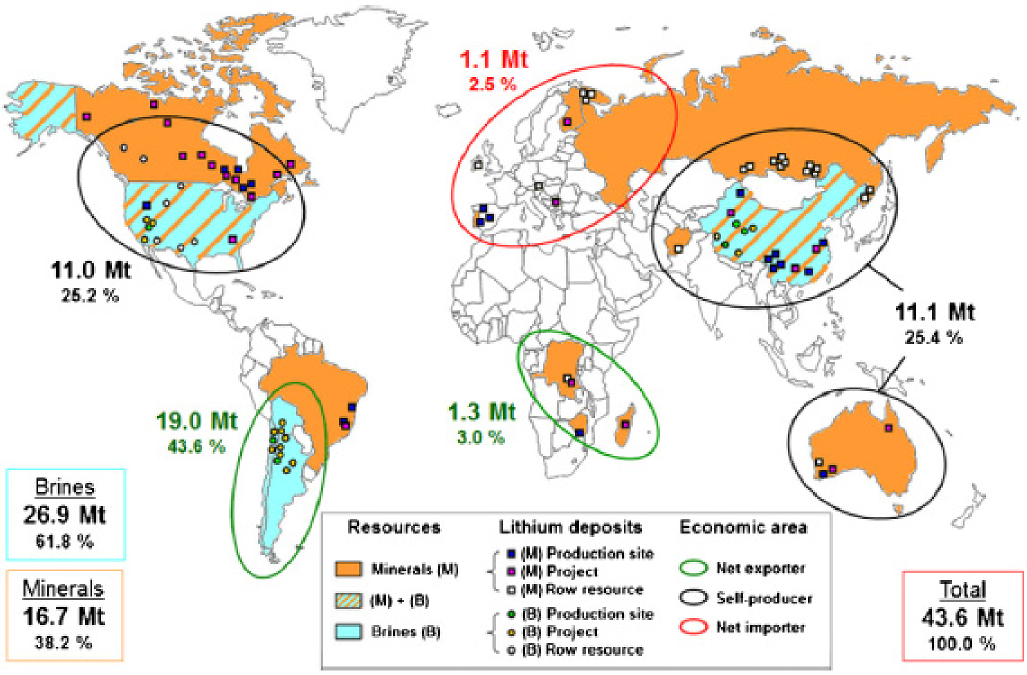

Figure 3. Map showing the global distribution of lithium resources. Resource base is differentiated as countries having either mineral or brine deposits or both. The deposits are classed as existing production (reserves), proposed projects (potentially recoverable resources), and resources [39].

3.2. Challenges of Lithium Mining

It is not easy to launch a major lithium mining project. To illustrate the challenges, we explore recent developments in several countries that are trying to expand lithium mining: the United States, China, Chile, Portugal, and Australia. The underlying challenges are somewhat similar to what many parts of the world already face when trying to site locally unwanted facilities such as landfills, incinerators, and wind turbines. In this case, the locally unwanted facility—a lithium mine or processing facility—is central to the globe's clean-energy transition. The local communities near lithium mines may experience the downsides of mining without experiencing much of the benefit from lithium in the energy transition. We do not address early-stage planning efforts in Mexico, Serbia, and Peru that could have a significant long-term impact on the global lithium market [40–42].

3.2.1. United States

From the 1950s to the 1980s, the US was the world's leading producer of lithium, mostly for military and aerospace applications. The resource was derived from spodumene reserves in western North Carolina mined with open-cut mining methods. A decline in demand from the US military and the emergence of relatively cheap foreign sources led to the virtual demise of lithium mining in the US. A revival of lithium mining is underway in the US, as the Trump and Biden administrations both recognized that it is a mineral of strategic significance. The barriers to expanded lithium mining and processing are formidable [43].

In North Carolina, the startup Piedmont Lithium Inc. (Belmont, NC, USA) has already spent $58 million planning a lithium mining/processing project west of Charlotte and is seeking $700 million more from investors to produce 30,000 tons per year to supply Tesla [44]. The company was founded by the Apollo Group, an Australian mining incubator. Piedmont obtained more than 1000 acres west of Gastonia—near the small town of Cherryville—in the "Carolina Tin-Spodumene Belt" but some local residents refused to sell their land and are quite disturbed about the project [45,46]. The company originally told investors it expected to obtain permits by the end of 2021. To obtain an operating permit, Piedmont must notify landowners within 1000 feet of its boundary and the permitting process allows for public comment and a possible public hearing [47]. As of July 2021, the company had not yet applied for a state mining permit or a necessary zoning variance in Gaston County, perhaps in part due to the unanticipated slump in lithium prices from 2018 to 2020. Figure 4 highlights the relative volatility in the price of lithium carbonate. Nor had the company fully consulted with county officials about the possible environmental and social impacts of the project or measures planned to prevent or mitigate those impacts. Members of the county's board of commissioners publicly expressed concerns about the project; in August 2019 the board imposed a temporary moratorium on mining while it reworks the applicable zoning regulations [48]. The company abandoned the original plan to process the lithium at a new plant in a neighboring county and instead is planning to build the processing plant at the mine, arguing this will reduce truck traffic in the community. The company's latest plan, assuming it acquires the necessary permissions, is to begin construction in April 2022 and start production in the second half of 2023 [49].

