2021–2024 Four-year Review of Supply Chains for the Advanced Batteries Sector

U.S. DEPARTMENT OF ENERGY

DECEMBER 2024

EXECUTIVE SUMMARY

Advanced batteries are critical for U.S. energy security and will play a vital role in affordable, decarbonized, and resilient future transportation and power sectors. A diversified, secure, and circular supply chain is imperative for energy security and will position U.S. manufacturing to compete in an industry poised to grow more than five-fold globally and six-fold domestically by 2035.

Advanced batteries are supported by a complex, multi-tiered supply chain that includes minerals extraction and processing, industrial chemicals, engineered materials, and sophisticated downstream manufacturing operations, as well as transportation and logistics. Growing the U.S. market share of emerging high-performance materials and battery chemistries will require further scale-up of advanced industrial and manufacturing capabilities.

The Bipartisan Infrastructure Law (BIL), Inflation Reduction Action (IRA), and Section 301 tariffs have helped spur unprecedented investment in the sector: more than $150 billion in battery manufacturing, creating more than 100,000 jobs. Nearly $33 billion of federal investment has supported onshoring of critical capabilities and commercialization of next-generation battery technologies.[105] Though economics can appear challenging compared to competitors, U.S. operations have a pathway to compete. The U.S. has already made substantial progress in building a pipeline of more than 1,100 gigawatt hours (GWh) per year of manufacturing capacity for battery cells, and the U.S. is investing in the first wave of projects that can help unlock massive domestic mineral resources for use in batteries.

Supply chain buildout is threatened by market uncertainty and structural challenges. Demand uncertainty and price volatility are holding back investment in key sectors. In several key segments, domestic operations face structural production cost disadvantages compounded by non-market policies and practices carried out by foreign governments.

Future priorities for supply-chain resilience include: providing support to existing investments to stabilize markets in the near-term, delivering first-of-a-kind domestic projects to onshore critical capabilities, continuing to build international partnerships to fill residual gaps and enhance the overall competitiveness of the supply chain, leveraging strengths in R&D and innovation to compete on next-generation technologies, and facilitating the emergence of a circular economy model for key input materials.

[105] Private investment from energy.gov/invest. Public investment tracked by U.S. Department of Energy, including awarded and selected grants, conditionally committed and closed loans, and publicly announced recipients of the 48C Qualifying Energy Project Tax Credit. Public investment figure includes investments in electric vehicles as well.

SECTOR OVERVIEW

Introduction

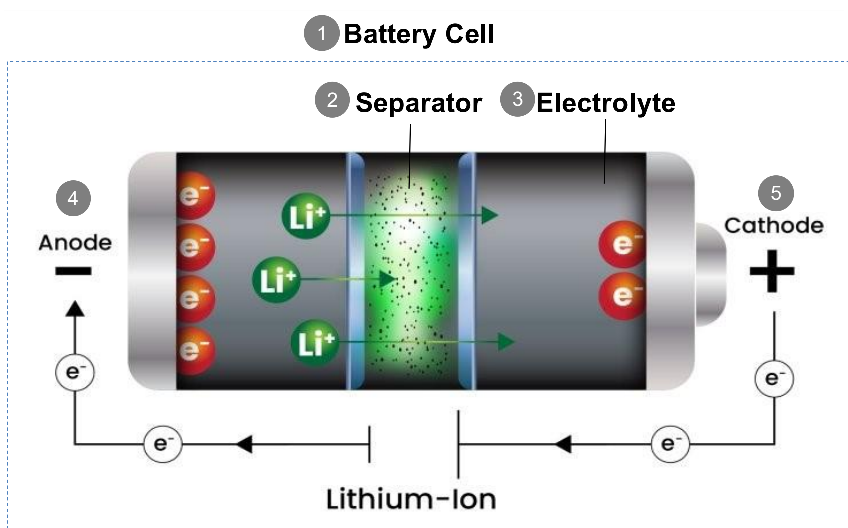
Advanced batteries are a critical technology needed for a resilient, affordable, and secure future energy system. As vital components of electric vehicles, stationary energy storage systems for grid resilience, and advanced electronics, they support fast-growing markets that will play an important role in U.S. economic competitiveness. Advanced batteries are also critical for a range of high-priority defense applications, including unmanned vehicles (particularly UAVs), directed-energy weapons, communications systems, sensors, and electronic warfare and countermeasures.

This Review details the range of advanced battery technologies under development and their associated supply chain inputs, sketches out challenges facing the domestic supply chain, benchmarks progress to date in battery processing and manufacturing, and concludes by identifying priorities for the federal government to pursue going forward.

Sector Overview and Key Trends

Advanced battery chemistries include lithium-ion formulations currently in widespread use (particularly nickel-manganese-cobalt and lithium-iron-phosphate cathode chemistries), as well as emerging formulations like sodium-ion and solid-state chemistries that are at earlier stages of development but may come with benefits related to performance, cost, and material availability. Other alternative chemistries like iron-air and flow batteries are also earlier-stage but may be better suited to stationary storage, including long-duration storage applications. Advanced batteries may likewise include a range of alternative materials that can come with similar performance and supply chain advantages, such as silicon anode blends to supplement graphite and alternative electrolyte and binder formulations. (Figure 1 provides a high-level view of battery cell components, while the manufacturing process and role of key inputs are discussed further below.)

Figure 1. Illustrative structure of a battery cell

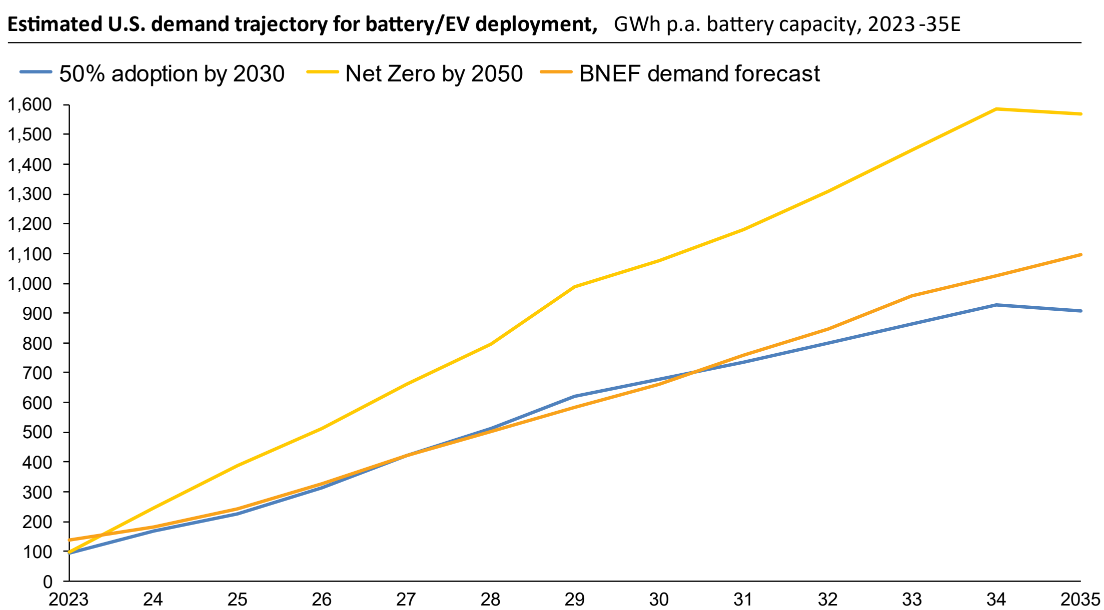


Source: U.S. Department of Energy

Demand for these kinds of advanced batteries continues to grow rapidly. In the U.S., battery deployment could increase by six-fold from 2024 to 2035 (Figure 2). Global deployment could similarly increase by five-fold in the same period. EV adoption is expected to drive 85 to 90 percent of the battery market, with other applications, particularly stationary storage for the grid, accounting for the remainder.[106] Accelerated adoption is a product not just of policy incentives, but also of a strengthening underlying value proposition for EVs, stationary storage, and other use-cases, reflected in market-driven demand forecasts (e.g., "BloombergNEF demand forecast" in Figure 2) and rapid growth in battery deployment across global markets. The battery market will be a key engine of growth for advanced manufacturing and presents an important opportunity to create middle class jobs, grow an advanced manufacturing industrial base, and ensure future energy security and economic competitiveness.

For the automotive industry specifically, cost and performance improvements in EVs are likely to drive continuing growth in market share. Successful integration of advanced batteries will accordingly be critically important for the long-term competitiveness of U.S. automakers and for the long-term health of the U.S. automotive manufacturing base, which directly employs roughly 1.1 million American workers,[107] accounts for roughly 7 percent of U.S. manufacturing output,[108] and provides peacetime support for a range of dual-use industrial capabilities, such as metal-working, that are vital for defense production.

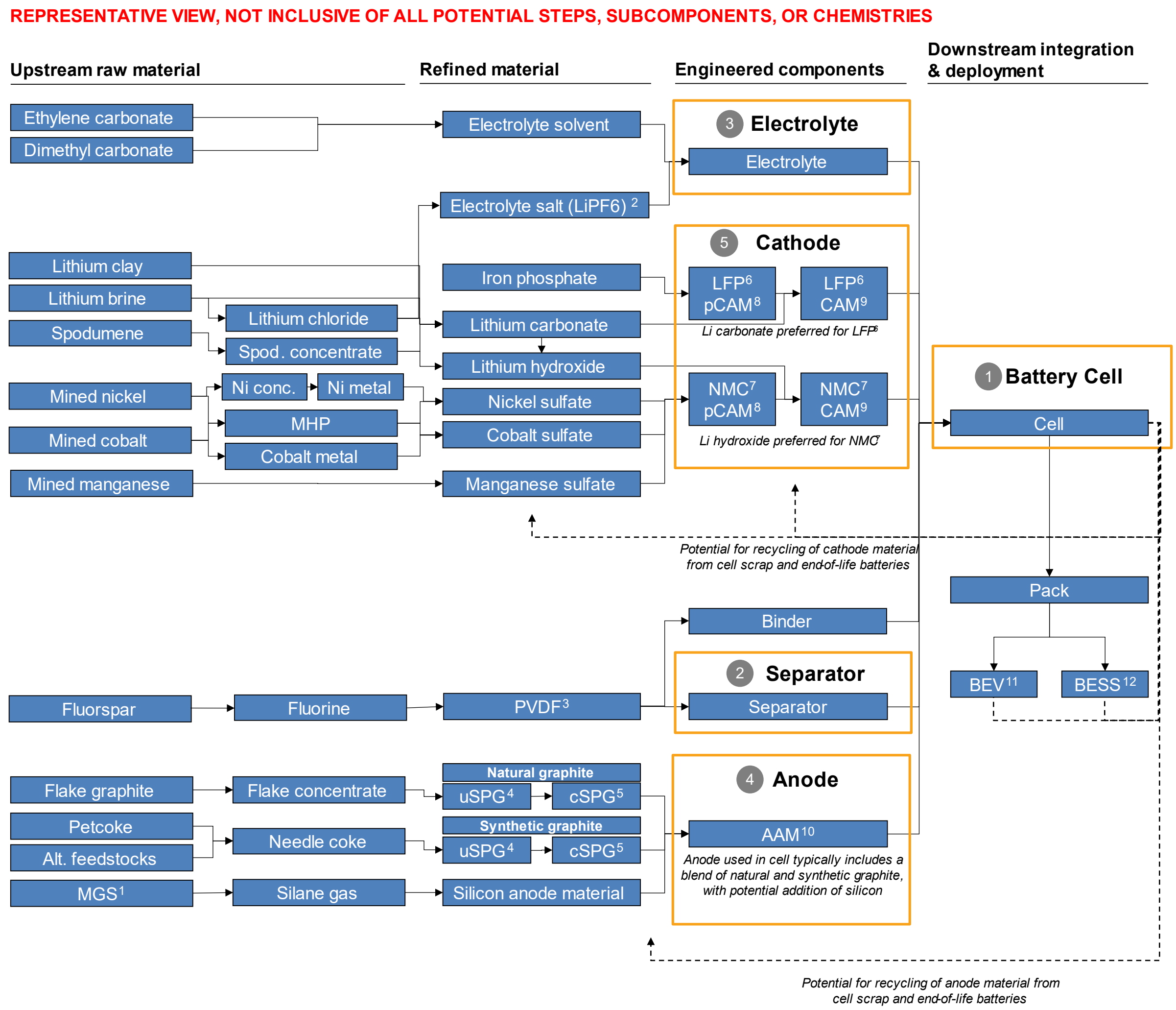
Figure 2. Battery deployment trajectories



Source: Illustrative scenarios, based on analysis of Administration targets and Net Zero scenarios from Argonne National Laboratory. Other scenario from BloombergNEF.

