2021–2024 Four-year Review of Supply Chains for the Energy Sector Industrial Base

U.S. DEPARTMENT OF ENERGY

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EXECUTIVE SUMMARY

The U.S. Government is advancing a more secure and diversified energy sector industrial base to support an evolving energy system. While the United States has long been a leading energy economy, maintaining this position and global competitiveness will require substantial and rapid transformation from a focus on producing hydrocarbons to manufacturing energy technologies.

Leadership in the energy sector industrial base (ESIB) requires action across a diversified set of technologies, infrastructure, and industrial applications. A robust and resilient ESIB requires scaling a broad range of economic activities including extraction and processing of raw and materials for critical components, manufacturing and installation of energy technologies and key components, investment in the electrical grid to carry greater loads, development of new sources of fuel and industrial heat, and workforce development.

The U.S. Government is pursuing a modern industrial and innovation strategy to lead the energy transition. Working with partners around the world, the U.S. is leading a government-enabled, private sector–led approach that invests in our own economic and technological strength, promotes diversified and resilient global supply chains, and sets high standards for labor, the environment, cybersecurity, among other areas.

More secure and resilient supply chains are essential for the national security, economic security, and technological leadership of the United States. The long-standing approach of prioritizing of efficiency and low costs has increased supply chain risks. Foreign entities of concern (FEOC) are playing a larger role in production of critical upstream and midstream materials. Without a robust domestic and allied manufacturing ecosystem, the U.S. may remain reliant on competitor nations, posing a risk to national security and future economic prosperity.

The U.S. has made substantial progress in reinvigorating manufacturing and strengthened our energy supply chains by making them more resilient, robust, diverse, and competitive. In 2022, the U.S. Department of Energy (DOE) published "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition"—the first comprehensive U.S. Government plan to build an ESIB.[24]

The People's Republic of China (PRC) enjoys structural advantages in energy supply chains today, which threaten U.S. economic and national security. While the U.S. and trading partners are making considerable progress towards standing up supply chains for manufactured energy products, future investments must consider the structural advantages in production that PRC has built up over the last decade.

Several key challenges must be navigated to accelerate the pace of progress in building resilience in America's ESIB and its supporting supply chains. An intentional strategy to drive investment into high-priority sectors necessary for U.S. national and economic security, especially where PRC's dominance threatens the U.S. ESIB, will be critical to improve U.S. competitiveness.

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[24] U.S. Department of Energy. "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition," U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains", February 24, 2022. https://www.energy.gov/policy/articles/americas-strategy-secure-supply-chain-robust-clean-energy-transition.

SECTOR OVERVIEW

Introduction

The United States energy sector industrial base (ESIB) is a sprawling network of activities that enables the energy sector and propels the American economy. This vast, industrial system encompasses a wide range of activities including extraction of hydrocarbons, mining and processing of battery-grade metals, manufacturing and installation of energy technologies, and ultimately recycling or disposal of end-products. The shifts within this sector have ignited growth and investment in new industries, creating millions of well-paying jobs in the process. Indeed, the U.S. energy economy directly employs 8.4 million workers, of which 42 percent are employed in the burgeoning clean energy sector.[25]

Sector Overview

A robust U.S. energy sector is essential for achieving critical national economic and security objectives. First, affordable energy is a cornerstone of economic growth, job creation, and maintenance of a high standard of living. Second, a resilient and secure energy system is critical for ensuring national security. Third, U.S. leadership in the global energy transition and climate change mitigation is paramount to position the United States as a leader both today and in the future, as well as to mitigate the damaging impacts from climate change. A robust U.S. energy sector industrial base is on par with a robust defense industrial base—both are indispensable to the preservation of prosperity, economic vitality, and a secure future.

