



Identifying Risks in the Energy Industrial Base: Supply Chain Readiness Levels

January 2025

Acknowledgements

The U.S. Department of Energy (DOE) acknowledges all stakeholders that contributed to the development of this report including but not limited to individuals representing a range of Federal agencies, various White House offices, state and local governments, national labs, the academic and research communities, non-governmental organizations, and U.S. industry. DOE issued requests for information (RFIs) to the public on energy sector supply chains and critical materials markets and received comments that were also used to inform this report. In particular, acknowledgment is due to the following individuals who led the development of this analytical framework and report:

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Report Scope

The focus of this report is to introduce a methodology to evaluate and understand the increasingly global and complex supply chains underpinning the U.S. energy system. Our primary focus is on evaluating dependency of U.S. supply chains from covered nations or exposure to companies influenced by them. Our focus here is not on business operational or broader economic supply chain resilience modeling, for which many resources are available.^{1,2,3}

List of Acronyms

AAM	Active Anode Material
ANL	Argonne National Laboratory
ARLs	Adoption Readiness Levels
ATVM	Advanced Technology Vehicle Manufacturing (under DOE Loan Programs Office)
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
BIL	Bipartisan Infrastructure Law
CAM	Cathode Active Material
DOE	U.S. Department of Energy
FID	Final Investment Decision
FTA	Free Trade Agreement*
GW	Gigawatt
GWh	Gigawatt hour
INL	Idaho National Laboratory
IP	Intellectual Property
IRA	Inflation Reduction Act
ktpa	Kiloton per annum
LCOE	Levelized Cost of Energy
LFP	Lithium Iron Phosphate
LFPB	Lithium Iron Phosphate Battery

¹ White House, 2022, "Building Resilient Supply Chains", <https://www.whitehouse.gov/wp-content/uploads/2022/04/Chapter-6-new.pdf>

² MIT Sloan Management Review, 2014, "Reducing the Risk of Supply Chain Disruptions", <https://sloanreview.mit.edu/article/reducing-the-risk-of-supply-chain-disruptions/>

³ Mack Institute for Innovation Management, Wharton, University of Pennsylvania, 2021, "Building Supply Chain Continuity Capabilities for a Post-Pandemic World", <https://mackinstitute.wharton.upenn.edu/2021/building-supply-chain-continuity-capabilities-for-a-post-pandemic-world/>

LPO	Loan Programs Office
MESC	Office of Manufacturing and Energy Supply Chains
MMAC	Modeling, Mapping, and Analysis Consortium
MSP	Mineral Security Partnership†
NMC	Nickel-Manganese-Cobalt
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
p.a.	per annum
pCAM	Precursor Cathode Active Material
PV	Photovoltaic
SCRL	Supply Chain Readiness Level
T&D	Transmission and Distribution
TW	Terawatt
TWh	Terawatt hour
TRLs	Technology Readiness Levels
USEER	United States Energy & Employment Report

*Countries included in U.S. free trade agreements (FTAs) are: Australia, Bahrain, Canada, Chile, Colombia, Costa Rica, Dominican Republic, El Salvador, Guatemala, Honduras, Israel, Jordan, Japan (for free trade in critical minerals), South Korea, Mexico, Morocco, Nicaragua, Oman, Panama, Peru, Singapore.⁴

†Beyond the U.S., countries included in the Minerals Security Partnership (MSP) are Australia, Canada, Estonia, Finland, France, Germany, India, Italy, Japan, Norway, the Republic of Korea, Sweden, the United Kingdom, and the European Union.⁵

⁴ Office of the U.S. Trade Representative, 2024, “Free Trade Agreements”, <https://ustr.gov/trade-agreements/free-trade-agreements>

⁵ U.S. Department of State, “Minerals Security Partnership”, <https://www.state.gov/minerals-security-partnership/>

Summary of Key Findings

- **The U.S. energy system is undergoing significant transformation** driven by increasing electricity demand, aging grid infrastructure, and the rapid integration of variable energy resources. U.S. economic and national interests depend on maintaining this system's stability, affordability, and independence from foreign adversaries as it evolves.
- **The U.S. energy system increasingly depends on complex, global supply chains, each with embedded risks.** Modernization of the energy system and favorable economics are driving the rapid uptake of solar and battery technologies, as well as grid equipment. Supply chains for these products are currently concentrated among certain nations, presenting risks that geopolitical tensions may constrain supply chains and slow deployment.
- **Risks to U.S. energy supply chains include overreliance on covered nations—a group including China, Russia, Iran, and North Korea—for the production of critical minerals and other key inputs for energy technologies.** Substantial Chinese market share in minerals processing, metals production, and energy component manufacturing, fueled by decades of non-market practices, represents the most significant source of risk to energy supply chains.⁶
- **Recognizing the need to strengthen energy supply chains and the opportunity to create American jobs, the U.S. has taken unprecedented action to invest in domestic manufacturing of key energy technologies.** Spurred by tax incentives and more than \$80 billion in DOE grants and awards, the private sector has invested over \$450 billion⁷ in the energy industrial base since January 2021 and created 400,000 new jobs.⁸ This significant downpayment has begun to turn the tide for America's Energy Sector Industrial Base (ESIB).
- While these actions represent a critical step towards safeguarding U.S. energy security, **materially more investment in the U.S. and other countries will be required to meet escalating energy demands and mitigate the exercise of market power by covered nations.**
- **Driving efficient and sustainable investment requires a deep understanding of complex supply chains.** To enable transparency of supply chain risks, DOE's Office of Manufacturing and Energy Supply Chains (MESC) has collaborated with a consortium of National Laboratories to develop the Supply Chain Readiness Level (SCRL) framework.
- **The SCRL framework provides a consistent approach to assess readiness of energy supply chains to meet the needs of the U.S. energy system under a range of potential scenarios,** applying a consistent lens across technologies and within individual supply chain segments. This diagnostic informs where further private investment is needed and where U.S. government support may be required to mitigate risks within key energy supply chains.
- **As the U.S. works to reduce dependence on covered nations and reshore manufacturing jobs, data-driven tools like SCRL are essential to guide U.S. government decisions.** This report introduces SCRL as a tool to support efforts to scale and secure the U.S. Energy Sector Industrial Base.⁹

⁶ Congressional Research Service, 2024, "U.S.-China Trade Relations", <https://crsreports.congress.gov/product/pdf/IF/IF11284>

⁷ White House, 2024, "Investing in America", https://www.whitehouse.gov/invest/?utm_source=invest.gov

⁸ U.S. Department of Energy, 2024, "United States Energy & Employment Report 2024", https://www.energy.gov/sites/default/files/2024-10/USEER%202024_COMPLETE_1002.pdf

⁹ U.S. Department of Energy, 2022, "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition", <https://www.energy.gov/policy/articles/americas-strategy-secure-supply-chain-robust-clean-energy-transition>

I. Introduction: Preserving Energy Independence in an Evolving Energy System

The U.S. energy system is entering a period of substantial transformation. Following extended periods of low or no demand growth for electricity, driven by both efficiency increases and a decline in domestic manufacturing, the U.S. is reentering a period of rising electricity demand.¹⁰ Artificial intelligence and data center expansion, reshoring of manufacturing, and the electrification of transportation and industrial processes are all contributing to expected load growth. For example, U.S. data center load growth is projected to double or triple in the next few years, rising from 176 TWh in 2023 to 325-580 TWh in 2028.¹¹ As a result, overall U.S. electricity demand is projected to grow by 15-20% in the next decade and double by 2050.^{12,13}

Electricity Demand (TWh)

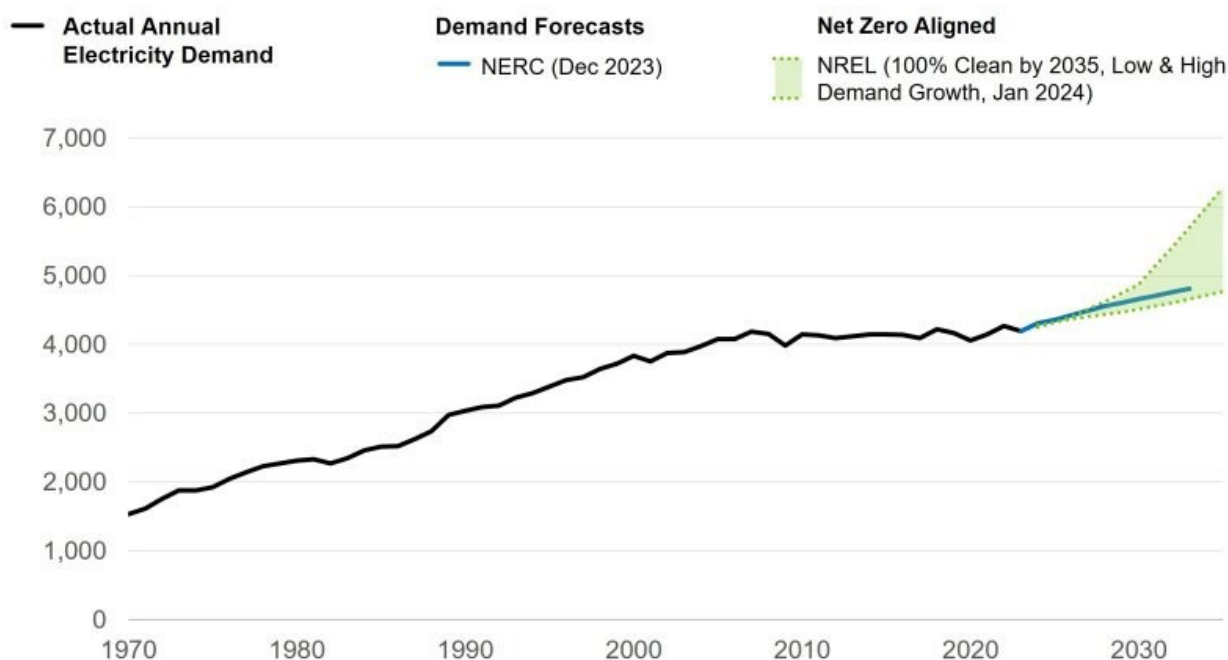


Figure 1. Historical and projected U.S. electricity demand.¹⁴

Meeting this demand will require historically unprecedented deployment of energy generation capacity – increasing from 1.25 TW of capacity in 2024 to 3.2 TW in 2050 according to National Renewable Energy Laboratory (NREL) models¹⁵ – and the expansion and enhancement of aging transmission and distribution infrastructure.¹⁶ While the U.S. has historically benefited from the development of multiple energy resources including fossil fuels, nuclear energy, hydropower, renewables, and others, the bulk of capital investments have historically flowed to fossil fuel power generation. The result is an energy system

¹⁰ Energy Information Administration, 2017, "Per Capita Residential Electricity Sales in the U.S. Have Fallen Since 2010", <https://www.eia.gov/todayinenergy/detail.php?id=32212>

¹¹ Lawrence Berkeley National Laboratory, 2024, "2024 United States Data Center Energy Usage Report", <https://www.lbl.gov/2024-united-states-data-center-energy-usage-report.pdf>

¹² North American Electric Reliability Corporation, 2023, "Electricity Supply and Demand Data"; Energy Information Administration, 2024, "Monthly Energy Review".