[106] U.S. demand estimates based on forecasts from Argonne National Laboratory. Other estimates based on "Economic Transition Scenario" battery deployment forecasts from BloombergNEF (updated July 2024, latest available).
[107] "Automotive Industry: Employment, Earnings, and Hours." Bureau of Labor Statistics (2024). https://www.bls.gov/iag/tgs/iagauto.htm.
[108] Measured by value added to GDP. "Value Added by Industry." Bureau of Economic Analysis (2024).

Figure 3. Battery supply chain map



Note: Battery supply chain map. Representative view, not inclusive of all steps, subcomponents, or chemistries. Notes: 1. MGS = Metallurgical Grade Silicon. 2. LiPF6 is common, but other electrolyte salts may also be used. 3. PVDF = Polyvinylidene Fluoride, polymers used as binders and in separator material. 4. uSPG = Uncoated Spherical Purified Graphite. 5. cSPG = Coated Spherical Purified Graphite. 6. LFP = Lithium-Iron-Phosphate cathode chemistry. 7. NMC = Nickel-Manganese-Cobalt chemistry. 8. pCAM = cathode precursor. 9. CAM = Cathode Active Material. 10. AAM = Anode Active Material. 11. BEV = Battery Electric Vehicle. 12. BESS = Battery Energy Storage System (e.g., for stationary storage).

Advanced batteries sit at the end of a complex, multi-tiered supply chain that cuts across mining, chemicals, and advanced manufacturing (representative view in Figure 3). Upstream raw materials include critical minerals, extracted through a variety of potential routes,[109] carbon feedstocks, and industrial chemicals. In the midstream, raw materials are refined and processed in capital-, energy-, and reagent-intensive operations to produce refined materials specialized for use in batteries. These intermediate inputs are further processed into precursors and then major engineered components

[109] This chapter focuses on midstream processing and refining of critical minerals specifically for battery applications. Critical minerals are addressed in greater detail, including extraction, in a separate chapter.

like cathode and anode active material, electrolyte, separator material, and binders. Specifically, critical minerals like lithium, nickel, cobalt, manganese, and phosphate are refined and used in the cathode; natural graphite, synthetic graphite, and, increasingly, silicon are blended in the anode. Lithium and other salts are combined with specialized chemical solvents to produce electrolyte. These major components are assembled at large-scale manufacturing plants into battery cells. Cells are then assembled into battery packs for use in EVs, stationary storage systems, advanced electronics, and other applications.

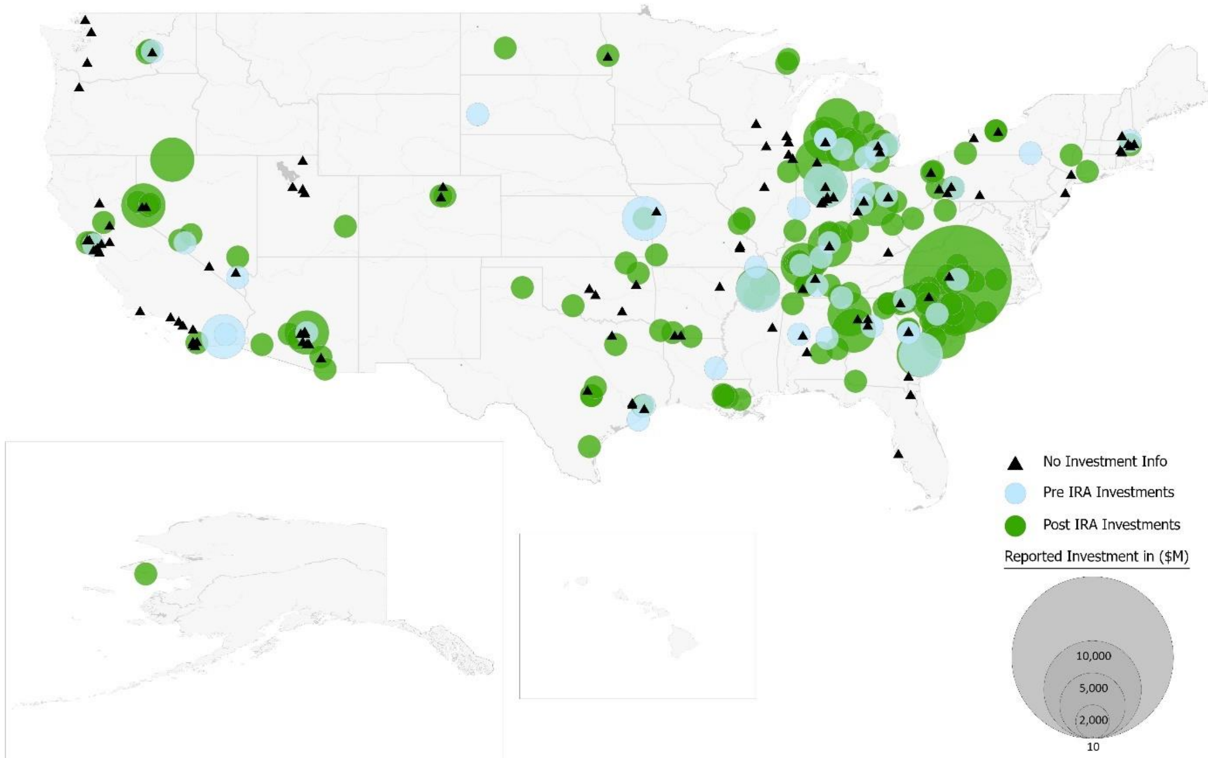
The battery manufacturing ecosystem is also increasingly adopting a "closed-loop" or "circular economy" model, particularly for scarcer and higher-value input materials, in which recycling is an integral part of a secure supply chain. Scrap from manufacturing lines and eventually the large volume of material from end-of-life batteries may be collected and treated by pyrometallurgical, hydrometallurgical, or direct recycling processes to extract constituent materials, particularly critical minerals and electrode active materials (e.g., cathode material).[110] In this way, the domestic manufacturing base can better secure access to scarce materials while improving sustainability and often reducing cost as well.

[110] See, e.g., National Renewable Energy Laboratory's Battery Recycling Supply Chain Analysis portal. "Battery Recycling Supply Chain Analysis." National Renewable Energy Laboratory. https://www.nrel.gov/transportation/battery-recycling-supply-chain-analysis.html.

PROGRESS TO DATE

Progress from 2021 to Present

Figure 6. U.S. investments in the battery supply chain



Source: Energy.gov/invest. As of December 2024.

Significant progress has been made over the past four years in strengthening supply chains and building the foundations of an American industrial base for advanced batteries. Since 2021, the U.S. has seen more than $150 billion of announced investment in the batteries supply chain, with projects potentially creating more than 100,000 manufacturing jobs across the country (Figure 6).

The impact is being felt in key segments of the supply chain. The U.S. has developed a pipeline of cell manufacturing projects with more than 1,100 GWh per year of capacity, enough to supply on the order of 11 to 17 million light-duty EVs[111] (discussed in more detail in a case study at the end of this Review). These downstream operations can anchor a thriving industrial base and allow American manufacturers to begin benefitting from some of the same advantages of colocation and economies of scale enjoyed by foreign competitors. In the upstream and midstream, the U.S. is developing a pipeline of mining, refining, and subcomponent manufacturing projects that are beginning to onshore critical capabilities, and associated technical knowledge, and close domestic supply gaps. These projects include investments that could bring competitive advantages to the domestic supply chain, including novel lithium projects that can help unlock massive, economically

[111] Assuming 65 to 100 kWh per EV battery pack.

competitive domestic resources (discussed in detail in a case study at the end of this Review) as well as advanced recycling technologies that could address other supply chain vulnerabilities.

Government action has played a vital role in catalyzing development of this industrial base. The U.S. Department of Energy, Department of the Treasury, and other agencies have provided more than $33 billion of direct investment in the form of grants, conditional loan commitments, and investment tax credits.[112] (Figure 7 gives a view of companies that have received federal investment.) Federal funding has supported commercial-scale projects across the full value chain, ranging from minerals processing, production of precursors and electroactive materials, and downstream cell and battery production. The Department of Energy has provided additional support for fundamental R&D and continues to support a thriving research ecosystem at the National Labs focused on advanced batteries. Investments to date include the following:

- Under the Department of Energy Office of Manufacturing and Energy Supply Chains (MESC) Battery Materials Processing and Manufacturing Grants Program, DOE has committed approximately $5 billion to approximately 40 projects.
- Since the start of 2022, the Loan Program Office's (LPO) Advanced Technology Vehicle Manufacturing (ATVM) Loan Program has closed approximately $5.5 billion of battery-related loans, with another $22 billion in projects reaching conditional commitment.
- The Export–Import Bank of the U.S. has approved a loan package of up to $50 million for long-duration energy storage company ESS Inc. and another $51 million to battery manufacturer Electrovaya USA.[113]
- The Economic Development Administration has invested more than $66 million in Tech Hubs in New York, Nevada, and South Carolina.

The Inflation Reduction Act (IRA) provides further economic investment to domestic operations. The 45X advanced manufacturing production tax credit created by the IRA provides support to domestic manufacturers across the value chain of battery components and the refining or recycling of critical minerals. The 48C qualifying advanced energy project credit helps offset upfront capital expenditures for manufacturing projects in the battery supply chain. The 30D tax credit for electric vehicles both supports end demand for batteries and, through content requirements, creates demand for materials from the U.S., North America, and countries with which the U.S. has a free trade agreement, as well as ex-PRC materials.

Based on its finding that China has persisted, and in some cases become more aggressive, in its use of harmful forced technology transfer–related acts, policies and practices, in September 2024, the Office of the U.S. Trade Representative also imposed 25-percent tariffs on certain batteries and battery components from China, helping to further offset disadvantages from the PRC's non-market policies and practices.

