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News & Highlights

Booming Demand for Lithium Drives Extraction Innovation

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As the world races to electrify everything from vehicles to energy grids, demand for lithium—a key ingredient in lithium-ion batteries (LIB)—has exploded. Yet conventional lithium mining has long carried a heavy environmental toll, including massive water usage, toxic chemical processes, and significant land disruption. Now, scientists and engineers across the globe are pioneering innovative direct lithium extraction (DLE) techniques, including electrochemical separation methods, that promise to supply lithium more efficiently and with far less environmental harm.

"There will be no energy transition without lithium," said Alexandre Chagnes, professor of chemistry at the University of Lorraine in Nancy, France, and an expert in LIB chemistry. "We need ways to store energy, and today's choice is lithium-ion batteries."

To meet climate change mitigation goals, the annual demand for lithium is expected to increase by 15 times between 2020 and 2040, from 74 to 1160 kt (Fig. 1) [1]. Some forecasts suggest that existing lithium supplies may be insufficient to meet demand as early as 2029, even with the completion of numerous mining projects currently underway [2]. Furthermore, under current projections, the demand for the battery sector alone could exhaust 74% to 248% of existing lithium reserves by 2050, underscoring the need to secure sustainable sources of lithium [3].

As for supply, the US Geological Survey estimates that global lithium reserves from known sources total around 105 million tonnes, of which 28 million tonnes can be economically extracted with current technologies [4]. However, the standard ways of obtaining lithium—largely from brine evaporation in South America's "Lithium Triangle" of Argentina, Bolivia, and Chile and hard rock mining in Australia (Fig. 2)—have proven increasingly problematic for environmental reasons [5].

In brine extraction, lithium-rich water is pumped from underground caverns to the surface and into massive evaporation ponds (Fig. 3), where it sits for up to two years [5]. As the water evaporates, the lithium in it concentrates, eventually to be collected. This process requires vast quantities of water—more than 1.9 million liters per tonne of lithium produced [6]—often in arid regions where water is scarce. It can also lead to groundwater contamination and depletion of freshwater aquifers, adversely affecting local communities and biodiversity [5]. While it can deliver lithium more quickly, hard rock mining requires blasting through tonnes of rock and processing ore with chemicals and heat. The process

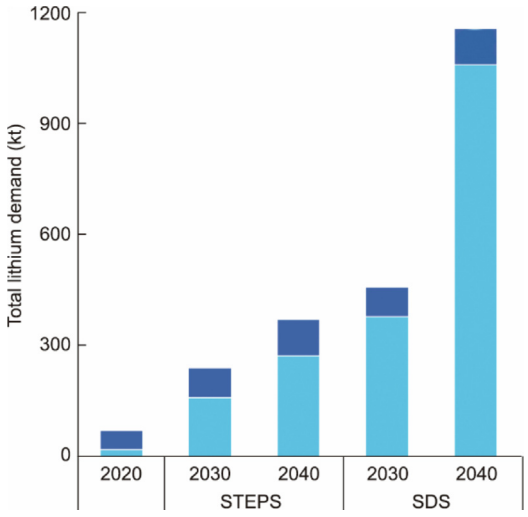

Fig. 1. Under the International Energy Agency (IEA)'s Sustainable Development Scenario (SDS)—defined as an integrated approach to achieving internationally agreed objectives on climate change, air quality, and universal access to modern energy—demand for lithium will grow from 74 kt in 2020 to 1160 kt in 2040, mostly for electric vehicles and energy storage (light blue) [1]. STEPS: Stated Policies Scenario. Credit: IEA (CC BY 4.0).

Fig. 2. The Greenbushes mine in Western Australia is the largest hard rock lithium mine in the world, producing 1.95 million tonnes of lithium spodumene annually. Credit: Calistemon/Wikimedia (CC BY-SA 4.0).

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Fig. 3. This satellite image shows three groups of lithium evaporation ponds in Chile's Salar de Atacama region. The area's groundwater brines contain the highest-known concentrations of lithium in the world. Each group of ponds measures approximately 9 km across at its widest point. Credit: Earth Observatory/NASA (public domain).

is carbon-intensive, land-destructive, and generates mine tailings that can leach toxins.