The challenges ahead to ensuring ongoing strength and resilience of the U.S. ESIB are significant. While the United States has long been a leading energy economy, maintaining this position will require substantial and rapid shift in focus from producing hydrocarbons to manufacturing low carbon energy and grid technologies. The pace of climate change demands a swift diversification of energy resources, and global markets are embracing these technologies at an accelerating pace. New technologies will be indispensable for this transition, from renewable energy generation to energy storage to industrial decarbonization solutions. The Biden–Harris Administration has taken historic steps to accelerate the deployment of these technologies and bolster supply chains, ensuring a resilient and sustainable energy future for the nation. By addressing these challenges, the United States can maintain its leadership in the global energy market and secure a prosperous future for generations to come.

Evolution of the U.S. Energy Sector Industrial Base

The United States energy sector has undergone significant changes in the past two decades and will continue to evolve at an accelerated pace in the next 30 years due to rapid innovation, investment trends in private capital markets, and the urgent need to combat global climate change. Over the last few decades, the ESIB has undergone significant transformation: shifting energy market economics have led to the displacement of coal as the lowest-cost fuel for electricity generation by natural gas and renewable energy; solar and wind capacity have been added to the grid at an unprecedented

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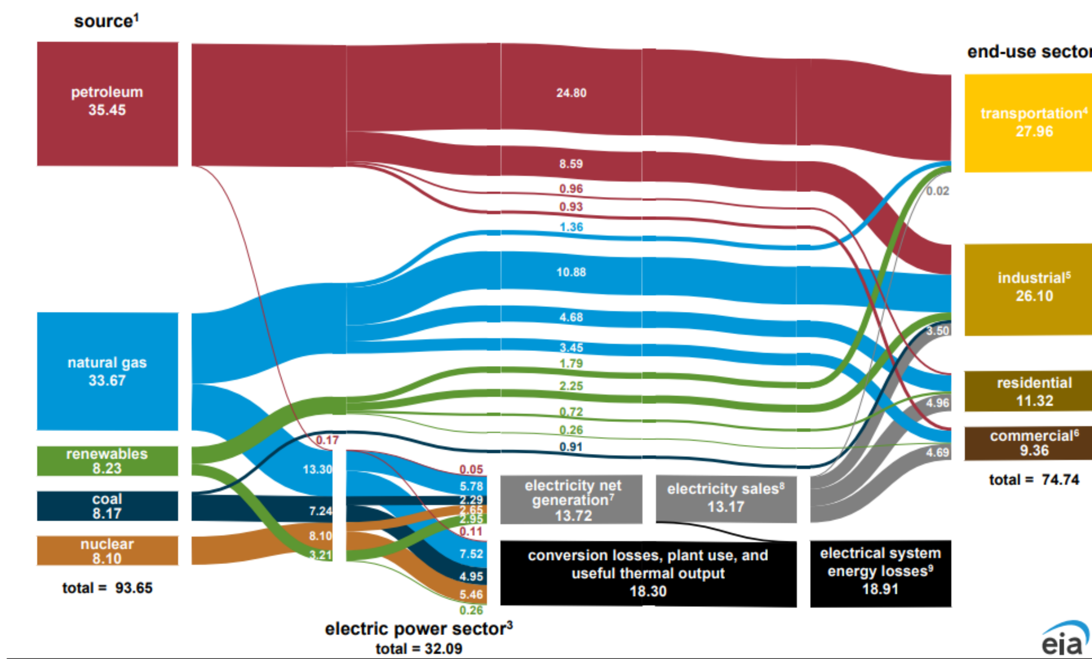
[25] U.S. Department of Energy. Energy.gov. "2024 U.S. Energy & Employment Jobs Report (USEER)," n.d. https://www.energy.gov/policy/us-energy-employment-jobs-report-useer.

pace; advanced batteries have become viable for use in the power and transportation sectors, and grid components have accelerated their shift from an analog to digital model. However, risks have emerged in the system as these changes have taken place. Low-cost production from abroad, at times driven by non-market state policies in the case of energy technologies and noncompliance with international labor standards, has led to the offshoring of supply chains needed to support many of the technologies that are increasingly critical within the U.S. ESIB. Non-market practices by PRC such as overproduction of supply have also distorted global markets. This pattern has had consequences for the American worker, with communities across the United States grappling with deindustrialization as scores of manufacturing facilities jobs moved overseas.