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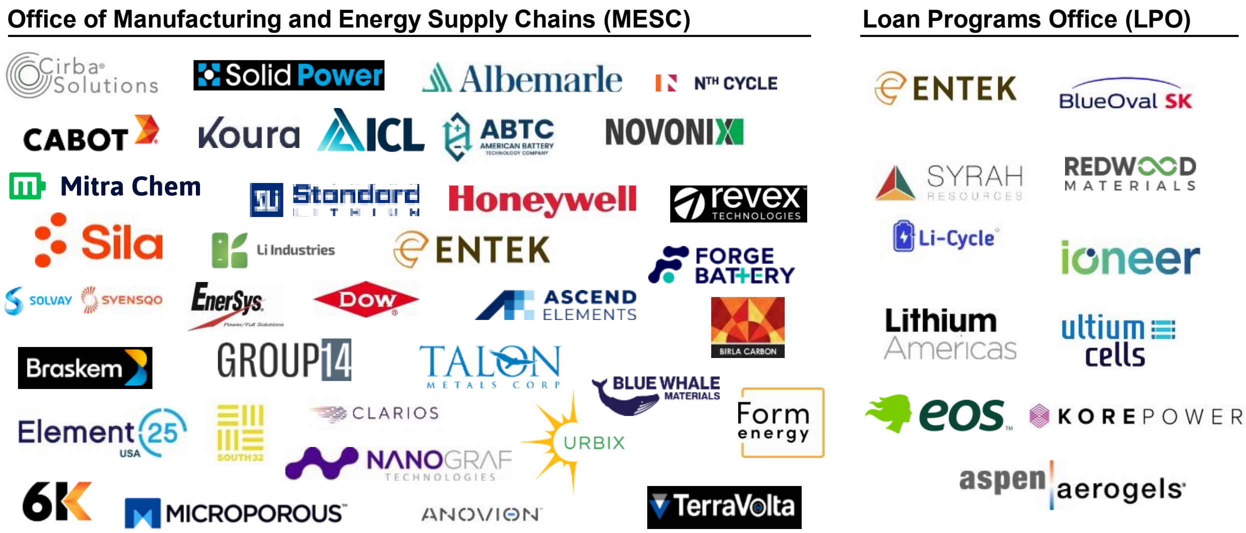
[112] Value of investment tax credits estimated based on companies that have voluntarily announced their receipt of the 48C ITC.

[113] "Export-Import Bank of the United States Board of Directors Approves Fifth Make More in America Transaction." Export-Import Bank of the United States (2024). https://www.exim.gov/news/export-import-bank-united-states-board-directors-approves-fifth-make-more-america-transaction.

Figure 7. Example recipients of federal investment



Note: Companies with projects funded by the Department of Energy Office of Manufacturing and Energy Supply Chains and Loan Programs Office.

Outside of direct funding and economic support, the federal government has worked to build the institutional infrastructure for long-term engagement and is helping to shape a supportive ecosystem in which domestic projects can succeed. Efforts to date include the following:

- The Department of Energy Office of Manufacturing and Energy Supply Chains is developing a range of analytical tools to improve market transparency, situational awareness of key vulnerabilities, and assessments of U.S. economic competitiveness at different parts of the supply chain.
- The Department of the Interior, through the U.S. Geological Survey's National Minerals Information Center, has developed sophisticated understanding and models of the supply chains for the critical minerals needed for advanced batteries.
- Led by DOE, The Federal Consortium for Advanced Batteries (FCAB) encourages cooperation and coordination across Federal agencies that are interested in ensuring a domestic supply of lithium batteries and are committed to accelerating the development of a robust and secure domestic industrial base.
- Led by DOE, the Conference on Critical Materials and Minerals (CCMM) is a G7 + Australia forum for technical exchanges and government-to-government discussions aimed at enhancing security of supply, R&D, cooperation, standards, and multinational cooperation.
- The White House, Department of Energy (through MESC), and other agencies are continuing to engage and coordinate with industry on supply chain challenges through the American Battery Materials Initiative and other forums.
- The Department of State is leading international engagement and coalition-building with likeminded nations through forums like the Minerals Security Partnership,[114] deepening relationships and helping to mobilize investment to diversify and secure supply chains while promoting high environmental, social, and governance standards.

[114] "Minerals Security Partnership." U.S. Department of State. https://www.state.gov/minerals-security-partnership/.

- The Department of Commerce is continuing to engage key countries in the battery supply chain through the Net Zero World Initiative. After hosting the Net Zero World Industry Forum in December 2022 alongside DOE, Commerce co-hosted both the Battery Energy System Seminar and the Battery to Electric Vehicle Workshop in Jakarta in May 2024 with Indonesia's Ministry for Energy and Mineral Resources. These initiatives advertised U.S. technological solutions to energy storage challenges and solicited input for roadmap reports that continue to guide U.S. policy.
- The Department of Commerce also leads efforts in the IPEF Supply Chain Council, established under The IPEF Supply Chain Agreement that entered into force in February 2024. During its meeting in September 2024, the Council established an Action Plan team on critical minerals, with a focus on batteries, under the IPEF Supply Chain Council. Action Plan teams are a core activity under the Council and will work to compile recommendations to increase the resilience and competitiveness of critical sectors and key goods of mutual interest among IPEF countries. Commerce is leading U.S. participation on this Action Plan team, which will build on the successes of the Critical Minerals Dialogue and establish a workplan on by the end of 2024.
- DOE has led bilateral engagement to increase access to critical minerals and materials for the battery supply chain (e.g., U.S.–Canada Joint Action Plan for CM Cooperation, focused on the battery supply chain, and work with Australia and others on international standards that support U.S. competitiveness).

U.S. support has been substantial but varies meaningfully in how it materializes and impacts underlying unit economics in different parts of the battery supply chain. This Review includes two case studies to illustrate in more detail how U.S. firms are building a robust industrial base: one focused on battery cells to represent downstream manufactured components and one focused on lithium chemicals to represent upstream and midstream activities. Each case study shows how the U.S. Government is working to overcome distinct challenges at each step of the battery production process and enabling the private sector to build out more robust and resilient supply chains.

RESILIENCE AND VULNERABILITY ASSESSMENT

Overview

This section offers a view of the challenges that will have to be overcome to build a secure, resilient battery supply chain. The first subsection provides a high-level assessment of supply chain resilience and vulnerability across the supply chain using the standard framework. The second considers eight particularly important challenges in greater detail.

2024 Resilience and Vulnerability Assessment

Transparency

The advanced batteries supply chain has limited transparency today due to challenges with data availability and market maturity. A lack of established ex-PRC exchanges and indices for price and the limited commoditization of many midstream components makes it challenging to track supply, demand, and price dynamics across the supply chain.

Government is investing in building additional capabilities to monitor supply-chain and industrial-base resilience for advanced batteries, including DOE MESC's "Supply Chain Readiness" assessment tool. Government and industry are also developing channels to facilitate communication, including the American Batteries Materials Initiative, Minerals Security Partnership, and Argonne National Laboratory's Li-Bridge partnership.[115]

Domestic capacity

The U.S. has made progress in onshoring downstream manufacturing capacity in key areas, with a pipeline of cell manufacturing plants that could provide more than enough capacity to meet 2030 demand. However, domestic capacity remains more limited midstream and upstream, and limited domestic capacity for refining and electrode active material production makes it difficult to onshore recycling capabilities and build a domestic circular economy.

A pipeline of domestic projects is developing that could meet a significant share of domestic demand across tiers of the supply chain, but challenges related to a difficult market environment, delivery of first-of-a-kind projects, and fundamental availability of resources (e.g., critical minerals) will have to be navigated (discussed in greater detail in the pages ahead). Finally, residual import reliance can be further mitigated by deepening strategic relationships with international partners and diversifying international sources of supply.

Trade concentration

The U.S. has significant import reliance today, particularly in upstream and midstream portions of the supply chain. The PRC has significant global market share (~70–90 percent) for many battery-grade refined minerals and engineered subcomponents, while ex-PRC options for subcomponents are largely concentrated in Japan and the Republic of Korea (ROK).

[115] "Li-Bridge." Argonne National Laboratory. https://www.anl.gov/li-bridge.

U.S. and partner countries (such as Canada, Australia, Japan, ROK, the European Union, United Kingdom, and countries in southern Africa) are investing to diversify the supply chain and reduce import dependence. Significant progress to date has been made in onshoring cell manufacturing, and an ex-PRC supply pipeline is also developing for upstream and midstream. To come online, projects must navigate challenges discussed in the rest of this section.

Supplier diversity

Production has traditionally been dominated by a smaller set of large tier-1 battery majors, with many based in the PRC, Japan, and ROK.

The supply base is now diversifying with new entrants. These include both established companies in "adjacent" sectors (e.g., chemicals, oil and gas) standing up battery-focused production and smaller companies, including junior miners and start-ups bringing novel technologies and production approaches to market.

Agility

The supply chain has some potential for material substitution over longer timelines (e.g., alternative chemistries for the cathode and anode), but operations generally require retooling, new investment, and potentially investment in development of new IP and product validation to pivot, limiting their ability to do so quickly in response to unexpected supply disruptions.

Security

In its current state, the supply chain has security risks from geographic concentration. Global production of input materials is concentrated in the PRC and other countries in East Asia, and individual countries still account for disproportionate shares of the global supply of critical minerals like cobalt. Risks from geographic concentration are heightened by the potential for adversarial policy actions, such as export restrictions.

The developing pipeline of domestic and international projects offers an opportunity to diversify the supply mix and hedge against risk. However, the formation of geographic clusters (e.g., for domestic battery cell production, as discussed in the case study at the end of this Review) may create additional risk from geographic concentration of operations.

Economic health and compliance

U.S. manufacturers are commercially well-positioned in parts of the supply chain where they can benefit from policy support, domestic resource endowments, technological advantages, or potential for differentiation on quality and performance (e.g., cell, lithium, and subset of cost-advantaged or high-performance projects elsewhere).

However, much of the supply chain faces challenging market headwinds relative to competitors (particularly established PRC firms). Key drivers include cost and IP advantages of incumbent firms, structural disadvantages on cost of capital and key inputs, market volatility and demand uncertainty, market immaturity and opacity, and workforce constraints, both in construction and operation of large-scale manufacturing projects.

Challenges in Focus

The U.S. has started from a position of limited domestic capacity across the steps of the supply chain. Early global demand for batteries and battery critical minerals, constituent materials, and battery components has largely been met by foreign producers, including the PRC, which has built a dominant market share at key chokepoints (see Figure 4). Batteries are expected to become an increasingly critical part of the energy ecosystem, making it imperative to reduce foreign reliance, even as the rapid growth of the sector makes doing so even more challenging. Building out a secure domestic supply chain will require the U.S. to overcome several cross-cutting challenges, including:

(a) Aggressive PRC actions to support its domestic industry

PRC firms have a commanding market share today in many segments of the battery supply chain, benefitting from decades of state-backed investment, subsidies, and incumbency in developing a strong industrial base. At important chokepoints like midstream minerals processing and subcomponent manufacturing, PRC firms account for roughly 70 to 90 percent of global production capacity today (Figure 4), giving them significant leverage to shape market dynamics. In many parts of the supply chain, PRC firms have significantly increased capacity to exceed both to domestic and even to projected global demand,[116] and the resulting oversupply has helped hold down prices and crowd out potential entrants. This dynamic has already been seen in other sectors targeted as strategic priorities by Chinese industrial policy, including steel, aluminum, and solar panels, with similarly damaging results for domestic industry.[117]

China's longstanding non-market industrial policies and practices have played an important role in building up this entrenched position. Advanced battery research and development and manufacturing, including coverage of the full supply chain, has been treated as a strategic sector by the PRC government, which has supported its domestic industry previously through years of mandatory joint ventures requirements that facilitated technology transfer and government-approved whitelists that explicitly preference domestic battery manufacturers. The PRC continues to release policies including with massive subsidies for consumer demand, manufacturer sales requirements, favorable access to land, utilities, and other inputs, and large supplies of low-cost capital (a particularly important lever to bolster competitiveness in capital-intensive battery supply chains, discussed in more detail in challenge (c)).

