ANL/ESIA-23/8

Lithium Production in North America: A Review

Energy Systems and Infrastructure Analysis

About Argonne National Laboratory

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory’s main facility is outside Chicago, at 9700 South Cass Avenue, Lemont, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

DOCUMENT AVAILABILITY

Online Access: U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free at OSTI.GOV (http://www.osti.gov/), a service of the US Dept. of Energy’s Office of Scientific and Technical Information.

Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312
www.ntis.gov
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: **orders@ntis.gov**

Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
www.osti.gov
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: **reports@osti.gov**

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor UChicago Argonne, LLC, nor any of their employees or officers, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

ANL/ESIA-23/8

Lithium Production in North America: A Review

Prepared by:
Rakesh Krishnamoorthy Iyer and Jarod C. Kelly
Energy Systems and Infrastructure Analysis, Argonne National Laboratory

October 1, 2023

Contents

Figures

Tables

Acronyms and Abbreviations

BLM	U.S. Bureau of Land Management
CMI	Critical Materials Institute
DFS	detailed feasibility study
DLE	direct lithium extraction
DOE	U.S. Department of Energy
EVs	electric vehicles
ILiAD	integrated lithium adsorption desorption
km	kilometer
LCA	life cycle analysis
LCE	lithium carbonate equivalent
LCI	life cycle inventory
LIB	lithium-ion battery
m	mile
mg/L	milligram per liter
MMT	million metric tonnes
MT	metric tonne
MW	megaWatt
PEA	preliminary economic assessment
PLS	pregnant liquor solution
ppm	parts per million
PSS	pregnant stripping solution
SLE	selective leach extraction

Acknowledgments

This activity was supported by the Vehicle Technologies Office, Office of Energy Efficiency and Renewable Energy, United States Department of Energy Under Contract Number DE-AC02-06CH11357. The authors would like to thank Steven Boyd and Brian Cunningham of that Office for their guidance and support. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, or process disclosed, or represents that its use would not infringe privately owned rights.

Abstract

This report provides a detailed literature review and preliminary life cycle inventory for producing lithium (Li) chemicals—lithium carbonate (Li_2CO_3) and lithium hydroxide (LiOH)—from sedimentary clays in the North America, as was incorporated into the GREET® 2023 model release. It also updates the status and life cycle inventory of Li chemical production from low Li content brines via direct lithium extraction (DLE) from our previous work in GREET 2022. All life cycle inventory updates are based on preliminary economic assessment studies conducted by various commercial entities engaged in this industry. If produced successfully, Li chemicals from North American reserves can be significant in meeting the United States' strategic goal of ensuring a robust and secure supply of a strategic mineral that is critical to its decarbonization initiatives.

1. Introduction

A sustained and robust lithium (Li) supply is essential for the mass deployment of low-carbon technologies that use Li-ion batteries, such as electric vehicles (EVs) and energy storage systems. This has led to Li's inclusion in the United States' list of critical materials that are pivotal to its economic, environmental, and security imperatives (U.S. DOE 2020; USGS 2022a). Currently, the U.S. depends almost entirely on imports to meet its Li demand, a sea change from its dominance in global Li production from 1950 to 1970 (Miatto et al. 2020; USGS 2022b). To address this situation, the U.S. is undertaking initiatives to establish a robust Li supply chain by incentivizing domestic Li production and securing its supply from reliable nations (U.S. DOE 2020; White House 2022; U.S. DOE 2022a; U.S. DOE 2022b). This also means a shift away from the Salar brines and spodumene reserves that currently dominate global Li production towards alternative brines and sedimentary clays that dominate the North American landscape.

In an earlier report, we provided extensive details about the ongoing Li production projects in North America that use alternative brines (geothermal, industrial, and oil), including their locations and owners, resource potential, current status, and expected startup dates (Iyer and Kelly 2022). There, we briefly described the direct lithium extraction (DLE) technology that will be employed to produce Li chemicals from these brines and provided a preliminary life cycle inventory (LCI) for Li chemical production from geothermal brines based on relevant literature (Huang et al. 2021). The report also listed the potential environmental and economic benefits of producing Li chemicals from brines via DLE technology over the conventional solar evaporative concentration technique.

Here, we provide a detailed summary of the current status of Li production in the U.S. As in our prior report on Li chemical production from brines via DLE (Iyer and Kelly 2022), the main focus here is production from sedimentary clays. We provide a brief summary of major Li-bearing clays and the primary extraction techniques used (Section 2). Next, we discuss the ongoing projects in the U.S. and North American regions, including their specific locations, production technologies, resource potential, and other important aspects (also in Section 2).

We also provide an update on the current status of DLE-based projects in the U.S. and North America since our previous report on the subject (Iyer and Kelly 2022) (Section 3). Further, we provide the first-ever LCI for both clay-based and DLE-based Li resources provided by companies engaged in this domain, based on their individual preliminary economic assessment (PEA) reports and/or detailed feasibility study (DFS) reports (Section 4). Finally, we provide a brief summary of this report in the concluding section (Section 5).

It must be noted that the speed of announcements of new projects and their subsequent development has significantly increased over the past two years due to federal, state, and local governmental incentives and higher Li chemical prices. While it is not possible to account for all these projects, we have made our best attempt to highlight each project for which adequate data could be obtained from publicly available sources.

The project announcements in the past two years also include conventional Li extraction projects, in particular from spodumene reserves in North America, such as Piedmont Lithium (Piedmont Lithium 2023). However, this report does not cover such conventional Li-based projects: it is confined solely to the hitherto unconventional means of Li chemical production from DLE-based brines and sedimentary clays.

2. Li Chemical Production from Clays

2.1. Clay Minerals—A Brief Review

In addition to brines and spodumene rocks, clays constitute an important source of Li globally (Meshram et al. 2014; Stringfellow and Dobson 2021). From a structural point of view, clays refer to phyllosilicate minerals or silicate compounds that contain parallel sheets of silica tetrahedra (Zhao et al. 2023). Here, we refer only to clay minerals found in sedimentary rocks and do not consider Li-bearing phyllosilicates that are considered pegmatites (such as lepidolite and zinnwaldite)—a classification also applied to spodumene reserves (Zhao et al. 2023).

The presence of Li in sedimentary clays is attributed to the leaching of Li from volcanic precursors and its embedding into clay mineral structures and/or hydrothermal alteration of reserves (Grant 2019; Pell et al. 2021). Regardless of its origin, Li's bonds with other elements in these minerals are significantly weaker than its corresponding bonds with elements in pegmatites (Grant 2019). Also, sediments have dirt-like consistency and can disintegrate more easily in water than spodumene rocks (Grant 2019). Hence, from a theoretical perspective, Li extraction from sedimentary clays is a relatively easier process than extraction from pegmatites, generating further interest in its prospects as a potential Li resource.

Table 1 lists the major sedimentary clay minerals along with their important properties, including chemical composition, color of appearance, Li_2O content (a parameter typically used to estimate the Li content of reserves), and a brief description of their structure. Though our focus is confined to sedimentary clays, we also include pegmatite minerals (including spodumene) in Table 1 for reference. Like their pegmatite phyllosilicate counterparts, sedimentary clay minerals comprise tetrahedral layers that sandwich octahedral and other inter-layers (water, hydroxide, and others). Sedimentary clays also exhibit properties similar to pegmatite phyllosilicates, such as substantial adsorption and dispersion capabilities, expansibility, and ion exchange, due to their unsaturated charge, the presence of metal ions, and large specific surface area (Zhao et al. 2023). All these properties play an enabling role with regard to Li extraction.

Table 1: Major Li-bearing clay minerals and their critical properties (based on Zhao et al. 2023)

Mineral	Chemical composition	Color	Li_2O content (%)	Crystal structure
Lepidolite	$K[Li_{2-x}Al_{1+x}(Al_{2x}Si_{4-2x}O_{10})(OH,F)_2]$ (x=0-0.5)	Rosy, light purple, or white	1.2-5.9	Monoclinic, trigonal
Zinnwaldite	$K[(Li,Fe,Al)_3(Al,Si)_4O_{10}(OH,F)_2]$	Grayish- or yellowish-brown	2-3	Monoclinic
Masutomilite	$K[Li_{1+x}(Mn^{2+}Fe^{2+})_{1-x}Al(Al_{1-x}Si_{3+x}O_{10})F_{1+x}(OH)_{1-x}]$ (x=0-0.5)	Purple	3.5-5.0	Monoclinic
Swinefordite	$(Li,Ca,Na)_{1-x}(H_2O)_4[(Al,Li,Mg)_{2+x}(Si,Al)_4Si_3O_{10}(OH,F)_2]$ ($x < 1$)	Light gray/olive-green	4.2-5.7	Monoclinic
Hectorite	$(Ca_{0.5}Na)_x(H_2O)_4[(Mg_{3-x}Li)_3Si_4O_{10}(OH,F)_2]$ ($x \approx 0.33$)	Light apple-green	1.1-1.3	Monoclinic
Cookeite	$LiAl_2(OH)_6Al_2[AlSi_3O_{10}](OH)_2$	Yellowish white, or pale green to rose-red	2.4-4.1	Monoclinic
Jadarite	$LiNaSiB_3O_7(OH)$	Dark grey	7.3	Monoclinic

2.2. Extraction Technologies

The similarities of pegmatite and secondary clay phyllosilicates extend to the processing methods for extracting Li from them. Figure 1 shows the schematic for clay-based Li extraction, with a brief description of the figure given below, based on multiple references (Meshram et al. 2014; Tran and Luong 2015; Swain 2017; Grant 2019; Zhao et al. 2023).

The mined clay is beneficiated and screened and then treated via one of two pathways: one that involves roasting (*sulfonation roasting*, followed by acid leaching), and one without roasting (*acid leaching*; Figure 1). For most clays, roasting can be avoided, as the above-mentioned weak bonding of Li with other elements in these clays makes it easier to separate and produce the Li chemical (Grant 2019). If used, roasting is generally conducted at ~700°C–1100°C in the presence of reagents such as limestone ($CaCO_3$) and gypsum ($CaSO_4.2H_2O$); the exact reagent used depends on the chemical composition of the clay. The next step is acid leaching of ores using water and acid (typically sulfuric acid or H_2SO_4) in a countercurrent flow at 80°C–100°C. This step yields a pregnant leach solution (PLS) that contains Li and other cations (Na, K, Rb, Cs, Ca, and Mg). PLS is treated through a series of steps:

a. Neutralization by addition of reagents to neutralize the acid used during leaching, such as lime (CaO) and limestone ($CaCO_3$)
b. Reaction of neutralized PLS with soda ash (or Na_2CO_3) to produce lithium carbonate (Li_2CO_3)
c. Filtration and/or evaporation to remove the sulfate salts, water, and other impurity ions, while substantially increasing the concentration of Li salt in the final solution (a step analogous to the solar evaporation step in the case of Salar brines)
d. Crystallization, in which the Li_2CO_3 obtained post-filtration is crystallized into a battery-grade form for use in producing LIB cathodes while any left-over impurities are removed

Li_2CO_3 can also be used to subsequently produce lithium hydroxide (LiOH) for battery applications. Earlier studies have shown that high Li recovery rates (>70%) can be achieved via this route for Li_2CO_3 production, indicating its suitability from a technical perspective.

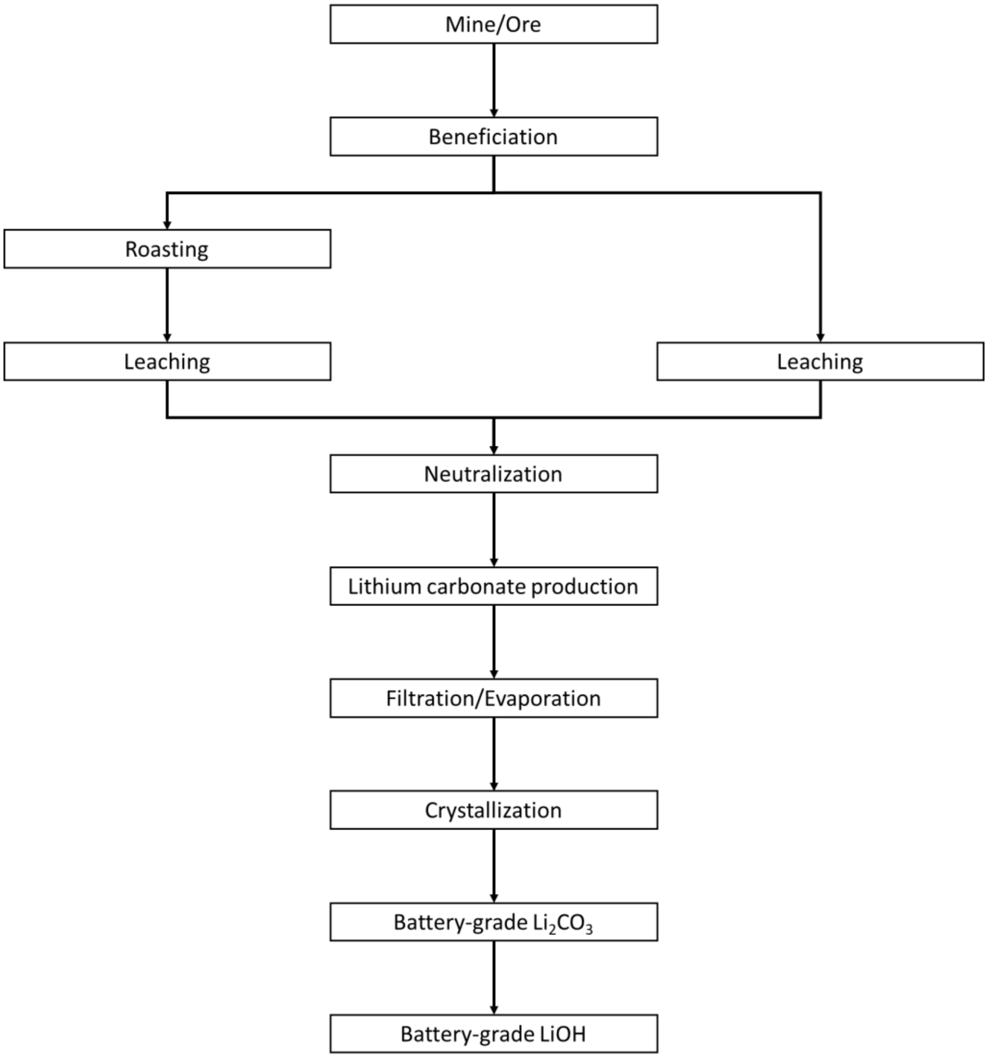

Figure 1: General schematic of Li chemical production from sedimentary clays

2.3. Ongoing Projects: Current Status

Multiple projects for Li extraction from sedimentary clays are currently in various stages of exploration, development, and future production across North America. Figure 2 shows the major ongoing projects in this domain, and Table 2 summarizes the key features of these projects. We provide a brief description of these projects by company in the subsections below.