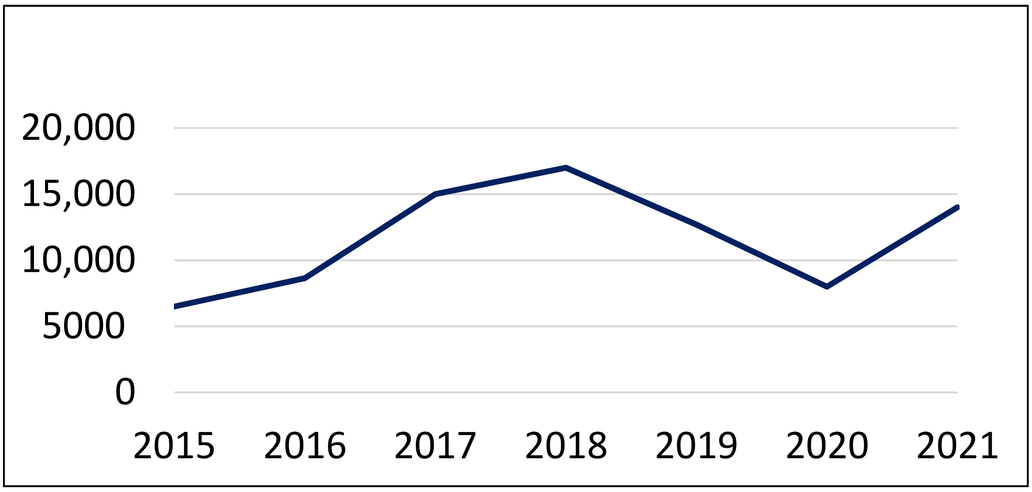

Figure 4. Average global lithium carbonate prices from 2015–2021 (Q2) [50].

The Silver Peak Mine in south-central Nevada began in the 1860s as a silver mine but focused on lithium starting in the 1960s. As of 2021, it is the only active lithium mine in the US. The mine struggled through several owners but in 2010 was boosted with a $28.4 million grant from the US Department of Energy [51]. The owner, Rockwood Lithium, planned a doubling of lithium output to 6000 metric tons of lithium carbonate per year in support of the Obama administration's electric vehicle strategy. Low lithium prices from a depressed global market, and slow electric vehicle sales in the US, did not permit the planned expansion. Albemarle acquired Rockwood Lithium in 2015 and the mine was temporarily closed during the COVID-19 pandemic but is scheduled to reopen in 2022. In 2021, Albemarle announced a $30–50 million investment to expand production at Silver Peak [52]. The nearby town is so depressed economically that the mine expansion is viewed as a helpful economic stimulus.

Unlike the hard rock mining in North Carolina, the Silver Peak Mine withdraws subsurface lithium-containing brine from an old lakebed that is then evaporated in a sequence of numerous large, shallow ponds that are chemically treated. After 12–18 months of evaporation, the lithium is concentrated enough for offsite factory processing into lithium carbonate. The ponds, which are spread widely throughout the Clayton Valley, do not require the ecologically disruptive excavation associated with hard rock mining. The official environmental assessment of the Silver Peak mine expansion found no significant environmental risks from the project except some migratory birds could be harmed by the evaporation ponds. Albemarle also is collaborating with Argonne National Laboratory (US Department of Energy) on an advanced process that would streamline the production of lithium hydroxide from brine resources.

Meanwhile, ten miles away at the Rhyolite Ridge in the Silver Peak Range, the Australian company Ioneer, in a joint venture with Sibanye Stillwater, proposed a new lithium mine that could produce almost four times as much lithium than is planned at Silver Peak. The lithium will initially be produced as lithium carbonate followed by the addition of a lithium hydroxide processing facility after production has initially been established. Beginning in 2024, the company expects to mine and process 63.8 million metric tonnes over the 26-year mine life at an average annual rate of 2.5 million metric tonnes per year. Although final permits have not yet been granted, Ioneer was awarded exploration permits in 2020 by the Bureau of Land Management (BLM) [53].

The Center for Biological Diversity (CBD), a national conservation advocacy group, sued the Bureau of Land Management for failure to account for how the Ioneer mine might harm a rare desert flower called Tiehm's buckwheat (see Figure 5) [54]. Separately, in 2019, CBD petitioned the US Fish and Wildlife Service to list the flower as a threatened or endangered species under the Endangered Species Act (ESA) [55]. The rare flower is found nowhere else in the world except on 21 acres spread across three square miles at the Ioneer mine site. When the Service was slow to respond during the Trump administration, CBD obtained a court order forcing the Service to issue a decision. In June 2021, the Service announced, with scientific support in a detailed Species Status Assessment, its intention to list the rare flower under the ESA [56].

Figure 5. Tiehm's buckwheat; flowering (**left**)and dormant (**right**) [57,58].

Ioneer argues that the rare flower and the mining project can co-exist and has been developing protection and conservation plans assuming that the plant would have ESA protection [59]. By transplanting the flower to safer soils nearby, Ioneer argues that the mining project will help the flower survive current threats from climate change and other factors that are already jeopardizing its survival. CBD disagrees, pointing to evidence from the 1990s that the flower is highly sensitive to soil conditions. The Service notes that Ioneer has not yet demonstrated, through a multi-year demonstration project and detailed monitoring, that it is feasible to transport the flower to other soils [60]. It is difficult to estimate how long it will take to resolve the issues with the Ioneer mine.