¹³ National Renewable Energy Laboratory, 2022, "Pathways to 100% Clean Electricity"; Note: electricity demand referenced includes transmission losses and direct use.

¹⁴ U.S. Department of Energy, 2024, "Clean Energy Resources to Meet Data Center Electricity Demand", <https://www.energy.gov/policy/articles/clean-energy-resources-meet-data-center-electricity-demand>

¹⁵ National Renewable Energy Laboratory, 2023, "Standard Model: Current Policies", <https://www.nrel.gov/news/program/2024/nrel-releases-the-2023-standard-scenarios.html>

¹⁶ U.S. Department of Energy, 2023, "National Transmission Needs Study", https://www.energy.gov/sites/default/files/2023-12/National%20Transmission%20Needs%20Study%20-%20Final_2023.12.1.pdf

that still relies on fossil fuels for 84 percent of primary energy end-use and 60 percent of electricity generation as of 2023.¹⁷ Despite this legacy, NREL's Current Policies Scenario predicts that 96% of future capacity additions between now and 2050 will come from a newer, more economical set of technologies: solar, wind, and batteries.¹⁸ Notably, in 2024 (Jan-Oct), 92% of energy system capacity additions have come from these three technologies.¹⁹

The rapid cost reductions seen across wind, solar, and battery technologies have led to commensurate acceleration in their deployment. Figure 2 shows the historical cost of utility scale generation by source since 2009, with the levelized cost of energy (LCOE) for solar PV and wind falling 83% and 63% respectively.²⁰ While Figure 2 focuses on the comparison of costs of wind and solar compared with traditional sources of fossil fuel generation, nuclear, geothermal, and hydropower also play a critical role as sources of clean, firm power operating at scale.

Historical Utility-Scale Generation Comparison for Key Technologies – Levelized Cost of Energy (\$/MWh)

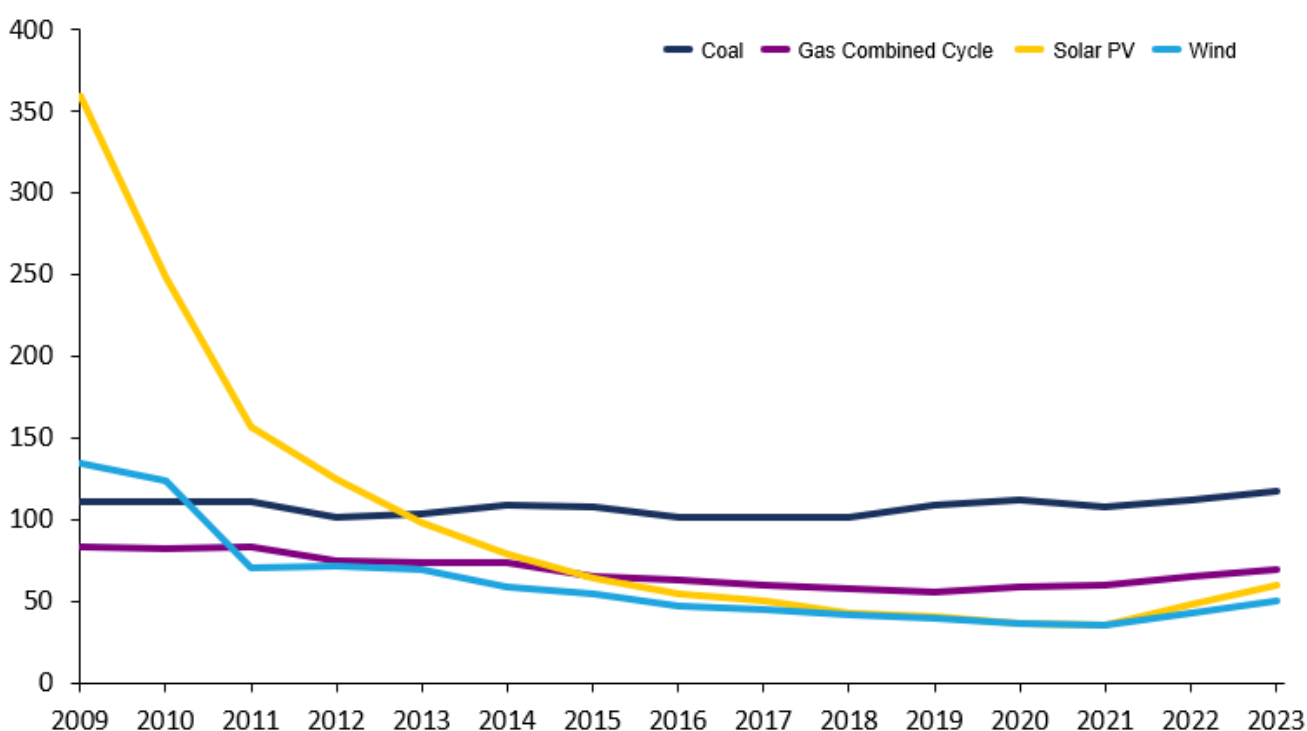


Figure 2. Analysis of selected mean unsubsidized Levelized Cost of Energy (LCOE) values.²¹

The impact of these cost declines of energy technologies can be clearly observed, for example, in the Texas power market, which is currently leading the nation in wind deployment and second in solar and storage deployment.²² While these patterns are driven fundamentally by economics, environmental and geopolitical considerations serve as a further tailwind in many markets.

¹⁷ U.S. Energy Information Administration, 2024, "United States Produces More Crude Oil Than Any Country, Ever", <https://www.eia.gov/todayinenergy/detail.php?id=61545>

¹⁸ National Renewable Energy Laboratory, 2023, "Standard Model: Current Policies", <https://www.nrel.gov/news/program/2024/nrel-releases-the-2023-standard-scenarios.html>

¹⁹ U.S. Energy Information Administration, 2024, "Preliminary Monthly Electric Generator Inventory, Inventory of Operating Generators as of October 2024," <https://www.eia.gov/electricity/data/eia860m/>; Note: includes all operating facilities from Jan-October 2024.

²⁰ Lazard, 2023, "2023 Levelized Cost of Energy", <https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/>; Note: average of the high and low LCOE for each respective technology in each respective year.

²¹ Lazard, 2023, "2023 Levelized Cost of Energy", <https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/>; Note: average of the high and low LCOE for each respective technology in each respective year.

²² Environment America, 2024, "News analysis: Texas Continues Dominance in Wind and Solar Power Generation", <https://environmentamerica.org/texas/media-center/new-analysis-texas-continues-dominance-in-wind-and-solar-power-generation/>

Each of these technologies, as well as the grid equipment that will carry increased loads, is an engineered product that relies on complex supply chains. While many of these technologies were invented and commercialized in the U.S., much of their manufacturing occurs abroad today. Rapid cost reductions over the past decade have been achieved through both specialization in energy supply chains and offshoring associated with globalization.²³ Large production facilities now serve as anchors for industrial clusters as second and third tier sub-component and material suppliers relocate nearby to service these expansive manufacturing facilities and improve production economics.²⁴ However, while this concentration of production can drive meaningful cost efficiencies, it also introduces risk into supply chains.

These trends, further reinforced by decades of non-market practices and policies, have resulted in China amassing a dominant market position across energy technology manufacturing.²⁵ Companies subject to Chinese influence collectively control overwhelming global market shares in the solar and battery supply chains and have claimed similar market positions for the processing of key engineered metals (e.g., aluminum, electrical steel), minerals (e.g., nickel, graphite), and rare earth elements (e.g., neodymium, dysprosium). This degree of market power presents multiple risks to U.S. energy security, ranging from inability to access materials to manipulation of global market prices for critical energy inputs.

II. Harnessing the Full Potential of Energy Technologies

Modernizing the energy system—and maintaining the existing one—will require a range of technologies and robust supply chains to support them. Each of these technologies and their accompanying supply chains play a unique role in the energy system and are likely to face a distinct set of challenges to meet rising U.S. demand. While SCRL can be applied to a broad range of energy technologies—ranging from traditional generating turbines to carbon capture equipment to renewables—a summary of key supply chain challenges has been provided below for the technologies driving the bulk of capacity additions in NREL’s Current Policies Scenario:

- **Batteries.** Battery demand is expected to grow substantially to 2030. Demand will largely be driven by the automotive sector as battery electric vehicles are projected to represent up to half of global light vehicle sales by 2030.²⁶ Batteries will also play a key role on the grid, accounting for nearly 20% of added capacity to 2050. While a range of battery technologies will be deployed (including various long-duration energy storage solutions for grid storage), most projections show ongoing reliance on lithium-ion batteries in the near-to-medium-term.²⁷ Several initiatives are underway to diversify battery supply chains with a focus on U.S. and North American sourcing to decrease China’s significant market share across the battery supply chain.²⁸
- **Grid Components.** Rising demand for grid components—driven by rapidly increasing electricity demand, the build-out of distributed electricity generation, and aging grid infrastructure further stressed by severe weather events—has exerted pressure on supply chains. The result is long lead times and increasing prices. For example, across transmission and distribution (T&D) equipment, the lead time for components range from an average of 51 weeks for distribution

²³ The World Bank, 2020, "Trading for Development in the Age of Global Value Chains", <https://openknowledge.worldbank.org/server/api/core/bitstreams/3df67ad2-367c-5718-ba97-edd213723bb3/content>

²⁴ Research Policy, Volume 52, Issue 2, 2023, "Geographic Clusters, Regional Productivity and Resource Reallocation Across Firms: Evidence from China," <https://doi.org/10.1016/j.respol.2022>.