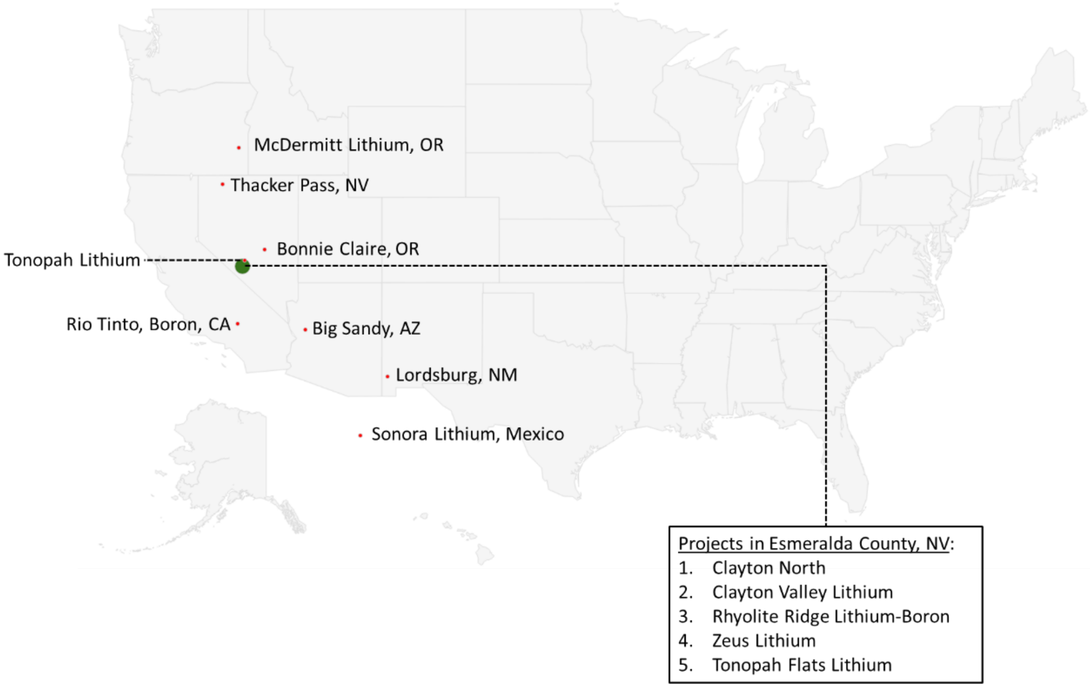

Figure 2: Prominent sedimentary clay-based Li chemical production projects in North America

Table 2: Details of prominent sedimentary clay-based Li chemical projects in North America (based on Ausenco Services 2018; Ioneer 2020a; Ioneer 2020b; Stantec Consulting Ltd. 2020; Fayram et al. 2021; Global Resource Engineering Ltd. 2022; Roth et al. 2022; American Lithium 2023b, a; Jindalee Resources Ltd. 2023b; Nevada Lithium 2023b; Noram Lithium 2023c; Arizona Lithium 2023b; Bacanora Lithium 2023a; Century Lithium Corp. 2023a; ABTC 2023; and American Lithium Corp. 2023a,b)

Owner/ Resource Developer	Project	Resource Estimate MMT LCE			Cut-Off Li Grade ppm	Li Chemical Produced/To Be Produced	Annual Production MT/Year	Costs		
		Measured	Indicated	Inferred				Capital Cost $ Million	Operating Cost $/MT LCE	Total Cost $ Million
Jindalee Resources Limited	McDermitt Lithium		11.1 @ 1,340 ppm Li	10.4 @ 1,340 ppm Li	1,000					
	Clayton North									
Lithium Americas	Thacker Pass	7 @ 2,450 ppm Li	9.1 @ 1,850 ppm Li	3 @ 1,870 ppm Li		Li_2CO_3	66,783		7,198	5,600
Century Lithium	Clayton Valley Lithium		6.28 @ 905 ppm Li		400	Li_2CO_3	27,400	493	3,387	
Ioneer USA	Rhyolite Ridge Lithium-Boron	0.36 @ 1,700 ppm Li	0.73 @ 1,550 ppm Li	0.17 @ 1,600 ppm Li	B-grade: 5,000	LiOH and Li_2CO_3	20,558 Li_2CO_3 22,000 LiOH			
Noram Ventures	Zeus Lithium	0.532 @ 860 ppm Li	4.643 @ 951 ppm Li	1.090 @ 871 ppm Li	400	Unclear	5,971	528	4,017	
American Lithium Corporation	Tonopah Lithium	4.2 @ 924 ppm Li	4.63 @ 727 ppm Li	1.86 @ 713 ppm Li	500	Unclear	24,000 Years 1-6 48,000 Year 7+	1,460	7,443	
Arizona Lithium	Big Sandy		0.151 @ 1,940 ppm Li	0.170 @ 1,780 ppm Li	800	Unclear				
	Lordsburg									
Rio Tinto	Boron						10 current; 5,000 future			

Owner/ Resource Developer	Project	Resource Estimate MMT LCE			Cut-Off Li Grade ppm	Li Chemical Produced/To Be Produced	Annual Production MT/Year	Costs		
		Measured	Indicated	Inferred				Capital Cost $ Million	Operating Cost $/MT LCE	Total Cost $ Million
Bacanora Lithium	Sonora Lithium	1.91 @ 3,480 ppm Li	3.13 @ 3,120 ppm Li	3.80 @ 2,650 ppm Li	1,000	Li_2CO_3	17,500 Years 1-4 35,000 Year 5+	800	3,900	
American Battery Technology Company	Tonopah Flats			15.80 @ 561 ppm Li	300	LiOH	5,000 Initial 30,000 Future			
Nevada Lithium Resources	Bonnie Claire			18.37 @ 1,013 ppm Li	700	Li_2CO_3	32,300			

2.3.1. Jindalee Resources Limited

Jindalee Resources Ltd. is an Australian company involved in metal extraction projects across the U.S. and Australia (Jindalee Resources Ltd. 2023a). Within the U.S., the company is working on two projects—McDermitt Lithium and Clayton North—through its 100% owned subsidiary, HiTech Minerals Inc. (Jindalee Resources Ltd. 2023a). McDermitt Lithium is currently in the extensive exploration and development stages, while Clayton North is in the early stages of exploration.

The McDermitt Lithium project is located in Malheur County on the Oregon-Nevada border in south-east Oregon (Figure 2) (Jindalee Resources Ltd. 2023b). The project is claimed to have the second-largest Li resource in the U.S. after the Thacker Pass project (discussed later in this report), with its claims spread over 54.6 km^2. It is currently in the exploration phase, with a resource base estimated at 11.1 million metric tonnes (MMT) of indicated and 10.4 MMT of inferred lithium carbonate equivalent (LCE) resources at an average Li grade of 1,340 ppm (cut-off Li grade: 1,000 ppm; Jindalee Resources Ltd. 2023b).

In addition to exploration, the company is evaluating the appropriate technologies for mining and subsequent Li chemical production. It claims low costs for ore mining and crushing due to the flat-lying and soft nature of the reserve's sediments as well as direct access to ore at the surface (ASX Investor 2022; Jindalee Resources Ltd. 2023c). The company has also tested the acid leaching and sulfation roasting routes to Li chemical production (Figure 1) at laboratory scale (Proactive Investors 2021). Using acid leaching, the company claims an ~60% increase in the Li content of clays via beneficiation and >95% Li extraction rates at moderate temperatures and pressures (Proactive Investors 2021; Jindalee Resources Ltd. 2023d). The company has reported an 89.5% Li extraction rate as lithium phosphate (Li_3PO_4) using sulfation roasting, which acts as the precursor to subsequent Li chemical production (Jindalee Resources Ltd. 2023d). The company is still examining the optimal cost-effective process among these technologies for commercial production (Jindalee Resources Ltd. 2023d).

Jindalee Resources Ltd. is also working on the Clayton North project, located 23 km north of the only Li-producing reserve (brine) in the U.S. at Silver Peak, Nevada (Figure 2; Jindalee Resources Ltd. 2023e). The company has claimed up to 930 ppm Li grade in its initial mineralization studies at this site (Jindalee Resources Ltd. 2023e) and is conducting more exploration to ascertain Li grade continuity in other parts of the project area (Jindalee Resources Ltd. 2023f).

2.3.2. Lithium Americas

Lithium Americas owns and operates the Thacker Pass project, which has the biggest Li resource in the U.S. and is expected to be the first such project to commercially produce Li chemicals (Lithium Americas 2023). It is located at the southern end of the McDermitt caldera, opposite the McDermitt Lithium project, in Humboldt County, Nevada (Figure 2; Lithium Americas 2023). The project area consists of old claims (previously part of the now-defunct Kings Valley Lithium Project) and new claims, encompassing 4,236 hectares (or 42.36 km^2; Roth et al. 2022).

According to the company's studies (Roth et al. 2022; Lithium Americas 2023), the project area contains alternate layers of sedimentary claystone and volcanic ash. The clays (along with ash) extend ~90 m down from the surface, with alluvium soil on top (average thickness: ~5 m) and hard volcanic rock underneath (Lithium Americas 2023). Claystone consists of two minerals: smectite (Li grade: 2,000-4,000 ppm, bluish-gray and light-colored) at shallow depths, and illite (Li grade: 4,000-9,000 ppm, gray to dark-gray/black colored) at moderate-to-deep depths, with a mix of both clays in the middle region (Roth et al. 2022; Lithium Americas 2023). The deposit also contains other minerals, including fluorite, calcite, quartz, potassium (K) feldspar, plagioclase, and dolomite (Roth et al. 2022). The Thacker Pass site contains Li at depths up to 120 m or 390 ft, much less than for other Nevada-based sedimentary resources (which lie below 330 m or 1,100 ft), making this project more attractive for producing Li chemicals (Lithium Americas 2023).

Based on its feasibility study (Roth et al. 2022), the company's production schematic—in line with the typical acid leaching flowsheet in Figure 1—is described below in brief.

Ore is mined, stockpiled based on clay type (smectite and illite), and blended such that 59% of the Li comes from illite and the remainder from smectite. Coarse, non-Li gangue is removed from the ore through a four-step beneficiation process: (a) Comminution, or breaking the ore to smaller size (150 mm to 25 mm), (b) attrition scrubbing, or aggressive particle-to-particle contact to separate clay from gangue, (c) classification, or separating undersized clay from oversized gangue, and (d) solid-liquid separation and recombination, or solidifying clay by removing water from it and then remixing it with water to produce the desired slurry. The beneficiated clay is leached with sulfuric acid (H_2SO_4) at 75°C–90°C in tanks for 1 hour, with acid use of 490 kg (100%) per MT of input feed and a Li recovery rate of ~86%.

Li is leached along with other elements (Na, K, Mg, Fe etc.) into a slurry that is neutralized in a two-step process. It is first reacted with ground limestone ($CaCO_3$, 35 wt.%) at a pH of 3–4 to precipitate most of the Fe and Al in the clay. It is then combined with magnesium hydroxide ($Mg(OH)_2$) at a pH of 6.5 to neutralize the slurry and avoid any redissolution of calcium borate ($B_2Ca_3O_6$). The residual slurry is sent to the clarifier tank, where it is thickened and sent to the countercurrent decantation and filtration unit. Here, the slurry is washed using water and then reacted with the overflow from subsequent stages to produce solid filter cake (61 wt.%) and filtrate. The filtrate is concentrated and reacted with milk-of-lime to precipitate Mg (as $Mg(OH)_2$) and Ca (as $CaSO_4.2H_2O$ or gypsum), and then reacted with soda ash (Na_2CO_3, 25 wt.%) to produce $CaCO_3$.