The Ioneer project is not the only proposed lithium project in Nevada. In the last week of the Trump administration, BLM approved a large lithium project at Thacker Pass in north-central Nevada, near the Oregon line [61]. The developer, Vancouver-based Lithium Americas, estimates that the mine can produce 30,000 tons per year, enough to support batteries for 475,000 plug-in electric vehicles [62].

Significant opposition to the Thacker Pass project has emerged from ranchers, a Native American tribe, and environmentalists [63]. The primary concerns are that the proposed project will consume large amounts of scarce groundwater resources and there could be mismanagement of mining wastes [64].

Separately, CBD sued BLM, arguing that BLM did not adequately consider the potential harm to the sage grouse, a rare bird in the West that nests under sagebrush or grass patches. The sage grouse is pictured in Figure 6. Its survival is threatened by the effects of invasive plants and energy development projects in the West. When the local Great Basin Resource Watch (GBRW) joined in the litigation against the mine, a prominent conservationist named Glenn Miller (a retired professor at the University of Nevada) resigned from the board of GBRW. Miller noted that lithium is crucial to fight climate change, stressing that the proposed mine is "one of the least impactful mine plans I have ever seen" [65].

Figure 6. Greater sage grouse photo by Bob Wick/BLM [66].

When a federal judge in Reno indicated that she was considering an injunction against the mine, the company agreed to delay the first excavation activities, which were scheduled to occur in June 2021. A final decision by the judge is expected in 2022 but that decision could be appealed by either side.

In summary, environmental and social concerns about lithium mining and associated processing facilities are slowing the development of lithium resources in the US. It is difficult to forecast how rapidly the US will expand lithium mining and processing since there are numerous opportunities and mechanisms for opponents of a new lithium project to halt or delay the process.

3.2.2. China

China has large lithium reserves and some production, but the country imports more lithium than it produces domestically. In recent years China has imported more than 80 percent of the lithium it consumes (mostly from Australia).

One of the explanations is that China's history with lithium mining is controversial, and the facts are not entirely clear. The country's largest known lithium deposits are near the town of Ganzi (2010 population = 10,000), the western autonomous prefecture of Sichuan province. It is an ethnic Tibetan township located in the historical Tibetan region of Khan [67]. Local officials envisioned that Ganzi could become "China's lithium capital".

A subsidiary of Guangzhou's Youngy Company, Gangzizhou Rangda Lithium Company, opened a lithium mine [68]. Several years of active mining triggered concerns and protests from local villagers. The first incident occurred in 2009 when impacts were felt in the downstream village of Balang. A second incident in 2013 was followed by villager protests. The villagers alleged that the lithium mine spawned toxic chemical pollution that led to fish kills and the death of yaks that drank water from the nearby Liqi River. The company denied that the environmental damages were related to the mine's operations. The government responded to the protests with security crackdowns.

In 2014, the mine was shut down temporarily, as the company sought to resolve some land acquisition issues. Local authorities pledged to villagers that the mine would not restart until environmental concerns were resolved. Villagers claimed that the mine restarted operations in May 2016, which led to additional fish kills. The company denied that the mine was restarted.

Several years later, in mid-2019, Youngy Company announced that the mine would re-open, coupled with a $201.1 million investment in a new lithium ore processing plant in Sichuan. The company also announced stronger environmental controls at the mine [69].

China's largest producing mine is at Lake Zabuye in Tibet, where Zabuye Lithium has been producing since 2005 under a 20-year exclusive license. Roughly the same mining processes that are used in Chile are used at Lake Zabuye. The barriers to expanded lithium production at Lake Zabuye are related more to operational issues than environmental concerns or community protests.

Instead of giving strong priority to lithium mining, Chinese companies, supported by Chinese banks and the central government, have purchased substantial interests in the major lithium mines of Australia, South America, and Africa. Even in the United States, Chinese companies are seeking an interest in nascent lithium mines.

On the other hand, China has sought and established a global leadership position in lithium processing. This is consistent with the country's industrial policy, China 2025, which seeks to emphasize those parts of the industrial supply chain that have high value-added and a limited environmental impact. In 2018, for example, China accounted for a much larger share of the world's lithium processing than lithium mining (see Figure 7). Most of the lithium mined in Australia is shipped to China for processing before being used in the production of cathodes for LIB cells.

3.2.3. Chile

The largest lithium resources in the world reside in a remote desert region of the world, Atacama, near the borders of Chile, Bolivia, and Argentina ("the Lithium Triangle"). The intense sunlight, low humidity, and hot winds evaporate most of the water and leave behind brine that contains the "white gold" for extraction. Orocobre, an Australian company operating in Argentina is the only greenfield lithium chemical producer that has been successfully developed in the last ~50 years. They are aligned with Toyota and JEMSE and are expanding their processing capability by building a lithium hydroxide plant in Japan. Additionally, Lithium Americas, together with the Chilean company SQM, is developing the Cauchari-Olaroz lithium project, located in Jujuy, Argentina. Chemical processing into commercially-ready lithium carbonate occurs on the Chilean coast near Antofagasta, where marine desalination plants assist with substantial water demands [38].

As recently as 2014, Chile was the largest lithium-producing country in the world, but production has not increased significantly since then. The two lithium producers in Chile, state-owned Sociedad Química y Minera de Chile (SQM) and Albemarle, have been engaged in a multi-year dispute with each other and the Chilean government on multiple issues.