²⁵ Congressional Research Service, December 2024, "U.S.-China Trade Relations", <https://crsreports.congress.gov/product/pdf/IF/IF11284>

²⁶ S&P Global (formerly IHS Automotive), Retrieved December 2024, "The Journey to Further EV adoption", <https://www.spglobal.com/en/research-insights/special-reports/look-forward/the-journey-to-further-ev-adoption>

²⁷ National Renewable Energy Laboratory, 2023, "Standard Model: Current Policies Scenario", <https://www.nrel.gov/news/program/2024/nrel-releases-the-2023-standard-scenarios.html>

²⁸ International Energy Agency, Retrieved December 2024, "Status of Battery Demand and Supply – Batteries and Secure Energy Transitions – Analysis - IEA", <https://www.iea.org/reports/batteries-and-secure-energy-transitions/status-of-battery-demand-and-supply>.

transformers to 137 weeks for power transformers with prices up 37% to 80%.²⁹ Risks in the transformer and grid components supply chain are primarily driven by insufficient production capacity, labor shortages, and constrained upstream material availability for grain-oriented electrical steel and copper.³⁰

- **Solar.** Solar energy is playing a central role in our future energy system, accounting for over 45% of capacity additions between now and 2050 based on NREL projections.³¹ While recent U.S. solar module assembly has grown to nearly 50 GWdc of annual nameplate manufacturing capacity³²—enough to satisfy nearly all domestic demand with U.S. produced modules³³—substantial resiliency risks remain in essential upstream segments of the solar supply chain. Production of polysilicon, ingot/wafer, and cells remains overwhelmingly concentrated in Chinese or Chinese-controlled manufacturers. The enormous scale of these producers dictates global production economics for the industry.³⁴
- **Wind.** Land-based and offshore wind are expected to total roughly one-third of new generation to 2050.³⁵ Because U.S. manufacturing capacity for offshore wind components is still scaling up, developers are often dependent on foreign manufacturers to ship large components over long distances at substantial cost. While supply chain challenges are less pronounced for land-based wind, both land-based and offshore wind share common challenges for manufacturing and sourcing of materials. For example, multiple components create sourcing challenges including large castings and forgings, rare earth metals (e.g., neodymium, dysprosium) used in high-capacity magnets, and final assembly of products including blades and nacelles. Investing in innovative solutions to increase production volumes and reach globally competitive price points is critical to capturing opportunities in this sector. The lack of U.S.-flagged wind turbine installation vessels and onshore substations are supply chain bottlenecks for U.S. offshore wind.³⁶
- **Nuclear.** Nuclear power provides a key value proposition for energy independence and the electrical grid. Nuclear generates large quantities of zero emission electricity at stable prices, produces firm power to meet industrial needs and growing AI/data center demand, and lowers land-use and, in some cases, transmission needs relative to other generation sources. DOE estimates that U.S. domestic nuclear capacity has the potential to triple in scale from ~100 GW in 2023 to ~300 GW by 2050—driven by deployment of advanced nuclear technologies that may also be more dispatchable than conventional nuclear reactors.³⁷ The build out of new nuclear power generation capacity in the U.S. will require an increase in capacity for its supporting supply chain including fuel enrichment capacity, production of specialized materials for reactor components, and equipment to produce reactor components.³⁸

²⁹ Wood Mackenzie, 2024, "Making the Connection: The Electric T&D Supply Chain Challenge",

<https://www.woodmac.com/news/opinion/making-the-connection-the-electric-td-supply-chain-challenge/>.

³⁰ U.S. Department of Energy, 2022, "Electric Grid Supply Chain Review: Large Power Transformers and High Voltage Direct Current Systems Supply Chain Deep Dive Assessment", <https://www.energy.gov/sites/default/files/2022-02/Electric%20Grid%20Supply%20Chain%20Report%20-%20Final.pdf>.

³¹ National Renewable Energy Laboratory, 2023, "Standard Model: Current Policies", <https://www.nrel.gov/news/program/2024/nrel-releases-the-2023-standard-scenarios.html>

³² National Renewable Energy Laboratory, 2024, "Fall 2024 Solar Industry Update", <https://www.nrel.gov/docs/fy25osti/92257.pdf>

³³ National Renewable Energy Laboratory, 2024, "Summer 2024 Solar Industry Update", <https://www.nrel.gov/docs/fy24osti/91209.pdf>

³⁴ BloombergNEF, 2024, <https://www.bnef.com/shorts/sje1z4dwx2ps00>.

³⁵ National Renewable Energy Laboratory, 2023, "Standard Model: Current Policies", <https://www.nrel.gov/news/program/2024/nrel-releases-the-2023-standard-scenarios.html>

³⁶ National Renewable Energy Laboratory, 2024, "Offshore Wind Market Report", <https://www.nrel.gov/docs/fy24osti/90897.pdf>

³⁷ U.S. Department of Energy Loan Programs Office, 2024, "Pathways to Commercial Liftoff: Advanced Nuclear", https://liftoff.energy.gov/wp-content/uploads/2024/10/LIFTOFF_DOE_AdvNuclear-vX7.pdf

³⁸ U.S. Department of Energy Office of Policy, 2022, "Nuclear Energy- Supply Chain Deep Dive Assessment", <https://www.energy.gov/sites/default/files/2022-02/Nuclear%20Energy%20Supply%20Chain%20Report%20-%20Final.pdf>

Encouraging investment in U.S. manufacturing for these technologies represents an opportunity to safeguard U.S. energy independence, create economic prosperity including high-quality jobs for American workers, and build supply chains that are secure from influence from covered nations.

III. A Government-Enabled, Private Sector-Led Manufacturing Renaissance

The U.S. is undergoing a government-enabled, private sector-led energy manufacturing renaissance. Transformation of the U.S. energy industrial base has occurred through a range of tools and strategic investments: tax incentives for manufacturing across several energy supply chains, government capital for new commercial-scale manufacturing facilities, loans for a variety of energy technologies, and production and investment tax credits for clean energy generation (Figure 3).

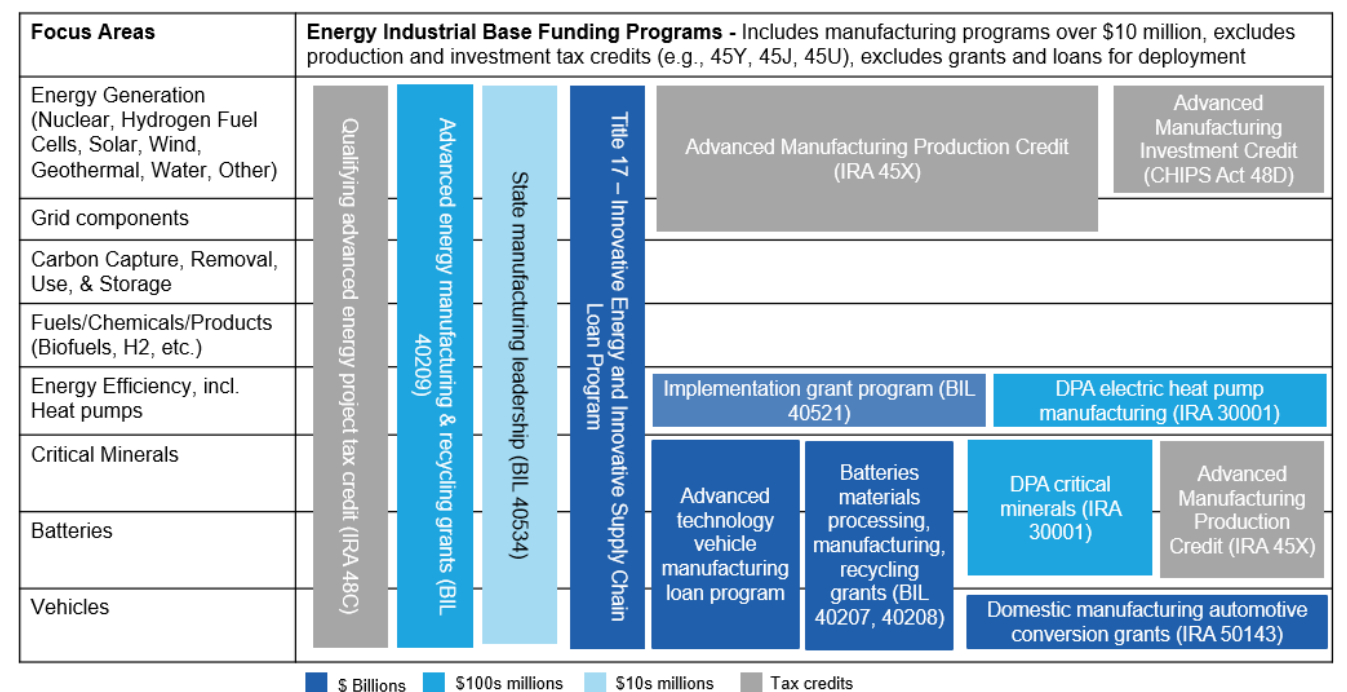


Figure 3. Overview of incentives for energy manufacturing by technology area. Tax credits are shown in gray irrespective of amount, while blue colors show relative funding total specified in a grant or loan.³⁹

Charged with modernizing the U.S. energy system to support a competitive national economy, the Department of Energy (DOE) was authorized to deploy roughly \$90 billion in grant and rebate programs from Congress to coinvest with the private sector. Congress provided an additional \$300 billion in loan and loan guarantee authority for DOE to support investment in a range of new energy projects and supply chains. To date, DOE has allocated \$85 billion⁴⁰ in grants and rebates and approximately \$55 billion in loans and loan guarantees.⁴¹ The result of these investments, combined with the long-term certainty provided by production and investment tax credits, has been a historic surge in industrial and energy investment. Since January 2021, private companies have announced \$1 trillion in new investment, including over \$450 billion of investments in energy manufacturing, EVs and batteries, and clean power generation (Figure 4).⁴²

³⁹ U.S. Department of Energy Office of Manufacturing and Energy Supply Chains, 2024, "Program Summary".
⁴⁰ White House Executive Office of the President, 2024, "2021 – 2024 Quadrennial Supply Chain Review", <https://www.whitehouse.gov/wp-content/uploads/2024/12/20212024-Quadrennial-Supply-Chain-Review.pdf>
⁴¹ U.S. Department of Energy Loan Program Office, 2024, "Figures for Loans Reaching Conditional Commitments or Financial Close."
⁴² White House, 2024, "Investing in America", https://www.whitehouse.gov/invest/?utm_source=invest.gov.