Building on these subsidies, PRC firms are investing to maintain their position in the market in the long term. Firms have announced plans to build production capacity that would provide 80 to 90 percent global market share at key points in the supply chain into the 2030s.[118] PRC operations are also investing heavily in the next generation of advanced battery technologies (e.g., sodium-ion) and account for the bulk of planned capacity buildout and deployment of these technologies today.

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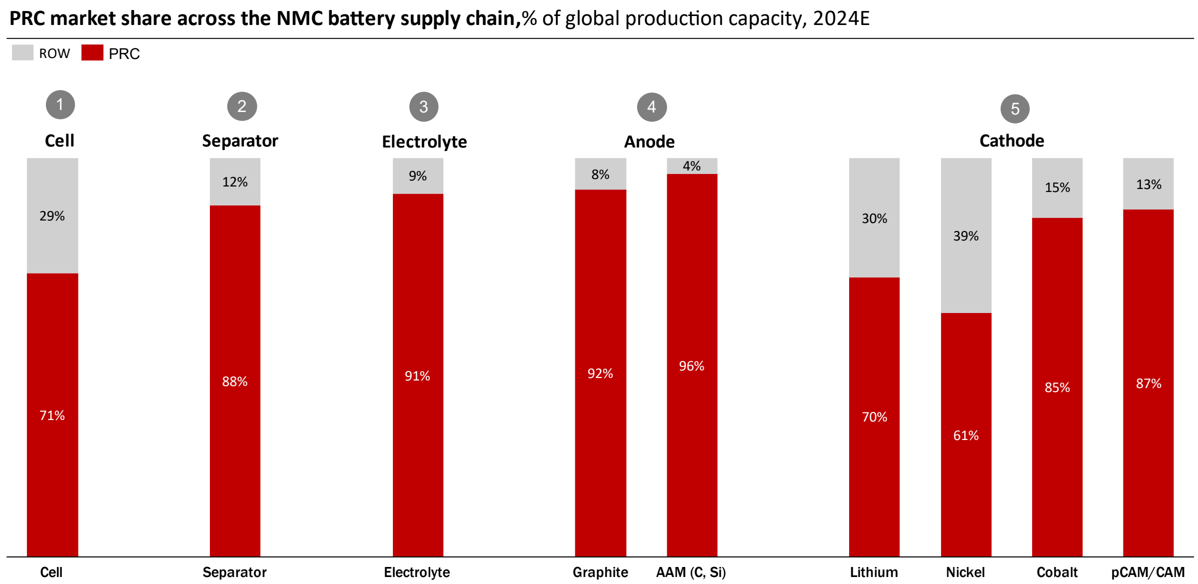
[116] E.g., BloombergNEF is tracking nearly 6 TWh of battery capacity announced in PRC for 2025, compared to estimated *global* demand of under 2 TWh. Though significant portions of this announced capacity may be delayed or canceled, even a fraction of this pipeline of projects coming to fruition would represent a significant overbuild. Colin McKerracher. "China Already Makes as Many Batteries as the Entire World Wants." BloombergNEF (2024). https://about.bnef.com/blog/china-already-makes-as-many-batteries-as-the-entire-world-wants/.
[117] Discussed in *2023 Report to Congress on China's WTO Compliance*. U.S. Trade Representative (2024).
[118] Based on announced project capacity tracked by BloombergNEF.

Figure 4. PRC market share across the battery supply chain



Note: PRC market share across the battery supply chain. Lithium, nickel, cobalt, and graphite from BloombergNEF 2024E refined mineral supply figures for lithium carbonate and hydroxide, nickel sulfate, cobalt sulfate, and both natural and synthetic graphite. All others from BloombergNEF-tracked "fully commissioned" facilities. Est. market share does not include operations outside of PRC that may be owned by Chinese companies, therefore likely understates true PRC market share.

(b) Structural cost disadvantages

PRC firms benefit from structural advantages on cost, bolstered by state industrial policy. These include lower costs of labor, environmental compliance, and key inputs. The strong incumbent position of PRC operations has brought additional important benefits, including mature domestic markets with firm demand, well-established upstream supply chains, and strong positioning on IP and technical knowledge.

Mature PRC operations have realized significant cost benefits from vertical integration, colocation of operations, economies of scale, and long-term learning effects. For example, concentrating sequential parts of the supply chain in geographic clusters helps PRC firms dramatically reduce the costs associated with logistics while enabling quicker material qualification and process improvement. Similarly, by co-locating with chemical plants as part of large industrial complexes, PRC refining and cathode manufacturing operations can secure low-cost access to reagents that may be waste products of other chemical processes while more easily monetizing the waste byproducts of their own operations.

Conversely, midstream gaps in U.S. domestic supply chains, such as slower buildout of cathode precursor and material plants, can deny domestic firms the structural advantages of colocation, requiring domestically produced material to be shipped overseas for intermediate processing, and challenge the business case for long-term investment.

PRC operations also benefit from significant investment in IP and technical knowledge amassed through years of operating at scale. U.S. companies trying to break into the market often must partner with foreign firms to secure IP or invest heavily in developing new IP for themselves, at added cost. Limited technical experience can increase the cost of first-of-a-kind domestic projects, which can incur additional costs in fine-tuning and ramping production for the first time, as well as increase the perceived risk of projects to potential investors.

(c) Limited domestic resource supply

For some critical inputs, particularly raw materials like critical minerals, the U.S. has limited domestic resources available for battery manufacturing, creating a dependence on foreign sources of supply. In some cases, such as nickel and cobalt, the U.S. has limited domestic mineral deposits that can be economically developed. In other cases, such as natural graphite, the U.S. has large-scale mineral deposits but faces lengthy development timelines to bring mining capacity online. Without appropriate mitigations, reliance on foreign sources of supply can create risk downstream in the supply chain and to the broader economy by leaving operations vulnerable to supply shocks, both from unexpected disruptions like natural disasters and bottlenecks in global shipping and logistics, and from adversarial state policy, such as export controls.[119] The lack of upstream resources can also compound cost disadvantages in the midstream by limiting opportunities for vertical integration and colocation of operations.

(d) High capital costs for new domestic projects

U.S. operations are especially disadvantaged by high capital costs, relative to other countries and to the PRC in particular. Capital repayment can be one of the largest drivers of unit costs, particularly in the midstream, where projects are often at greater than $1 billion scale, and projects can be anywhere from two to seven times more expensive to build in the U.S. compared to the PRC and other countries. Higher U.S. capital costs are a result of constraints in the construction sector (including shortages in the trade workforce, also discussed in challenge (h)), significantly slower timelines for project delivery (typically multiple years compared to 6 to 12 months), and a higher baseline cost of doing business. First-of-a-kind domestic projects are particularly exposed to these pressures because of the unique challenges in initial project delivery and commissioning (see challenge (g)).

High project delivery costs are compounded further by the high return expectations of U.S. investors and the high cost of capital for many domestic project developers. Due to China's large-scale industrial policy support and non-market policies and practices, PRC firms can leverage cheap, in some cases, effectively free, capital from state-owned financial institutions and other low-cost providers, allowing them to overbuild capacity relative to domestic demand and compete more readily in low-price environments. In contrast, to attract private capital, U.S. projects must deliver a highly competitive return to investors, particularly in parts of the supply chain perceived as high-risk like minerals processing, which requires higher prices for their refined and manufactured products. Projects that would break even on operating cost in a low-price environment can nonetheless

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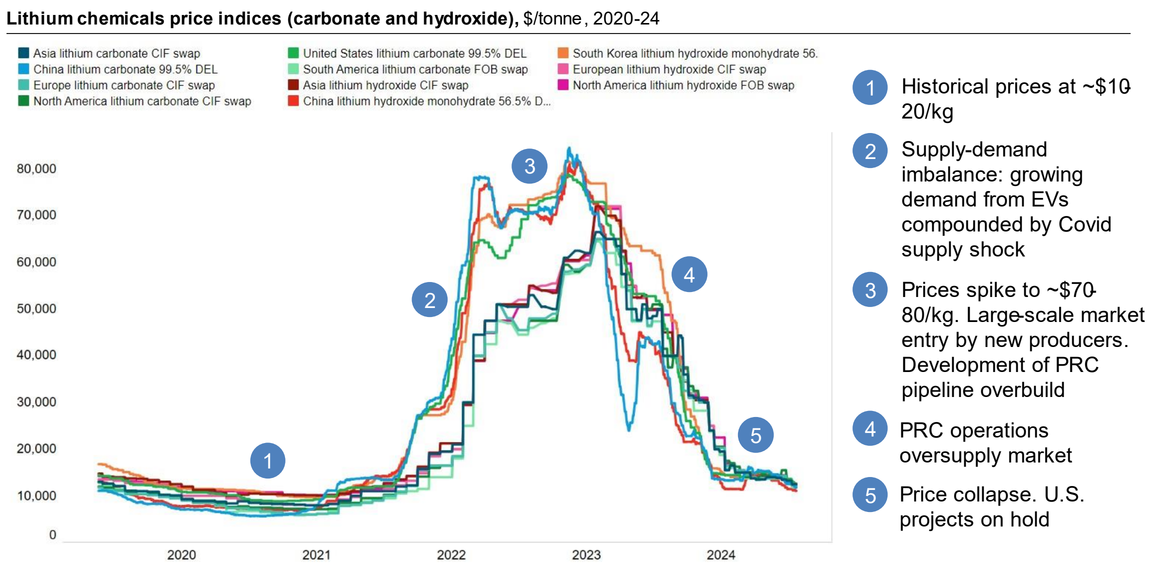
[119] *E.g.*, potential risk to domestic manufacturing from PRC export controls on graphite. Sybil Pan. "China's Jan-Feb graphite exports plunge amid export controls." Fastmarkets (2024). https://www.fastmarkets.com/insights/chinas-jan-feb-graphite-exports-plunge-amid-export-controls/.

struggle to generate sufficient margin to repay capital with a competitive return, deterring domestic investment and slowing buildout of the domestic industrial base.

(e) Market volatility and demand uncertainty

Market volatility is another major threat to the development of the domestic industrial base. Supply-demand imbalances catalyzed in part by pandemic-related disruption drove dramatic increases in price in 2022, particularly for battery minerals, but market conditions today are characterized by relative oversupply and overcapacity across much of the global supply chain, particularly driven by PRC activities. Though EV sales have continued to grow, fluctuating demand in some markets has created short-term uncertainty about future need for battery materials, with a resulting impact on prices and project development. For some key inputs, prices have fallen by as much as 80 percent since their peak in 2022, driven by uncertainty about the trajectory of the future demand ramp-up and mass-buildout of low-cost capacity by PRC firms. (As an illustrative example, Figure 5 maps price dynamics over the last four years for battery-grade lithium chemicals, showing the run-up in prices as supply tightened in 2022 and 2023, followed by a price collapse in response to softening short-term demand and oversupply by PRC operations.)