The Socialist Party President of Chile, Michele Bachelet (2006–2010; 2014–2018), helped broker an unusual deal that called for an expansion of lithium production to support the electric-vehicle industry. Samsung pledged, based on long-term contracts with favorable pricing, to build three factories in Chile that would make lithium-ion batteries for electric vehicles.

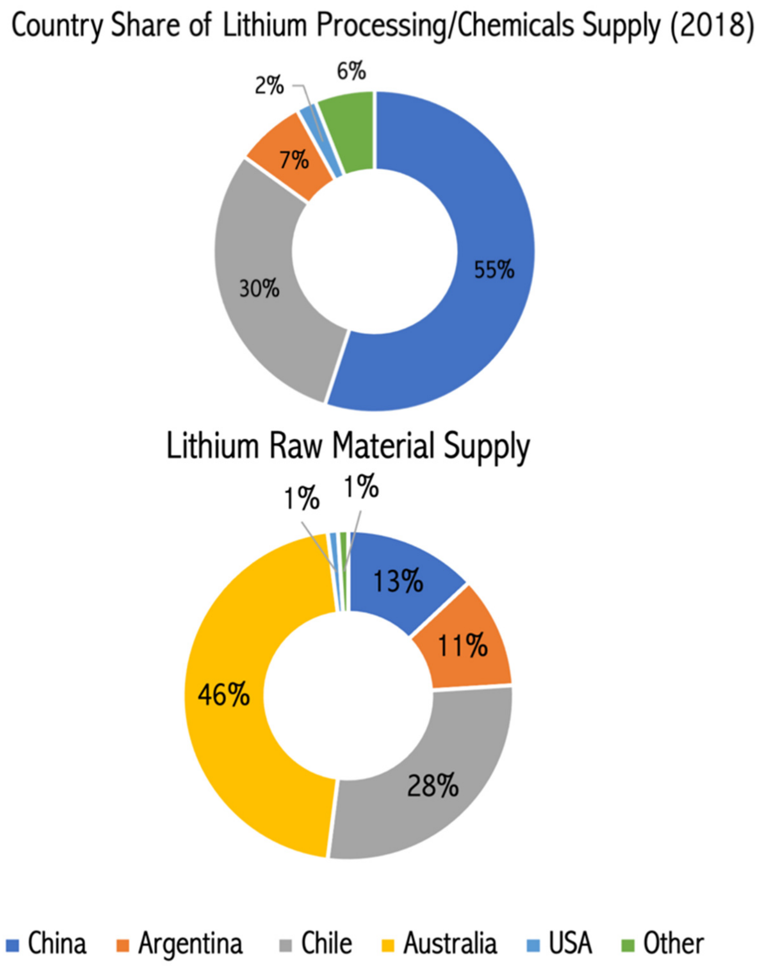

Figure 7. Comparison of top lithium producing countries separated by percentage of raw lithium from mining and chemical processing [70].

The deal unraveled. Albemarle and SQM first delayed the deal and then scrapped expansion plans due to the Chilean government's increasing concerns about water use and environmental impacts. Indigenous groups and environmental activists opposed the new mining projects in the Atacama desert. Eighteen indigenous communities live near the mining operations and fear that their access to freshwater is threatened. Environmentalists argue that habitats of species such as Andean flamingoes are disrupted by mining operations [71].

One study of lithium mining found that four out of five measures of environmental disruption are correlated with Chilean lithium mining from 1997 to 2017. The metrics examined include a vegetation index, daytime surface temperature, soil moisture, nighttime land surface temperature, and net evaporative aspiration. The indications of degradation were especially evident in drought conditions in reserve areas [72].

On the other hand, a comparative lifecycle study found that freshwater consumption and GHG emissions can be lower for brine operations than ore-based projects. More research is needed to determine how much project-to-project variation in lifecycle impacts there is for brine vs. ore projects [73].

In late 2019, Chile's First Environmental Court sided with indigenous groups on the grounds that SQM had "insufficient" plans to conserve water supplies. Moreover, SQM and Albemarle disputed which company is primarily responsible for the overdraws of brine that have already occurred. The demands for water resources induced by brine operations help explain why, according to one lifecycle analysis, EVs based on LIBs consume 58% more water resources to fabricate and operate than do conventional vehicles powered by gasoline engines [74].

Chile's mining system is highly bureaucratic. During the Pinochet administration of the 1970s, the government designated lithium as a "strategic resource" because of its use in nuclear power generation systems. As a result, new companies seeking to mine in Chile must either collaborate with the state-owned corporation or obtain a special permit. The process for acquiring the special permit lacks transparency and guidelines; no new firm has acquired one since 2014, which means there are few prospects for new competitors to SQM and Albemarle. The current Chilean administration plans to open the licensing process to more competitors [75]. A new Responsible Lithium Partnership, with funding from BASF, Daimler, Fairphone, and Volkswagen, is designed to bring the principles of sustainable development to Chile's lithium mining sector [76].

Meanwhile, China's Tianqi Lithium Corporation acquired a 25% interest in SQM for $4.1 billion. SQM's largest shareholder sought to block the Tianqi purchase on antitrust grounds. Nonetheless, Chile's antitrust regulator approved the deal with limited conditions, and the Chilean Supreme Court allowed the Tianqi purchase to proceed. Thus, reliance on SQM's lithium is no longer fully secure from Chinese influence.

