EXECUTIVE SUMMARY

Critical Minerals: The Opportunity in Direct Lithium Extraction

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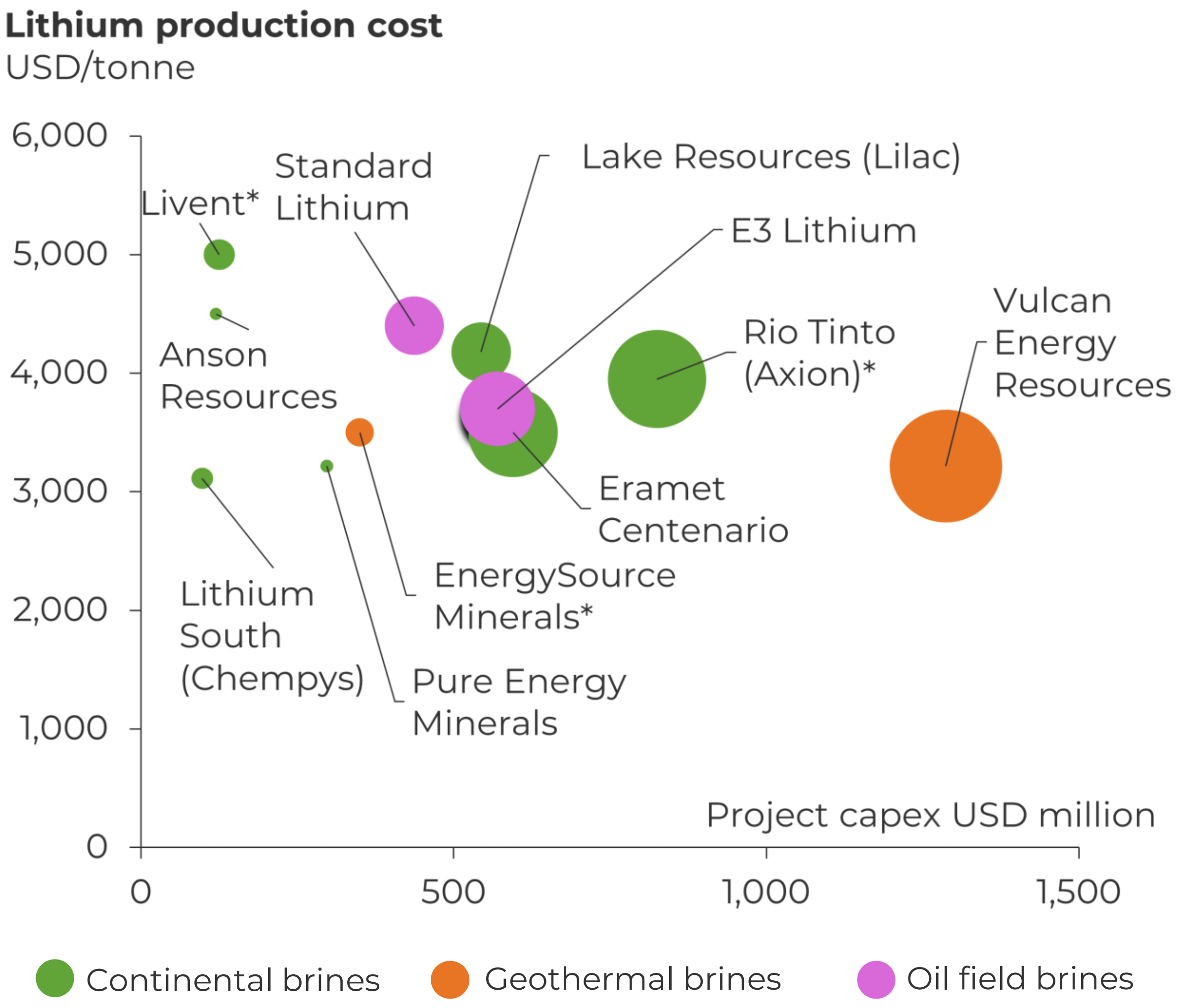
Lux Research | The Deciding Factor

Direct lithium extraction (DLE) will phase out evaporation as long-term pressure mounts on the battery supply chain



While DLE is not a new concept, finding the right partners will lead to success

The first commercial projects in DLE were mounted in the '90s, but current high prices of lithium and growing environmental concerns are driving new interest in the technology.