Figure 5. Recent market volatility: collapse in lithium prices



Note: Recent market volatility: collapse in lithium prices. Price data and visual from BloombergNEF (data reported through July 2024).

The resulting low-price environment has hurt the investment case for new U.S. and ex-PRC projects, causing companies to delay or cancel capacity expansions in some cases. The prospect of future volatility serves as an additional deterrent to private investors, who may now require higher returns and shorter payback periods commensurate to the perceived risk of projects operating in a market with high levels of demand and price volatility, all of which make it more difficult for domestic projects to attract capital. This dynamic is a particular challenge for projects in the early stages of commissioning and material qualification with OEMs, when their financial position is at especially high risk (discussed in more detail in challenge (g)).

(f) Immature, opaque markets

Challenges with market volatility are compounded by the relative immaturity and opacity of markets for many key battery components and inputs. Some are not listed on commodities exchanges and have no public trading price. While mature, commoditized markets offer financial instruments and other mechanisms for hedging against price volatility and risk of downcycles, markets for battery components like refined mineral products and specialty chemicals tend to be shallower and insufficiently developed for these tools and approaches to mitigating risk. Opacity also increases the difficulty of monitoring market activity and identifying potential supply–demand imbalances, including policies of overcapacity, and other related vulnerabilities.

Market data are limited for many segments of the battery supply chain, particularly midstream products like cathode and anode materials, electrolyte, and other subcomponents. Markets have limited liquidity, poor price transparency, and less mature indices and exchanges for pricing, trading, and hedging. Existing indices are largely centered on the Chinese market, and thus are particularly susceptible to price-manipulation activities. Farther downstream, products are likelier to be bespoke and non-commoditized, making it still more difficult to monitor supply and hedge against risk of disruption. These challenges have encouraged recent consideration of measures to monitor global metals markets at the Commodities Future Trading Commission.[120]

(g) First-of-a-kind project risks

Once developers secure funding, they may still face significant challenges related to project delivery for first-of-a-kind domestic operations. In the construction and commissioning stages, because the domestic industry is starting from a limited foundation, U.S. operations often rely on foreign engineering knowledge and equipment suppliers (including from the PRC) to deliver initial projects, or else they must develop their own IP at higher risk, higher cost, and on longer timelines. Compounding the challenge is the fact that companies developing projects are often smaller and new entrants in the market, with limited experience and higher delivery risk.

New operations face additional delays and related funding challenges from the need to qualify material with potential downstream customers. Suppliers must generally build a full-scale facility to undergo qualification, incurring significant upfront capital expense (on the order of hundreds of millions or billions of dollars), but may not see revenue for as much as 12 to 18 months while the qualification process is underway. Smaller, new-entrant companies are especially exposed to these pressures, as they are unlikely to have existing operations and prequalified material and, with smaller balance sheets, also struggle to secure the working capital needed to bridge extended qualification periods.

(h) Constrained workforce in key technical occupations and geographies

Both construction and ongoing operation of projects are challenged by constraints in the available workforce. Limited labor supply in key construction trades (e.g., welders, pipefitters, and electricians) can increase construction costs and timelines for domestic projects, and limited supply

[120] "CFTC's Energy and Environmental Markets Advisory Committee to Meet February 13." U.S. Commodity Futures Trading Commission (2024). https://www.cftc.gov/PressRoom/Events/opaeventeemac021324.

of skilled manufacturing labor in some regions can similarly constrain production ramp-up. Workforce challenges are compounded in cases where projects must be built in more remote areas, as is often the case for the upstream and midstream supply chain (e.g., processing facilities that must be adjacent to mineral resources).

PRIORITIES AHEAD

Four-year Resilience Goals and Priorities

Overview

More progress remains to be made, both to fully capitalize on opportunities in areas like cell manufacturing and lithium refining, and to ensure a secure and resilient supply chain for other inputs. Ensuring the large pipeline of domestic projects comes to fruition, developing strong supply chains and a resilient industrial base, and capitalizing fully on U.S. opportunities to compete and win will require a concerted effort by government, industry, investors, labor, and local communities.

However, with targeted policy and concerted action, the U.S. is well-positioned to build resilient supply chains that can deliver energy security and economic opportunity. The U.S. can capitalize on domestic strengths to build a vibrant domestic manufacturing base for advanced batteries, onshore critical supply-chain capabilities, and realize economic benefits for workers and communities, while deepening relationships with international allies and partners, leveraging complementary strengths to secure supply chains and improve economic competitiveness.

Goal 1: Stabilize markets and firm demand to backstop domestic investment

Demand and price uncertainty, particularly the risk of a persistent low-price environment driven by PRC overcapacity, are key deterrents to domestic and 'friendshored' investment in mining, refining, manufacturing, and recycling projects.

Priority action 1.1: Move towards firmer offtake commitments from industry

Firmer offtake commitments by downstream industry, particularly automotive OEMs and battery Tier 1s, can help unlock needed capital for domestic projects across the value chain.

Priority action 1.2: Provide clarity and consistent enforcement of content requirements

Clarity on and consistent enforcement of domestic and 'friendshored' content requirements can further improve the credibility of the demand signal to industry and capital markets.

Priority action 1.3: Leverage stockpiles to mitigate demand uncertainty

Stockpiling of selective critical minerals may have positive impacts including price stabilization and increased certainty for investors. These benefits are substantial and would likely play a role to enhance national security, but further engagement is needed on potential approaches and focus for stockpiling efforts. The Departments of Energy, State, and Defense have executed a memorandum of agreement formalizing an interagency partnership on stockpiling of critical minerals needed for energy technologies to advance this dialogue.[121]

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[121] "U.S. Departments of Energy, State and Defense to launch Effort to Enhance National Defense Stockpile with Critical Minerals for Clean Energy Technologies." Office of International Affairs, U.S. Department of Energy (2022). https://www.energy.gov/ia/articles/us-departments-energy-state-and-defense-launch-effort-enhance-national-defense.

Goal 2: Successfully deliver first-of-a-kind domestic projects

Targeted action will be needed in the next four years to ensure domestic projects are successfully delivered and critical supply-chain capabilities successfully onshored.

Priority action 2.1: Help project developers address barriers to delivery

Developers will have to navigate challenges related to permitting, workforce constraints, and fine-tuning operations that may be active for the first time at true commercial scale. Government has a key role to play as a facilitator and partner to ensure the success of investments.

Priority action 2.2: Facilitate successful engagement with communities

Community buy-in is particularly critical for project success. Government facilitation can ensure close collaboration between project developers and community, labor, and Tribal stakeholders to ensure projects earn and maintain support and license to operate from fenceline communities.

Goal 3: Continue strengthening international partnerships to address residual gaps in the supply chain

In parts of the supply chain where the U.S. lacks critical IP or technical knowledge, faces particularly acute structural disadvantages, or has limited domestic resources (e.g., certain critical minerals), deeper international partnerships will be essential to ensure the availability of affordable and competitive ex-PRC supply. International partnerships also ensure U.S. interests continue to be represented and PRC influence does not go unchecked and unchallenged around the world.

Priority action 3.1: Continue to advance multilateral and bilateral engagement

The U.S. can build on existing multilateral and bilateral forums and relationships to deepen partnerships on supply-chain security. Forums like the Minerals Security Partnership and Net Zero World Initiative, as well as ongoing multilateral and bilateral with key allies and partners, allow for international coordination to build secure battery supply chains.

Priority action 3.2: Facilitate joint ventures for U.S. projects

For domestic projects, joint ventures allow U.S. firms to leverage partnerships on IP and ensure successful delivery. Government action can help facilitate engagement between domestic firms and international partners and can attract investment in domestic projects.

Priority action 3.3: Provide investment to scale supply chains with partners

Where other countries may be more competitively positioned, the U.S. and its partners can build shared, mutually beneficial supply chains that leverage different strengths to compete more effectively, while advancing complementary goals for economic development, integration, and security. Potential areas of focus could include refining of battery-grade nickel and cobalt chemicals, low-cost anode material, and cathode precursors, where the U.S. has limited domestic resources or may face structural headwinds to onshoring.

Goal 4: Expand pools of patient capital for projects

Patient capital is often critical for project success, especially in a low-price environment where foreign competitors often have access to cheap capital from state-backed financial institutions. Mobilizing patient capital from both public and private sources can support buildout of a domestic and "friendshored" supply chain even in the face of challenging market headwinds.

Priority action 4.1: Continue to provide low-cost financing and capital support to projects

Additional government lending and grantmaking can help unlock the business case for further supply-chain investment, improving commercial viability of projects even in the face of challenging market headwinds.

Priority action 4.2: Create conditions for strategic private investment

With firmer demand, more mature markets, and demonstrated success on first-of-a-kind projects, government action can attract additional private capital from strategic investors on more favorable terms to projects.

Priority action 4.3: Mobilize patient capital for investment in partner countries

It will be important to grow these pools of capital for projects in partner countries as well. Development finance institutions and multilateral development banks can play an important role in mobilizing capital behind projects in emerging markets, while advancing complementary objectives for economic development.[122] Coordination between government finance arms playing at different parts of the supply chain can serve as a "force multiplier" to enable project success and facilitate greater investment.[123]

Goal 5: Facilitate market maturation

The long-term health of the industrial base will benefit from a more mature market for inputs, including development of trusted indices, deep, liquid markets, and improved price-transparency—all of which can enable improved situational awareness of vulnerabilities and more effective hedging against market risk. Market maturation will be led and driven by the private sector, but government attention can help ensure the market develops favorably in the long term.

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122 For example, the International Development Finance Corporation (DFC) has invested $55 million in nickel and cobalt mining for battery markets in Brazil. "Sourcing critical minerals to support the global clean energy transition." U.S. International Development Finance Corporation. https://www.dfc.gov/investment-story/sourcing-critical-minerals-support-global-clean-energy-transition.

123 For example, the Department of Energy Loan Programs Office (LPO) and DFC have effectively partnered to support complementary parts of the supply chain for graphite anode, with DFC financing an upstream graphite mine in Mozambique and LPO financing a project in Louisiana to refine that mined graphite feedstock to anode-grade material. Interagency collaboration helped streamline project diligence, and funding both parts of the supply chain helps to de-risk both projects. "DFC Makes More Than $9.1 Billion in Financial Commitments for Fiscal Year 2023." U.S. International Development Finance Corporation (2023). https://www.dfc.gov/media/press-releases/dfc-makes-more-91-billion-financial-commitments-fiscal-year-2023. "LPO Offers First Conditional Commitment for Critical Materials Project for Syrah Vidalia to Support Domestic EV Supply Chain." Loan Programs Office, Department of Energy (2022). https://www.energy.gov/lpo/articles/lpo-offers-first-conditional-commitment-critical-materials-project-syrah-vidalia.

Priority action 5.1: Improve market liquidity and foster use of non-PRC market indices

Creating market liquidity as projects bring supply to market and encouraging use of trusted, U.S.-centric or non-PRC indices can help accelerate this process. Market maturation will be led and driven by the private sector, but government attention can help ensure the market develops favorably in the long term.