In late 2020, SQM initiated an ambitious $1.9 billion investment plan to expand mining activities for lithium, iodine, and nitrate. Most of the investment will occur in Chile with some in Western Australia. The plan calls for Chile's production of lithium carbonate to increase from 70,000 tons per year currently to 180,000 tons per year in 2023 [77]. Meanwhile, Albemarle is moving forward with expansion plans now that it has resolved some disputes with the Chilean government [78]. A $200 million 18-month initiative seeks to raise the share of lithium recovered from salts from 50–55% currently to 80–85%. This approach will not entail a significant increase in the ecological footprint of Albemarle in Chile [79].

The leftists in Chilean politics have a strong hand in writing the country's new constitution, a process now underway in response to a public referendum. Indigenous groups seek to persuade Constitution writers that brine should be classified as water rather than a strategic mineral, a legal change that would give indigenous groups greater leverage over how the resources in their community are managed [80]. Given the recent changes in Chilean politics, it is difficult to have confidence that Chile will accomplish a dramatic increase in lithium mining even though the current administration supports lithium mining.

3.2.4. Portugal

As of 2019, Europe had no mines producing automotive-grade lithium for use in electric vehicles. In 2020, the European Commission designated lithium as a critical raw material for the region [81]. Commission officials argue that "green lithium mining" in Europe can be undertaken more sustainably than mining in Chile and China [82]. The planning phase of new lithium projects is underway in western Finland, Germany, the United Kingdom, the Czech Republic, Spain, Serbia, and Austria, but Portugal has dedicated the most effort to mine lithium and has encountered determined opposition in affected communities.

By itself, Portugal cannot meet Europe's demand for lithium because its known reserves are only 60,000 tons; however, the country builds on a history of producing lower-grade lithium for use in ceramics and other applications, and the depressed mountainous regions of Portugal where lithium resides need economic development, or so the national government of Portugal argues.

One of the initial project proposals in Portugal, in the northern municipality of Montalegre, was canceled after intense local controversy and concerns about the quality of the environmental impact assessment commissioned by the developer, LusoRecursos [83]. A community group, Montalegre com Vida, spearheaded local opposition. The group fears that the project would damage the region's farm and tourism sectors. They also see risks to water flows in nearby mountain streams and runoff of pollutants from the company's facilities. More generally, the group argues that "green mining doesn't exist. Politicians need to stop trying to get rid of pollution in cities by polluting our villages instead".

As numerous communities sensed the European Union's pressure for lithium mining, local officials and activists pressured the minority socialist government to enact a new mining law. It requires more rigorous environmental impact statements, requires distribution of 50% of royalties to local communities (rather than 100% being kept by the national government), and authorizes a municipal-level veto of mining projects. The ramifications of the new law are not yet fully apparent, but projects are already moving at a slower pace [84].

One of the projects that are progressing is sponsored by Savannah Resources (London, UK) near the village of Covas do Barros (Barroso) in northern Portugal (municipality of Botticas). The company acquired rights to the lithium in 2017 and the national Ministry of Environment approved their preliminary environmental impact statement [85]. The next phase, public consultation, will be challenging, as substantial public opposition to the project has developed in the village [86]. If the experience in Portugal is indicative of what will happen to other projects in Europe, it is safe to predict that Europe's lithium production initiative will progress slowly.

3.2.5. Australia

Figure 8 offers a comparison of the top four producing countries (Australia, Chile, China, and Argentina). In 2017, Australia significantly surpassed Chile as the leading global producer of lithium [87]. By 2019, the growth in Australia's lithium mining was so robust that Australia accounted for 54.4% of the world's lithium production, more than double the output of the second largest national producer (Chile) [88]. Despite the recent efforts of other countries, forecasters predict that Australia will dominate lithium production in the decade ahead [89]. Of the ten largest new lithium mines now in the planning stages, five are in Australia and several of the non-Australian projects face significant opposition or are in countries with little experience with lithium mining (e.g., Mexico) [36]. All of Australia's production yields a ~6% lithium contrate that is refined in China.