U.S. Energy Industrial Base Private Sector Investment Since 2021, \$B

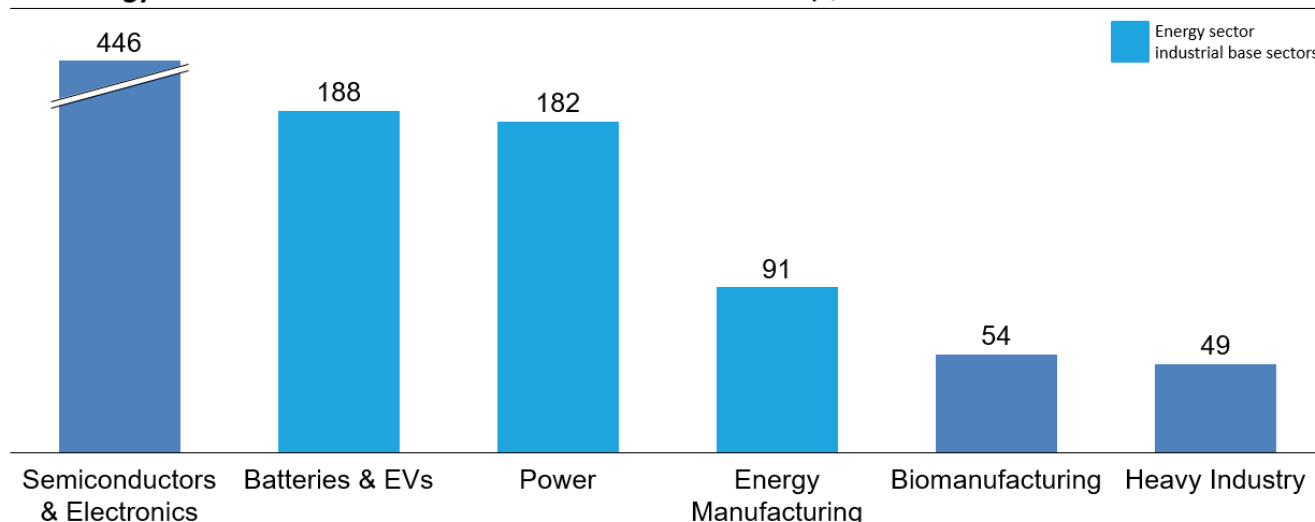


Figure 4. Private sector investment in energy industrial base since 2021.⁴³

The Office of Manufacturing and Energy Supply Chains (MESC) has played a key role in spurring investments in American energy manufacturing by helping administer nearly \$20 billion in grants and tax credits authorized by Congress.⁴⁴ These investments have catalyzed 66 manufacturing projects across 29 states, and created or retained over 25,000 jobs in the energy industrial base. Building on decades of work by DOE technology offices⁴⁵ and work in collaborations with the National Labs,⁴⁶ MESC has also built a leading analytical function to enable data-driven project selection for the U.S. energy industrial base. This funding, paired with billions of dollars in low-cost financing available from DOE's Loan Programs Office and tax incentives, has sparked significant investments from the private sector and renewed growth in domestic manufacturing of energy technologies. In addition to creating tens of thousands of new construction and manufacturing jobs,⁴⁷ these investments are strengthening energy supply chains with significant benefits to U.S. economic and national security.⁴⁸

Despite this significant progress, additional investment is needed to further secure U.S. energy supply chains. Taking lithium-ion batteries as an example, recent investments under BIL and IRA represent a downpayment towards building battery supply chains that can operate more independently from covered nations—the beginning of a phase of investment rather than the successful completion of one. To fully realize the energy security and economic benefits from building U.S. manufacturing capacity in these sectors, and to enable these investments to withstand anticompetitive pressures from competitors, further action will likely be needed.

⁴³ White House, 2024, "Investing in America", https://www.whitehouse.gov/invest/?utm_source=invest.gov.

⁴⁴ U.S. Department of Energy Office of Manufacturing and Energy Supply Chains supported project review and selection for \$10 billion in funding through "The Qualifying Advanced Energy Project Credit" (48C) administered by the U.S. Department of the Treasury and the Internal Revenue Service.

⁴⁵ U.S. Department of Energy technology offices include the Advanced Materials and Manufacturing Technology Office, Bioenergy Technologies Office, Building Technologies Office, Hydrogen and Fuel Cell Technologies Office, Office of Electricity, Solar Energy Technologies Office, Wind Energy Technologies Office, Vehicles Technologies Office, among other offices.

⁴⁶ National Laboratory partners within the current Mapping and Modeling Analysis Consortium (MMAC) include Argonne National Laboratory, Idaho National Laboratory, and the National Renewable Energy Laboratory.

⁴⁷ U.S. Department of Energy, 2024, "Fall 2024 Infrastructure Funding Progress Update"; <https://www.energy.gov/sites/default/files/2024-11/2024%20Fall%20Infrastructure%20Progress%20Report.pdf>

⁴⁸ Department of Energy, 2024, "Progress Update Summer 2024", <https://www.energy.gov/sites/default/files/2024-07/Summer%202024%20Progress%20Snapshot%20-%20Department%20of%20Energy%E2%80%99s%20Bipartisan%20Infrastructure%20Law%20and%20Inflation%20Reduction%20Act%20Funding.pdf>

Having visibility into each segment of our most critical energy supply chains is critical to allow us to monitor their development and ensure continued progress towards U.S. energy security. In some areas, such as critical minerals, further investment and policy measures will likely be needed to reinforce segments at risk of market power wielded by countries exercising non-market policies and practices.⁴⁹ For example, prices for lithium chemicals used to produce batteries have decreased substantially as excess Chinese production capacity has come online, exacerbating commodity price risk for U.S. projects.⁵⁰ Multiple approaches could be deployed to mitigate this risk ranging from trade policy to economic support for U.S. projects facing an artificially low price environment. In this scenario, a robust understanding of the lithium processing market—including the degree to which U.S. companies rely on Chinese lithium chemical imports today, as well as capacity and production costs for processed lithium in other nations—becomes essential to determining the most effective and efficient policy response.

To meet this challenge, MESC has developed a framework to measure readiness of energy supply chains to meet U.S. energy system needs under a range of scenarios, as well as to identify specific risks within supply chains. The remainder of this report introduces the Supply Chain Readiness Level (SCRL) framework, which can be applied to a broad range of energy technologies to evaluate readiness and identify specific supply chain risks. The following section describes the SCRL methodology and the subsequent section illustrates the framework's application using an example from the lithium-ion battery supply chain.

IV. The Supply Chain Readiness Level (SCRL) Framework

Energy supply chains comprise a complex network of production steps: from raw material extraction and processing, to manufacturing of intermediate sub-components, to final product assembly, and ultimately to end-of-life management to recover and reuse key materials. Each of these segments in the supply chain requires specialized equipment, skilled labor, permits to operate, relationships with suppliers, and customers.

It is important to note that supply chains are not static. Producers and manufacturers will continue to innovate, developing new intellectual property (IP), and to react to an evolving market and regulatory environment. The challenge of understanding these systems is more difficult when supply chains scale rapidly. Most supply chains are built to keep up with average commercial growth rates of 1-2% each year,⁵¹ but emerging energy technologies are expected to grow exponentially over the coming years and decades. The unprecedented scale, speed, and coordination of investment in U.S. energy manufacturing is further accelerating the development of U.S. energy supply chains.

Recognizing the need for precise visibility into energy supply chains, DOE's Office of Manufacturing and Energy Supply Chains (MESC) established the Modeling, Mapping, and Analysis Consortium (MMAC), a collaboration across MESC and DOE's National Laboratories. Leveraging supply chain and technology expertise from across the National Renewable Energy Laboratory, Argonne National Laboratory, and Idaho National Laboratory, the consortium set out to develop analytics tools including a consistent approach to measure supply chain risk from the perspective of the U.S. government. To address this challenge, MMAC assembled metrics used to evaluate supply chain risk based on laboratory expertise, industry engagement, and literature review and prioritized those that most closely reflect key risks to the U.S. energy system or to the durability of U.S. energy manufacturing investment. These metrics became

⁴⁹ U.S. Department of Commerce, 2024, "U.S.-Norway Critical Minerals Memorandum of Cooperation Report on Non-Market Policies and Practices in the Critical Minerals Sector", https://www.commerce.gov/sites/default/files/2025-01/US_Norway_Critical_Minerals_NMPP.pdf

⁵⁰ BloombergNEF, 2024, "Lithium Chemical Price Indices, Refined Mineral Supply."

⁵¹ National Institute of Standards and Technology, 2024, "U.S. Manufacturing Economy", <https://www.energy.gov/sites/default/files/2024-07/Summer%202024%20Progress%20Snapshot%20-%20Department%20of%20Energy%E2%80%99s%20Bipartisan%20Infrastructure%20Law%20and%20Inflation%20Reduction%20Act%20Funding.pdf>

the Supply Chain Readiness Level (SCRL), a framework intended to quantify risks in supply chains and, ultimately, to guide private investment and policymaking to increase U.S. energy system resilience.

Modeling, Mapping, and Analysis Consortium (MMAC)

- MMAC is a consortium of National Labs, established by MESC, to collaboratively develop state-of-the-art research focused on domestic manufacturing and energy supply chains.
- MMAC leverages capabilities across laboratories and unmatched access to complex datasets to identify supply chain gaps and opportunities.
- MMAC's objective analyses of the material supply and manufacturing base are intended to guide private and public investments to strengthen U.S. energy supply chains.



The SCRL framework builds on the foundation of Technology Readiness Levels (TRLs) and the newer Adoption Readiness Levels (ARLs), recently developed by the Department of Energy's Office of Technology Transitions. While these frameworks seek to answer different questions – TRLs focus on the underlying reliability and performance of technologies⁵² and ARLs strive to measure commercial viability of technologies – they both apply a consistent and replicable framework to determine the maturity of a technology along a particular dimension. The Supply Chain Readiness Level framework seeks to apply the same programmatic approach to understand the degree of risk, or inversely readiness, present in key energy supply chains.⁵³ A high SCRL score therefore indicates high readiness, or low risk, within a supply chain.

The development of MESC's SCRL is part of a whole of government effort, outlined in a recent paper from the Office of the United States Trade Representative, to build analytical capabilities to assess supply chain vulnerabilities and build future resilience.⁵⁴ For example, the Department of Commerce launched the new SCALE supply chain risk assessment tool. SCALE enabled Commerce to conduct its first whole-of-economy analysis of U.S. supply chains, giving the U.S. Government more quantitative insight into structural supply chain challenges that have been decades in the making. While the SCALE tool evaluates economy-wide resilience, the SCRL framework focuses more narrowly on readiness and resilience at the level of individual supply chain segments for key energy technologies.