Improved DLE approaches, including next - generation adsorbents and ion exchange resins will unlock lithium brines that were previously uneconomical. This will help expand lithium supply, though painful shortages are still likely. In the long term, environmental concerns around the water and land impact of evaporation-based production will cause that approach to lithium production to be phased out in favor of DLE.

Clients can get involved to support this space with materials innovations or to build out lithium capacity. DLE is not a silver bullet, however — every brine is different, and upstream and downstream partners are needed to succeed in the risky lithium space.

Bubble size represents the size of the lithium asset.
*Estimated production cost based on similar projects or range provided by company.

Critical minerals play a crucial role in the energy transition

The convergence of political, economic, social, and technological drivers is accelerating the global energy transition. Lux's goal is to enable our clients to succeed in this transition by analyzing emerging issues like the availability of materials needed to meet carbon-neutrality targets.

Rising demand, disrupted supply chains, and concerns around shortages of lithium, cobalt, nickel, copper, and rare earths are driving prices to record highs, as more countries pursue deep decarbonization strategies through renewables and electrification. Like our previous report "Critical Minerals for the Hydrogen Economy," this report highlights the growing challenges in the lithium industry and their direct effect on the rollout of clean energy technologies.

This report focuses on the widening divide between lithium supply and demand and the emergence of new raw material extraction technologies to get this critical metal to market faster. Lithium supply chains not only affect battery producers and automakers, who are aggressively vertically integrating their operations to improve their margins, but they also create opportunities for chemicals companies, upstream energy players, and engineering and equipment providers. To help our clients navigate this space, we lay out a landscape of lithium production approaches and issues and analyze the competitiveness of emerging DLE techniques and unconventional lithium resources.

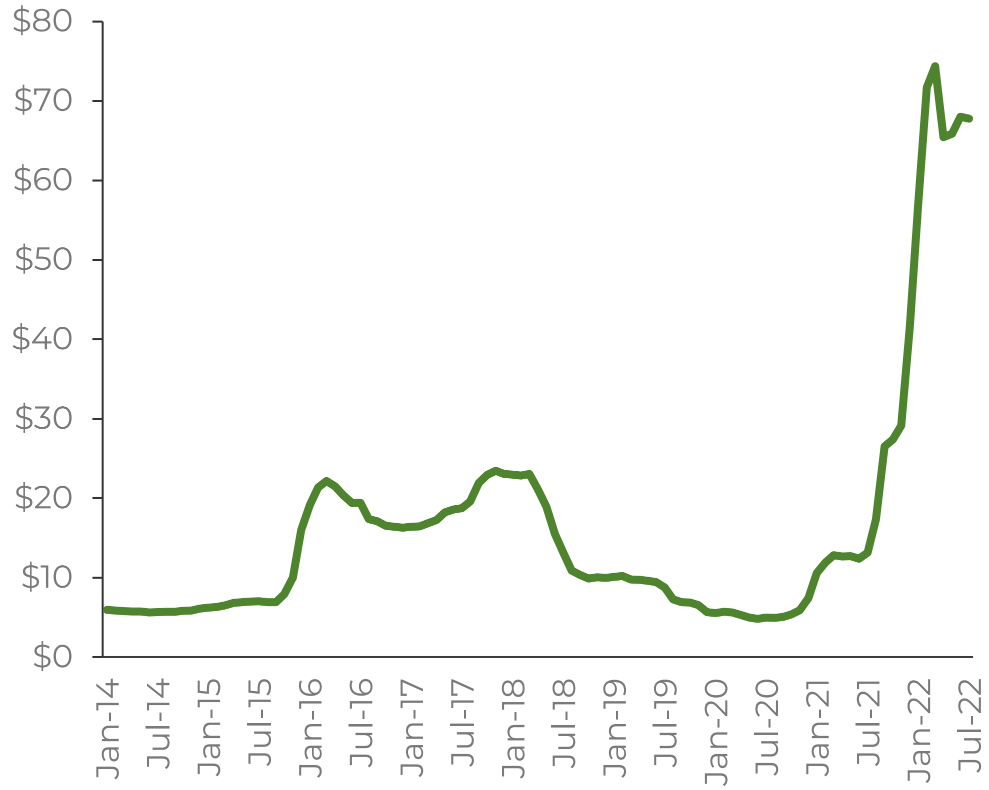
Lithium prices soar as miners haven't kept up with demand from electrification

In April 2022, lithium spot-market prices skyrocketed to a record USD 78,000/tonne primarily because of rising demand strongly supported by electrification goals in Europe, the U.S., and China and supply shortage due to underinvestment. Under pressure of rapid electrification strategies worldwide, the lithium supply gap is expected to rise to 2.4 Mtonne as soon as 2030. The soaring cost and growing scarcity raise questions of how countries will meet their net-zero-emissions deadlines to mitigate climate change. Growing energy prices, inflation, and other global headwinds have compounded the effect on the lithium market.