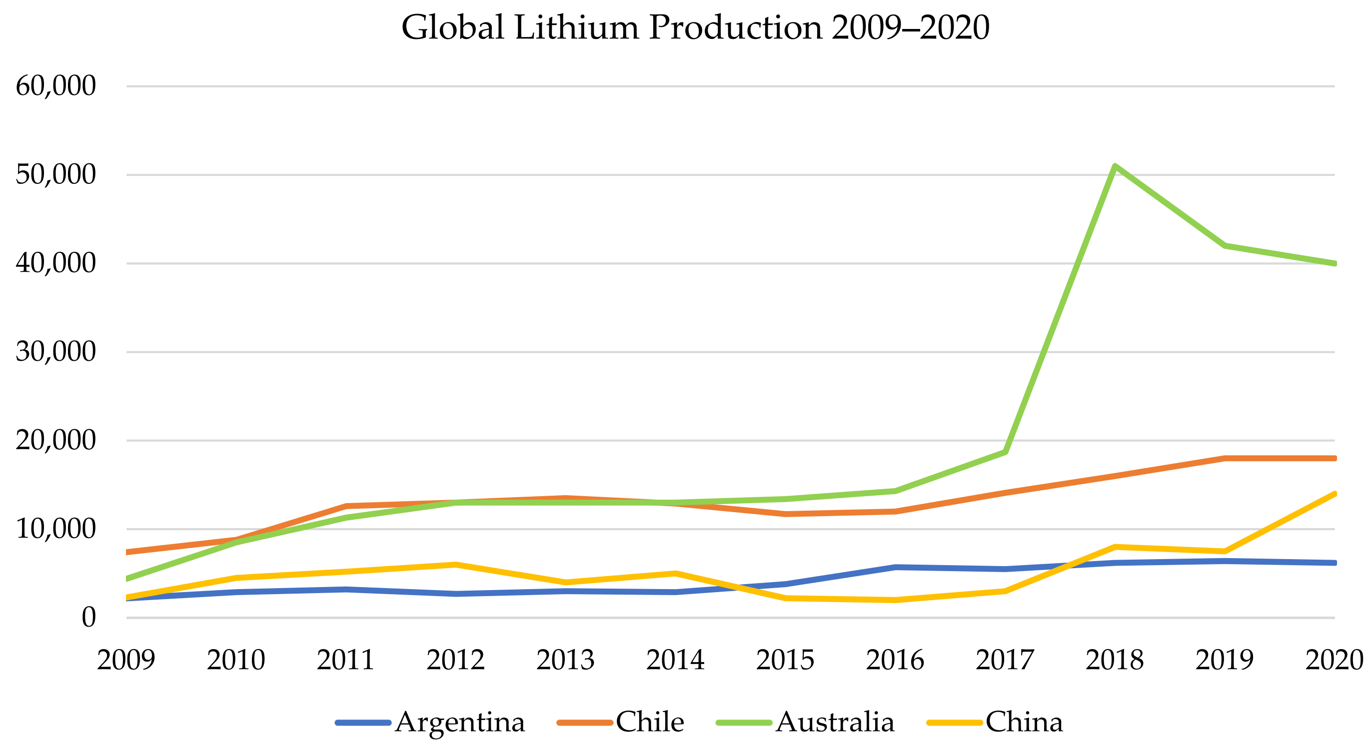

Figure 8. Australia captures 50% of global lithium production, though Chinese companies have purchased large stakes in Australian mines. Based on 2020 mine production [90].

Why is Australia the global leader in lithium mining? We advance some possible explanations more as hypotheses than proven fact, as this is a complex, multi-faceted issue.

Australia is certainly not a major producer of motor vehicles or lithium-ion batteries. Nor is the country at the forefront of policies to address climate change through expanding the market for plug-in electric vehicles. Australia is a leading global producer of coal, which would seem to be a conflict with respect to lithium production, and has an extensive environmental movement, including an official Green Party that was the third-largest party by vote count in 2019 [91]. However, the Australian Greens, especially the Greens of Western Australia, are not in opposition to the development of the region's lithium resources [92].

Australia certainly has plenty of lithium reserves. More importantly, Australia has a long tradition of natural resource development, particularly mining, and has generated significant economic progress through exports of natural resources around the world. Australia has invested in the infrastructure and ports to facilitate the exportation of its mined resources. Australia has also been receptive to foreign investment, as lithium miners would have found it difficult to expand based on Australian sources of capital alone.

Investments from China have played an especially important role in Australian lithium production. Indeed, the country's leading producer of hard rock spodumene is Talison Lithium Limited, a joint venture of China's Tianqi (51%) and the US' Albemarle (49%). Great Wall Motor and Gangfeng Lithium have also developed deep ties to Australia's lithium mining projects.

Features of Australia's lithium resources may also play a role Australia's comparative advantage. As with most of the nations' hard rock resources and associated mining operations, the lithium reserves are concentrated in western Australia, far from the big population centers of Sydney and Melbourne and near villages and communities that respect natural resource development and seek economic development. Although Australia's production from hard-rock mining is more expensive than mining from brines, the hard-rock (spodumene) mining supplies the metal in the form of either lithium carbonate or hydroxide. Lithium hydroxide is preferred by auto and battery producers (because it is compatible with low-cobalt battery chemistries). The Tesla–Panasonic partnership, for example, uses only lithium hydroxide.

The central government of Australia is also enterprising. It seeks to move up the value chain by producing components of lithium-ion batteries. It has an ambitious "Lithium-Ion Battery Value Chain Strategy" that would produce LIBs (at least the cells) near the lithium mines rather than near the world's auto assembly plants. Australia is openly seeking foreign investment from non-Chinese sources as well as from China. Whether Australia can pull this off remains to be seen but the mere existence of the visionary proposal reflects Australia's enterprising spirit about economic development.

3.3. Lithium Processing

LIB manufacturers prefer lithium hydroxide over lithium carbonate because lithium hydroxide cathodes can support a longer driving range without as much use of expensive cobalt in the battery chemistry. As cathode makers demand lithium hydroxide, it tends to advantage Australia's hard rock mines over South America's brine operations. Lithium carbonate from brine can be converted to lithium hydroxide, but that adds another costly processing step in the supply chain. Some brine operations are accessing China's lithium hydroxide converter plants but only because they have access to low-cost lithium carbonate from brine (e.g., Livent of Philadelphia supplies Tesla through a complex arrangement involving brine operations in Argentina and processing in China) [93].