Due to concerns about environmental destruction, lawsuits against lithium mining companies have proliferated globally [7]. People in Argentina and Chile have protested lithium mining citing water scarcity, land contamination, and the lack of informed consent from Indigenous groups [8,9].

Responding to these problems, the European Union has proposed new regulations requiring lithium imports to meet environmental and social standards [10]. At the same time, the US Department of Energy has funded DLE projects with billions of USD as part of a push to expand domestic minerals production [11]. Auto manufacturers, too, are supporting cleaner lithium extraction. Tesla (Austin, TX, USA), General Motors (Detroit, MI, USA), and Bavarian Motor Works (Munich, Germany) have all signed deals with companies that promise low-impact lithium production [12–14].

The same concerns, in addition to the looming increased demand, have driven research aimed at developing DLE technologies. Unlike evaporation-based mining, DLE extracts lithium directly from brine using chemical processes, enabling faster and cleaner production. "With DLE, we do not have to wait a year for evaporation," Chagnes said. "Instead, we use reagents to extract lithium directly from the brine."

These reagents can include solid absorbents with a high affinity for lithium or solvents for liquid–liquid extraction. "With DLE, you are not heating anything. You use electricity to pump and process, which consumes far less energy," Chagnes said. "And if you are in sunny regions like Argentina and Chile, you can use photovoltaic panels to generate that electricity."

And unlike evaporation ponds, which leave behind enormous amounts of salt waste, DLE systems can reinject the lithium-depleted brine back into the ground. "You continuously pump, process, and reinject," Chagnes said.

Possibly offering even greater environmental benefits are membrane-based and electrochemical methods at the cutting edge of DLE science. These technologies are not just greener; they are also faster. Such DLE processes can capture lithium in hours or days, making production more responsive to market demand.

One example comes from a lab at Stanford University (Palo Alto, CA, USA). The Stanford group has developed a high-selectivity membrane to separate lithium from other cations in the brine [15]. The method uses electricity to move lithium through a solid-state electrolyte membrane from water with a low lithium concentration to a more concentrated, high-purity solution. Each of a series of cells increases the lithium concentration to a solution from which isolating the final chemical is relatively easy. The approach uses less than 10% of the electricity required by absorbent- and solvent-based brine extraction and has a lithium selectivity of nearly 100%, making it highly efficient.

According to Ge Zhang, a lab member and postdoctoral scholar in Stanford's Department of Materials Science and Engineering, the system operates effectively in brines with high salinity, which is common in areas such as the Salton Sea in California, where the lithium concentration is lower compared to South America. "Many brines have a lower concentration of lithium, so they are not suitable for evaporation methods," Zhang said. "That is why alternative methods like ours are gaining attention."

Saudi Arabia, too, is betting on DLE innovations. At King Abdullah University of Science and Technology (KAUST) in Thuwal, Saudi Arabia, Zhiping Lai, professor of chemical engineering, and his team have developed a method to extract lithium even from ultra-low concentration sources, such as oil field wastewater and seawater [16,17]. In their method, iron phosphate electrodes selectively intercalate lithium from saltwater and then release it into freshwater. Charge balance is provided by silver oxidation and reduction at paired counter electrodes in each medium, keeping all other cations on the salt side. "We demonstrated our membrane technology using Red Sea water, which contains only 0.2 ppm lithium," Lai said. "The beauty is that we add only an electrical field, not any chemicals—there is no impact to the local environment."

While high-grade lithium sources are found in a few regions, low-grade resources such as geothermal fluids, oil field brine, and seawater are globally abundant. "The total amount of low-grade lithium is probably 100 or even 10 000 times higher than high-quality resources," Lai said. "If we can extract lithium from those sources, we could essentially provide unlimited amounts of energy storage to support global needs."