If the world is to meet COP26 goals of transitioning to zero-emission vehicles by 2040, the demand for the necessary minerals is projected to soar over the next two decades by over 40 times for lithium and by around 20 times for graphite, cobalt, and nickel (see the IEA forecast).

Lithium pricing and supply dynamics

Price thousand USD/tonne

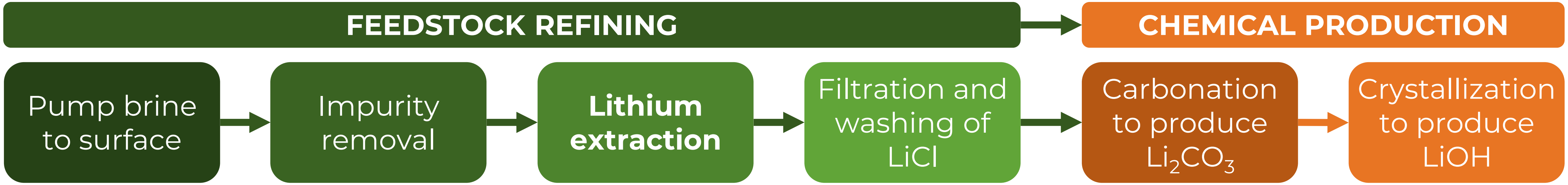


DLE targets the most problematic part of brine-based lithium production

Lithium is made in two main ways: hard-rock mining and conventional-brines extraction; production is dominated by South America and Australia. Hard-rock mining of lithium more closely resembles traditional metals mining, with miners focusing on pegmatite deposits to extract spodumene. A typical hard-rock mine ore contains around 1%–2% Li_2O (~20% spodumene). After processing, lithium concentrate ready for Li_2CO_3 production contains 6%–7% Li_2O (~80% spodumene).

Brine extraction begins with drilling at salars to access underground deposits. The brine is pumped to the surface to collect at evaporation ponds. Conventional brines (from South America) contain less than 0.3% to 0.4% lithium; concentration by evaporation takes 12 to 18 months.

Lithium extraction from brines
DLE replaces evaporation ponds in the **lithium extraction** step.



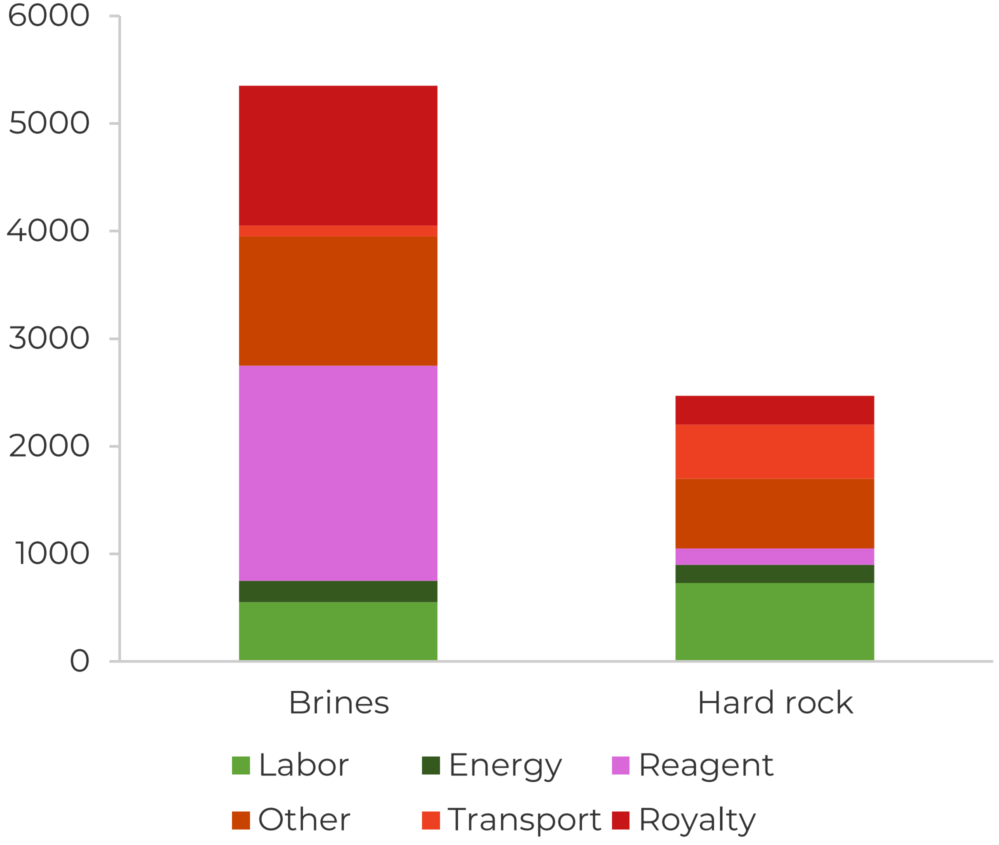
Brine processing is significantly more opex intensive, while hard-rock mining has higher capex demands