Other elements are removed through additional steps, while the remaining liquor solution (containing lithium sulfate or $LiSO_4$) is converted to lithium carbonate (Li_2CO_3) via a three-step process: (a) reaction with Na_2CO_3 (25 wt.%), followed by dewatering and watering to produce the slurry of desired flowability (which contains low-grade Li_2CO_3), (b) reaction of the slurry with carbon dioxide (CO_2) to produce lithium bicarbonate ($LiHCO_3$) that is filtered to remove any undissolved Li_2CO_3, and (c) removal of K and Na sulfate salts and drying of the milled crystals to obtain battery-grade Li_2CO_3.

Lithium Americas has estimated its LCE resource base at 7 MMT of measured (Li grade: 2,450 ppm), 9.1 MMT of indicated (Li grade: 1,850 ppm), and 3.0 MMT of inferred (Li grade: 1,870 ppm) resources (Roth et al. 2022). The company estimates an overall mine/project life of 40 years over two phases of LCE production (Phase I: years 1-3; and Phase II: years 4-40; Roth et al. 2022). According to its feasibility study (Roth et al. 2022), the company estimates an average annual production of 66,783 metric tonnes (MT) LCE at an operational cost of $7,198/MT LCE over its entire life. The total costs over the entire project life are estimated at $5.6 billion (capital + operating + closure costs), based on an expected Li recovery rate of 73.2%, with battery-grade LC produced from the ore within 24 hours (Roth et al. 2022).

The company plans to build two sulfuric acid production plants—one for each phase—with a nominal capacity of 3,000 MT/day (100 wt.%; Roth et al. 2022; Lithium Americas 2023). Sulfuric acid will be produced from liquid sulfur procured from suppliers, while other reagents will be procured directly from their respective suppliers and/or obtained via internal recycling (Roth et al. 2022). The acid plant will produce a large amount of steam (37,900 kg/hour for each plant, excluding the steam consumed by acid plant; Roth et al. 2022). This steam will either crystallize $MgSO_4$ (and be condensed into water) or be injected into a crystallizer (to condense into a fluid) and then evaporate water (Roth et al. 2022). The acid plant will also generate 90 MW of electricity, while the company will import 30.5 MW and 21.4 MW of electricity in Phases 1 and 2, respectively (Roth et al. 2022). The entire plant setup (acid plant, Li_2CO_3 plant, mining, and other facilities) will consume substantial amounts of water, but will also include facilities for water treatment and recycling to minimize freshwater use (Roth et al. 2022; Lithium Americas 2023).

2.3.3. Century Lithium

Century Lithium Corporation, formerly known as Cypress Development Corporation, is a Canada-based company that fully owns the Clayton Valley Lithium Project in Esmeralda County, Nevada (Figure 2; Fayram et al. 2021; Century Lithium Corp. 2023a). Although adjacent to the Silver Peak brine, this project has a flat-lying claystone deposit and covers a total claims area of 5,430 acres (or ~22 km^2; Century Lithium Corp. 2023b).

The project area consists of four kinds of layers, which are described below in some detail based on the company's prefeasibility study, first published in August 2020 and subsequently amended in March 2021 (Fayram et al. 2021). The layer closest to the surface is alluvium (0-10 m thick), consisting of polylithic sand, gravel, cobble, and boulder, but without any Li. The second layer is tuffaceous mudstone (0-15 m thick), comprising interbedded silty mudstone (70 wt.%) and hard tuffaceous beds (30 wt.%) with an average Li content of 850 ppm. The third layer is ash-rich claystone (60-120 m thick), composed of illite and smectite clays, and is the main source of Li in this deposit (average Li grade: 1,600 ppm). This layer consists of three Li-containing material zones: (a) Zone 1, abundant in iron oxide and hematite, (b) Zone 2, with a mix of oxidized and unaltered material, and (c) Zone 3, which begins with an ash-fall turf and extends up to a completely oxidized zone. The last layer is siltstone—firmer and more coarse-grained than the claystone layer (average Li content: 545 ppm). It contains oxidized hematite, sand, and silt in significant amounts.

Apart from the project area's geology, Century Lithium's prefeasibility study also details the company's expected production flowsheet, resource estimates, annual production, and likely production costs (Fayram et al. 2021). Its expected production technology (acid leaching) is in line with the schematic in Figure 1, with more specific details given below (Fayram et al. 2021).

Claystone ore is broken into large lumps (~125 mm), crushed, dewatered (via an attrition unit), and then mixed with water in tanks to prepare the feed (slurry). This feed is pumped in leach trains composed of fiberglass or stainless-steel tanks that are connected to each other, are insulated (to prevent evaporative/heat losses), and are equipped with mechanical agitators (for mixing) and steam coils (to keep slurry temperatures at 60°C–70°C). Dilute sulfuric acid (H_2SO_4, 5-10 wt.%) is introduced in the first tank and retained for ~2 hours, then sent to the second tank; this procedure is repeated till all the tanks are leached with sulfuric acid. Clay reacts with H_2SO_4 to produce a discharge that is collected in a conditioning tank, and then washed with water and drained of PLS. The PLS is treated to remove impurities (Mg, Ca, etc.), while H_2SO_4 and water are recycled back to the leaching facility.

The final product is concentrated lithium sulfate (Li_2SO_4), which is converted to battery-grade lithium hydroxide ($LiOH.H_2O$) via electrolysis and crystallization. The obtained crystals are washed, dried, and used for lithium-ion battery (LIB) cathodes. Additional products from this process include potassium (K), rare-earth elements, and other salts. The plant will also have the capability to produce Li_2CO_3 (Fayram et al. 2021). The company will build its own H_2SO_4 plant (capacity: 2,500 MT/day) to generate the needed electricity input for its entire plant setup (Li chemical production plus H_2SO_4 plant; Fayram et al. 2021).

Apart from the production technology, the company's prefeasibility study also highlights the project's resource potential, annual production estimates, and expected costs (Fayram et al. 2021). Century Lithium claims that the flat-lying deposit will allow mining with a low strip ratio of 0.29:1 (Century Lithium Corp. 2023b), while the soft mine material at shallow depths is expected to enable surface mining without any drilling/blasting (Fayram et al. 2021). The project's LCE resource potential is estimated to be 6.28 MMT of indicated resources (Li grade: 905 ppm; cut-off Li grade: 400 ppm; Fayram et al. 2021; Century Lithium Corp. 2023a). These estimates are based only on the initial pit area, which is expected to last for over 40 years and will be mined over 11 phases (Fayram et al. 2021). The company expects to produce 27,400 MT/year LCE on average, assuming an average mine feed rate of 15,000 MT/day, an average Li grade of 0.114%, and Li recovery rate of 83% (Fayram et al. 2021; Century Lithium Corp. 2023a). Based on its metallurgical test results, Century Lithium Corp. claims that its method yields low-cost Li with high Li recovery rates (>85%) and low acid use (126.5 kg/MT LCE; Fayram et al. 2021). The company estimates a total capital cost of $493 million and an operating cost of $3,387/MT LCE (Fayram et al. 2021).

2.3.4. Ioneer USA

Among the prominent Li extraction projects in North America is Ioneer's Rhyolite Ridge Lithium-Boron project in Esmeralda County, Nevada (Figure 2; Ioneer 2023a). This project is famous for being one of only two major global deposits to contain both Li and boron (B) (Ioneer

USA 2020a). This is due to the presence of both Li-containing smectite-illite clays (which contain 1,500-2,000 ppm Li but no B) and extremely fine searlesite crystals (a B-containing mineral with up to 30,000 ppm Li) that constitute 40% of the reserve (Ioneer USA 2020a) The ores also contain carbonates of Mg and Ca, and K feldspar (Ioneer USA 2020a).

Since the material composition of this project's reserve is significantly different from that of other projects in this report, it uses a different process for Li extraction (see Figure 3; Ioneer USA 2020a; Ioneer 2023a, b). Below is a brief description of this flowsheet based on the company's feasibility study and other literature (Ioneer USA 2020a; Ioneer 2023a, b).

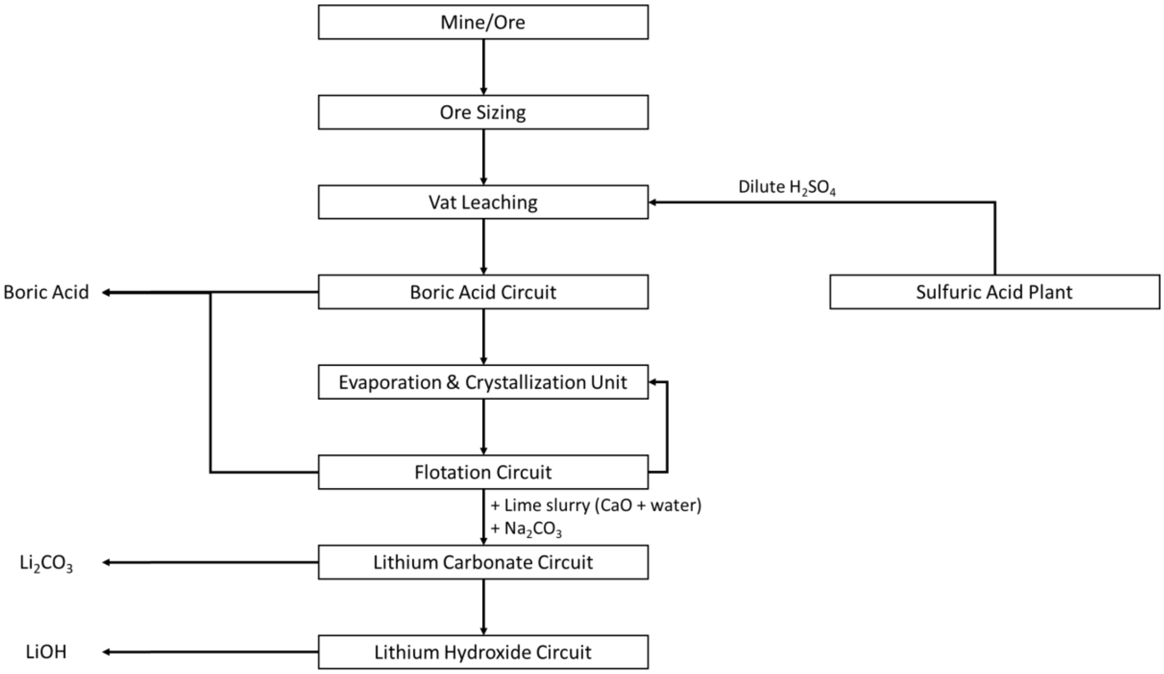

Figure 3: Process schematic for Li chemical production in Rhyolite Ridge Lithium-Boron project (based on Ioneer USA 2020a; Ioneer 2023a, b)

After conventional open pit mining, ore is blended and crushed to <¾ inch in a three-step process. The crushed ore is sequentially vat leached using dilute H_2SO_4 at 60°C in a countercurrent configuration (i.e., water and H_2SO_4 are sent in opposite directions to ensure that the acid content is in dilute range or ~100 g/liter). Leaching drains off interstitial Li and B in the leached solution (called mother liquor or PLS). Vat leaching is used as it minimizes acid usage and leaching time, enables temperature control, and maximizes Li and B recovery (to >90%). In leaching, Li reacts with H_2SO_4 to produce Li_2SO_4, while calcium carbonate ($CaCO_3$) in the ore reacts with H_2SO_4 and water to produce gypsum ($CaSO_4.2H_2O$). Gypsum's nature is similar to sand's, which allows for filtering the PLS. Potassium feldspar does not react with H_2SO_4, making it easier to separate it from Li and B. The filtered PLS is sent for subsequent processing, while the generated residue is removed and dry-stacked.

The leached PLS is saturated with boron (B) as boric acid (H_3BO_3). It is sent for crystallization (at 15°C) to the boric acid circuit. This step is called primary crystallization, in which the crystallized H_3BO_3 is removed from the PLS via centrifugation. About half of all the B in clay is removed in this step. The residual PLS from this step contains Li (~ 1,000 ppm) and other impurities, mainly sulfates of Mg, aluminum (Al), sodium (Na), K, and iron (Fe), along with water.

The residual PLS from the boric acid circuit is sent to the evaporation and crystallization unit. Here, it is first pumped through a four-stage evaporator circuit to remove 70% of the water (as vapor) and sulfates (using centrifuges), which raises the Li content of the remaining liquor to ~5,000 ppm. Water vapor is condensed to water and reused as water/steam through the plant setup (with 50% loss). The residual liquor is crystallized to remove the remaining sulfates and H_3BO_3 crystals; this is called secondary crystallization, and it further increases the Li content of liquor to ~10,000 ppm, similar to that of Salar brines after solar evaporation. According to the company's feasibility study (Ioneer USA 2020a; Ioneer 2023a, b), evaporation is done in a vacuum to allow the use of lower temperatures (70°C–73°C), while secondary crystallization is conducted at 5°C–6°C.

Crystals from primary and secondary crystallization are sent to the flotation circuit, where high-purity H_3BO_3 crystals are separated out as flotation concentrate. The remaining H_3BO_3 crystals are crude and sent back to the secondary recrystallization unit for recrystallization. Reagents are not needed in this step due to the hydrophobic nature of H_3BO_3, which makes it float.