Lai's startup, Lithium Infinity (Thuwal, Saudi Arabia), recently launched a pilot facility with a 6 million USD investment from Ma'aden (Saudi Arabian Mining Company; Riyadh, Saudi Arabia) and the KAUST innovation fund [18]. "We identified oil field-produced water in Saudi Arabia that contains about 20 ppm of lithium. With our technology, we can produce up to 100 000 tonnes of lithium carbonate per year," Lai said. "That means we could build localized lithium supply chains in countries that lack high-quality brines."

In another innovative research effort, a research team at Nanjing University (China) was inspired by the ability of plants to selectively extract ion species during transpiration to develop a hierarchically structured solar transpirational evaporator [19]. The device creates a pressure gradient that extracts lithium from brines through a silica ceramic membrane, capturing it in a vascular storage layer. The researchers note that the process is inexpensive to operate because it works passively [19].

Outside of the lab, several companies are moving to commercialize DLE. Backed with 145 million USD from Bill Gates' Breakthrough Energy Ventures (Kirkland, WA, USA), Lilac Solutions (Oakland, CA, USA) has developed an ion-exchange technology that captures lithium using ceramic beads and returns the brine underground [20]. Lilac's pilot project at its Sydney, Australia-based lithium developer partner Lake Resources' Kachi site in Argentina has yielded promising results, achieving lithium recovery rates of

more than 80% in under three hours—a fraction of the year or more required using traditional evaporative methods [21].

EnergyX (Austin, TX, USA), another American firm, uses a combination of technologies—adsorption, solvent extraction, and selective membranes with both electrodialysis and selective bipolar electrodialysis—in its DLE system. The company claims its process can extract lithium with up to 94% efficiency while reducing costs by up to 50% and water usage by 90% compared to traditional evaporative extraction [22].

Despite their promise, the new extraction methods are not without challenges. Water consumption and residual waste remain problems that need better solutions, Chagnes said. "Even with DLE, you use water to recover the lithium from the reagent," he said. "We need to develop ways to recycle and minimize water use."

Reinjection of lithium-depleted brine into underground caverns also requires careful hydrological planning, Chagnes said. "If you do not reinject properly, you could change the water table—that could affect rivers, lakes, and local ecosystems." Another issue is dilution. Reinjecting the waste brine into the wrong part of the basin could reduce the concentration of lithium in the area you want to extract from, Chagnes said. "You need a detailed three-dimensional (3D) understanding of the sedimentary basin."

Even hard rock lithium mining is getting an eco-makeover. In Australia, where lithium is extracted from spodumene ore, companies are turning to electric mining fleets, on-site solar power, and chemical process improvements to reduce emissions and waste. Pilbara Minerals (West Perth, WA, Australia), for instance, has partnered with technology company Calix (San Jose, CA, USA) to trial a new kiln-based refining process. The method uses renewable energy to convert lithium ore to a more brittle and porous form that makes it easier to leach out lithium by heating the ore to a temperature of 900 °C. The companies say the process reduces CO_2 emissions by 80% to 90% compared to conventional methods [23]. Another company, Canada's Snow Lake Lithium (Winnipeg, MB, Canada), is designing what it claims will be the world's first all-electric lithium mine [24]. The company says the site, located in Manitoba, will use hydropower, electric drilling equipment, and sustainable transportation to deliver lithium with a minimal carbon footprint.

New technologies are also transforming the way lithium deposits are discovered. Exploration has long relied on costly, time-consuming geological surveys and drilling. However, startups like KoBold Metals (Berkeley, CA, USA)—another Breakthrough Energy Ventures-backed firm—aims to use artificial intelligence to identify promising lithium targets faster and with less environmental impact. The company claims its technology can identify unconventional lithium sources like geothermal brines, oilfield wastewater, and clay deposits by examining satellite imagery, soil samples, and historical records, thus minimizing invasive exploratory drilling [25].

The lithium economy could also become increasingly circular. Recycling technologies are making progress, offering the prospect of turning end-of-life LIB into new raw materials [26]. Companies like Redwood Materials (Carson City, NV, USA) have developed liquid–solid separation processes that recover lithium, cobalt, and nickel with about 95% efficiency. Redwood is currently building a processing center just east of Reno, NV, that will create battery cathode materials composed of 30% recycled nickel, 30% recycled lithium, and 100% recycled cobalt. The company says the center will eventually produce 20 GW·h of cathode materials every year. Once it has built four more planned centers in the United States and European Union (EU) countries, the company anticipates its annual output will be 100 GW·h, or enough to build batteries for an estimated 1.3 million electric vehicles [27].