Brine production is less capital intensive than hard-rock mining. The lower capital cost of brine operations is largely due to the geography of salars, which require less geological exploration and development. However, hard-rock operations typically experience lower operating costs and have the edge on time-to-market. Reagents, which are chemical solvents used to precipitate lithium, typically compose a third of brine production opex. Royalties in the brine production jurisdictions are typically much higher than those paid by hard-rock miners.

There are also differences in the product. Brine processors make lithium carbonate while hard rock miners produce spodumene. Brine operators receive lithium carbonate equivalent contract prices or closer to market prices while hard-rock operators receive (generally lower) concentrate pricing. While the carbon footprint for hard-rock mining is nearly twice that of brine processing, extracting lithium from brines uses more water and is highly politicized in regions with higher water stress.

Estimated brine vs. hard-rock operational costs

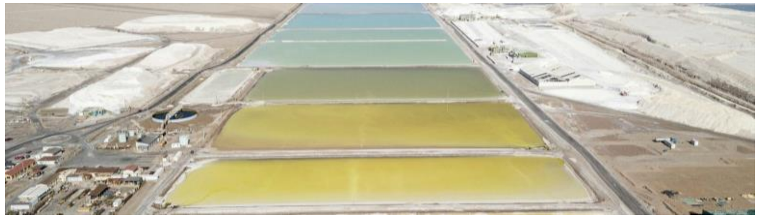
USD/Tonne $LiCO_3$ equivalent



Source: Lux Research, S&P Global Market Intelligence, National Renewable Energy Laboratory

DLE can target conventional and unconventional brines

Conventional Brines



Continental brines

Salars and salt pans in enclosed basins with lithium-enriched brines. These brines are some of the highest-grade brines in the world — 0.04% to 0.15% Li.

Stage of development

Continental brines are commercial today and predominantly located in South America. Salars in Argentina and Chile are operational, while brines in Bolivia are under development.

Unconventional Brines

Oil field brines

Also known as petrobrines, these oil and gas waste products are some of the lowest-grade brines, containing as little as 0.007% to 0.02% Li.

Stage of development

These are precommercial brines. Extracted in conjunction with oil and gas, typically found in the U.S. Smackover Formation and Canadian oil sands (Alberta).

Geothermal brines

These brines come out of the ground hot, which facilitates certain DLE processes. These are low-grade sources containing as little as 0.01% to 0.04% Li.

Stage of development

Developers are scaling up from pilot production. Brines are located in geothermally active areas in California and the Upper Rhine Valley of Germany and France.

DLE can reduce operational risk and expedite lithium supply to market

Time-to-market	A new evaporation-based brine resource requires anywhere between 12 and 18 months to get to market, not including the four- to five-year timeline to capitalize projects in the first place.
Environmental concerns	Concerns about hard-rock mining's high carbon footprint (around 15 tonne CO_2/tonne LiOH) and water loss to evaporation from traditional brines are forcing project developers to seek sustainable extraction processes. Mining companies already risk heavy fines on excess water use in South America.
Reducing operational risk	Traditional brine projects are highly weather dependent, which can further delay the already time-intensive evaporation process. DLE processes aren't weather dependent and operate continuously with shorter production time — days instead of months
Improved yield	DLE technologies can improve lithium recovery from 40% to 50% for evaporation ponds to over 85%. New lithium extraction processes can also commercialize low-grade lithium brines found in geothermal and other unconventional sources.