Goal 6: Invest in workforce development and domestic talent pipeline

The ability to build robust and resilient U.S. supply chains will also depend on a strong domestic workforce, both for construction and long-term operation of projects.

Priority action 6.1: Invest in recruitment and training

Investments in training and growing local talent pipelines will be crucial to enable project success, particularly in regions with constrained labor supply, while ensuring that economic benefits flow to fenceline communities. A coordinated approach can leverage federal and state resources, local educational and labor organizations, and industry investment for maximal result. The Department of Commerce Economic Development Administration has already invested $21 million in a Nevada Tech Hub focused on lithium-ion batteries and EV components[124] and $45 million in a South Carolina and Georgia Tech Hub focused on grid resilience (including battery energy storage systems),[125] and EDA designated another Tech Hub in New York focused on battery manufacturing.[126] The Department of Energy's Vehicle Technologies Office and Argonne National Laboratory are taking additional steps to coordinate with industry in developing a comprehensive workforce development program for battery manufacturing through the Battery Workforce Challenge.[127]

Goal 7: Support movement towards a circular economy for battery materials

A mature industry can leverage recycling and circular economy models to address residual supply gaps, further strengthen the supply chain, and improve the sustainability of U.S. operations. DOE's Office of Energy Efficiency and Renewable Energy has developed a draft strategic framework that lays out how a circular economy for batteries could be structured. Overall, RMI has estimated that recycled content could meet roughly 45 to 55 percent of U.S. demand for lithium, nickel, and cobalt

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[124] "Biden-Harris Administration's Tech Hubs Program Awards Approximately $21 Million to Nevada Tech Hub to Strengthen the Region's Capacity as a Global Leader in Lithium Batteries and Electric Vehicle Materials." U.S. Economic Development Administration (2024). https://www.eda.gov/news/press-release/2024/07/02/Nevada-Tech-Hub.

[125] "Biden-Harris Administration's Tech Hubs Program Awards Approximately $45 Million to SC Nexus for Advanced Resilient Energy in South Carolina to Strengthen the Region's Capacity as a Global Leader in Clean Energy." U.S. Economic Development Administration (2024). https://www.eda.gov/news/press-release/2024/07/02/Nevada-Tech-Hub.

[126] "New Energy New York (NENY) Battery Tech Hub." U.S. Economic Development Administration. https://www.eda.gov/funding/programs/regional-technology-and-innovation-hubs/2023/New-Energy-New-York-Battery-Tech-Hub.

[127] "Battery Workforce Challenge Programs." Argonne National Laboratory. https://www.anl.gov/taps/step/battery-workforce-challenge-programs.

by 2040.[128] As the supply of material in circulation from manufacturing scrap and end-of-life batteries grows, government and industry action can position domestic firms to capitalize on the opportunity to bring additional cost-competitive supply to market.

Priority action 7.1: Continue to support commercialization of novel recycling technologies

Government support can help deliver first-of-a-kind projects and commercialize novel, low-cost recycling technologies. DOE MESC and LPO have already selected a combined $3.5 billion of advanced recycling projects for grants and loans, helping to build the initial tranche of projects that can de-risk recycling technologies and lay the groundwork for longer-term buildout.

Priority action 7.2: Foster broader market ecosystem needed for a successful circular economy

Areas of focus can include support for necessary logistics and infrastructure, facilitating joint ventures and colocation of recycling operations with battery manufacturing clusters, and, longer term, incentives to encourage and facilitate recycling of end-of-life materials by consumers. The Department of Energy's Vehicle Technologies Office has selected $85 million of projects focused on improving the economics and logistics of transporting and processing end-of-life batteries,[129] as well as $14 million of projects to increase participation by consumers in existing battery recycling programs.[130] EPA is developing voluntary battery labeling guidelines and battery collection best practices in order to increase the number of batteries available for recycling.[131]

Goal 8: Continue to invest in R&D and commercialization of the next generation of advanced battery technologies

Traditional U.S. strengths in innovation will be vital to ensure long-term competitiveness and continuing technological leadership.

Priority action 8.1: Continue investment in R&D and commercialization

Public and private efforts can provide ongoing support to perfect and scale the next generation of advanced battery technologies, including alternative chemistries, high-performance substitute materials, novel recycling approaches, and high-efficiency, low-impact extraction, refining, and processing techniques for input materials. Government action can play a key role in accelerating progress at all stages of technology development. Public investment in basic research through DOE, DOD, the National Laboratories, National Science Foundation, and other agencies can advance foundational battery science and complement private-sector R&D efforts. Later-stage grants and loans can facilitate initial scale-up and commercialization of emerging technologies.

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128 "Battery Circular Economy Initiative Dashboard." RMI. https://rmi.org/battery-circular-economy-initiative/resources/dashboards/?dashboard=0.

129 "Funding Selections: Bipartisan Infrastructure Law Battery Recycling, Reprocessing, and Battery Collection Funding Opportunity." U.S. Department of Energy. https://www.energy.gov/eere/vehicles/funding-selections-bipartisan-infrastructure-law-battery-recycling-reprocessing-and.

130 "Biden-Harris Administration Announces Nearly $45 Million to Slash Electric Vehicle Battery Recycling Costs." U.S. Department of Energy (2024). https://www.energy.gov/articles/biden-harris-administration-announces-nearly-45-million-slash-electric-vehicle-battery.

131 "Battery Collection Best Practices and Battery Labeling Guidelines." U.S. Environmental Protection Agency. https://www.epa.gov/infrastructure/battery-collection-best-practices-and-battery-labeling-guidelines.

Priority action 8.2: Continue to pursue international partnerships on advanced battery science and technology

Deeper international partnerships on science and technology, particularly with nations that have their own robust advanced battery ecosystems, can help further speed development, commercialization, and deployment of advanced technologies across friendly markets.

Priority action 8.3: Pursue policies that are technology-agnostic and preserve a competitive marketplace

The federal government can pursue technology-agnostic policies and affirmatively fund and scale multiple technologies to create a market environment that preserves competition and enables the emergence and scale-up of the next-generation of advanced batteries.

Conclusion

As batteries continue to grow in importance to the global energy system, diversifying and strengthening supply chains will be both critical for energy security and a significant opportunity for the U.S. economy and international cooperation. Building battery supply chains can strengthen the U.S. economy, create opportunities for American workers, and deepen U.S. ties with likeminded partners around the globe.

CASE STUDIES

Cell Manufacturing

The U.S. is onshoring substantial capacity for downstream cell manufacturing, operations that account for much of the value-add in finished batteries and serve as 'anchor tenants' for the rest of the supply chain. Domestic cell capacity is scaling rapidly, supported by strong underlying economics and a robust policy regime. Announced U.S. projects represent $94 billion in potential investment, supporting more than 62,000 manufacturing jobs. These projects would provide more than 1,100 GWh of annual cell manufacturing capacity by 2030, enough to meet demand from 50-percent EV penetration of light-duty vehicle sales and expected scale-up of stationary storage, with hundreds of GWh of residual capacity for other uses and potential export. In total, the U.S. and ex-PRC pipeline could meet 100 percent of ex-PRC demand, with U.S. production potentially increasing 18-fold from 2021 to 2030 (Figure 6). Though not all announced projects are likely to come to fruition and a haircut is expected on ultimate capacity additions, projects representing roughly 690 GWh per year of capacity are already active or under construction, and the robust project pipeline is indicative of strong tailwinds for this portion of the industrial base.

This domestic pipeline includes a mix of established tier 1 suppliers, including experienced Korean and Japanese battery majors that can leverage existing IP to accelerate development while deepening ties with key partners and allies, as well as new entrants bringing domestically developed technologies to market at scale. The largest projects are often joint ventures between tier 1s and automotive companies, with closely integrated technical partnerships and cell specifications tailored to meet the unique requirements of each OEM and vehicle model. Smaller operations may be focused on scaling novel technologies or meeting demand from niche, high-performance markets.

Onshoring of cell production is undergirded by a strong competitive advantage on unit economics. With production tax credits and recent tariff modifications, domestic manufacturers of nickel-manganese-cobalt (NMC) batteries could have a landed-cost advantage of 45 percent or more relative to foreign competitors. Figure 8 provides a more detailed breakdown of estimated U.S. vs. PRC production costs.[132] At baseline, U.S. manufacturers likely operate at a premium relative to Chinese production due to lower costs of labor, capital, and other inputs, but the policy regime has offset this disadvantage to create a level playing field. At $35/kWh, the 45X production tax credit for cell manufacturing can offset the conversion cost (operating cost net of materials) for cell production and the cost to repay invested capital with a healthy return, providing an advantage over competitors.[133] In some cases, projects have also been supported by direct federal investment, including $12.5 billion in closed and conditionally committed loans from the Department of Energy Loan Programs Office, focused on large-scale joint ventures between established battery majors and American automotive OEMs, and $450 million in announced selections from the Department of Energy Office of Manufacturing and Energy Supply Chains, focused on commercializing and scaling

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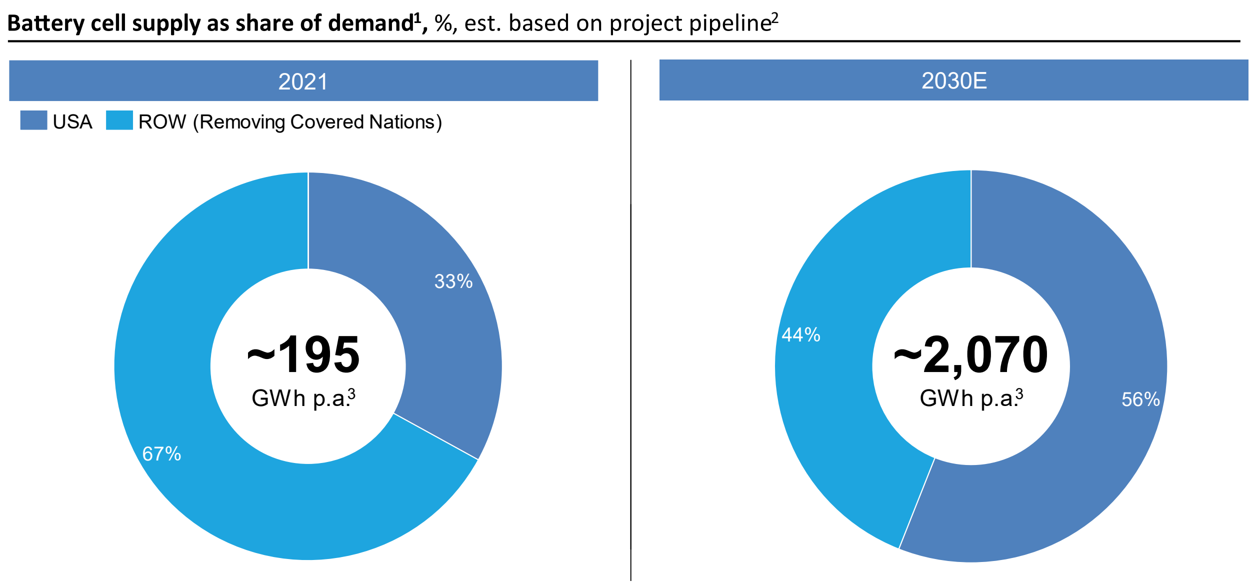
[132] Bottom-up cost estimate based on Argonne National Laboratory 'BatPaC' cost model, including power, labor, materials, other operating costs, and capital recovery. Discussed in Figure 8. "BatPaC: Battery Manufacturing Cost Estimation." Argonne National Laboratory. https://www.anl.gov/partnerships/batpac-battery-manufacturing-cost-estimation.