While only 5% of LIB are currently being recycled [28], some experts believe that up to 50% of lithium demand could be met through recycling [29]. But in the short term, mining remains crucial and making that extraction more efficient and cleaner is a key objective. "Lithium is everywhere," Chagnes said. "We just have to be smarter about how we get it."

References

[1] International Energy Agency (IEA). The role of critical minerals in clean energy transitions. Report. Paris: IEA; 2021 May.

[2] Marjolin A. Lithium M&A involving assets with resources, H2′21–H1′22. New York City: S&P Global; 2022 Nov 22 [cited 2025 Jun 13]. Available from: https://www.spglobal.com/market-intelligence/en/news-insights/research/lithium-ma-involving-assets-with-resources-h221-to-h122.

[3] Pehlken A, Albach S, Vogt T. Is there a resource constraint related to lithium-ion batteries in cars? Int J Life Cycle Assess 2017;22:40–53.

[4] Jaskula B. Lithium. In: U.S. Geological Survey, editor. Mineral commodity summaries 2024. Reston: U.S. Geological Survey; 2024. p. 110–11.

[5] Yang S, Wang Y, Pan H, He P, Zhou H. Lithium extraction from low-quality brines. Nature 2024;636:309–21.

[6] The Environmental Impact of Lithium Batteries [Internet]. Washington, DC: Institute for Energy Research; 2020 Nov 12 [cited 2025 Jun 13]. Available from: https://www.instituteforenergyresearch.org/renewable/the-environmental-impact-of-lithium-batteries/.

[7] Lakhani N. Revealed: how US transition to electric cars threatens environmental havoc [Internet]. London: The Guardian; 2023 Jan 24 [cited 2025 Jun 13]. Available from: https://www.theguardian.com/us-news/2023/jan/24/us-electric-vehicles-lithium-consequences-research.

[8] Greenfield N. Lithium mining is leaving Chile's Indigenous communities high and dry (literally) [Internet]. New York City: National Resources Defense Council; 2022 Apr 26 [cited 2025 Jun 13]. Available from: https://www.nrdc.org/stories/lithium-mining-leaving-chiles-indigenous-communities-high-and-dry-literally.

[9] Chambers B. Environmental defenders join forces across Argentina to stop mining boom [Internet]. Brooklyn: Waging Nonviolence; 2023 Jan 11 [cited 2025 Jun 13]. Available from: https://wagingnonviolence.org/2023/01/environmental-defenders-argentina-stop-mining-boom/.

[10] Circular economy: new law on more sustainable, circular and safe batteries enters into force [Internet]. Brussels: European Commission; 2023 Aug 17 [cited 2025 Jun 13]. Available from: https://environment.ec.europa.eu/news/new-law-more-sustainable-circular-and-safe-batteries-enters-force-2023-08-17_en.

[11] Bradstock F. U.S. races towards lithium independence with ambitious mining projects [Internet]. London: Oilprice.com; 2024 Sep 28 [cited 2025 Jun 13]. Available from: https://oilprice.com/Metals/Commodities/US-Races-Towards-Lithium-Independence-with-Ambitious-Mining-Projects.html.

[12] Lambert F. Tesla explains its approach to sourcing lithium, nickel, and cobalt directly from mines in impressive detail [Internet]. Fremont: Electrek; 2022 May 9 [cited 2025 Jun 13]. Available from: https://electrek.co/2022/05/09/tesla-sourcing-lithium-nickel-cobalt-directly-mines-details/.

[13] Williment C. How is GM leading on sustainable EV battery technology? [Internet]. London: Electric Vehicle Magazine; 2025 Apr 16 [cited 2025 Jun 13]. Available from: https://evmagazine.com/articles/how-is-gm-leading-on-sustainable-ev-battery-technology.