Activity in DLE is accelerating

1990s–2010s | 2012 | 2015 | 2020 | 2025

1995

Argentina, Livent (FMC)

First commercial DLE plant comes online in Hombre Muerto, Argentina ~20,000 tpa.

2008–2012

Simbol Materials

First lithium extraction pilot plant from geothermal resource in North America.

Simbol would go on to bankruptcy, but its IP is currently marketed by Terralithium.

2015–2022

Chinese players develop brine lakes in China

Commercial DLE projects commissioned between 2017 and 2020.

Jiagxi Ganfeng takes 49% stake in Qinghai Lake.

2018–2022

DLE startups raise funding

Multiple DLE companies including Lilac Solution, Mangrove Lithium, Summit Nanotech, EnergyX, Adionics and others raise hundreds of millions in growth funding.

2020–2022

Energy companies and automakers strike deals

After the first DLE pilots, upstream energy companies like Berkshire Hathaway and Occidental Petroleum and automakers like BMW invest in DLE startups and projects.

2022–2025

Commercial production

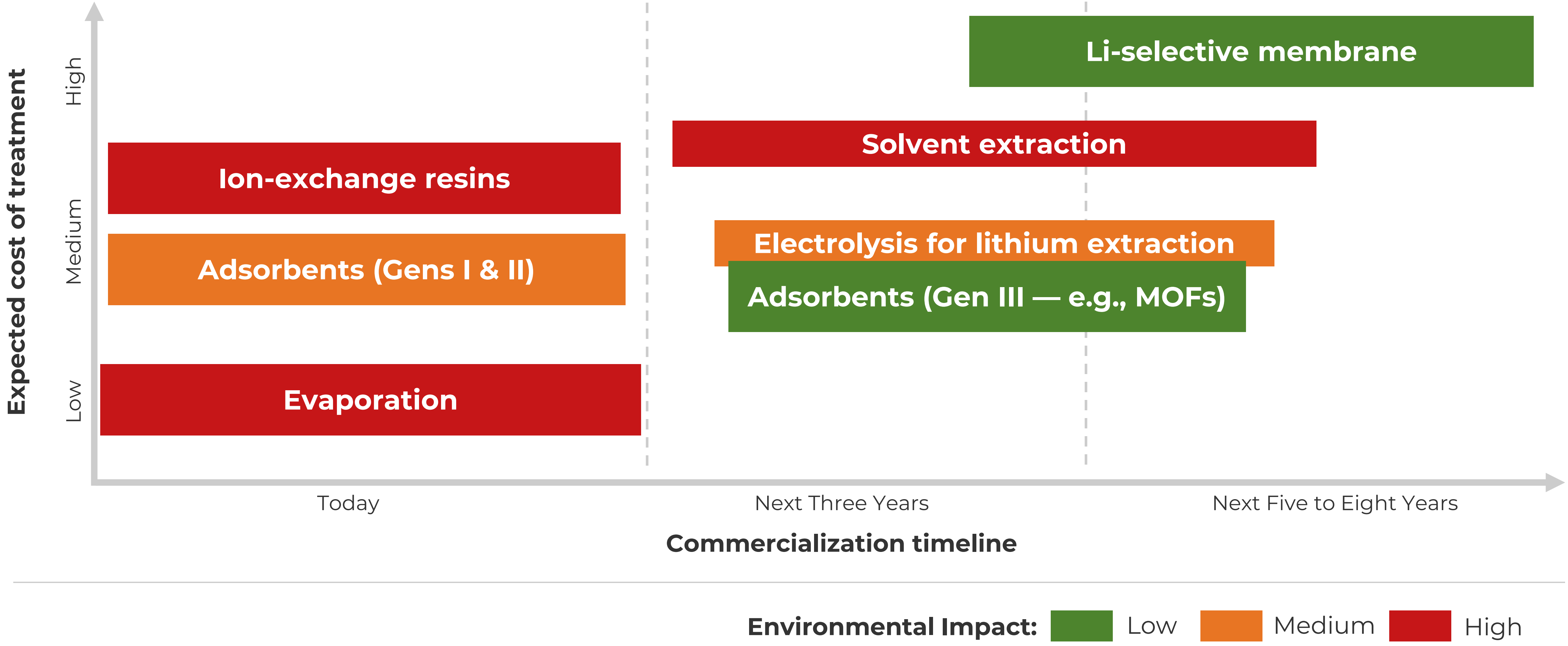
DLE projects led by lithium juniors like Lithium South and Lake Resources and some majors are slated to begin commercial production by 2025.