SCRL defines "readiness" within the context of the current challenges facing U.S. energy supply chains and seeks to address two key questions. First, how reliable is the supply that will be needed to meet rapidly growing demand for key energy products? This must consider the possibility of global shortages

⁵² National Aeronautics and Space Administration, 2023, "Technology Readiness Levels Demystified", <https://www.nasa.gov/aeronautics/technology-readiness-levels-demystified/>; Department of Energy, 2024, "Adoption Readiness Levels (ARL) Framework", <https://www.energy.gov/technologytransitions/adoption-readiness-levels-arl-framework>

⁵³ Note: other supply chain frameworks have been developed across the U.S. government. Each has a distinct use case and application. For example, the Department of Commerce's SCALE tool establishes common measures of criticality and risk for supply chains across the whole of the U.S. economy. This establishes surveillance capabilities over U.S. supply chains and informs where U.S. efforts to strengthen supply chains should focus. DOE's SCRL framework endeavors to provide a monitoring tool for a subset of energy supply chains that are likely to be assessed as critical and high risk by the SCALE framework. By providing a monitoring capability that can provide a deep-dive into these supply chains, SCRL can provide unique insights about the relative readiness of various energy technologies, as well as discrete bottlenecks that may exist.

⁵⁴ The Office of The U.S. Trade Representative, "Adapting Trade Policy for Supply Chain Resilience: Responding to Today's Global Economic Challenges", https://ustr.gov/sites/default/files/USTR_Adapting%20Trade%20Policy%20for%20Supply%20Chain%20Resilience_0.pdf

for key resources as well as the level of dependence on production from countries that could act to disrupt U.S. supply chains. Second, how effectively can U.S. and allied production compete within the global marketplace? Assessing commercial viability and competitiveness includes several considerations including relative production costs under existing policy, the availability of skilled workers, and the scale of a customer base in the U.S. and partner countries. To answer these questions, SCRL assesses six distinct metrics for every production step, or supply chain segment, within a technology supply chain. The metrics are summarized in Figure 5 and outlined in greater detail below.

	METRICS	ASSESSMENT FOCUS
Supply Reliability Factors	Global Supply Availability	Projected global demand relative to all known sources of supply
	Sourcing Risk Management	Projected US & partner demand relative to supply from reliable sources
	Supplier Maturity	Availability of upstream materials/components from established, reliable sources
Commercial Competitiveness Factors	Customer Maturity	Strength of demand at sufficient price levels to make US production viable
	Cost Competitiveness	US competitiveness relative to other global producers
	Workforce Readiness	Availability of workers with necessary skills

Figure 5. Metrics evaluated within the Supply Chain Readiness Level framework.

- Global Supply Availability** – *Assesses the balance between global supply and demand for each supply chain segment based on projected demand for the finished technology.*

At-scale deployment of new energy technologies globally, combined with efforts to invest meaningfully in the electric grid, will require enormous quantities of raw and processed materials. While demand for some materials will be driven primarily by a single technology, such as lithium for batteries, other materials like copper, aluminum, and steel will see substantial demand pull from a range of technologies being deployed simultaneously. The varied nature of demand for these materials increases coordination challenges and the associated risk that production capacity lags demand.

- Sourcing Risk Management** – *Assesses reliance on covered nations for production within any given supply chain segment based on projected demand for the finished technology.*

While there may be sufficient supply to meet global demand, sources of supply may not be reliable and secure. In areas such as critical minerals, where covered nations have dominant market share, supply can be limited by trade risk, as evidenced by recent Chinese export bans on key critical minerals.⁵⁵ Inability to access these materials risks shortages of key energy products required to keep the U.S. energy system functioning effectively.

⁵⁵ Reuters, 2024, “China bans export of critical minerals to US as trade tensions escalate”, <https://www.reuters.com/markets/commodities/china-bans-exports-gallium-germanium-antimony-us-2024-12-03/>

- **Supplier Maturity** – *Assesses reliance on covered nations for feedstocks or inputs into production capacity in the U.S. or other non-covered nations.*

Even when control of production is diversified for a given supply chain segment, reliance on covered nations to source key inputs also presents a risk. For many energy technologies, U.S. companies control meaningful market share in the final assembly of goods. However, if key upstream inputs—solar wafers, graphite, or transformer cores for example—are sourced solely or predominantly from a single country, U.S. production could still be slowed or even stopped for a period of time.

- **Customer Maturity** – *Assesses reliance on covered nations to directly purchase goods produced by firms established in the U.S. or other non-covered nations.*

Many of the energy supply chains being discussed are nascent but quickly growing in the U.S. and partner countries, particularly for upstream and midstream inputs. As these supply chains are developed, the relative timing of investments becomes critical. For example, if upstream investments in materials processing outpaces midstream investments in subcomponent manufacturing, the material processor's utilization may decrease, undermining the company's economics. While this is not a major risk in more mature markets, it can be a significant one in the early stages of supply chain development.

- **Cost Competitiveness** – *Assesses relative production costs, including policy support, between the U.S. and other global producers.*

While the factors discussed above represent risks for the health of a supply chain, companies are unlikely to act solely for the sake of addressing these risks. Rather, they will invest only where the business case appears strong. Cost competitiveness is an important indicator of whether a sector can attract investment and remain durable over the long-term.

- **Workforce Readiness** – *Assesses the ability for producers to find a sufficiently skilled workforce to operate their facilities.*

Growth in U.S. manufacturing is creating high demand for workers and craft labor necessary to build and operate facilities. Many jobs require specialized skills (e.g., working in a clean room setting) for production and facility operations. As new energy supply chains develop, so must programs that train workers with the requisite skills. By identifying workforce needs in collaboration with workers, employers, and other workforce stakeholders, training programs can be developed to build sufficient labor supply.

Each of these metrics is evaluated and scored using publicly available market data, studies from a range of National Laboratories, and DOE proprietary research for each step of an energy supply chain. Supply chain segments are assigned as raw materials or manufacturing steps and aggregated into sub-scores. Raw Material and Manufacturing sub-scores are then combined with a Workforce Readiness Score to arrive at an overall Supply Chain Readiness Level for a given technology. This analysis is performed to assess readiness today and in 2030, considering expected demand evolution and announced projects.

Looking forward, MMAC will continue to evolve the Supply Chain Readiness Level framework, recognizing the opportunity for continuous improvement. Potential enhancements to the framework include project-level assessments to discount future supply announcements based on likelihood of final investment decision, the inclusion of material recycling pathways within the framework, and the

refinement of labor assessments to capture more granular sources of risk including at the segment and geographic level.

The outputs of the SCRL framework are intended to be used by a range of audiences to inform decision-making related to these supply chains. The tool can provide investors with a guide to the supply chain segments with greatest value and growth potential and provide policymakers with crucial information on what specific areas require policy intervention to protect American energy security. And because the SCRL framework considers global production, it can also inform where international partners can play essential roles to provide materials and products that are scarce domestically or to leverage lower cost production to build more efficient supply chains.

V. Applying Supply Chain Readiness Levels: Lithium-Ion Batteries

While the conceptual framework for Supply Chain Readiness Level (SCRL) is an important starting point, illustrating how it can be applied to a particular energy supply chain offers insight into how the tool functions in practice. For this purpose, we will focus on examples within the lithium-ion battery supply chain.⁵⁶ As we assess these examples, it is important to note that scores referenced below for a specific metric are not necessarily representative of the overall readiness level for a supply chain segment nor are scores immutable. In fact, the wave of battery investments enabled by BIL and IRA is expected to enhance readiness for the supply chain segments examined below.

Lithium-ion batteries are critical for U.S. energy security and will play an increasingly vital role in the defense, power, and transportation sectors. Transportation represents the largest market for advanced batteries, driving 85-90% of demand, as electric vehicles increase adoption in the domestic market.⁵⁷ Stationary storage represents the other major demand driver, with batteries poised to play an increasingly important role in grid resilience and balancing. While defense currently comprises a smaller portion of demand, batteries are projected to play an increasingly important role in weapons ranging from unmanned drones to enhanced energy weapons.⁵⁸ Many defense applications require higher standards of performance relative to commercial applications and may serve as an accelerant for leading-edge, frontier technology development, where U.S. producers may be particularly well-positioned. The result is that demand for batteries is expected to grow dramatically over the next decade (Figure 6).

⁵⁶ Note: initial SCRL analysis discussed here focuses on the NMC battery chemistries with graphite-based anodes. It is a static scenario that does not consider substitutes for anodes (e.g., silicon) and is meant to focus on the readiness of a graphite-based anode battery supply chain. The analytical framework allows for future analysis to cover additional battery chemistries (e.g., NMCA, NCA, SIB, silicon-based or graphite / silicone-blended anodes) and technologies (e.g., long duration energy storage, flow).

⁵⁷ S&P Global, Retrieved on 12/16/2024, "New Battery Technology for the Future", <https://www.spglobal.com/esg/s1/topic/the-future-of-battery-technology.html>

⁵⁸ U.S. Department of Defense, 2021, "Deputy Secretary of Defense Dr. Kathleen Hicks Remarks at Wayne State University, Detroit, Michigan, on Climate Change as a National Security Challenge", <https://www.defense.gov/News/Transcripts/Transcript/Article/2838082/deputy-secretary-of-defense-dr-kathleen-hicks-remarks-at-wayne-state-university/>

Potential battery deployment trajectories, GWh p.a. by 2030E, transport and stationary applications

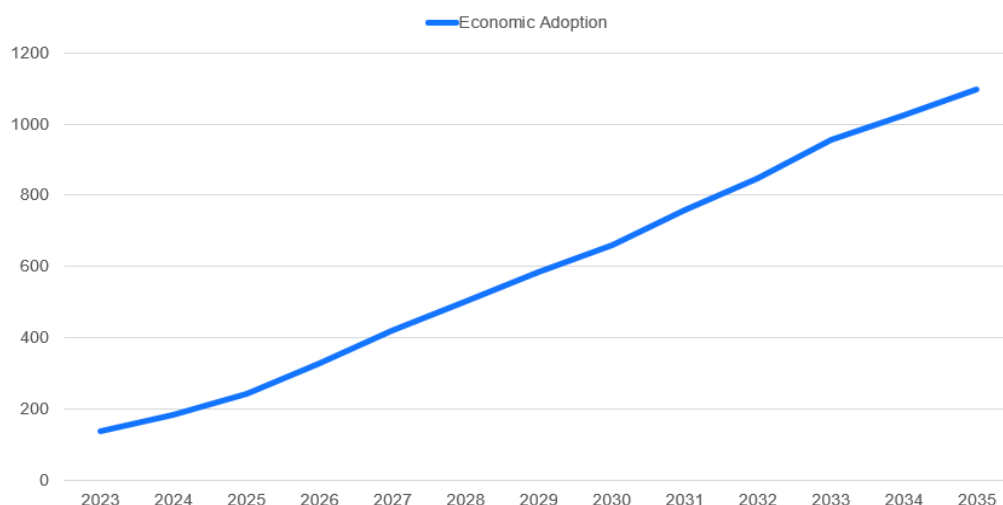


Figure 6. Projected battery demand based on market-driven scenario.⁵⁹

Applying the SCRL framework to lithium-ion batteries requires assessing the metrics outlined in Figure 5 against each segment of the battery supply chain shown in Figure 7 below. While this exercise requires considerable resources, it provides the benefits of a robust fact base summarizing the competitive global landscape, early identification of risks as they emerge in evolving supply chains, and a consistent measuring stick to evaluate policies and other efforts to build more resilient supply chains. It is important to note that the illustration provided in the following section is not intended to provide a holistic assessment of the battery supply chain as a whole or even of any individual supply chain segment. Rather, supply chain segments examined below have been selectively identified to effectively illustrate how each SCRL metric functions in practice.