Separately, Li liquor obtained after the secondary recrystallization is converted to Li_2CO_3 via a two-step process. First, the liquor is mixed with lime slurry (CaO + water) at a high pH (8.5–10.5) to remove impurities (Fe, Mg, and Al). Next, Li_2SO_4 (in liquor) is reacted with soda ash (Na_2CO_3) at >90°C to produce Li_2CO_3 precipitate, which is filtered, washed, and dried to produce battery-grade Li_2CO_3. To convert Li_2CO_3 to LiOH, a separate lithium hydroxide circuit will be established that recycles the $CaCO_3$ obtained as an impurity in the leaching step, thereby reducing both the reagent cost and Li losses.

The company also intends to produce its own H_2SO_4 through an in-house plant, using solid sulfur procured from suppliers. However, the acid plant capacity in the prefeasibility study (3,500 MT/day; Ioneer USA 2020a) varies from that on its website (3,860 MT/day; Ioneer 2023c). The acid production route is discussed in the feasibility study (Ioneer USA 2020a). Sulfur is melted, filtered, and combusted in air to produce sulfur dioxide (SO_2) gas, which is further combusted to produce sulfur trioxide (SO_3) gas. Both reactions are highly exothermic, and the heat generated is used to convert water (in an Li chemical plant) to steam. This cools the SO_3, after which it is mixed with water to produce H_2SO_4. The acid is collected, cooled, and stored for use. The company expects to generate 35 MW of electricity (for use in the entire setup) and steam (for the evaporation and crystallization unit) from this plant, terming it "green co-generation," and they expect only minimal grid-based electricity for plant operations. The plant will also be equipped with a tail gas scrubber system to achieve ultra-low NO_X and SO_X emissions.

Table 3: Resource estimates for Rhyolite Ridge project (based on Ioneer 2020; Ioneer USA 2020a)

Classification	Metric Tonnes	Li grade (ppm)	B grade (ppm)	Equivalent Contained Tonnes (MT)	
				Li_2CO_3	H_3BO_3
Measured	39.0	1,700	14,550	0.36	3.24
Indicated	88.0	1,550	14,150	0.73	7.11
Inferred	19.5	1,600	13,800	0.17	1.53
Grand Total	146.5	1,600	14,200	1.25	11.89

The company intends to use only searlesite in its Li chemical production process (Ioneer 2019). It will separate Li-rich clays from searlesite and stockpile them, hoping to use these for Li chemical production once a viable technology is developed for this in the future (Ioneer 2019; Ioneer USA 2020a). Based on only searlesite use, the project's resource potential is estimated at 1.25 MMT of LCE (Li grade: 1,600 ppm) and 11.89 MMT of H_3BO_3 (B grade: 14,200 ppm), assuming a cut-off B-grade of 5,000 ppm (Ioneer 2020a, b) . The company expects a further increase in its resource base from an increase in its total mining area—about two to three times its current mining area (Ioneer 2021). More details are provided in Table 3.

Ioneer expects the Rhyolite Ridge project to start up in 2023 and estimates an average annual production of 20,558 MT Li_2CO_3 (or 22,000 MT of LiOH from year 4 onwards) and 0.174 MMT of H_3BO_3 over the project lifetime of 26 years (Ioneer USA 2020a). Per the company's feasibility study and other literature (Ioneer USA 2020a; Ioneer 2021), Li_2CO_3 and H_3BO_3 will be produced in a 1:9 mass ratio but will generate revenues in a 70:30 ratio.

The company also claims other advantages from operational and environmental perspective. It claims to use 1/30 of the water used in current Li chemical production in the U.S. (Ioneer 2021). It also plans to use automated mine hauling—a first for U.S. greenfield projects—to improve operational efficiency and reduce its carbon intensity (Ioneer 2021). The plant is also expected to cost $785 million in capital and ~$6,290/MT LCE in operating costs (Ioneer USA 2020a).

2.3.5. Noram Ventures

Noram Ventures is a Canada-based company that owns and is developing the Zeus Lithium project in Esmeralda County, Nevada (Figure 2; Noram Lithium 2023a, b). The reserve's perimeter lies within one mile of Silver Peak, and the Clayton Valley project owned by Century Lithium lies between the Zeus and Silver Peak deposits (Noram Lithium 2023a, b). The Zeus Lithium project area spans 1,133 hectares (11.33 km^2) on U.S. government land that neither contains buildings/structures nor is known for any mineralized zones except for Li (ABH Engineering 2021; Noram Lithium 2023b).

The deposit is located in Clayton Valley, a basin in which sediments consist of silt, gravel, sand, and chlorite, combined with illite, smectite, and kaolinite clays (ABH Engineering 2021). Like Century Lithium, Noram is exploring tuffaceous claystones and mudstones in the eastern region of its property that are ~100 m thick and ~350 m deep (ABH Engineering 2021).

The company conducted two studies in 2021: a resource estimate study and a preliminary economic assessment (PEA; Peek 2021; ABH Engineering 2021). The company's PEA, backed by its metallurgical test results, outlines its production process (similar to that in Figure 1; ABH Engineering 2021). The production steps and their associated parameters are in line with those used by Century Lithium (see Section 2.3.3; ABH Engineering 2021). The company also plans to build its own H_2SO_4 plant with the same capacity (2,500 MT/day) as that of Century Lithium, based on dry sulfur as the initial precursor (ABH Engineering 2021). Noram Ventures Ltd. expects to meet its electricity needs from this acid plant and also export the excess electricity generated to the grid and/or procure electricity from the grid as needed (ABH Engineering 2021). It also proposes using an indirect water circulation closed-loop arrangement combined with a turbine condenser to cool the H_2SO_4 plant (ABH Engineering 2021).

The project has been in the exploration stage since 2016, and the company estimates its Li resources at 5.17 MMT of measured + indicated (Li grade: 941 ppm) and 1.09 MMT of inferred LCE resources (Li grade: 871 ppm), based on a cut-off Li grade of 400 ppm (Noram Lithium 2023c). More details on these estimates are given in Table 4 (Noram Lithium 2023c).

Table 4: Resource estimates for Zeus Lithium Project (based on Noram Lithium 2023c)

Type of Reserve	Li Cutoff (ppm)	Li Grade (ppm)	LCE (MMT)
Measured + Indicated	400	941	5.174
	500	951	5.123
	1,000	1189	2.552
	1,200	1326	1.191
Inferred	400	871	1.090
	500	882	1.074
	1,000	1115	0.389
	1,200	1268	0.070

According to the company's PEA, the most cost-optimal mining method involves truck-to-shovel operation over the first 11 mining phases, resulting in an extremely low strip ratio of 0.07:1 (ABH Engineering 2021). The company's metallurgical test results indicate that moderate temperatures and H_2SO_4 quantities are sufficient to achieve >80% Li recovery rates (ABH Engineering 2021). The company has also tested hydrochloric acid (HCl) and salts (sodium chloride/NaCl and potassium chloride/KCl) as leaching alternatives to H_2SO_4, with mixed results (ABH Engineering 2021).

The mining output from the initial 11 phases is expected to be sufficient for 40 years of Li chemical production, with the PEA assuming an input feed rate of 17,000 MT/day (ABH Engineering 2021). The company plans to store mined ore from these phases in a pit that will be eventually used to store Li chemicals for over 190 years (ABH Engineering 2021). Per the PEA, the plant will annually produce 5,971 MT LCE, assuming an anticipated Li recovery rate of 89% (Li grade: 1,093 ppm; ABH Engineering 2021). Total capital costs are estimated to be $528 million, while the operating cost is calculated as $4,017/MT LCE (ABH Engineering 2021).

2.3.6. *American Lithium Corporation*

American Lithium Corporation operates three Li extraction projects globally, among which one is located in the U.S.—the Tonopah Lithium Claims or TLC project, spread over 3,343 hectares (33.43 km^2) in Tonopah County, Nevada (Figure 2; American Lithium 2023a, b). This project is in the exploration and development phase, and the company estimated its mineral resources as part of its PEA study in 2022 (Stantec Consulting Ltd. 2020; American Lithium 2023a, b, c, d).

The company claims that the deposit is located close to the surface, and Li is weakly bound to the clay minerals, making it easy and inexpensive to produce Li chemicals (Stantec Consulting Ltd. 2020; American Lithium 2023b). Although the company has not shared details on its production technology publicly, other details suggest that it will use the acid leaching route (Figure 1). The company has also claimed that its production method is superior to those of other companies as it can recover >90% of the Li from ore within 10 minutes—much less than the 2–24 hours reported by other companies in this study (Stantec Consulting Ltd. 2020; American Lithium 2023c, d). The company also says that gravity separation will upgrade the resource's Li content from 1,300 ppm to 2,220 ppm, making this deposit suitable for commercial production (Stantec Consulting Ltd. 2020; American Lithium 2023c, d).

The company has published a NI 43-101 technical report, a PEA study, and other mineral resource estimates (Stantec Consulting Ltd. 2020; American Lithium 2023c, d). Based on these reports, the total LCE resource base is estimated at 4.2 MMT of measured (Li grade: 924 ppm), 4.63 MMT of indicated (Li grade: 727 ppm), and 1.86 MMT of inferred (Li grade: 713 ppm) resource, assuming a Li grade cut-off of 500 ppm (Stantec Consulting Ltd. 2020; American Lithium 2023a, b, c, d). More details are provided in Table 5.

Table 5: Resource estimates for Tonopah Lithium Project (based on Stantec Consulting Ltd. 2020; American Lithium 2023a, b, c, d)

Type of Reserve	Cut-off Li (ppm)	Volume (mm^3)	Tons (MT)	Li (ppm)	LCE Resource (MMT)
Measured	500	506	860	924	4.2
	1,000	203	345	1,255	2.29
	1,200	104	177	1,401	1.33
Indicated	500	701	1,192	727	4.63
	1,000	80	136	1,148	0.85
	1,200	22	37	1,328	0.27
	1,000	283	481	1,227	3.14
	1,200	126	214	1,402	1.6
Inferred	500	286	486	713	1.86
	1,000	31	53	1,151	0.32
	1,200	8	14	1,315	0.11

The PEA estimates an overall project life of 40 years, and a strip ratio of 0.93:1—much higher than that reported for other projects in this study (Stantec Consulting Ltd. 2020; American Lithium 2023a, b, c, d). The company intends to jointly produce Li with magnesium sulfate in its monohydrate ($MgSO_4.H_2O$) and heptahydrate ($MgSO_4.7H_2O$) forms (American Lithium 2023c, d), provided it is financially viable. To evaluate this prospect, the company has considered four production scenarios in its PEA, details of which are given in Table 6 (American Lithium 2023c, d).

Table 6: Prominent details of Tonopah Lithium Project (based on American Lithium 2023c, d)

Scenarios/ Parameters	Annual LCE Production (MT/Year)	Production Schedule	Total Costs		Annual $MgSO_4$ Production (MMT)
			Capital ($Million)	Operating ($/MT LCE)	
Scenario 1	• 24,000 (Years 1-6) • 48,000 (Years 7-40)	• Years 1-19: Initial focus on high-grade Li (1,400 ppm) • Year 20 and after: Lower-grade Li (> 1,000 ppm) stockpiled in years 1-19 used to produce Li chemicals	1.43	$7,443	Not applicable
Scenario 2			1.44	$817	1.66
Scenario 3	24,000	• No increase in production after Year 6 • Mining continues till year 20, followed by 16 years of Li chemical production from stockpiled material	0.813	$7,543	Not applicable
Scenario 4			0.822	$1,330	0.91

American Lithium says it is considering several environmental aspects of its project. The company states its entire resource is above the water table, making it easier to secure water rights while avoiding the possibility of groundwater contamination, water run-off, or watershed issues (American Lithium 2023b). It also reports that no species/habitat in the Endangered Species Act will be harmed due to this project (American Lithium 2023b). The company states that only minor quantities of harmful radioactive and contaminating elements (such as mercury, arsenic, and uranium) will be produced because of their minimal presence in the ore/mine (American Lithium 2023b). It is also using the services of Minviro Sustainability Consultants to conduct a life cycle analysis (LCA) of battery-grade Li chemical production from this project to minimize its environmental impacts (American Lithium 2023b).

2.3.7. *Arizona Lithium*

Arizona Lithium is an Australian company (formerly known as Hawkstone Mining Ltd.) engaged in the exploration and development of its fully owned Big Sandy project in Arizona (Arizona Lithium 2023a, b). The Big Sandy project is located on Interstate I93 between Phoenix (Arizona) and Las Vegas (Nevada) in the U.S. "battery corridor" (Figure 2) and covers ~25 km^2 (Arizona Lithium 2023b). The deposit comprises flat-lying sediments that combine analcime and potassic alteration zones, with the Li-bearing region being at/near the surface (Arizona Lithium 2023b).

The company began its exploration program in February 2019 and obtained exceptional results in the form of high-grade Li intercepts (peak Li grade: 4,380 ppm; Arizona Lithium 2023b). It has estimated a total base of 0.32 MMT LCE of indicated and inferred resources (Li grade: 1,850 ppm) at a 800 ppm Li grade cut-off (Arizona Lithium 2023b). These resources are estimated for only 4% of the total deposit area, indicating a strong potential of increased resources with the expansion of the exploration zone (Arizona Lithium 2023b). The company is currently working on securing approvals for further exploration (Arizona Lithium 2023b). More details on its resource estimates are provided in Table 7.