China does not have a dominant position in lithium mining, but it has acquired over the last decade a dominant position in lithium processing, especially processing to lithium hydroxide [94]. Virtually all of the raw material mined in Australia is processed in China into lithium hydroxide. Even Albemarle (Charlotte, NC, USA), which has mines in South America and Australia, does much of its processing in China [95]. It acquired lithium processing facilities in Jianxi and Sichuan in 2017 when it acquired a Chinese company. Those facilities have expanded to supply 15,000 tons per year of lithium hydroxide [96].

The Chinese companies that dominate lithium refining/processing are Ganfeng, General Lithium, Tianqi, and Sichuan Yahua Industrial Group. From a business perspective, there are three key advantages of siting lithium hydroxide plants in China. The capital costs of plant construction are about 50% less than in the West. A comparison of new processing facilities by Ganfeng and Tianqi shows that the construction process was much cheaper and faster for Ganfeng in China than for Tianqi in Australia [97]. To lessen financial burdens, Tianqi formed a joint venture with Australia's IGO that includes the Kwinana Lithium Hydroxide Refinery and the Greenbushes lithium mine [98]. Second, operations in China are not as encumbered by strict environmental regulations as is typical in Western countries [99]. The third advantage is the presence of intellectual property or specific chemical engineering experience in this specific area. Chinese processors are capitalizing on their advantages by expanding their capacities to process lithium. General Lithium currently has a processing capability of 20,000 tons in the city of Yichang, Hubei province, but plans to expand that capacity to 60,000 tons per year in the near future. Most (90%) of the expansion will be lithium hydroxide processing; the remainder (10%) will be lithium carbonate processing [100]. Overall, China has established a strong hold on all aspects of the lithium supply chain, from the mining of raw materials to recycling. Figure 9 provides a high-level overview of the steps associated with lithium use in batteries.

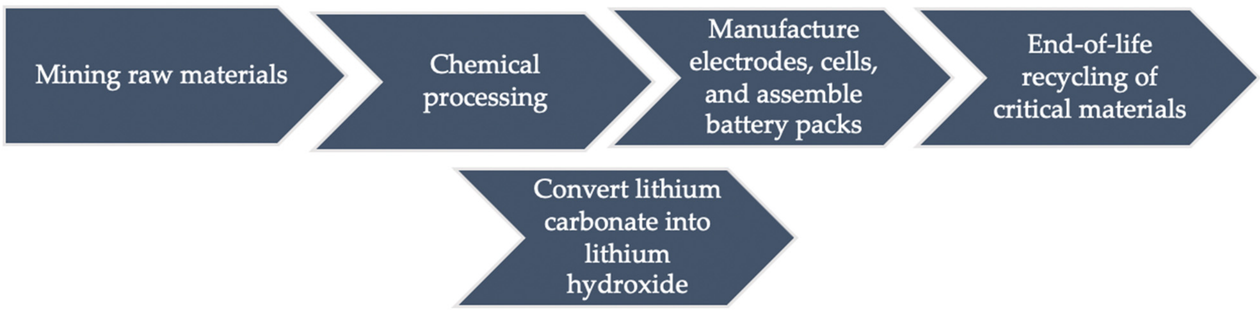

Figure 9. An overview of the lithium supply chain. The chemical processing required for lithium carbonate has the additional step of conversion to the more usable lithium hydroxide when used for lithium-ion batteries.

To lessen dependence on China's processing facilities, Albemarle undertook to build one of the world's largest lithium hydroxide plants in Kemerton, Western Australia [101]. The initial planned capacity was 50,000 tons per year, with a long-run capacity of 100,000 tons per year [102]. Construction began in 2019 but delays occurred due to COVID-19; the revised plan is to begin operations in 2022 [103].

The company's relations with community leaders were strained when its waste management partner, Cleanaway, applied to expand the nearby Banksia Hill Waste Facility to store 500,000 tons of waste from the huge facility. The application was withdrawn after public protests ensued in the small town of Dardanup [104]. Albemarle followed up with a proposal to truck the waste 580 km inland to the Koolyanobbing iron ore mine, near Southern Cross. Leaders of the Shire of Yilgarn registered concerns about the truck traffic along the Great Eastern Highway. Community leaders argued that if the wastes were truly "benign," as Albemarle claims, they should be stored at the mine site to avoid all the trucking [105]. A final resolution on waste management was not reached as construction continued in 2021.

In summary, reducing dependence on China's lithium refining/processing facilities has proven to be more challenging than expected. If Europe and the United States are determined to be independent of China in the lithium supply chain, they will need new lithium refining facilities as well as mining operations or they will need reliable corporate partnerships with companies and countries that are not influenced by Chinese ownership.

4. Alternative Technologies

Given the SD and ES challenges of lithium mining and processing, a variety of strategies are under consideration to reduce dependence on lithium, at least as it is practiced today. Some strategies entail the invention and application of new technologies in the mining process. Others help by reducing the amount of virgin lithium that must be mined (e.g., recycling and remanufacturing), and still, others entail battery technologies that do not require lithium (e.g., zinc-iron or solid-state technologies). Each strategy is discussed briefly below.