DLE technologies come in 5 main types

DLE comes in many approaches and scales. The main approaches are listed below:

- **Adsorbents:** Adsorbents physically capture LiCl molecules on their surface while water acts as a stripping solution. This technology is at commercial scale today and is used for brines in South America.
- **Ion-exchange resins:** Lithium ions in the brine are chemically adsorbed onto the ion-exchange material and swapped for other positive ions from the resin. Ion exchange uses acidic reagents like HCl to strip lithium. The technology is nearing commercialization for continental and geothermal brines.
- **Solvent extraction:** Not unlike the solvents used in hard-rock mining, DLE solvents are organic chemicals with adsorptive or ion-exchange capabilities that strip the brine of lithium to form either LiCl or lithium ions in solution. No commercial operations use solvents today, but the technology has been demonstrated in pilots.
- **Membranes:** Lithium extraction relies on membrane selectivity and pore size as brine is pushed across the membrane surface. It's an early stage technology with innovations in using metal organic frameworks (MOFs) infused with polymer substrates and chemically modified ion-exchange membranes. Companies testing membranes are currently in lab or early pilot testing.
- **Electrolysis:** Like membrane technology, electrolysis can extract lithium from brines using ion-selective membranes or adsorbents, but most companies will likely end up using electrolysis as a lithium-refining step to convert LiCl to LiOH and recycle water.

Adsorbents are the go-to-solution for DLE in the short to medium term, but next-generation technologies are on the horizon