Table 7: Resource estimates for Big Sandy Lithium Project, based on Arizona Lithium 2023b

Li Grade Cut-Off	Resource Classification	Li Grade (ppm)	Contained LCE (t)
800	Indicated	1,940	150,900
	Inferred	1,780	169,900
2,000	Indicated	2,330	79,800
	Inferred	2,390	79,800

Based on its preliminary metallurgical tests in 2019, the company reports high Li recovery rates (85%–97%) through leaching over 1–24 hours, with its acid use ranging from 529 to 585 kg/MT of feed (Arizona Lithium 2023b). The company is working to optimize these results to reduce both leaching time and acid consumption (Arizona Lithium 2023b). The details provided by the company indicate that acid leaching is used for Li chemical production (Figure 1).

Apart from the Big Sandy project, Arizona Lithium is working on the Lordsburg Lithium project in Lordsburg, New Mexico, close to its border with Arizona, which covers ~25 km^2 (Arizona Lithium 2023c). The deposit is bounded on its western and eastern fronts by mountains, and its lithology is similar to that of Clayton Valley in Nevada (Arizona Lithium 2023c). The company has reported its intention to begin exploration in 2019, but no further details are available at this writing.

2.3.8. Rio Tinto (U.S. Borax)

Rio Tinto is developing a pilot-scale project to produce Li chemicals from waste rock at its mine site in Boron, California (Figure 2; RioTinto 2023). This mine is the state's largest open pit mine producing boron (B) and has been in operation for over 90 years. At present, it meets 30% of the global refined borate demand (U.S. Borax 2023). The company has set up a pilot-scale demonstration plant that combines roasting and leaching (Figure 1) of waste rock to produce high-grade Li (RioTinto 2023). While this plant's capacity is 10 MT/year at present, the company aims to expand it to 5,000 MT/year in the future (RioTinto 2023). Rio Tinto is also working with the U.S. Department of Energy (DOE) Critical Materials Institute (CMI) for economically viable recovery of critical mineral byproducts from present-day refining and smelting processes (RioTinto 2023).

2.3.9. Bacanora Lithium

Note: Bacanora Lithium was originally owned by Ganfeng Lithium (Bacanora Lithium 2023a), but its current status remains unclear after the Mexican parliament's approval of a lithium nationalization policy (Jamsmie 2022; Reuters 2023). Hence, the details below are based only on the information provided on Bacanora Lithium's website.

Bacanora Lithium PLC is fully owned by Ganfeng Lithium, a Chinese entity (Bacanora Lithium 2023a, b). It owns ten mining concessions covering 10,000 hectares (100 km^2) in northeastern Sonora State in Mexico, of which seven concessions constitute the Sonora Lithium project—the company's flagship project in which Li deposits are expected to last ~250 years (Ausenco Services 2018; Bacanora Lithium 2023a, b). The project benefits from its well-connected infrastructure and connectivity to centers of Li demand as well as suitable ambient temperatures and weather conditions that enable Li extraction throughout the year (Ausenco Services 2018).

The deposit lies within mountains whose peaks extend up to 1,440 m above sea level, with Li clays housed in the deeply incised valleys as lower and upper units (Ausenco Services 2018). The lower clay unit is ~20 m thick, and lies below the ignimbrite layer and on top of basaltic flows, tuffaceous rocks, and breccias. The upper clay unit is ~22-70 m thick and lies over the ignimbrite layer and below a sequence of basaltic flows and breccias (Ausenco Services 2018). Both units comprise a mix of smectite, illite, and other minerals (Ausenco Services 2018).

Unlike the other projects described in this study, the Sonora Lithium project employs roasting (Figure 1), as described in its feasibility study published in 2018 (Ausenco Services 2018). A description of the production stages involved is given below, based on this study.

After gangue is rejected, the clay ore is ground and then beneficiated in a three-step process:

a. Screening to remove oversized particles
b. Classification via hydrocyclone treatment
c. Concentrate thickening, where the ore is reacted with limestone to ensure the presence of calcium in the beneficiated product

The beneficiated ore is mixed with milled gypsum ($CaSO_4.2H_2O$) and sodium sulfate (Na_2SO_4) and the blend is compressed into briquettes. These briquettes are solar-dried and roasted at 900°C for one hour in the presence of limestone ($CaCO_3$), hydrated lime ($Ca(OH)_2$), and kiln gases, and then cooled to ambient temperature. The mixture is ball-milled and then leached using H_2SO_4, with lithium sulfate (Li_2SO_4) and other water-soluble impurities (such as Fe, Mg, Ca, and Na) leached into the solution to form a slurry. The slurry is purified using a multi-step process:

a. The addition of sodium carbonate (Na_2CO_3) to the leached solution to convert metal sulfates into metal carbonates while also producing sodium sulfate (Na_2SO_4)
b. Indirect steam heating at 85°C to maximize the precipitation of $CaCO_3$
c. Filtration to remove $CaCO_3$ precipitate and other solids
d. Vacuum flash cooling at 10°C to remove the hydrated Na_2SO_4 crystals (Glauber's salt), that is melted, recrystallized, and recycled for use in roasting
e. Removal of cesium (Cs) and rubidium (Rb) via partial acidification using H_2SO_4

f. Neutralization via treating the filtered liquid with caustic soda (NaOH) to convert the residual Al to aluminum hydroxide ($Al(OH)_3$).

After the impurities are removed, the PLS is evaporated to remove water and increase the Li content. The concentrated PLS is cooled, pumped through several columns and an ion exchange circuit (to remove fluorine and boron, respectively), and then sent to the precipitation circuit. Here, Li precipitates as crude Li_2CO_3, which is reacted with CO_2 gas in bicarbonation dissolution tanks to produce soluble lithium bicarbonate ($LiHCO_3$). This solution is filtered and passed across an ion exchange circuit to remove impurities, and then recrystallized at 95°C to produce Li_2CO_3 and CO_2, which is recovered and recycled back to the bicarbonation tanks. The obtained Li_2CO_3 is filtered, dried, and packaged as battery-grade Li_2CO_3. The company also produces glaserite (or potassium sulfate, K_2SO_4) through this process.

Based on the company's feasibility study and other reports (Ausenco Services 2018; Bacanora Lithium 2023a), the project's latest LCE resource base is estimated to be 1.91 MMT of measured, 3.13 MMT of indicated, and 3.80 MMT of inferred resources (Ausenco Services 2018; Bacanora Lithium 2023a). More details on these estimates are provided in Table 8. However, some questions have been raised about the actual size of these resources (Deslandes 2022).

Table 8: Resource estimates for Sonora Lithium project (based on Ausenco Services 2018; Bacanora Lithium 2023a)

Category	Cut-Off (Li ppm)	Li (ppm)	LCE (MMT)
Measured	1,000	3,480	1.91
Indicated	1,000	3,120	3.13
Inferred	1,000	2,650	3.799

According to the company's PEA, the project will have an open pit mine (mine life: 19 years) with an associated processing facility and an average strip ratio of 2.85—a very high value compared to other projects in this study (Ausenco Services 2018). The PEA projects annual production of 17,500 MT Li_2CO_3 in Stage 1 (years 1-4) and 35,000 MT Li_2CO_3 in Stage 2 (years 5-19), along with a peak glaserite production of 28,805 MT/year for sale to fertilizer plants (Ausenco Services 2018). The plant will also produce 42,000 MT/year of Na_2SO_4, that will be stored or given away, as it cannot be sold due to its lower quality (Ausenco Services 2018). The PEA also estimates total capital cost of $800 million and operating costs at ~$3,900/MT LCE (Ausenco Services 2018).

2.3.10. American Battery Technology Company (ABTC)

ABTC is a U.S. company that has operated in Nevada over the past few years and is an integrated battery materials company engaged in both recycling of lithium-ion battery (LIB) components and developing a resource for primary production of LIB materials (ABTC 2023a). The company is based in Reno, NV, and operates in four locations in the state, with co-funding from two grants from U.S. DOE (ABTC 2023a). Among these is the Tonopah Flats Lithium

Exploration Project in Esmeralda County, Nevada, where the company is engaged in exploration and development of the resource for Li chemical production (ABTC 2023a).

The project area for the Tonopah Flats project encompasses 517 mining claims spanning 10,340 acres (or 41.85 km^2) of land administered by the U.S. Bureau of Land Management (BLM; ABTC 2023c). It is located in a broad alluvial basin surrounded by the San Antonio and Monte Cristo Mountains, with the basin lying over a mix of volcanic material, sandstone, siltstone, claystone, and tuff (ABTC 2023c). The claystone reserve to be used for Li chemical production is reported to be over 800 ft deep (ABTC 2023c).

ABTC initiated its exploration activities in 2021, and subsequently published its inferred resource report in 2023 (ABTC 2023c). While the company has not estimated any reserves, it has estimated an inferred resource base of 15.8 MMT LCE at an average Li grade of 561 ppm (cut-off Li grade: 300 ppm) (ABTC 2023c). ABTC aims to use its selective leach extraction (SLE) technology to extract and purify battery metals, including Li, from these deposits ABTC 2023c). According to ABTC, SLE has multiple advantages, including low reagent and water use, lower production costs, and low contaminant levels in the leach liquor, all of which are expected to result in lower environmental impacts (ABTC 2023c). While the company does not provide additional details, SLE seems to be similar to the non-roasting route shown in Figure 1. Using this technology, ABTC intends to produce lithium hydroxide monohydrate ($LiOH.H_2O$), initially 5,000 MT/year using DOE grants and later scaling to 30,000 MT/year using its own resources and funding secured from investors (ABTC 2023b; ABTC 2023c).

2.3.11. Nevada Lithium Resources

Nevada Lithium Resources Inc. is a Canada-based company that has partnered with Iconic Minerals Ltd. (50:50 stake) to jointly explore and develop the Bonnie Claire project in Nye County, Nevada (Global Resource Engineering Ltd. 2022; Nevada Lithium 2023b, a). The project is among North America's largest Li resources, and comprises 915 claims across 18,300 acres (74.06 km^2; Global Resource Engineering Ltd. 2022; Nevada Lithium 2023b). The project is unique for two reasons. First, unlike the other projects described above, Li occurs not in clays but as lithium compounds (salts and Li_2CO_3) within the pore spaces among clay, sand, and silt particles. Second, in addition to clays, the project area also contains Li-containing brines (Global Resource Engineering Ltd. 2022; Nevada Lithium 2023b).

Overall, the Bonnie Claire basin contains alluvial fans that hold significant amounts of Li (Global Resource Engineering Ltd. 2022; Nevada Lithium 2023b). The company has estimated this basin to contain an estimated inferred resource of 18.37 MMT LCE at an average Li grade of 1,013 ppm (cut-off Li grade: 700 ppm; Global Resource Engineering Ltd. 2022; Nevada Lithium 2023b). Nevada Lithium Resources is currently working on updating this resource base via a detailed exploration study to be completed in 2023 (Nevada Lithium 2023b).

According to Nevada Lithium Resources' PEA (Global Resource Engineering Ltd. 2022), this project involves roasting (the schematic in Figure 1) but in basic conditions via the use of sodium sulfate or Na_2SO_4 instead of acid (like H_2SO_4). Initially, extracted ore is screened, thickened, dewatered/filtered, dried at 200°C, and then calcined/roasted at 850°C for one hour to convert the Li in the ore to Li_2SO_4 (Global Resource Engineering Ltd. 2022). Subsequently, Li_2SO_4 is quenched to 70°C–80°C via water leaching, after which the leached solution (PLS) is treated with Na_2CO_3 to reduce Ca, Mg, and Mn content at high pH (9-10) (Global Resource Engineering Ltd. 2022). The PLS is then evaporated to increase the Li content and recover the condensate as process water and Glauber's salt, and then treated using ion exchange to remove the remaining Mn and Ca (Global Resource Engineering Ltd. 2022). Finally, the clarified PLS is reacted with Na_2CO_3 at 90°C–95°C to produce crude Li_2CO_3, which is then converted into bicarbonate (by the addition of CO_2) and later reconverted back to battery-grade Li_2CO_3 (by removing the CO_2) for drying and packaging (Global Resource Engineering Ltd. 2022). The project also envisions treating the barren leach solution (after Li removal), using reverse osmosis to recover water for reagent makeup, filter cake washing, and ion exchange rinsing purposes (Global Resource Engineering Ltd. 2022).

The PEA assumes annual Li_2CO_3 production to increase from 16,500 MT in Year 1 to 38,000 MT in Year 17 for an average annual production of 32,300 MT (Global Resource Engineering Ltd. 2022). The company estimates that the actual mine life would extend beyond 40 years, with an average Li grade of 1,556 ppm over this duration (Global Resource Engineering Ltd. 2022).

3. Li Chemical Production from Brines via Direct Lithium Extraction (DLE): A Status Update

In an earlier report (Iyer and Kelly 2022), we analyzed the status of projects using brine-based production of Li chemicals via DLE technology in North America. Some of these projects have reported further progress in terms of updates in their resource estimates, more details on their likely production process, and/or updates of their expected annual production values and resultant costs. Here we provide a brief overview of these updates for DLE-based Li chemical projects. More details on these projects are provided in the following sub-sections and in Figure 4 (for their locations) and Table 9 (for resource estimates).