[133] Modeling based on cost analysis from BloombergNEF suggests potential for a similar cost advantage for U.S.-made lithium-iron-phosphate battery cells, which are generally cheaper to produce and thus see a proportionally greater impact from the production tax credit. Source: BloombergNEF "Bottom-Up Battery Cost Model" ("BattMan 3.1.0"), DOE analysis of representative capital recovery scenarios and potential impact of 45X tax credit.

manufacturing of novel technologies for high-performance and long-duration stationary storage markets.

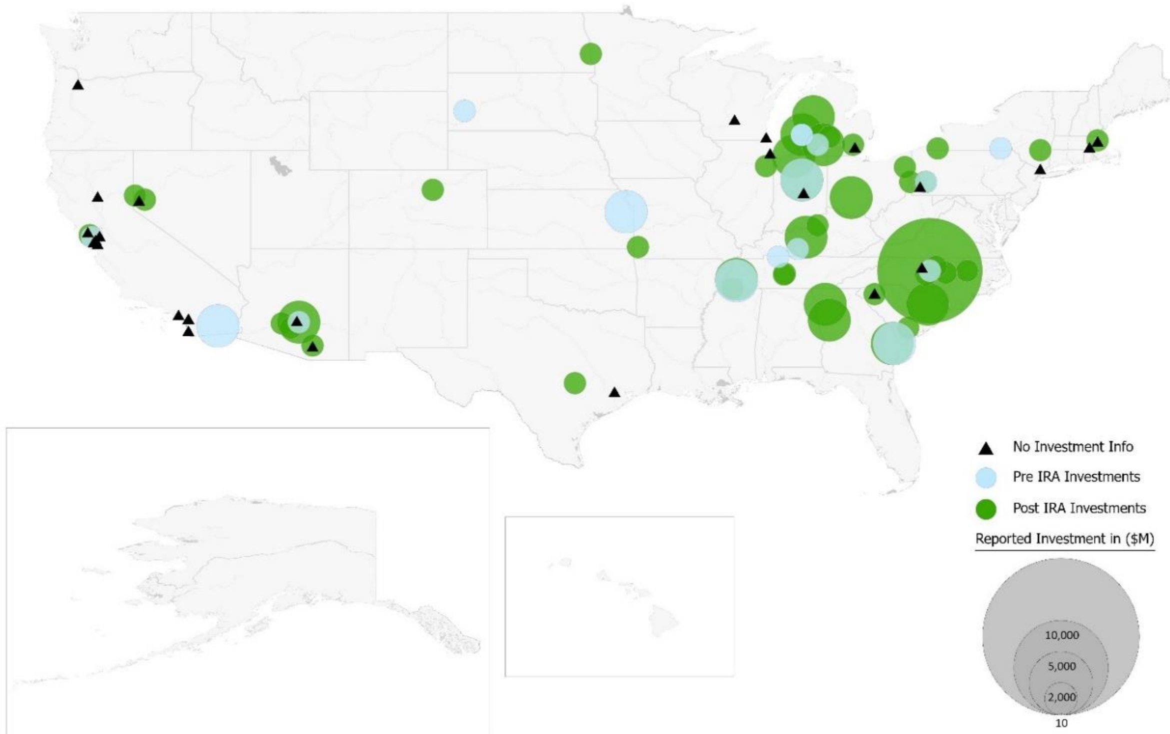
Regional clusters are forming where there is proximity to critical infrastructure and labor. Projects have generally been drawn to areas that offer access to low-cost power and short timelines to interconnect, a ready supply of trained labor, and cost-efficient logistics like rail and water transport. Developers cite affordable and abundant power supply as a particularly critical enabling factor, as well as strong workforce development programming by state and local authorities. Clusters are forming in the Southeast, catalyzed by ready access to power and labor, the Midwest, leveraging existing automotive and battery manufacturing infrastructure, and the Southwest, where there is an existing gigafactory presence (see Figure 7).

Figure 6. Improving supply chain resilience for cell manufacturing



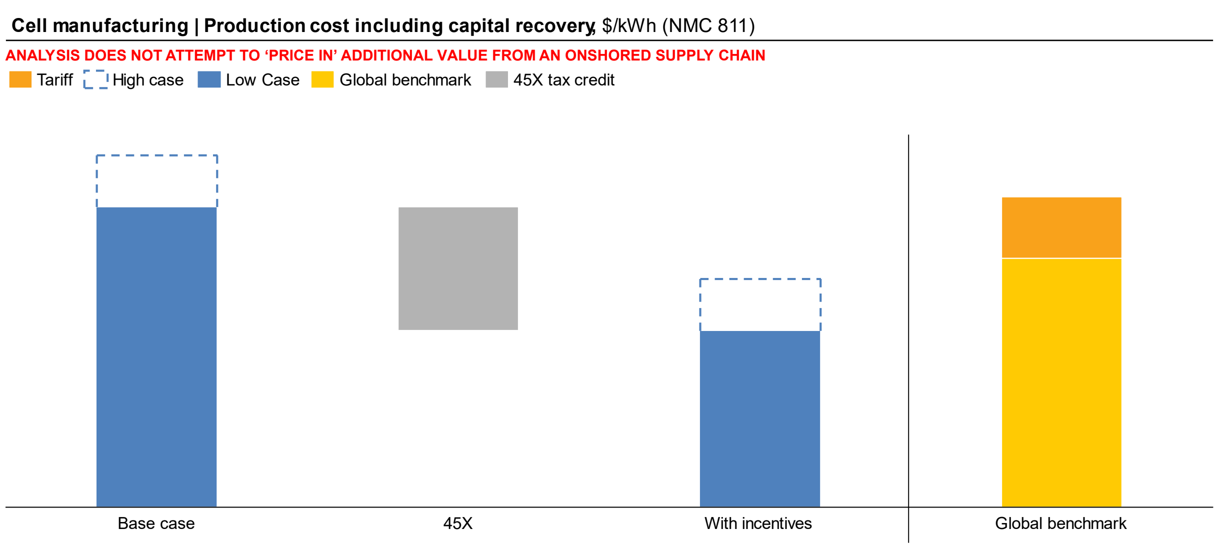
Note: Improving supply-chain resilience for cell manufacturing, measured by battery cell supply share of demand for market outside covered nations. Notes: 1. Representing globally available supply, adjusted to remove PRC supply net of PRC domestic demand (assuming PRC domestic demand is met out of domestic supply). 2. Project pipeline is based on tracked projects operating, announced, and under construction. 3. Figure represents global demand for battery cells, adjusted to remove PRC demand. Sources: DOE internal project data, Argonne National Laboratory, BloombergNEF project trackers.

Figure 7. project map, cell manufacturing



Source: U.S. investments in battery cell manufacturing projects. Source: Energy.gov/invest. As of Dec. 2024.

Figure 8. Representative unit economics, cell manufacturing



Note: Representative unit economics for cell manufacturing (NMC 811). Bottom-up cost estimate based on Argonne National Laboratory "BatPaC" Battery Manufacturing Cost Model, including power, labor, materials, other operating costs, and capital recovery. 'High' and 'low' scenarios reflect different assumptions for capital recovery (high vs. low benchmarks for capital intensity, hurdle rate, and payback period). 45X impact modeled as $35/kWh reduction in cost. 'Global benchmark' is based on estimated PRC-centric costs, with the addition of estimated freight cost and 25-percent tariff to reflect landed cost of imported material. To isolate the cost of the cell manufacturing step (i.e., conversion), materials for both U.S. and global benchmark estimates are assumed to be procured at global commodity prices; with domestic sourcing of materials, base case cost of cell manufacturing may be higher.

Challenges remain for the domestic cell industry to navigate: Uncertainties about the exact timing and trajectory of the demand ramp-up could lead to investment being delayed or project aspirations being scaled back in the short and medium term. Many cell producers are additionally looking to adopt lower-cost lithium-iron-phosphate chemistries already widely used by PRC manufacturers and being commercialized in other countries as well. But onshoring and scaling this technology will likely require joint ventures or additional investment to develop new IP with a significant learning curve to ramp production of a less-familiar chemistry. The scale of the buildout could also strain local labor and power markets, as projects have significant power demand and can employ thousands of skilled manufacturing workers.[134] The federal government is working across agencies and in collaboration with state and local authorities to identify potential bottlenecks and proactively target mitigations. Despite these challenges, U.S. firms enjoy a strongly supportive ecosystem and are well-positioned to compete in battery cell production as the market continues to develop.

Lithium Refining

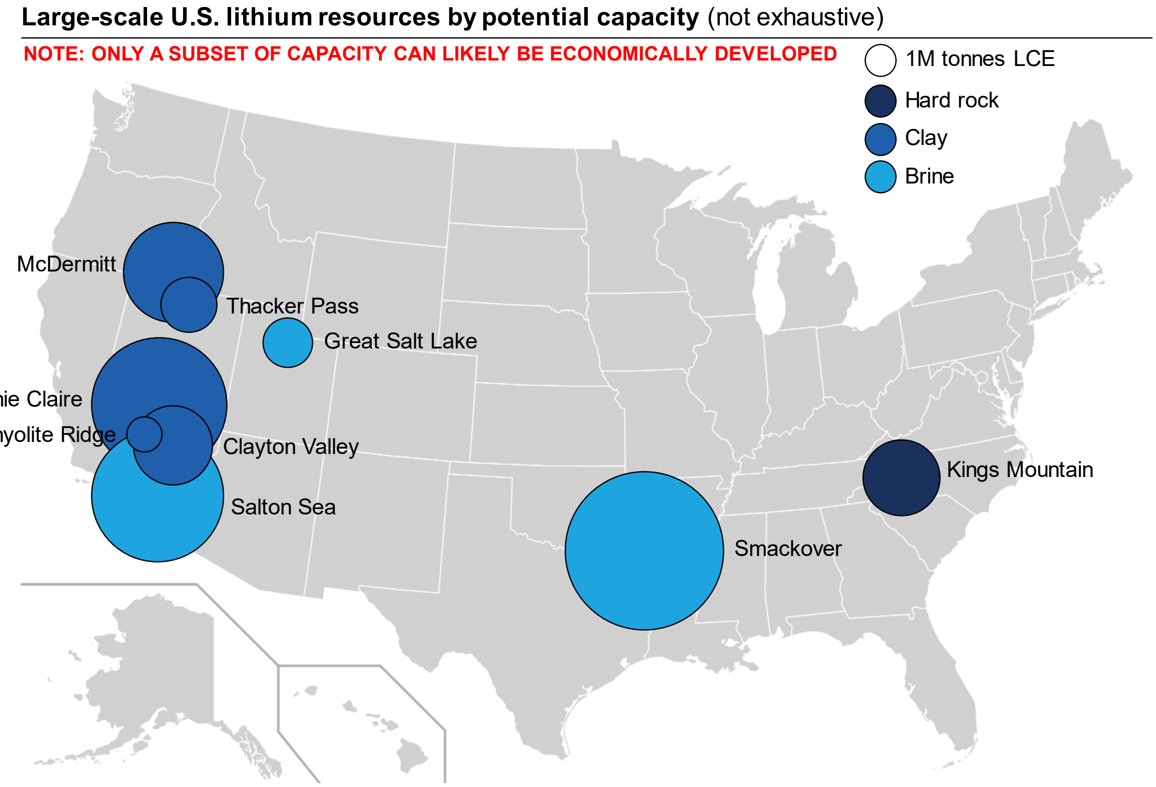
Lithium extraction and refining are other areas of the supply chain where the U.S. is well-positioned to compete given its substantial lithium reserves, and firms are taking the first steps towards building a robust domestic industrial base.