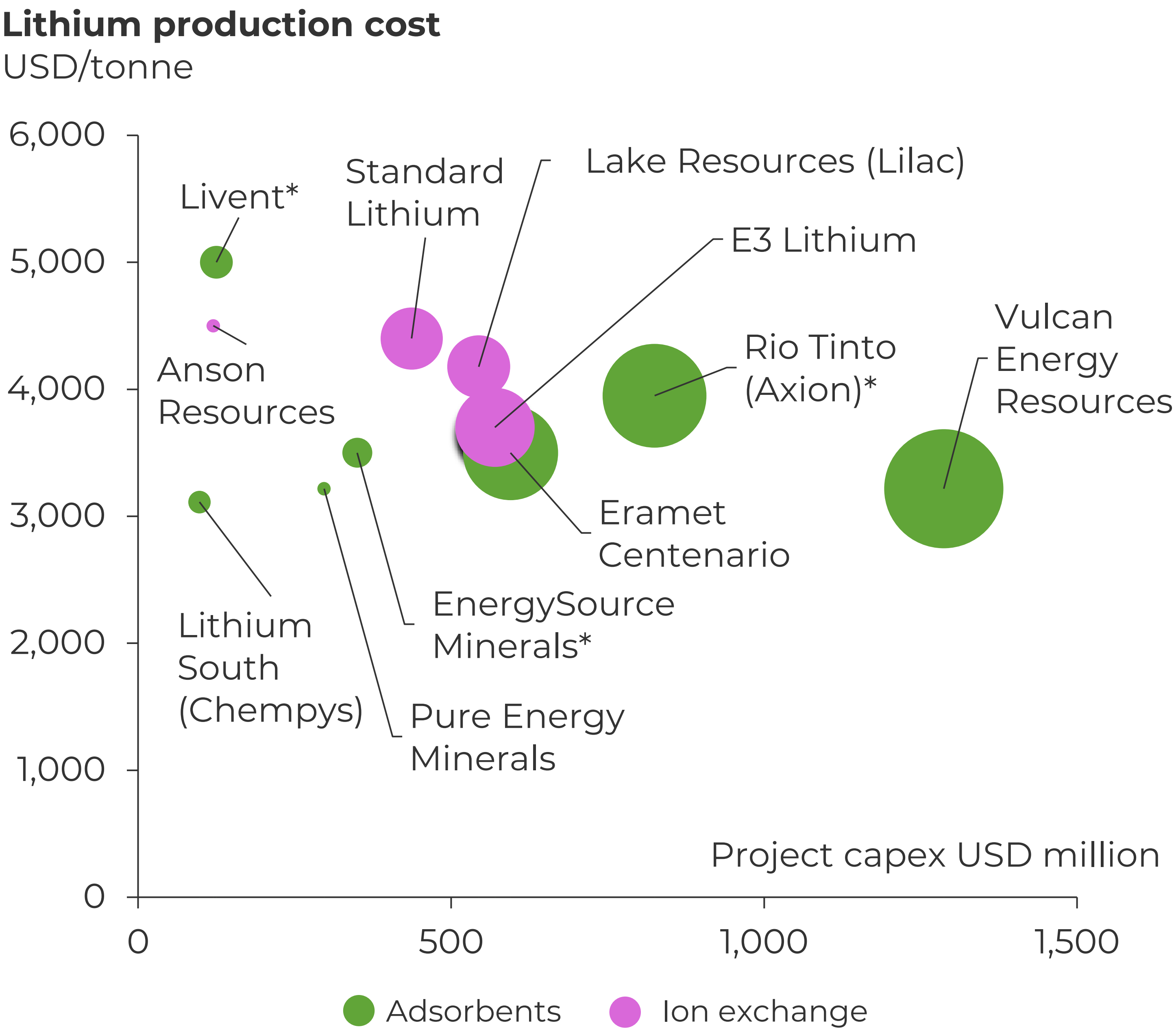


"Environmental impact" refers to estimated water use/loss, reagent usage, and CO2 footprint.

DLE production costs for projects by technology

Both technology and type of resource are key drivers in determining lithium production costs. Livent, for instance, uses adsorbents patented by DuPont, but the technology needs the brine to be preheated to enable better adsorption kinetics, which increases opex. Lithium-rich brines have a lower operational cost due to few concentration and purification steps downstream of the DLE process.

Technologies like membranes and solvents are conspicuously missing from this chart as they aren't yet commercially viable. Most companies are producing lithium carbonate using DLE, but future demand for hydroxides could increase costs.



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Adsorbents are clearly winning the DLE technology race; future iterations could see ion exchange and MOFs improve efficiencies

The first lithium adsorbent patents, from DuPont, date back to the 1970s. Adsorbent technology is well understood for South American brines but is also showing promise in geothermal brines today. Next-generation adsorbents will look to improve on water usage, keeping overall opex lower than for competing technologies. A good example of this can be seen in the pilots been run by Summit Nanotech, a Canadian company, using nanosorbents. The company uses less water for stripping LiCl but also manages to recycle up to 95% of its water back to the adsorbent regeneration step. In contrast to ion-exchange technologies, avoiding chemical reagents helps lower the trucking costs by 20% and associated carbon emissions for the production site. Other companies to watch for include Terralithium, which has licensed Simbol Materials' adsorbents and patented chemically modified versions of the same. Eramet's adsorbents were developed in partnership with the French Institute of Petroleum and New Energies, and molecular purifications company Seprosys promise to extract over 90% of lithium from most types of brines.