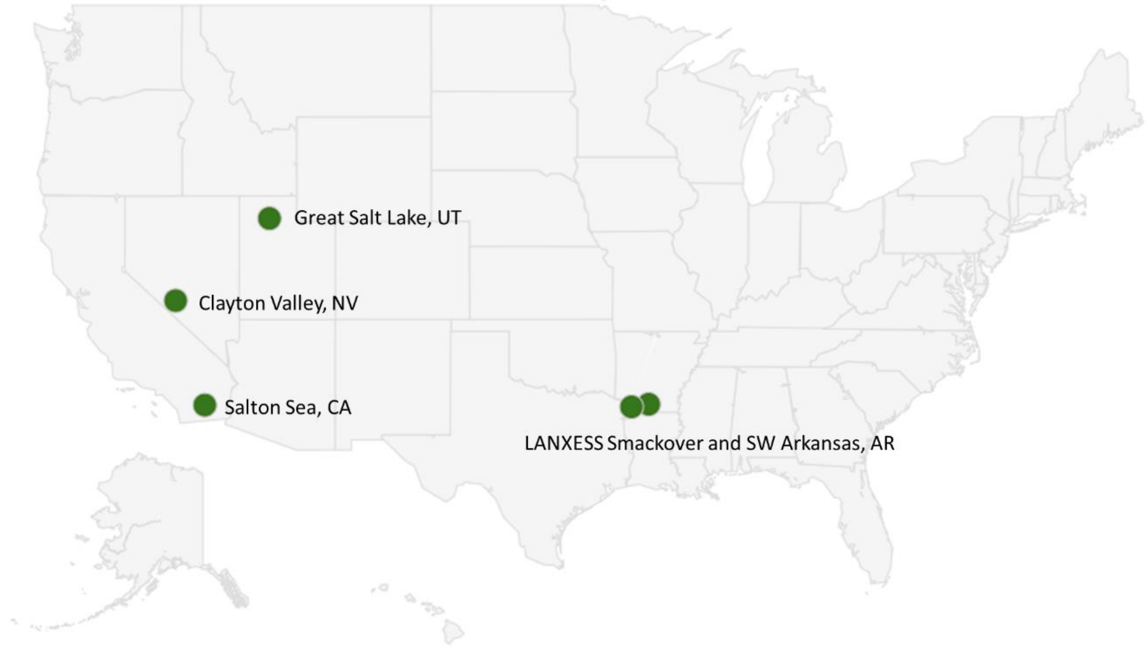

Figure 4: Locations of major DLE-based brine projects in the United States

Table 9: Major details of DLE-based brine projects in the United States

Owner/ Resource Developer	Project	Resource Estimate MMT LCE		Average Li Grade mg/L	Cut-Off Li Grade mg/L	Project Life Years	Li Chemical Produced/ To Be Produced	Annual Production MT/Year	Capital Cost $Million	Operating Cost $/MT
		Indicated	Inferred							
Compass Minerals	Ogden: East	2.36 @ 256 mg/L	0.045 @ 256 mg/L	256	9	35	Li_2CO_3	10,791	262	3,137
	Ogden: West					34	LiOH	27,712	710	1,986
Controlled Thermal Resources	Hell's Kitchen						LiOH	25,000 in 2024 300,000 Future		
Standard Lithium	LANXESS - Standard Lithium	3.14 @ 168 mg/L			100	>25	Li_2CO_3	20,900	437	4,319
	Southwest Arkansas		1.195 @ 255 mg/L		50	20	LiOH	30,000	870	2,600
Pure Energy Minerals	Clayton Valley Brine		0.247 @ 123 mg/L		22		LiOH	11,500	359	3,217

3.1. Compass Minerals

As noted in Iyer and Kelly (2022), Compass Minerals intends to produce Li chemicals from the brine resource at its Ogden facility in Utah (Figure 4). Since our earlier report, the company has updated its resource estimates, selected technology providers for its production process, and published an economic feasibility analysis of its expected annual production and resultant costs (Compass Minerals 2022a, b).

For their DLE process, Compass Minerals will use the integrated lithium adsorption desorption (ILiAD) technology (Compass Minerals 2022a, b). ILiAD is a proprietary technology of EnergySource Minerals, another company engaged in DLE-based Li chemical production in the Salton Sea region in California (EnergySource Minerals 2021; Compass Minerals 2023). Separately, Compass Materials has engaged Veolia Water Technologies—an established technology solutions provider—for converting the lithium chloride (LiCl) obtained from the brine to battery-grade Li chemicals (Compass Minerals 2022a, b).

Compass Materials has updated its resource base from the 0.127 MMT LCE noted in our previous report (Iyer and Kelly 2022) to 2.405 MMT LCE (2.36 MMT indicated and 0.045 MMT inferred) at an average Li grade of 256 mg/L (cut-off Li grade: 9 ppm; Compass Minerals 2022a, b). This base is distributed over the project area in two sets of ponds—those on the eastern side adjacent to its Ogden plant in Bear River Bay that produce its existing range of chemicals, such as magnesium chloride, and those on the western side opposite the Great Salt Lake, Utah (Compass Minerals 2022a, b). Processing plants will be set up on both sites (termed East and West sides, respectively) to produce Li chemicals. More details on these sites, including the Li chemicals they will produce, their expected production values and costs, and the technology used to produce the Li chemical, are provided in Table 10.

Table 10: Details on Compass Minerals' production sites (based on Compass Minerals 2022a, b)

Parameters	East Site	West Site
Li chemical produced	Li_2CO_3	LiOH
Technology used for Li chemical production	Single reactive crystallization step (using soda ash/Na_2CO_3)	Double steps (using a mix of soda ash/Na_2CO_3, lime/CaO, and limestone/$CaCO_3$)
Phase in which the plant will be developed and functional	Phase 1	Phase 2
Years of operation	2025-2059	2026-2059
Annual production (MT Li chemical)	10,791	27,712 (17,957 MT LCE)
Expected capital cost ($ million)	262	710
Expected operational cost ($/MT Li chemical)	3,137	1,287 (1,986/MT LCE)

3.2. Controlled Thermal Resources

Since our prior report (Iyer and Kelly 2022), Controlled Thermal Resources (CTR) has provided a few updates on its project involving Li chemical production via DLE from geothermal brines in the Salton Sea, California (Hell's Kitchen project; Figure 4).

The company says it has optimized its process to enhance its Li recovery rate in its pilot plant, which has been operational since the fourth quarter of 2022 (Controlled Thermal Resources 2023a). The company aims to operate this plant until 2023, when full plant construction will be completed, and then reassemble it for the next production plant as needed (Controlled Thermal Resources 2023a). For its initial phase, CTR expects to begin its combined production of geothermal electricity (49.9 MW) and LiOH (25,000 MT) in 2024, and plans to scale this to 1.1 GW of clean electricity and 0.3 MMT (300,000 MT) of LiOH annually (Controlled Thermal Resources 2023a, b). The company has also signed agreements with Stellantis and General Motors for future LiOH supplies (Whitaker 2023).

3.3. Standard Lithium

As noted in our previous report (Iyer and Kelly 2022), Standard Lithium has been working on two projects in the Smackover Arkansas basin (Figure 4). The company has published PEA studies on both these projects that together provide extensive updates regarding their resource estimates, annual production values and costs, and other details (Worley 2019; APEX Geoscience Ltd. et al. 2021). The reports also provide details about the production technology used for these projects. Table 11 provides the resource estimates and production quantities and costs of these projects, while Figures 5 and 6 provide the respective production schematics used for these projects, with more details given below.

Table 11: Details on Standard Lithium projects (based on Worley 2019; APEX Geoscience Ltd. et al. 2021)

Parameters	LANXESS–Standard Lithium	Southwest Arkansas
Li chemical produced	Li_2CO_3	$LiOH.H_2O$
Resource estimate (MMT)	Indicated: 3.14 @ 168 mg/L (cut-off Li grade: 100 mg/L)	Inferred: 1.195 (@ 255 mg/L Li; cut-off Li grade: 50 mg/L)
Annual production (MT)	20,900	30,000
Capital cost ($ million)	437	870
Operating cost ($/MT)	4,319	2,600
Plant life (years)	More than 25 years	20

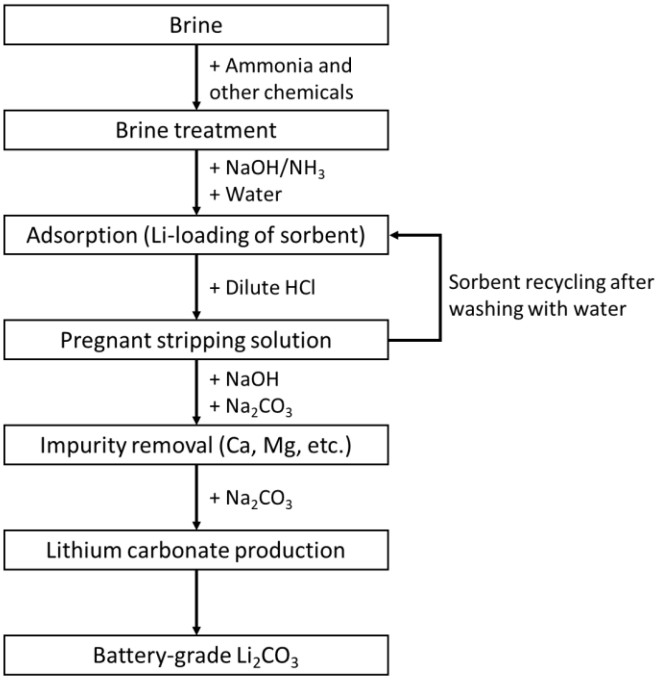

Figure 5: Schematic of Li chemical production in LANXESS Smackover project (based on Worley 2019)

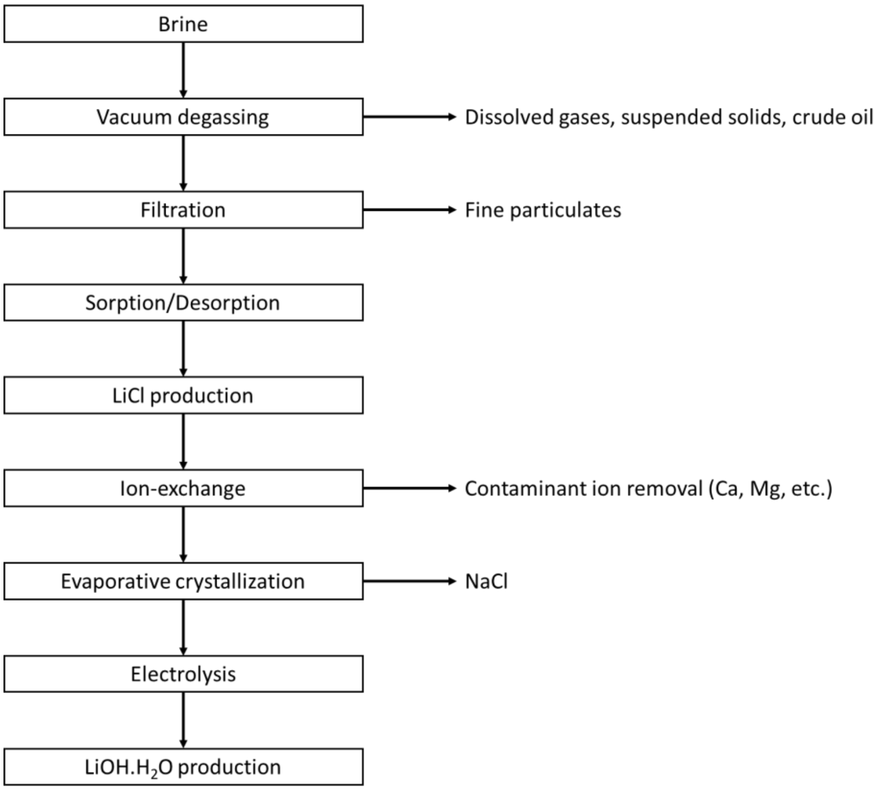

Figure 6: Production route schematic for Li chemical production in SW Arkansas project (APEX Geoscience Ltd. et al. 2021)

Standard Lithium's joint venture with LANXESS, focusing on the latter's bromine brines, is being developed to produce battery-grade Li_2CO_3 (Worley 2019). As shown in Figure 5, the brines will be pre-treated with anhydrous ammonia (NH_3) and other chemicals to adjust their pH to near-neutral values (Worley 2019). A sorbent with selective Li adsorption capability is mixed with pre-treated brine in the presence of caustic soda (NaOH)/NH_3 and then washed with water to thicken the slurry (Worley 2019). The Li-loaded and washed sorbent is reacted with dilute HCl to produce a pregnant stripping solution (PSS), which is separated from the sorbent by being washed with water (Worley 2019). The sorbent is recycled back for reuse, while PSS is concentrated to remove Ca and Mg (via reaction with NaOH and Na_2CO_3). The purified LiCl is subjected to reverse osmosis and then reacted with Na_2CO_3 to produce Li_2CO_3, which is filtered, washed, dried, and micronized to make it battery-grade (Worley 2019).