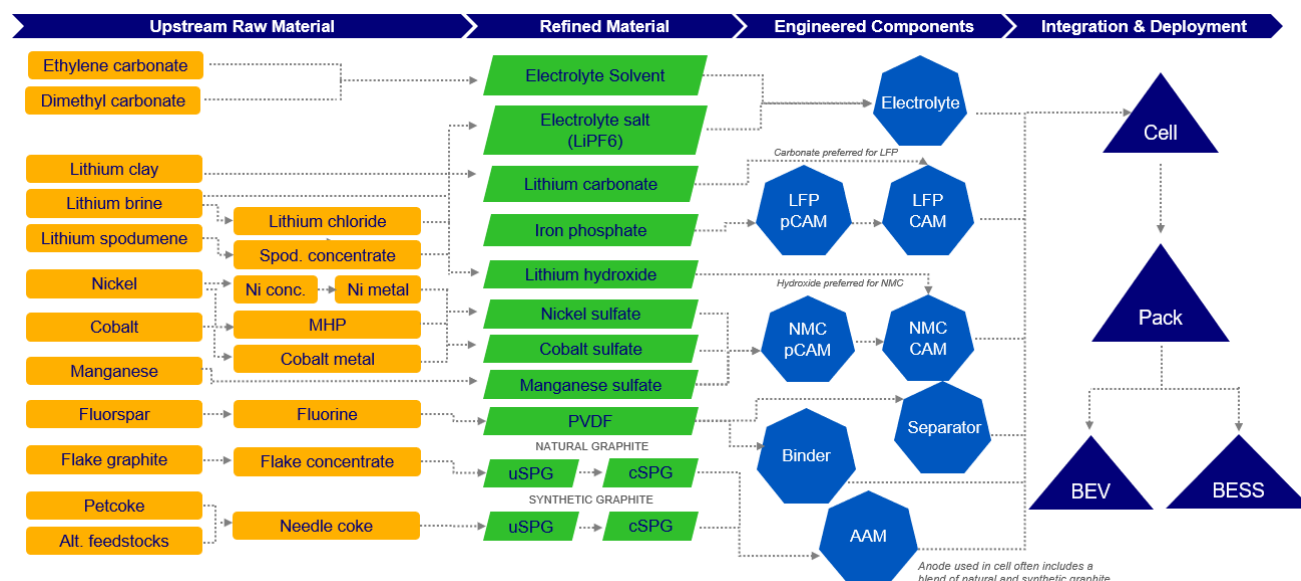


Figure 7. Lithium-ion battery supply chain map.⁶⁰

⁵⁹ Argonne National Laboratory, 2024, "U.S. Battery Demand Estimates and Forecasts"; BloombergNEF, 2024, "Economic Transition Scenario".

⁶⁰ Note: representative supply chain 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

Global Supply Availability

Multiple critical minerals will be needed at unprecedented scales to meet growing battery demand, most notably graphite, lithium, nickel, and cobalt. While the risks related to Global Supply Availability vary for each of these minerals, most projections indicate there will be sufficient global supply to meet the rapidly growing demand. Examining the specific example of refined graphite, which comprises a critical input as the material most frequently used for the battery anode,⁶¹ the Global Supply Availability score would be high. While global demand for battery-grade refined graphite is projected to be over 2.6 million tons by 2030, global supply is expected to exceed this figure at 3.8 million tons per year. At present, this excess capacity is driven overwhelmingly by Chinese production, a pattern present across the supply chain.

Sourcing Risk Management

Across the battery supply chain, Sourcing Risk Management emerges as a common challenge. Firms controlled or influenced by China hold significant global market shares across the battery supply chain, accounting for between 70% and 90% of global production capacity for mineral processing and subcomponent manufacturing as shown in Figure 8. It is important to note that this market position is not organic and has been achieved through decades of non-market practices and policies as outlined in a recent report from the Office of the U.S. Trade Representative.⁶² The result is low Sourcing Risk Management scores across many segments of the battery supply chain today, though substantial steps are being taken—including \$33 billion in catalytic government financing for U.S. projects across the battery supply chain—to mitigate the market power of Chinese firms.

China market share across the NMC battery supply chain, % of global production capacity, 2024E

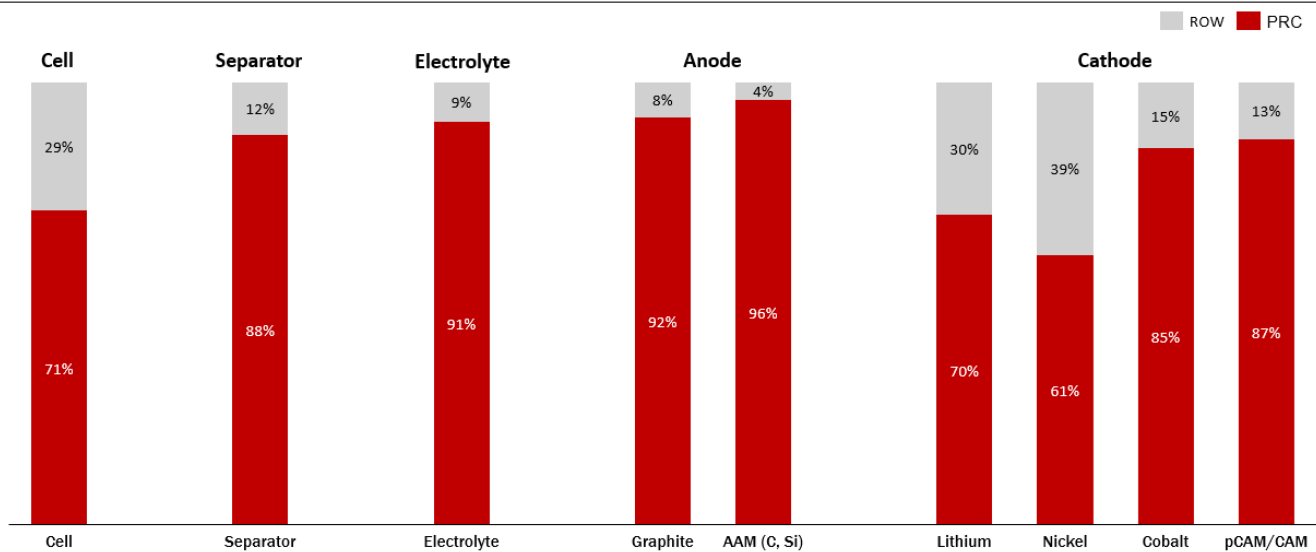


Figure 8. Market share of producers domiciled in China across the battery supply chain.⁶³

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.

⁶¹ Note: silicon is being mixed with or substituted for graphite to enhance performance and manage risks related to graphite scarcity.

⁶² The Office of the U.S. Trade Representative, 2025, "Adapting Trade Policy for Supply Chain Resilience", https://ustr.gov/sites/default/files/USTR_Adapting%20Trade%20Policy%20for%20Supply%20Chain%20Resilience_0.pdf

⁶³ BloombergNEF, 2024. Note: lithium, nickel, cobalt, and graphite from BNEF 2024E refined mineral supply figures for lithium carbonate and hydroxide, nickel sulfate, cobalt sulfate, and both natural and synthetic graphite. All others from BNEF-tracked "fully commissioned" facilities. Est. market share does not include operations outside of China that may be owned by Chinese companies, therefore likely understates true market share controlled or influence by China.

Supplier Maturity

Sourcing Risk Management alone does not provide a complete picture of risks from production concentration in covered nations. Some supply chain segments have sufficient capacity to meet demand, but they rely on covered nations for key inputs. NMC cell manufacturing exemplifies this pattern with sufficient current and announced capacity, but with a risk that key inputs such as anode active material or cathode active material may not keep pace with announced cell production. Thus, reflecting this segment as high readiness would offer an incomplete assessment due to its reliance on producers in covered nations for key inputs.

Supplier Maturity addresses this by specifically assessing the production capacity at each supply chain step and calculating the volume of each input required to support that level of production. For example, the current NMC battery cell capacity outside of covered nations is estimated to be roughly 200GWh.⁶⁴ This capacity of battery cell production would require 300,000 tons on NMC cathode active material (CAM) to support cell manufacturing operating at full utilization. Current NMC CAM production capacity outside of covered nations is just under 350,000 tons per annum indicating high Supplier Maturity for the NMC Cell and NMC CAM linkage today.⁶⁵ Notably, because the Supplier Maturity score is assessing the interface between actual capacity at each supply chain step, the score would be high in this example regardless of whether cell and CAM capacity are sufficient to keep pace with overall battery demand outside of covered nations.

This metric can prove particularly valuable when considering forward-looking project announcements. Continuing with the example of NMC cell capacity, announced production capacity outside of covered nations is 2,000GWh, a tenfold increase from current levels.⁶⁶ Meanwhile, announced NMC CAM projects in the same geographies will increase capacity by only four-fold according to available market data, resulting in a decrease of the 2030 NMC Cell Supplier Maturity score.⁶⁷ It is important to note that this risk is not immutable and suppliers may successfully bring projects online in time to meet the needs of cell manufacturers by 2030. In fact, some announced projects funded by DOE are not yet reflected in industry databases and will provide additional CAM capacity. Additionally, yet-to-be-announced projects may still come online by 2030 given relatively short development timelines for CAM projects.⁶⁸ Nevertheless, tracking this metric may support early identification of potential or emerging gaps—and resulting opportunities—in supply chains, offering an important signal for market participants.