[14] Schillmoeller S. BMW Group steps up sustainable sourcing of lithium for battery cell production to ensure rapid e-mobility expansion [Internet]. Munich: Bavarian Motor Works; 2021 Mar 30 [cited 2025 Jun 13]. Available from: https://www.press.bmwgroup.com/global/article/detail/T0328669EN/bmw-group-steps-up-sustainable-sourcing-of-lithium-for-battery-cell-production-to-ensure-rapid-e-mobility-expansion?language=en.

[15] Xu R, Xiao X, Zhang G, Ye Y, Zhang P, Yang Y, et al. Continuous lithium extraction from brine by efficient redox-couple electrodialysis. Matter 2024;7(11):3876–90.

[16] Li Z, Chen IC, Cao L, Liu X, Huang KW, Lai Z. Lithium extraction from brine through a decoupled and membrane-free electrochemical cell design. Science 2024;385(6716):1438–44.

[17] Li Z, Li C, Liu X, Cao L, Li P, Wei R, et al. Continuous electrical pumping membrane process for seawater lithium mining. Energy Environ Sci 2021;14:3152–319.

[18] KAUST startup Lihytech raises $6 million for lithium extraction from seawater [Internet]. Thuwal: King Abdullah University of Science and Technology; 2023 Jan 31 [cited 2025 Jun 13]. Available from: https://www.kaust.edu.sa/en/news/kaust-startup-lihytech-raises-6-million-for-lithium-extraction-from-seawater.

[19] Song Y, Fang S, Xu N, Wang M, Chen S, Chen J, et al. Solar transpiration–powered lithium extraction and storage. Science 2024;385(6716):1444–2149.

[20] Blois M. Lilac raises $145 million for US lithium project [Internet]. Washington, DC: Chemical Engineering News; 2024 Feb 14 [cited 2025 Jun 13]. Available from: https://cen.acs.org/energy/energy-storage-/Lilac-raises-145-million-US/102/i5.

[21] Lilac unveils latest generation lithium extraction technology [Internet]. Oakland: Lilac Solutions; 2024 Jun 25 [cited 2025 Jun 13]. Available from: https://lilacsolutions.com/news/lilac-unveils-latest-generation-technology.

[22] Sparling C. EnergyX announces enhanced direct lithium extraction process [Internet]. Austin: EnergyX; 2023 Nov 10 [cited 2025 Jun 13]. Available from: https://energyx.com/press-release/dle-process/.

[23] Frost N. Australia tries to break its dependence on China for lithium mining [Internet]. New York City: The New York Times; 2023 May 23 [cited 2025 Jun 13]. Available from: https://www.nytimes.com/2023/05/23/business/australia-lithium-refining.html.
[24] Doll S. Snow Lake Lithium is developing the world's first all-electric lithium mine to support EV industry in North America [Internet]. Fremont: Electrek; 2022 Feb 10 [cited 2025 Jun 13]. Available from: https://electrek.co/2022/02/10/snow-lake-lithium-is-developing-the-worlds-first-all-electric-lithium-mine-to-support-ev-industry-in-north-america/.
[25] Goldman J, House K. This AI hunts for hidden hoards of battery metals [Internet]. New York City: IEEE Spectrum; 2023 Apr 29 [cited 2025 Jun 13]. Available from: https://spectrum.ieee.org/ai-mining.
[26] O'Neill S. Battery recycling challenge looms as electric vehicle business booms. Engineering 2021;7(12):1657–60.
[27] Stevens T. Recycled EV batteries are coming from redwood materials [Internet]. El Segundo: Motor Trend; 2024 Aug 22 [cited 2025 Jun 13]. Available from: https://www.motortrend.com/news/ev-battery-cathode-recycling-redwood-materials.
[28] Etude M, Ikeuba A, Njoku C, Yakuba E, Uzoma H, Mgbemere C, et al. Recycling lithium-ion batteries: a review of current status and future directions. Sustain Chem One World 2024;4:100027.
[29] Maisel F, Neef C, Marscheider-Weidemann F, Niseen N. A forecast on future raw material demand and recycling potential of lithium-ion batteries in electric vehicles. Resour Conserv Recycl 2023;192:106920.