In 2019, the U.S. achieved the long-held goal of producing more energy than it consumed, driven in large part by the development of hydraulic fracturing and horizontal drilling over more than a decade.[26] Today, the U.S. is the leading crude producer in the world, accounting for nearly 20 percent of the world's total oil production and producing more oil annually than any country in human history.[27] In the U.S., as of 2023, about 84 percent of primary energy end-use and 60 percent of electricity generation came from fossil fuels, including petroleum, natural gas, and coal (Figure 1).

Figure 1. U.S. energy consumption by source and sector, 2023[28]

quadrillion British thermal units (quads)



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[26] IER. "The United States Was Energy Independent in 2019 for the First Time Since 1957 - IER." IER, May 11, 2020. https://www.instituteforenergyresearch.org/fossil-fuels/gas-and-oil/the-united-states-was-energy-independent-in-2019-for-the-first-time-since-1957/.
[27] U.S. Energy Information Administration. "United States Produces More Crude Oil Than Any Country, Ever - U.S. Energy Information Administration (EIA)," n.d. https://www.eia.gov/todayinenergy/detail.php?id=61545.
[28] U.S. Energy Information Administration. "U.S. Energy Facts Explained - Consumption And Production - U.S. Energy Information Administration (EIA)," n.d., https://www.eia.gov/energyexplained/us-energy-facts/.

While the U.S. energy system remains dependent on fossil fuels, the impacts from climate change have hardened the global consensus that a shift to low-carbon energy solutions is needed. This will require the U.S. to establish a strategy to accelerate energy production and drive towards energy independence with a broad portfolio of technologies. To combat the climate crisis and avoid the most severe impacts of climate change, the United States has made several notable commitments that will require evolution in our energy sector:

- Achieving a 50- to 52-percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030
- Creating a carbon pollution-free power sector by 2035
- Achieving net zero emissions economy-wide by no later than 2050.[29]

While these commitments are one important reason to embrace the development energy technologies, it is equally important to consider that these technologies will drive the energy economy of the future. Countries around the world and private capital markets are increasingly embracing these technologies, and participating in these energy technologies offers substantial economic opportunity in addition to a pathway to meet stated energy transition goals.

A successful shift away from fossil fuels will require a multifaceted approach. While the challenge will be substantial, it is important to note that the U.S. is extraordinarily well-positioned to achieve clean energy independence and to emerge as a global clean energy leader given its unique ability to innovate, exceptional capital markets, and endowment of extraordinary clean energy resources to leverage.

The ESIB encompasses the "how" of the energy transition. No single technology or solution will be sufficient, and the future demands a holistic transformation of the global energy system. Carbon-free energy sources such as geothermal, nuclear, and renewables (e.g., solar and wind power) offer significant potential to drive emissions reductions in the near term. By accelerating investment in these technologies, the U.S. Government can accelerate economically favorable decarbonization while research, development, and demonstration continues in more challenging sectors like chemicals, metals, and aviation.

To face this challenge, the U.S. Government has pursued a modern industrial and innovation strategy, both at home and with partners around the world. This strategy prioritizes investment in American economic and technological strength, promotes diversification of global supply chains to reduce reliance of foreign nations, raises the standards for labor and environmental standards protections, and delivers public goods like better climate, environmental, and health outcomes to the American people. Building a clean-energy economy and navigating the energy transition is one of the most significant challenges—but also one of the most significant growth opportunities—of the 21st century. To harness that opportunity, the United States of America must pursue a deliberate government-enabled, private sector–led strategy to pull forward innovation, drive down costs, and create good jobs. This approach is represented in the Biden–Harris Administration's goals of the energy transition (Infographic).

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[29] The White House. "Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability." December 8, 2021. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/12/08/executive-order-on-catalyzing-clean-energy-industries-and-jobs-through-federal-sustainability/.