Additional opportunities for applying this metric in future versions of the tool include enabling more granular assessments of Supplier Maturity at a country or regional level. This can both account for logistics constraints that may be present for some supply chain segments, as well as help identify opportunities for greater colocation of supply chains. For example, the U.S. has invested in building local battery ecosystems domestically and with trade partners like India to garner the benefits of scaled and collocated production.⁶⁹

⁶⁴ BloombergNEF, Retrieved on 8/8/2024, Battery Cell Manufacturing Database. Note: Figures may be subject to adjustments based on MMAC analysis; most up-to-date figures may differ based on updated analysis.

⁶⁵ BloombergNEF, Retrieved on 8/8/2024, Cell Manufacturing Database. Note: Figures may be subject to adjustments based on MMAC analysis; most up-to-date figures may differ based on updated analysis.

⁶⁶ BloombergNEF, Retrieved on 8/8/2024, Battery Cell Manufacturing Database. Note: Figures may be subject to adjustments based on MMAC analysis; most up-to-date figures may differ based on updated analysis.

⁶⁷ U.S. Department of Energy internal analysis based on known funded projects and BloombergNEF tracking. Note: Figures may be subject to adjustments based on MMAC analysis; most up-to-date figures may differ based on updated analysis.

⁶⁸ U.S. Department of Energy internal analysis based on known funded projects and BloombergNEF tracking.

⁶⁹ The White House, 2024, "Roadmap for U.S.-India Initiative to Build Safe and Secure Global Clean Energy Supply Chains", <https://www.whitehouse.gov/briefing-room/statements-releases/2024/09/21/roadmap-for-u-s-india-initiative-to-build-safe-and-secure-global-clean-energy-supply-chains/>

Customer Maturity

A related concept is Customer Maturity, which looks downstream of a supply chain segment (rather than upstream as Supplier Maturity does). This metric seeks to understand whether sufficient direct customers—or in other words sufficient capacity at the next supply chain step—exist outside of covered nations to sustain production levels in the event of a trade disruption. To illustrate this concept, we will consider the example of lithium extraction.

Lithium is a critical input for battery production and can be extracted in multiple forms today, ranging from hard rock to clays to brines. Ample capacity for lithium extraction exists outside of covered nations and production in these geographies actually exceeded demand in 2023, leading to a high Sourcing Risk Management score. Notably, Australia controlled nearly 60% of production in 2023.⁷⁰ However, Sourcing Risk Management alone provides an incomplete picture of the readiness of the lithium extraction step.

Extracted lithium must be chemically converted to lithium hydroxide to serve as an effective input for NMC batteries. Today, that lithium processing is overwhelmingly concentrated in China, which controls more than 70% of market share for lithium processing.⁷¹ The result of this concentration is that firms extracting lithium often rely on buyers in a covered nation to purchase their products, creating a commercial risk for companies extracting lithium in the event of a potential trade disruption.

Substantial investments are being made in the U.S. to provide alternative processing options, including a range of battery recycling projects, to mitigate reliance on covered nations. Multiple lithium processing projects are being developed in the U.S., including seven that received DOE funding. These projects alone would add nearly 200,000 tons⁷² of lithium processing capacity each year, an enormous figure when considering the current U.S. processing capacity of roughly 30,000 tons annually.⁷³ A substantial number of additional projects announced by private investors have the potential to bring a similar level of processing capacity online if projects successfully move to final investment decision.⁷⁴

Cost Competitiveness

Cost Competitiveness is an additional metric within Supply Chain Readiness Level that evaluates the relative production costs, including the impacts of government policies, for U.S. battery manufacturing relative to other global producers. Given the U.S. battery sector is at the early stages of scale-up, production cost remains a challenge due to smaller scales of production and more limited experience manufacturing batteries relative to China, though this should improve as scale and experience is accrued. In many segments of the supply chain, Chinese production remains lower cost compared to U.S. production. This is driven primarily by low cost of capital due to access to state financing and low-cost land, but China has compounded its advantage with other real advantages including local access to equipment, intellectual property developed through years of operations, collocated production in industrial centers, and lower labor and construction costs.⁷⁵ Despite this starting point, U.S. production is becoming competitive as key areas of the battery supply chain scale up and are buoyed by policy incentives (e.g., competitive grants, production tax credits) to level the playing field with Chinese production.

⁷⁰ BloombergNEF, Retrieved on 8/8/2024, Cell Manufacturing Database. Note: most up-to-date figures may differ based on updated analysis.

⁷¹ BloombergNEF, 2024. Note: lithium, nickel, cobalt, and graphite from BNEF 2024E refined mineral supply figures for lithium carbonate and hydroxide, nickel sulfate, cobalt sulfate, and both natural and synthetic graphite. All others from BNEF-tracked “fully commissioned” facilities. Est. market share does not include operations outside of China that may be owned by Chinese companies, therefore likely understates true market share controlled or influenced by China.

⁷² U.S. Department of Energy internal tracking of announced projects. Note: the capacity includes both lithium hydroxide and lithium carbonate, which requires additional processing steps to be used for NMC batteries.

⁷³ Analysis based on data from BloombergNEF, Argonne National Laboratory, and public project announcements. Note: the capacity includes both lithium hydroxide and lithium carbonate, which requires additional processing steps to be used for NMC batteries.

⁷⁴ U.S. Department of Energy internal tracking of announced projects. Note: the capacity includes both lithium hydroxide and lithium carbonate, which requires additional processing steps to be used for NMC batteries.

⁷⁵ CICC Research, CICC Global Institute, 2024, “New Energy: Security Issues Amid Green Transition and Energy Crisis”, Ch. 13, “The Reshaping of China’s Industry Chains”, https://doi.org/10.1007/978-981-97-1647-0_13

To concretely illustrate what Cost Competitiveness evaluates, battery cell manufacturing provides an informative example. Figure 9 below illustrates that, while underlying U.S. cell production costs are slightly higher than the prevailing market price, the impact of the 45X manufacturing tax credit and Section 301 tariffs more than offset that delta to make U.S. a globally advantaged production location. The result is a high Cost Competitiveness score for battery cell manufacturing.

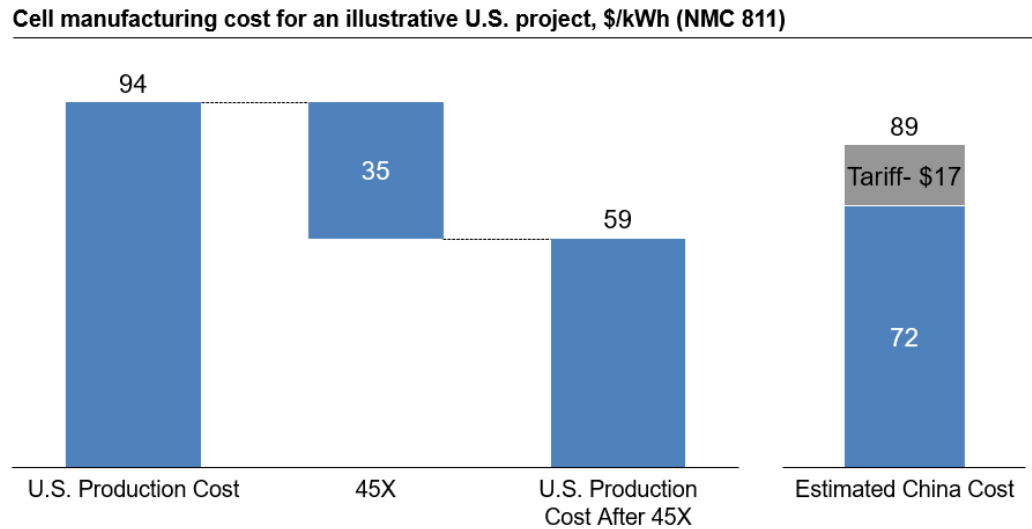


Figure 9. Production cost estimates for US vs. Chinese battery cell production.⁷⁶

Workforce Readiness

An additional potential barrier to investment is inability to find the necessary expertise and skilled labor to make a venture successful. Absent workers with the skills, training, and know-how to extract materials, operate production equipment, or install products, the U.S. energy industrial base and required supply chains will never reach their full potential. Therefore, labor availability represents the final SCRL factor.

Labor availability identifies the most relevant occupational and skill categories to produce a given energy technology. It then evaluates labor tightness using occupation-level supply and demand data or relevant proxies, such as structured surveys to employers gathered for the United States Energy & Employment Report.⁷⁷ Expected demand growth for these occupational categories is modeled based on underlying trends in energy deployment and manufacturing. Future opportunities to further refine this metric include increasing granularity of occupation-level data, incorporating regional data variation, and enhancing visibility to labor supply impacts from job training and reskilling programs.

In the case of battery manufacturing, both current labor tightness and expected demand growth for key occupations were evaluated as being among the highest across energy manufacturing sectors, resulting in a low Workforce Readiness score. It is important to note that multiple lines of effort are being pursued to develop the necessary integrated training and skills and worker retention and career pathways for increased U.S. energy technology manufacturing. One such example is MESC’s Industrial Training and Assessment Center (ITAC) Program, which has invested \$100 million in workforce development to date, funding over 200 projects to help ensure America has the skilled labor force necessary to sustain a restored manufacturing sector. Alongside ITAC, the DOE’s Battery Workforce Initiative is implementing sectoral workforce development programs to fast-track building and training the skilled workforce by

⁷⁶ U.S. Department of Energy internal analysis based on Argonne National Laboratory, 2024, “Cost Analysis and Projections for U.S.-Manufactured Automotive Lithium-ion Batteries”, <https://publications.anl.gov/anlpubs/2024/01/187177.pdf>
⁷⁷ U.S. Department of Energy, 2024, “United States Energy & Employment Report 2024”, https://www.energy.gov/sites/default/files/2024-10/USEER%202024_COMPLETE_1002.pdf. Note: data used in SCRL analysis includes non-public data.

convening employers, labor organizations, and training institutions to support manufacturing training ecosystems.⁷⁸

Assessing SCRL Battery Outputs

The six metrics discussed above are calculated to arrive at a Supply Chain Readiness Score. Applying the SCRL analysis to the two battery chemistries expected to comprise the majority of the battery market over the next decade—nickel manganese cobalt (NMC) and lithium iron phosphate (LFP) with graphite anodes—show limited supply chain readiness for both chemistries today. Because the SCRL framework considers all supply and demand outside of covered nations, production capacity from partner countries ranging from Australia and Chile for lithium to Japan and South Korea for engineered materials or manufactured components plays a key role in determining the current readiness scores. An emerging NMC battery cell manufacturing base in the U.S. also helps to support the NMC score despite challenges with key upstream materials. Meanwhile, LFP faces the opposite challenge with relatively more favorable access to cathode materials but minimal commercial-scale cell production outside of China.