Standard Lithium's Southwest Arkansas project, spread across Lafayette and Columbia counties in Arkansas, comprises 489 tracts across 14,638 hectares (146.38 km^2; APEX Geoscience Ltd. et al. 2021). The brines, which were previously used for crude oil production, exist at ~2,700 m (~8,800 ft) below ground level (APEX Geoscience Ltd. et al. 2021). Apart from LiOH, the company expects to produce ~50% of its total HCl demand on-site via electrochemical conversion of LiCl (brine) to LiOH, enabling significant cost savings due to lower electricity costs in Arkansas than in other states (APEX Geoscience Ltd. et al. 2021). Standard Lithium's expected production process, from the company's PEA (APEX Geoscience Ltd. et al. 2021), has four steps (Figure 6). First, LiCl is extracted from the brine through a combination of vacuum degassing to remove dissolved gases, suspended solids, and crude oil, filtration to remove fine particulates, and sorption/desorption, i.e., mixing with a sorbent in the presence of ammonium hydroxide, followed by washing and reaction with dilute HCl (APEX Geoscience Ltd. et al. 2021). While divalent contaminant ions (like Ca and Mg) are removed via ion exchange, LiCl is further concentrated and treated via evaporative crystallization to remove sodium chloride (NaCl). Pure LiCl is electrolyzed to produce LiOH, which is treated via evaporative crystallization to produce LHM (lithium hydroxide monohydrate or $LiOH.H_2O$), which is dried and packaged in an inert atmosphere to obtain battery-grade LHM (APEX Geoscience Ltd. et al. 2021).

3.4. Pure Energy Minerals

Pure Energy Minerals is operating a Clayton Valley brine project in Esmeralda County, Nevada, in addition to the sedimentary clay-based project described in Section 2 (Figure 4; Blois et al. 2018; Pure Energy Minerals 2023a). This project was not included in our prior report on DLE-based projects (Iyer and Kelly 2022). It is contiguous with Silver Peak and has similar brine chemistry and hydrogeology, rendering it suitable for low-cost DLE production because of its low Ca and Mg content (Blois et al. 2018). The company owns this project and has handed over the design, construction, and operation of its pilot plant to its project partner, SLB (formerly called Schlumberger; Blois et al. 2018; Pure Energy Minerals 2023a).

The project comprises 1,085 claims encompassing 26,300 acres (106.43 km^2) in the Clayton Valley, with the brines existing within unconsolidated sediments at depths of 130-600 m (450-2,000 ft.) below ground level (Blois et al. 2018; Pure Energy Minerals 2023b). According to the company's PEA study, the estimated inferred resource base is 0.247 MMT of battery-grade LiOH (0.218 MMT LCE) at an average Li grade of 123 mg/L (cut-off Li grade: 22 mg/L), with a Mg-to-Li ratio of ~2.9 (Blois et al. 2018). The PEA assumes annual production of 11,500 MT LiOH or 10,000 MT LCE at an expected Li recovery rate of 90% (Blois et al. 2018), with estimated capital and operating costs of $359 million and $3,217/MT LiOH ($3,652/MT LCE), respectively (Blois et al. 2018). The brine will be converted directly to LiOH, and no Li_2CO_3 will be produced as an intermediate step.

For LiOH production, the company intends to use a novel DLE process developed by Tenova Advanced Technologies (TAT) and its partners called the Tenova process (Blois et al. 2018), which consists of four individual processes (Blois et al. 2018):

a. LiP™, a membrane-based process that separates alkaline earth elements from brines by elevating the pH of the solution and filtering them out.
b. LiSX™, a solvent extraction process in which the brine is pre-treated with a barren solvent, then scrubbed with a dilute acid to remove co-extracted impurity ions, and then stripped to remove Li as high-purity Li_2SO_4 solution. The barren solvent is recycled back for reuse.
c. LiEL™, electrolysis of Li_2SO_4 to produce LiOH by removing the sulfate as sulfuric acid (H_2SO_4) using water as the electrolyzer.
d. Evaporation and crystallization to remove water and crystallize the LiOH as $LiOH.H_2O$, the form used for lithium-ion batteries.

3.5. Lilac Solutions

Not much is known about Lilac Solutions, but it claims to have developed a new ion-exchange technology for Li extraction from brines (Lilac Solutions 2023) that fits within the expected range of DLE technologies. The company has clarified that it is a technology solutions provider that delivers ion exchange beads to companies for Li absorption from brines upon percolation (Lilac Solutions 2023). Subsequently, the Li-adsorbed brines are reacted with hydrochloric acid (HCl) to yield lithium chloride (LiCl), which is processed to produce Li chemicals (Lilac Solutions 2023). The company claims that the entire process of Li chemical production from brines can be conducted within two hours using its technology (Lilac Solutions 2023), though no further details are provided.

4. Life-Cycle Inventory of Domestic Li Chemical Production

4.1. Sedimentary Clay-Based Production

Our literature review did not yield any study that provides LCIs and/or conducts life-cycle analysis (LCA) of existing Li chemical production from sedimentary clays. However, some of the above-mentioned companies involved in clay-based projects have provided their expected material and energy inputs procured from external suppliers for Li chemical production in their techno-economic feasibility/assessment reports (Ausenco Services 2018; Roth et al. 2022; ABTC 2023). We use these details to provide the LCIs for these clay-based projects in the updated GREET model (see the Li_Chemicals tab in GREET2 Excel). Table 12 provides these LCIs as obtained from the corresponding reports of different companies.

4.2. Brine-Based Production via DLE

Our prior report on DLE-based projects (Iyer and Kelly 2022) reported an existing study on LCA of Li chemical production via this route in literature (Huang et al. 2021) that was incorporated into the GREET 2022 model (Wang et al. 2022). At that point in time, this was the only LCI available in the public domain on this subject. Since then, a few companies have published their expected material and energy procurement and use quantities for their respective projects (Worley 2019; Compass Minerals International Inc. 2021; APEX Geoscience Ltd. et al. 2021; Compass Minerals 2022b). We provide these LCIs for DLE-based projects in the updated GREET model (shaded section in Li_Chemicals sheet of GREET2), alongside the earlier LCI on this subject from academic literature (Huang et al. 2021). Table 12 provides these LCIs as obtained from the reports on brine-based projects of different companies when available.

Table 12: Life-cycle inventory (LCI) of Li chemical production from sedimentary clays and brines (via DLE route)

Material & Energy Inputs for Li chemical production	**Li_2CO_3**					**$LiOH.H_2O$**	
	Sedimentary clays			**DLE**		**DLE**	
	Project 1: Thacker Pass	**Project 2: Lithium Flats**	**Project 3: Sonora Lithium**	**Project 4: Ogden (East)**	**Project 5: Standard Lithium**	**Project 6: Ogden (West)**	**Project 7: Standard Lithium**
Material Inputs (ton/ton of product)							
HCl	0.007			0.07	1.8	0.06	0.81
PVDF							
Na_2CO_3	3.7	2.0	2.3	1.67	0.08	1.2	
CaO	2.1	5.4				0.83	
H_2SO_4			0.97				
$CaCO_3$	6.52	4.9	3.85				
NaOH	0.05		0.26	0.7	0.78	0.48	
NH_3	0.005				1.04		
$FeSO_4$	0.003						
$Al_2(SO4)_3$			0.4				
Sulfur	9.814	20.6					
Water	3.3	172			125		5.53
Gypsum ($CaSO_4.2H_2O$)			9.2				
Carbon dioxide (CO_2)						0.04	0.005
Methanol							
NH_4OH							0.87
Nitrogen							11.38
Lithium titanate							0.008
Energy Inputs (mmBtu/ton of product)							
Diesel	8.172						
Gasoline	0.14						
Natural gas		127.65	85.92	112.126	7.874	139.223	11.384
Propane	0.674						

Material & Energy Inputs for Li chemical production	Li_2CO_3					$LiOH.H_2O$	
	Sedimentary clays			DLE		DLE	
	Project 1: Thacker Pass	Project 2: Lithium Flats	Project 3: Sonora Lithium	Project 4: Ogden (East)	Project 5: Standard Lithium	Project 6: Ogden (West)	Project 7: Standard Lithium
Energy Inputs (mmBtu/ton of product)							
Electricity (on-site)[a]	19.096	76.721	10.674				
Electricity (Grid)	32.675			6.188	22.958	5.349	16.410

[a] This refers to electricity that will be generated on-site by the sulfuric acid plant and will be used to meet the electricity needs of the entire plant setup, as well as exported to the grid if excess power is generated. Grid-based electricity may be imported if necessary.

5. Conclusions and Future Work

A secure, stable Li supply chain is critical to the United States' decarbonization goals in light of the expected many-fold increase in global battery demand over the next few decades. This has led to a sharper focus on domestic Li extraction from all possible sources, including brines and sedimentary clays that were traditionally ignored for their poor economic prospects for Li chemical production due to low Li content. The deployment of innovative production routes for Li chemical production from these resources (e.g., direct lithium extraction for brines) is in progress across multiple projects in the United States and North America. However, given that batteries can use clean energy as an environment-friendly alternative to fossil fuels, this shift to domestic Li must be analyzed for its environmental performance and compared with conventional spodumene and high Li content brine counterparts.

In this report, we discussed the prominent domestic commercial initiatives on Li extraction from low Li content brines (via DLE) and sedimentary clays within the U.S. and North America. For each project, we listed its location, resource potential, expected production levels, and year in which the project will be initiated, as well as other important specifics for each project. While this is the first-ever publication of its kind for Li-based sedimentary clays, we also updated the current project status for DLE-based projects that were studied in an earlier report. Additionally, we provide a detailed LCI for Li chemical production from both clays and DLE brines, based on data published by the concerned commercial entities as part of their (techno)-economic assessment studies. This LCI is used to estimate the energy use and emissions of Li chemical production from these resources in the GREET 2023 model.

Future efforts are needed to improve this inventory and make it more comprehensive by accounting for other inputs that may not have been provided in these economic assessment studies, as they are internal to the plant (i.e., they may be produced internally). Further, DLE brines often assume the use of geothermal energy and/or produce other products in addition to Li chemicals that may be economically viable. The exact pathways used in these processes are not always clearly provided, which creates challenges in developing a complete understanding of Li chemical production from these resources. Addressing these limitations can help provide a detailed, accurate, and holistic picture of environmental impacts stemming from Li chemical production from these alternative resources compared to their conventional spodumene and brine counterparts.

6. References

ABH Engineering. 2021. *Preliminary Economic Assessment Zeus Project.* https://noramlithiumcorp.com/site/assets/files/3911/noram_lithium_zeus_pea_dec_2021-min.pdf.

American Battery Technology Company (ABTC). 2023c. *Technical Report Summary For The Tonopah Flats Lithium Project, Esmeralda and Nye Counties, Nevada, USA*. https://americanbatterytechnology.com/wp-content/uploads/ABTC-TonopahFlats_InferredResourceReport_SK1300.pdf.

ABTC. 2023b. "Tonopah Flats Lithium Project." https://americanbatterytechnology.com/projects/tonopah-flats/.

American Battery Technology Company (ABTC). 2023a. "The Future Starts Today." https://americanbatterytechnology.com/about-us/.

American Lithium Corp. 2023a. "Enabling the New Energy Paradigm." https://americanlithiumcorp.com/.

American Lithium Corp. 2023b. "TLC Lithium Project ('TLC') Nevada." https://americanlithiumcorp.com/tlc-lithium-project/.

American Lithium Corp. 2023c. "American Lithium files TLC PEA Report Highlighting Potential for Excellent Project Economics PFS for TLC Immediately Launched with DRA Global; Bulk Sampling Commenced." https://americanlithiumcorp.com/american-lithium-files-tlc-pea-report-highlighting-potential-for-excellent-project-economics-pfs-for-tlc-immediately-launched-with-dra-global-bulk-sampling-commenced/.

American Lithium Corp. 2023d. "American Lithium Announces Positive Preliminary Economic Assessment for TLC, Base Case – After-tax NPV8% US$3.26 Billion & After-tax IRR of 27.5%." https://americanlithiumcorp.com/american-lithium-announces-positive-preliminary-economic-assessment-for-tlc-base-case-after-tax-npv8-us3-26-billion-after-tax-irr-of-27-5/.

APEX Geoscience. 2021. *Preliminary Economic Assessment of SW Arkansas Lithium Project: NI 43-101 Report*. https://www.apexgeoscience.com/knowledge/resource-technical-report/standard-lithium-ltd-preliminary-economic-assessment-of-sw-arkansas-lithium-project-national-instrument-43-101-technical-report-prepared-for-standard-lithium-ltd/

Arizona Lithium. 2023a. "Central to America’s Lithium Future: Developing a clean, low-cost lithium resource." https://www.arizonalithium.com/.

Arizona Lithium. 2023b. "Big Sandy Lithium Project." https://www.arizonalithium.com/big-sandy/.

Arizona Lithium. 2023c. "Lordsburg Lithium Project." https://www.arizonalithium.com/lordsburg-lithium/.

ASX Investor. 2022. "The 2nd Largest Lithium Resource In America – Jindalee JRL." https://www.youtube.com/watch?v=wibMVo7Wb5E.

Ausenco Services Pty Ltd. 2018. *Technical Report on the Feasibility Study for the Sonora Lithium Project, Mexico*. https://bacanoralithium.com/_userfiles/pages/files/documents/bacanorafstechnicalreport25012018_compressed.pdf.

Bacanora Lithium. 2023a. "Sonora Lithium Project – Overview." https://bacanoralithium.com/sonora_lithium_project/default.aspx.

Bacanora Lithium. 2023b. "About Us." https://bacanoralithium.com/about/default.aspx.

Blois, M., D.S. Weber, E. Burga, and V. Sawyer. 2018. *NI 43-101 Technical Report: Preliminary Economic Assessment of the Clayton Valley Lithium Project - Esmeralda County, Nevada.* https://minedocs.com/17/PureEnergy_ClaytonValley_PEA-2017.pdf.