Infographic: Biden–Harris Administration goals of the energy transition

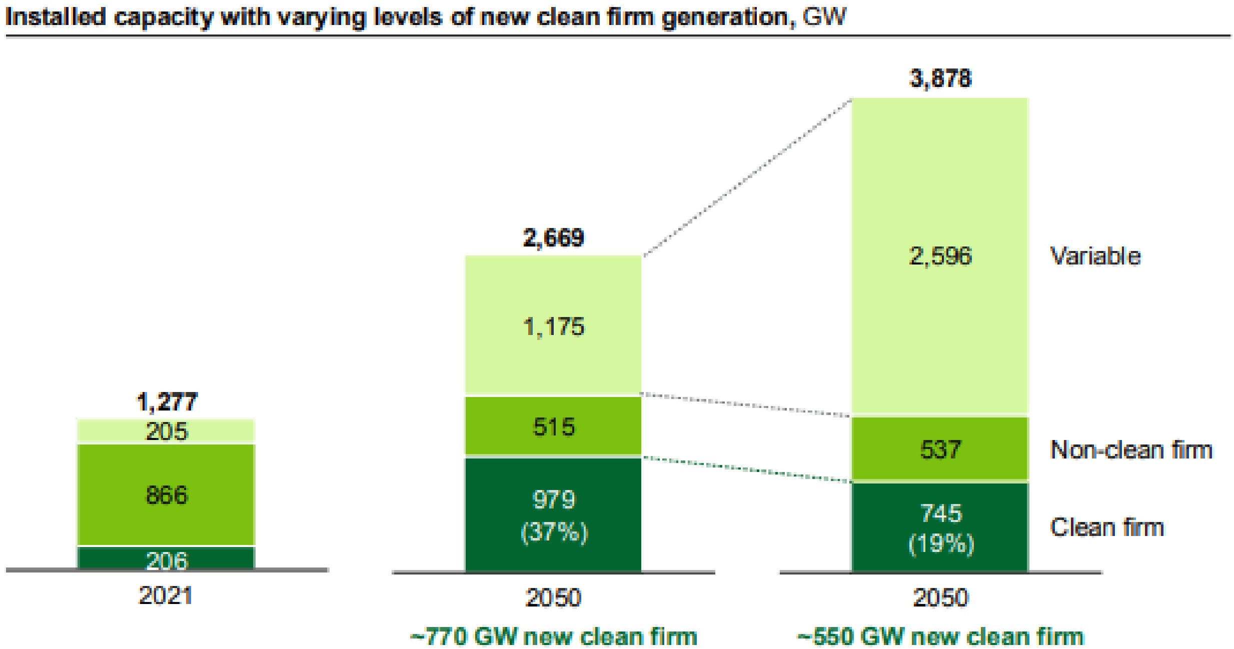
Expanding affordable clean energy for all	Build a more resilient and reliable grid Secure energy system against hazards (e.g., extreme weather, security risk) Provide homes, schools, buildings, and transportation with access to affordable clean energy
Renewing American manufacturing	Secure key U.S. clean energy supply chains including workforce Catalyze new manufacturing and support small- and medium-sized manufacturers Position U.S. energy-intensive industries to supply globally competitive products
Creating jobs and community benefits	Ensure benefits flow to communities at risk of being left behind Create high-quality, accessible, and career-track jobs Partner with state, local, and tribal governments for the clean energy transition
Catalyzing private sector investment	De-risk new clean energy technologies Galvanize broad and deep market demand Deploy co-investment opportunities with the private sector

Technologies for the Energy Sector Industrial Base and Key Trends

Under the leadership of the Biden–Harris Administration—including the passage of the Bipartisan Infrastructure Law (BIL), the Inflation Reduction Act (IRA), and executive branch actions—the U.S. has accelerated the pace of clean technology adoption, catalyzed historic investment in the clean energy manufacturing sector, and initiated transformative projects for industrial decarbonization and carbon management.