A new lithium mining technology called "direct lithium extraction" (DLE) could change the mining process in the future. Proponents of DLE argue that it will raise the lithium recovery rate from brines, reduce water consumption, reduce the amount of time required to extract lithium, reduce the carbon intensity of lithium development, and eventually reduce the cost of lithium mining [106]. One approach to DLE is the production of lithium hydroxide from brine using the geothermal energy of the brine itself as the process energy. It could have virtually zero carbon intensity. Demonstrations of DLE technology have been proposed or are underway in China (Qinghai Salt Lake, Qarhan Salt Lakes), France (Alsace), Germany (Upper Rhine Valley), Argentina, southern Arkansas (Smackover), Canada (Alberta), North Dakota, and at California's Salton Sea. General Motors is one of the first investors in a Salton Sea project [107,108]. Techno-economic analysis suggests the DLE may be economically feasible but the production costs, estimated around $4000 per metric ton of lithium carbonate equivalent, need to be validated in real-world demonstrations and large-scale commercialization [109]. It may be several years before DFE can be tried on a large commercial scale, as it needs further pilot testing and limited commercial demonstration [110]. Moreover, developers must handle large volumes of water and wastes on the surface and the re-injection of process water into the subsurface could create unintended risks to geothermal energy production. The Secretary of Energy Jennifer Granholm contends that the Biden administration supports "responsible" lithium mining that respects the environment and the welfare of Native American tribes. She made especially enthusiastic comments about DLE in the Salton Sea [9].

Another innovation in the mining process entails extracting high-purity lithium hydroxide directly from brine. This would eliminate the costly step of converting lithium carbonate into lithium hydroxide, and thereby make it easier for the West to reduce dependence on China's lithium hydroxide converter facilities. This innovation is currently the subject of R&D in a partnership between Albemarle and the US Department of Energy's Argonne National Laboratory.

The recycling of lithium could reduce the amount of virgin lithium that needs to be mined and processed. Given that millions of electric vehicles with LIBs are already on roads and highways throughout the world, it is concerning that current plans for the recycling of batteries or battery materials are primitive. Only about 5% of LIBs are currently being recycled. The European Commission is refining a battery directive that will place recycling obligations on automotive and battery producers [111]. About a hundred companies worldwide have entered the battery recycling market or have concrete plans to do so. The industry is concentrated in China and Korea where most batteries are made, but there are also dozens of startups in North America and Europe [112]. China's Ganfeng already has lithium recycling facilities in China capable of handling 65,000 tons of spent batteries per year; the company may construct additional facilities overseas [113].

The traditional process entails hydrometallurgical recycling, which involves dismantling the battery pack into cells, discharging the cells, and separating the materials that comprise the cell [114]. It is a dirty, dangerous, energy-intensive, and expensive process that cannot yet be performed profitably. Moreover, lithium is often burned rather than recovered because its price does not yet justify recovery; cobalt and other expensive materials are the focus of recovery. The Biden administration has requested $75 million from Congress to support a new lithium recycling project under the oversight of the US Department of Energy [115].

Innovations in recycling include the separation of the pack into larger modules and processing them without discharging. Alternatively, one can recycle components of the battery cell such as the cathode. The recycling of cathode powders might be commercially viable within five years.

Recycling is promising but will not eliminate the need for mined lithium [116]. Under optimistic assumptions, recycling might reduce the global demand for mined lithium by 25–40% but even this scenario is unlikely to occur until 2035–2040 [117].

Making batteries without lithium is another possibility. The most promising alternatives to LIBs are zinc–iron batteries and solid-state batteries. Both are the subject of intensive R&D around the world but neither appears likely to penetrate the global battery market in a significant way prior to 2030. In any event, the mining of zinc presents its own sustainability issues.

5. Conclusions

The market trends for plug-in electric vehicles and grid-scale energy-storage systems are set to increase the global demand for lithium substantially in the decades ahead. Since lithium is abundant and can be mined at a reasonable cost, meeting the future demand for lithium is technically and economically feasible. However, we found that efforts to expand lithium mining and processing raise significant energy security and sustainability trade-offs.

North America and Europe seek energy security vis-à-vis China for geopolitical reasons but China has a dominant position in the lithium supply chain through ownership interests in Chilean, Australian, and US mines. China also has a dominant position in the lithium hydroxide processing facilities that convert mined materials into processed lithium products appropriate for use by cathode manufacturers. Thus, the transition to electric vehicles with LIBs poses security risks for North America and Europe. Insofar as lithium mining and processing can occur outside of China, in countries and by companies not subject to Chinese influence, security concerns are lessened.

Opening new lithium mines presents sustainability and community-acceptance challenges. Local communities resist lithium mining because it places large demands on water supplies, entails significant ecological disruption, threatens the welfare of established industry sectors (e.g., tourism and agriculture), and has led to mismanagement of wastes and the contamination of water supplies. Local opposition to lithium mining is so strong in some communities that some developers face protracted timelines in obtaining the permits that are required. Australia has been the most successful in the expansion of lithium mining, but the circumstances of its success are not readily transferrable to Europe or North America. Western Australia and Nevada, for instance, have some geographical similarities but the cultures and legal systems are quite different.

The downsides of lithium mining can potentially be attenuated by new mining technologies, recycling of batteries or components, and new battery technologies that do not use lithium. Each of these advances has a different time frame for possible implementation, uncertain technical costs, and variable environmental impacts, all of which will entail tradeoffs with respect to sustainability. Between now and 2030, those technologies are unlikely to significantly curb explosive growth in the global demand for newly mined and processed lithium.

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