While nuance exists across battery chemistries and individual supply chain segments, evaluating trends across SCRL outputs uncovers three patterns challenging the battery supply chain today:

- **Chinese Market Share Concentration** – SCRL identifies a substantial reliance on production controlled by China across multiple segments, most notably cathode active materials (CAM) and upstream processing of cathode inputs (e.g., lithium, nickel, and cobalt), anode active materials (AAM), and battery electrolyte. To increase resilience of U.S. supply chains, MESC has made substantial investments in each of these areas through funds provided by BIL and IRA.
- **Production Competitiveness Challenges** – Less favorable unit economics emerged as a key driver of lower readiness for U.S. production. While relative production costs vary meaningfully across individual supply chain segments, Chinese firms have amassed substantial advantages across the battery supply chain due to access to non-market policies and practices, business scaling advantages (e.g., vertical integration), and IP development. Policies to support the competitiveness of U.S. battery manufacturing—such as the 45X advanced manufacturing production tax credit, the domestic sourcing requirements present in the 30D clean vehicle credit, non-dilutive equity grants, and government financing—are currently being implemented to boost competitiveness in U.S. battery manufacturing over time.
- **Workforce Readiness** – Multiple risk indicators including challenges reported by existing battery producers in finding domestic skilled labor today and rapid projected growth in the need for skills required for batteries manufacturing relative to other energy sectors have contributed to low Workforce Readiness. Efforts to mitigate these risks by developing education and training curricula with industry consensus for high-demand battery occupations, expanding career pathways to battery occupations, and investing in training—both upskilling and reskilling programs—to attract and retain workers in these sectors represent key interventions.

The United States has taken concerted action to increase resilience in the battery supply chain by catalyzing domestic investments in battery production. The U.S. government has provided \$33B in grants, loan commitments, and investment tax credits.⁷⁹ This investment, along with support from manufacturing tax credits like 45X, have led to over \$175B of combined private and public investment announced across battery supply chains and electric vehicle production.⁸⁰ DOE's Office of Manufacturing and Energy Supply Chains and the Loans Program Office are playing particularly notable roles driving

⁷⁸ U.S. Department of Energy, 2024, "Goals and Progress of the Battery Workforce Initiative (BWI)", <https://netl.doe.gov/sites/default/files/2024-12/Final%202024%20BWI%20Interim%20Report.pdf>.

⁷⁹ Value of investment tax credits estimated based on companies that have voluntarily announced their receipt of a 48C ITC allocation.

⁸⁰ U.S. Department of Energy, 2025, "Building America's Clean Energy Future", <https://www.energy.gov/invest>

the buildout of U.S. battery manufacturing. MESC has committed approximately \$5 billion in capital to roughly 40 projects to deploy at-scale battery manufacturing, including for upstream material processing and midstream engineered components. Meanwhile, the LPO's Advanced Technology Vehicle Manufacturing (ATVM) Loan Program has closed approximately \$23.6 billion of loans, with an additional roughly \$5 billion in conditional commitments.

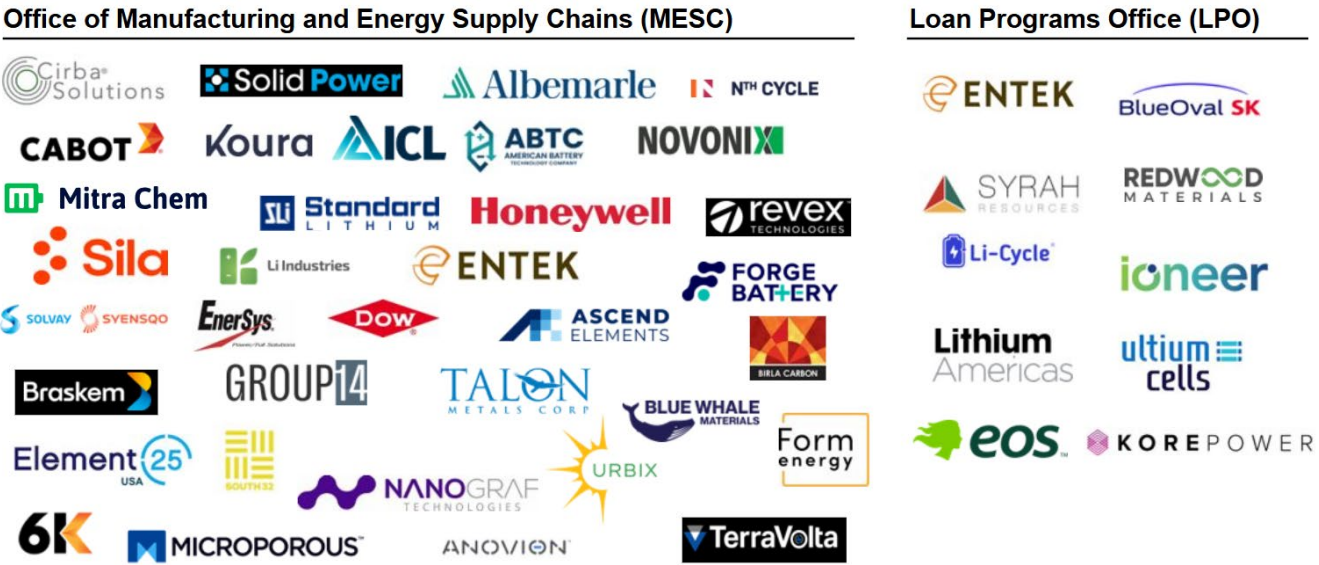


Figure 10. Example recipients of Federal funding through programs funded by BIL and IRA.

These investments are fundamentally reshaping U.S. energy supply chains and dramatically reducing dependence on covered nations for critical inputs to our energy system. In some segments of the supply chain, such as battery cell manufacturing, these investments alongside other privately funded projects will position U.S. producers to fully meet projected 2030 demand. In other segments, including key upstream inputs, announced U.S. projects could be capable of meeting more than half of U.S. demand, and investments into battery recycling are likely to further increase that figure.

Even with this historic wave of U.S. investment, international partners will play a key role in managing and mitigating risks in the battery supply chain. The natural dispersion of critical minerals across geographies makes international cooperation essential to build robust and resilient supply chains. Additionally, the substantial capacity for battery manufacturing already built out in Japan and South Korea—and the accumulated IP that comes from that experience—offers opportunities to accelerate the scale-up of battery manufacturing outside of covered nations. To leverage the relative strengths of like-minded international partners, the U.S. has established the Mineral Security Partnership (MSP), a coalition of 14 individual countries as well as the European Union.⁸¹ In addition, a broad range of government entities including the U.S. Agency for International Development (USAID), U.S. Development Finance Corporation (DFC), U.S. Export-Import Bank (EXIM), and the Departments of Defense, State, Energy, and Commerce have been activated across a range of bilateral and multilateral engagements focused on critical minerals.⁸² The continuation of this activity will be essential to maintain momentum towards critical mineral security.

⁸¹ U.S. Department of State, "Minerals Security Partnership", <https://www.state.gov/minerals-security-partnership/>; Note: Mineral Security Partnership countries include Australia, Canada, Estonia, Finland, France, Germany, India, Italy, Japan, Norway, the Republic of Korea, Sweden, the United Kingdom, the United States, and the European Union (represented by the European Commission).

⁸² Argonne National Laboratory, 2024, "Securing Critical Materials for the U.S. Electric Vehicle Industry", <https://publications.anl.gov/anlpubs/2024/03/187907.pdf>

The challenge ahead for these companies, whether in the U.S. or abroad, will be to reach final investment decision, put steel in the ground, and quickly scale manufacturing. This will require companies extracting and processing raw materials to navigate substantial commodity price risk while companies downstream must manage technical risk alongside price pressure from low-cost Chinese production. Successfully navigating these challenges will necessitate both private and public stakeholders to engage collaboratively to support the development of this sector. For private sector actors, this will mean mobilizing capital from financiers to fund these projects and commitment from purchasers to binding offtake agreements through the entire supply chain. For the public sector, it will require providing ongoing support for projects as they navigate challenges including permitting and environmental litigation, materials certification, and anti-competitive pressures from covered nations seeking to limit competition.

VII. The Path Forward: Building Resilience in Energy Supply Chains

The United States has made historic investments in batteries and energy manufacturing. In doing so, the U.S. has reasserted leadership across energy technologies—many of which were invented on American soil—while safeguarding American energy independence.

While these investments have provided a meaningful downpayment to build resilient energy supply chains in the U.S. and partner countries, more work lies ahead to minimize reliance on production from covered nations and to ensure that domestic investments have a path to sustained competitiveness. Competitor nations have supported manufacturing for decades through subsidies and non-market practices. Building competitive industries in these areas within the United States will require a sustained effort to develop these sectors and protect them from unfair competitive practices intended to undercut U.S. companies.

World class market intelligence will be required to successfully execute this mission for three primary reasons. First, understanding relative readiness at a technology level, including quantifying where competitors have built entrenched positions, will inform where to focus efforts to build domestic supply chains. Second, understanding where incremental investment and policy support is needed to develop robust production and innovation ecosystems will enable more efficient use of public funds. Third, the dynamic nature of these supply chains necessitates a data-based, system-level perspective to monitor risks as conditions change and evolve. Supply chains today will look very different in the future, reinforcing the need for clear and consistent visibility into the market structure.

Capabilities such as the Supply Chain Readiness Level framework can help address this need. MESC has developed this tool to supply policymakers with the information necessary to craft efficient and effective policy and to provide investors with a common set of facts to inform investment decisions. Extending these analyses to other technologies and building enduring infrastructure to maintain and strengthen this capability is an essential step to ensure policymakers have the tools necessary to secure America's energy supply chains. Combining this level of insight with the exceptional innovation of American entrepreneurs, drive of American workers, and strength of the American economy will enable the U.S. to chart a path to maintain energy independence as the global energy system evolves.



DOE/MESC-0110 | January 2025