The U.S. has massive domestic lithium resources and reserves, potentially enough to supply tens of millions of EV batteries per year and meet domestic demand several times over (Figure 9). These resources fall into three categories:

- The U.S. has some but more limited "hard-rock" spodumene mineral deposits from which lithium can be extracted and processed to battery-grade chemicals by conventional, widely used means.
- The U.S. has larger resources and reserves in 'unconventional' clay and brine deposits that can be unlocked at competitive cost by scaling novel extraction and processing routes like direct lithium extraction (DLE). Initial deployments may come with scaling risk as technologies are fine-tuned for the unique conditions of U.S. clay and brine deposits, but successful commercialization and scale-up of these approaches is a massive opportunity to unlock domestic supply. The U.S. has additional shallow brine resources that can be extracted by 'conventional' means of evaporation.
- Finally, advanced recycling techniques can allow for recovery of lithium in waste cathode material from manufacturing scrap or end-of-life batteries (This category is discussed in less detail here given its earlier stage of development and limited immediate supply potential, but the U.S. Department of Energy is making significant investments in first-of-a-kind domestic operations to commercialize and scale these technologies.)

[134] E.g., the Department of Energy-supported Ultium Cells and Blue Oval SK projects could create a total of 12,600 operations jobs across six facilities. "Ultium Cells." Loan Programs Office, U.S. Department of Energy. https://www.energy.gov/lpo/ultium-cells. "LPO Announces Conditional Commitment for Loan to BlueOval SK to Further Expand U.S. EV Battery Manufacturing Capacity." Loan Programs Office, U.S. Department of Energy. https://www.energy.gov/lpo/articles/lpo-announces-conditional-commitment-loan-blueoval-sk-further-expand-us-ev-battery.

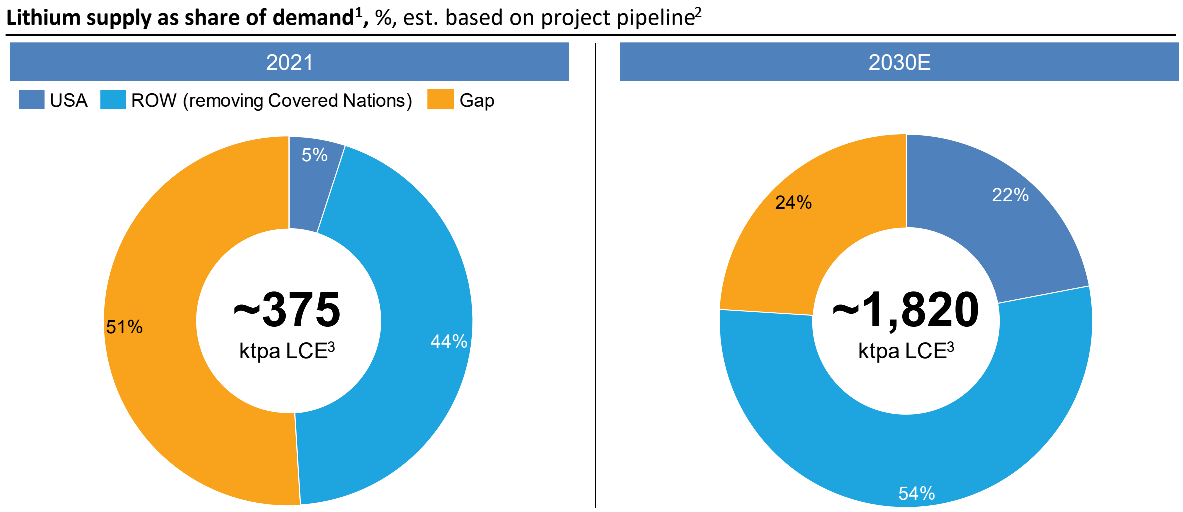
Figure 9. Large-scale U.S. lithium deposits



Note: Illustrative view of large-scale U.S. lithium deposits (not exhaustive of all domestic deposits). Includes measured, indicated, and inferred resources and reserves. Projects and deposits are in various stages of development. Many are pre-production. Only a subset of capacity can likely be economically developed.

A pipeline of domestic projects is developing to tap these resources, including first-of-a-kind deployments to extract and refine lithium from unconventional brine and clay resources, scaling production on domestic hard rock deposits, and first-of-a-kind advanced recycling operations. Active, under construction, and announced projects could meet roughly 50 percent of potential U.S. demand in 2030, and, if fully realized, the overall pipeline of ex-PRC lithium projects could reduce dependence on PRC from 51 percent in 2021 to 24 percent by 2030, even as demand increases by nearly five-fold (Figure 10), while further development of U.S. resources and reserves could support far more than the capacity expansion that would be required to meet remaining domestic demand.

Figure 10. Improving supply chain resilience for lithium extraction and refining



Note: Improving supply-chain resilience for lithium extraction and refining, measured by refined lithium supply share of demand for market outside covered nations. Notes: 1. Representing globally available supply, adjusted to remove PRC supply net of PRC domestic demand (assuming PRC domestic demand is met out of domestic supply). 2. Project pipeline is based on tracked projects operating, announced, and under construction. 3. Figure represents estimated global demand for refined lithium, adjusted to remove PRC demand. Sources: DOE internal project data, Argonne National Laboratory, BloombergNEF project trackers.

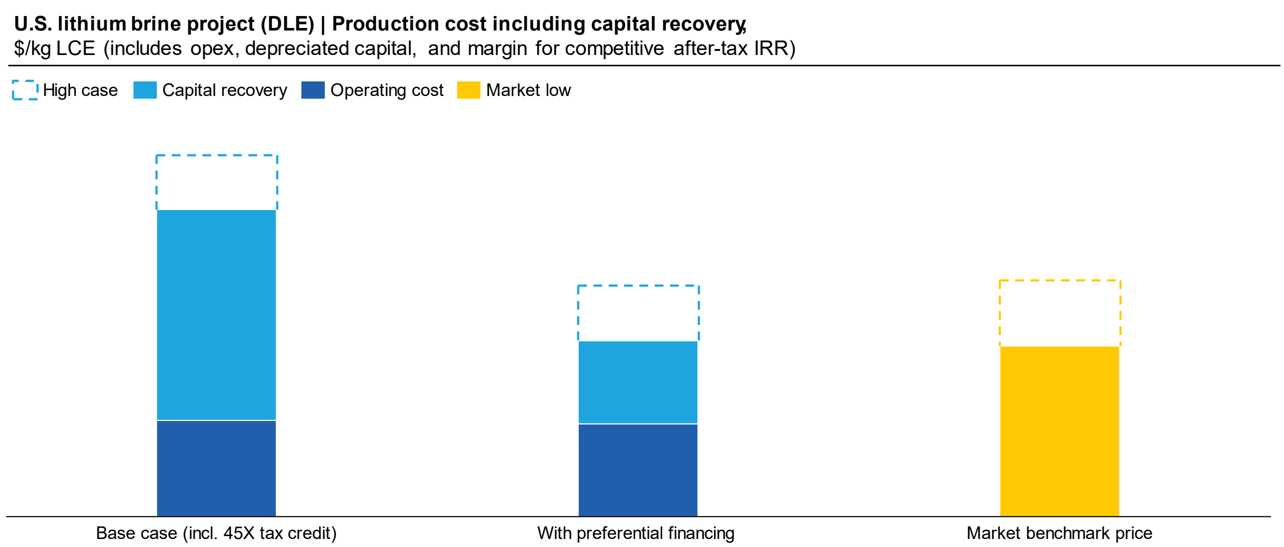
Although U.S. projects today can appear economically challenged relative to competitors, they have a pathway to compete. Figure 11 shows the potential unit cost buildup for a representative brine project using DLE, with the impact of potential levers to improve economics. Projects could be highly competitive on operating cost, potentially in the first and second quartiles of the global cost curve. Brine and clay projects can achieve extremely low operating costs per metric ton of refined lithium through novel approaches like DLE, once initial technology and scaling risk are addressed, and, for some projects, monetization of byproducts. Though cost positioning for hard-rock operations can be challenging, they can achieve meaningful cost reductions and more competitive positions in the cost curve through vertical integration with mining assets.

The primary challenge on the unit economics of domestic lithium projects is capital cost. U.S. projects are highly capital intensive, and the current low-price environment makes it difficult for projects to repay upfront capital quickly and with the high return expected by traditional mining and minerals investors. In contrast, competing PRC developers benefit from lower upfront capital costs, a function of cheap land, reduced construction costs both at baseline and from learning effects realized in a mature, experienced industry, as well as from access to cheap debt and other investment from state-owned and low-cost capital providers.

To unlock development, projects can build a capital stack that includes more patient capital, from investors that are willing to accept longer payback periods and more modest returns. Potential sources of this kind of capital include government debt and grants—which are particularly important for higher-risk first-of-a-kind deployments—and strategic investment from large-balance-sheet majors, including through joint ventures with end customers like automotive OEMs and players in 'adjacent' industries like oil and gas—which have the advantage of being able to secure lower-cost private debt for projects. With more patient capital in the mix, projects can likely deliver a competitive return to investors even at prices in the current range of $10–15/kg (see the "With preferential financing" scenario in Figure 11).

The federal government has been stepping forward to provide this low-cost capital to enable an initial tranche of projects. The Department of Energy Loan Programs Office has closed a loan for $2.26 billion to Lithium Americas' Thacker Pass and conditionally committed $700 million to Ioneer's Rhyolite Ridge, two large-scale clay projects that can help validate the commercial viability of substantial lithium resources in Nevada. The DOE Office of Manufacturing and Energy Supply Chains has similarly announced selection of two brine projects in the Smackover formation, one developed by TerraVolta Resources and the other by Standard Lithium and Equinor, to receive $450 million in grants. Successful delivery of these initial projects can eventually help unlock significant scale-up in the 2030s as the first set of projects add capacity at existing sites and the validation of their approaches catalyzes follow-on project development with support from strategic private investment.

Figure 11. Illustrative cost breakdown, lithium processing operation



Note: Illustrative cost breakdown for a U.S. lithium processing operation (brine DLE). Range of operating costs estimated based on third-party benchmarking of U.S. DLE brine projects and assuming 10-percent reduction in estimated eligible costs from the 45X production tax credit for minerals processing. Capital recovery is based on range of published capex figures for domestic projects, with representative financing scenarios. 'Base case' estimates margin needed for 20-percent after-tax IRR with 5-year payback period to approximate expectations of a traditional mining investor. 'With preferential financing' reflects a set of scenarios that assume additional support from federal grants, low-cost federal loans, and more patient private capital, significantly reducing the margin needed for capital recovery. 'Market benchmark price' reflects the range of prices currently observed in the market.