Century Lithium Corp. 2023a. "About Century Lithium." https://www.centurylithium.com/corporate/about/.

Century Lithium Corp. 2023b. "Clayton Valley Lithium Project." https://www.centurylithium.com/projects/clayton-valley-lithium-project/.

Compass Minerals. 2022a. "Compass Minerals Announces Selection of Direct Lithium Extraction DLE Technology Provider, Attractive Economics and Positive Sustainability Profile for First Phase of Lithium Project." News release. September 14, 2022. https://investors.compassminerals.com/investors-relations/investor-news/press-release-details/2022/Compass-Minerals-Announces-Selection-of-Direct-Lithium-Extraction-DLE-Technology-Provider-Attractive-Economics-and-Positive-Sustainability-Profile-for-First-Phase-of-Lithium-Project/default.aspx.

Compass Minerals. 2022b. *Technical Report Summary: Updated Initial Assessment Lithium and LCE Mineral Resource Estimate.* http://q4live.s22.clientfiles.s3-website-us-east-1.amazonaws.com/834578860/files/doc_downloads/2022/09/CMP-Ex96.1-Revised-Ogden-Lithium-Technical-Report-Summary.pdf.

Compass Minerals. 2023. "Sustainable, Secure Domestic Lithium." https://www.compassminerals.com/what-we-do/lithium.

Controlled Thermal Resources. 2023a. "CTR Q1 Update." https://www.cthermal.com/latest-news/ctr-q1-update.

Controlled Thermal Resources. 2023b. "California Governor Gavin Newsom visits CTR's Hell's Kitchen in Imperial County's 'Lithium Valley.'" News release. March 20, 2023. https://www.cthermal.com/latest-news/california-governor-gavin-newsom-visits-ctrs-hells-kitchen-in-imperial-countys-lithium-valley.

Deslandes, Ann. 2022. "Lithium in Mexico: a mirage in the desert?" *Diálogo Chino*, September 23, 2022. https://dialogochino.net/en/extractive-industries/58718-mexico-lithium-bacanora-sonora-a-mirage-in-the-desert/.

EnergySource Minerals. 2021. "Lithium. Delivered." https://www.esminerals.com/.

Fayram, T.S., T.A. Lane, and J.J. Brown. 2021. *NI 43-101 Technical Report - Prefeasibility Study Clayton Valley Lithium Project Esmeralda County, Nevada.* https://www.centurylithium.com/_resources/technical-reports/cyp_pfs_amended_march_15th-2021.pdf.

Global Resource Engineering Ltd. 2022. *Preliminary Economic Assessment NI 43-101 Technical Report: Bonnie Claire Lithium Project*. https://nevadalithium.com/wp-content/uploads/2023/08/Bonnie-Claire_PEA-Technical-Report_02-25-2022.pdf.

Grant, Alex. 2019. "The Sedimentary Lithium Opportunity." https://www.jadecove.com/research/sedimentarylithium.

Huang, T.Y., J.R. Pérez-Cardona, F. Zhao, J.W. Sutherland, and M.P. Paranthaman. 2021. "Life Cycle Assessment and Techno-Economic Assessment of Lithium Recovery from Geothermal Brine." *ACS Sustain Chem & Eng* 9: 6551–6560. https://doi.org/10.1021/ACSSUSCHEMENG.0C08733.Li

Ioneer USA Corp. 2023a. "Rhyolite Ridge Project." https://www.ioneer.com/projects/about-rhyolite-ridge/.

Ioneer. 2023b. "Mining & Processing." https://www.ioneer.com/projects/about-rhyolite-ridge/mining-processing/.

Ioneer. 2023c. "Processing Facilities." https://www.ioneer.com/projects/about-rhyolite-ridge/processing-facilities/.

Ioneer. 2021. Rhyolite Ridge Project: US Source of Lithium & Boron for a Sustainable Future. Presented at RIU Resources Round-up Conference, Sydney. https://www.youtube.com/watch?v=sexhXqkZpKM.

Ioneer. 2020a. *Rhyolite Ridge Lithium-Boron Project: Definitive Feasibility Study DFS. Report*. https://www.ioneer.com/wp-content/uploads/2022/07/300420-dfs-executive-summary-metric_final.pdf.

Ioneer. 2020b. "Reserves & Resources." https://www.ioneer.com/projects/about-rhyolite-ridge/reserves-resources/.

Ioneer. 2019. "Rhyolite Ridge Lithium-Boron Project." https://www.youtube.com/watch?v=cUHBc3JQl6w.

Iyer, R.K., and J.C. Kelly. 2022. *Lithium Production from North American Brines*. https://doi.org/10.2172/1891626.

Jamsmie, Cecilia. 2022. "Mexico nationalizes lithium mining." *Mining.com*, April 21, 2022. https://www.mining.com/mexico-passes-mining-reform-nationalizing-lithium/.

Jindalee Resources Ltd. 2023a. "Commodities." https://www.jindalee.net/site/projects/commodities.

Jindalee Resources Ltd. 2023b. "McDermitt Lithium." https://www.jindalee.net/site/projects/usa/us-lithium.

Jindalee Resources Ltd. 2023c. "Corporate Presentation." https://www.jindalee.net/site/pdf/b8f35cae-ddcc-4c1b-9860-598c24ea5bff/Corporate-Presentation.pdf.

Jindalee Resources Ltd. 2023d. "Preferred Lithium Extraction Process for McDermitt Project." https://www.jindalee.net/site/pdf/401ab05b-e1fd-4fe2-a8b6-6798a72ad4b5/Preferred-Lithium-Extraction-Process-for-McDermitt-Project.pdf.

Jindalee Resources Ltd. 2023e. "Clayton North." https://www.jindalee.net/site/projects/usa/clayton-north.

Jindalee Resources Ltd. 2023f. *Annual Report 2022*. https://www.jindalee.net/site/pdf/5a40ac0b-268c-493a-af69-d36f003ec56b/2022-Annual-Report-to-Shareholders.pdf

Lilac Solutions. 2023. "New extraction methods." https://lilacsolutions.com/technology/.

Lithium Americas. 2023. "Thacker Pass." https://www.lithiumamericas.com/usa/thacker-pass/.

Meshram, P., B.D. Pandey, and T.R. Mankhand. 2014. "Extraction of lithium from primary and secondary sources by pre-treatment, leaching and separation: A comprehensive review." *Hydrometallurgy* 150: 192–208. https://doi.org/10.1016/J.HYDROMET.2014.10.012.

Miatto, A., B.K. Reck, J. West, and T.E. Graedel. 2020. "The rise and fall of American lithium." *Resources, Conservation and Recycling* 162: 105034. https://doi.org/10.1016/J.RESCONREC.2020.105034.

Nevada Lithium. 2023a. "Iconic Minerals and Nevada Lithium Enter into Letter of Intent to Consolidate 100% Ownership Interest in the Bonnie Claire Lithium Property, Nevada." News release. January 9, 2023. https://nevadalithium.com/news-2023/iconic-minerals-and-nevada-lithium-enter-into-letter-of-intent-to-consolidate-100-ownership-interest-in-the-bonnie-claire-lithium-property-nevada/.

Nevada Lithium. 2023b. "Bonnie Claire Project." https://nvlithium.com/bonnie-clair-project/.

Noram Lithium. 2023a. "About Noram Lithium Corp." https://noramlithiumcorp.com/corporate/overview/.

Noram Lithium. 2023b. "Zeus Lithium Project." https://noramlithiumcorp.com/resource/clayton-valley/.

Noram Lithium. 2023c. "Resources." https://noramlithiumcorp.com/resource/clayton-valley/resources-1/.

Peek, B.C. 2021. *NI 43-101 Technical Report.Updated Lithium Mineral Resource Estimate, Zeus Project, Clayton Valley, Esmeralda County, NV, USA*. https://noramlithiumcorp.com/site/assets/files/3886/2021-09-21-ni-43-101-report.pdf.

Pell, R., L. Tijsseling, K. Goodenough, F. Wall, Q. Dehaine, A. Grant, D. Deak, X. Yan, and P. Whattoff. 2021. "Towards sustainable extraction of technology materials through integrated approaches." *Nature Reviews Earth & Environment* 2: 665–679. https://doi.org/10.1038/s43017-021-00211-6.

Piedmont Lithium. 2023. "Lithium Demand Is Positively Electric." https://piedmontlithium.com/.

Proactive Investors. 2021. "Jindalee Resources' McDermitt lithium project 'is a monster and is only going to get bigger.'" https://www.youtube.com/watch?v=lseFc4YNwyw.

Pure Energy Minerals. 2023a. "Pure Energy Minerals and SLB Receive Key Permits for DLE Pilot Plant at Clayton Valley Lithium Project, Nevada." News release. March 28, 2023. https://pureenergyminerals.com/pure-energy-minerals-and-slb-receive-key-permits-for-dle-pilot-plant-at-clayton-valley-lithium-project-nevada/.

Pure Energy Minerals. 2023b. "Projects: Clayton Valley." https://pureenergyminerals.com/projects1/.

Reuters. 2023. "Mexico's Lopez Obrador orders ministry to step up lithium nationalization." *Reuters,* February 18, 2023. https://www.reuters.com/world/americas/mexicos-lopez-obrador-orders-ministry-step-up-lithium-nationalization-2023-02-19/.

RioTinto, 2023. "Rio Tinto achieves battery grade lithium production at Boron plant." News release. April 7, 2021. https://www.riotinto.com/news/releases/2021/Rio-Tinto-achieves-battery-grade-lithium-production-at-Boron-plant.

Roth, D., L. Tahija, E. Iasillo, K. Martina, B. Chow, W. Mutler, K. Bahe, P. Kaplan, T. Cluff, and B. Shannon. 2022. *Lithium Americas: Feasibility Study - National Instrument 43-101 Technical Report for the Thacker Pass Project.* https://minedocs.com/19/Thacker-Pass-FS-11022022.pdf.

Stantec Consulting Ltd. 2020. *Technical Report: TLC Property, Nye County, Nevada, USA*. https://americanlithiumcorp.com/wp-content/uploads/2021/05/NI-43-101-Technical-Report_May-4_Final.pdf.

Stringfellow, W.T., and P.F. Dobson. 2021. "Technology for the Recovery of Lithium from Geothermal Brines." *Energies* 14: 6805. https://doi.org/10.3390/EN14206805.

Swain, B. 2017. "Recovery and recycling of lithium: A review." *Separation and Purification Technology*. 172: 388–403. https://doi.org/10.1016/J.SEPPUR.2016.08.031.

White House. 2022. "Biden-Harris Administration Driving U.S. Battery Manufacturing and Good-Paying Jobs." Fact sheet. October 19, 2022. https://www.whitehouse.gov/briefing-room/statements-releases/2022/10/19/fact-sheet-biden-harris-administration-driving-u-s-battery-manufacturing-and-good-paying-jobs/.

Tran, T., and V.-T. Luong. 2015. "Lithium Production Processes." In *Lithium Process Chemistry: Resources, Extraction, Batteries, and Recycling*, edited by A. Chagnes and J. Światowska, 81–124. http://dx.doi.org/10.1016/B978-0-12-801417-2.00003-7.

U.S. Borax. 2023. "About Us." https://www.borax.com/about.

U.S. Department of Energy (DOE). 2022a. "Biden-Harris Administration Awards $2.8 Billion to Supercharge U.S. Manufacturing of Batteries for Electric Vehicles and Electric Grid." News release. October 19, 2022. https://www.energy.gov/articles/biden-harris-administration-awards-28-billion-supercharge-us-manufacturing-batteries.

U.S. DOE. 2020. *Critical Minerals and Materials: U.S. Department of Energy's Strategy to Support Domestic Critical Mineral and Material Supply Chains FY 2021-FY 2031*. https://www.energy.gov/sites/prod/files/2021/01/f82/DOE%20Critical%20Minerals%20and%20Materials%20Strategy_0.pdf.

U.S. DOE. 2022b. "DOE Invests Millions in America's Massive Lithium-Production Potential." News release. November 11, 2022. https://www.energy.gov/articles/doe-invests-millions-americas-massive-lithium-production-potential.

U.S. Geological Survey (USGS). 2022a. "U.S. Geological Survey Releases 2022 List of Critical Minerals." News release. February 22, 2022. https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals.

USGS. 2022b. *Mineral Commodity Summaries 2022*. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022.pdf

Whitaker, B. 2023. "Lithium extraction coming to CA as U.S. auto industry goes electric." *CBS News*, May 7, 2023. https://www.cbsnews.com/news/lithium-extraction-california-electric-vehicle-batteries-60-minutes-transcript-2023-05-07/.

Worley. 2019. *NI 43-101 Technical Report: Preliminary Economic Assessment of LANXESS Smackover Project*. https://www.sec.gov/Archives/edgar/data/1537137/000119312521204052/d194326dex991.htm.

Zhao, H., Y. Wang, and H. Cheng. 2023. "Recent advances in lithium extraction from lithium-bearing clay minerals." *Hydrometallurgy* 217:106025. https://doi.org/10.1016/J.HYDROMET.2023.106025

Energy Systems and Infrastructure Analysis
Argonne National Laboratory
9700 South Cass Avenue, Bldg. *#
Lemont, IL 60439

www.anl.gov