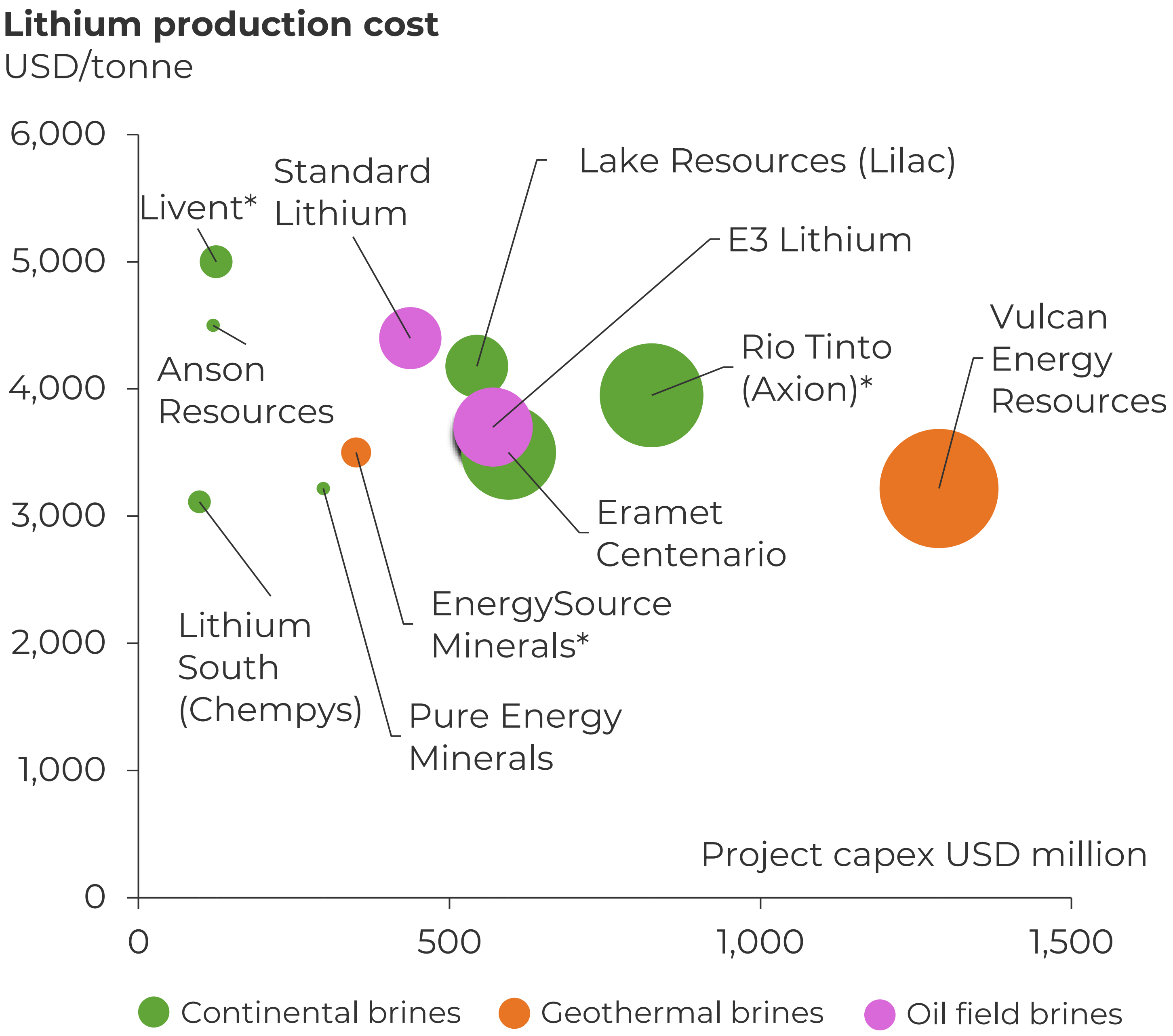
Clients should expect developments in adsorbents like molecular sieves, ion-exchange coatings, and MOFs like those being developed by EnergyX to potentially improve lithium selectivity. Other innovation areas to focus on include adsorbent robustness to improve cycle times (generally to over 10,000 cycles) while preventing issues like breakage and fines migration during regeneration. Lastly, look to adsorbent system design improvements like countercurrent processes that allow continuous adsorption–desorption cycles to improve productivity and lower water use (see Renix and EnergySource).

DLE projects by the type of lithium resource

While Livent commercialized the first DLE project back in the late 1990s, in the salars of Argentina, over 20 years later, lithium juniors Lithium South, Rincon (assets acquired by Rio Tinto), and Lake Resources are developing projects in South America.

Vulcan Energy is developing Europe's first geothermal brines, while EnergySource is exploiting North American geothermal resources.

Underground brines in North America contain a maximum of 0.02% to 0.03% lithium. Pure Energy Minerals and Anson Resource are developing the first U.S. brine projects, while Standard Lithium is completing the world's first commercial petrobrine plant.



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Outlook

1

Partnerships are crucial to succeed in future DLE projects

Clients pursuing DLE projects should interact with potential partners that can build teams of chemists, chemical engineers, and other technical experts who can demonstrate their products rather than transferring the responsibility of building pilots to external engineering companies.

2

There is no silver-bullet DLE technology

The opportunity today lies in improving on legacy technologies and reducing overall operational costs. To do so requires an integrated systems approach.

3

DLE is likely to phase out evaporation due to both operational and sustainability advantages

With lithium recovery improving from 40% to 80% (or more) in comparison to evaporation, DLE is likely to phase out evaporative brines in the next decade or two.

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