The increasing deployment of renewable generating assets and decarbonization technologies improves energy system resilience and insulates the U.S. from shocks in global market prices. Analysis from the Department of Energy shows that power system decarbonization modeling suggests that the U.S. will need about 2,500 GW of new variable renewable energy capacity and ~550–770 GW of additional "clean firm capacity"—nuclear, renewables paired with energy storage, geothermal, hydroelectric power, among others—to reach net-zero. Modeling of power generation by sources in Figure 2 shows two potential scenarios of clean firm power and relative amount of variable generation (e.g., solar, wind) for lowest-cost grid scenario.

Figure 2. System-level modeling shows increasing clean firm capacity complements variable generation for lowest-cost grid, 2023–2050[30]



Building and maintaining the U.S. energy system will require a myriad of technologies, both established and in early development, as well as robust supply chains to support them. Battery cells cannot be made without access to lithium and graphite, transformers and grid components require copper and specialized steel, solar cells are built from polysilicon, and wind turbines require rare earth magnets and specialized castings. The ramp-up in clean energy technologies requires the parallel scaling of critical minerals, materials, and manufacturing in the U.S. and from reliable trading partners.

Beyond securing current clean energy supply chains, it will be critical to look forward and consider how the United States can position itself for success in the next wave of clean energy technologies. This will require efforts to support innovation ecosystem from research and development through commercial deployment. Emerging technologies such as clean fuels, long-duration energy storage, and advanced nuclear, among others, have immense potential to support a resilient and reliable energy system and broader U.S. economy. This holistic approach must be applied to a range of key technologies across the ESIB.

[30] U.S. Department of Energy. "Advanced Nuclear - Pathways to Commercial Liftoff." Pathways to Commercial Liftoff, November 5, 2024. https://liftoff.energy.gov/advanced-nuclear-2/.

Overview of ESIB technologies and supply chains[31] (not exhaustive)

1. Power Generation

Solar. Solar energy is among the cheapest energy generation sources. Due to its favorable costs of deployment, solar is rapidly becoming the dominant form of generating capacity—accounting for 67 percent of all new electricity-generating capacity additions in 2024 H1 alone.[32] Demand for U.S. solar capacity is estimated to increase four-fold from 2020 levels to over 400 gigawatt direct current (GWdc) by 2030,[33] with high case estimates from outside clean energy experts suggesting a range of ~520[34] to 560[35] GWdc. Since the passage of the IRA, U.S. announced solar module assembly projects—nearly 50 GWdc of annual manufacturing capacity—is enough to satisfy 80 percent of domestic demand with U.S.-produced modules by 2026.[36]

While IRA incentives have driven significant progress in building out a domestic solar supply chain, the United States remains reliant on the PRC for the production of key upstream components including polysilicon, ingots, and wafers. In these upstream production steps, current domestic supply is expected to meet only about 30 percent of projected U.S. demand.[37] Closing this gap may prove challenging due to substantial production cost advantages enjoyed by PRC firms. These advantages are driven by multiple factors including lower capital and operating expenditures, vertically integrated business models, a set of favorable state policies, and restrictions on labor rights, including state-imposed forced-labor schemes, that have artificially lowered the cost of production. These include access to low-cost land and utilities, preferential state financing, and a range of trade policy tools. While these advantages are significant, the U.S. has leading solar research and development (R&D) facilities and researchers, including from national laboratories (e.g., NREL) and academic ecosystems, that continue to generate new IP that may enable innovation into new solar technologies.

Wind. Land-based and offshore wind play a key complementary role to solar as part of what will be a diverse, lowest-cost, and low-pollution energy mix. While the U.S. land-based wind market is stable with incremental growth to occur year-over-year, offshore wind is positioned to be a major driver of renewable power generation. Despite recent challenges, the sector is adapting, and improved risk mitigation is being built into industry planning. U.S. offshore wind is now poised for a breakthrough, beginning with the 10–15 GW of projects with a path to final investment decision in

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[31] U.S. Department of Energy. "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition," U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains", February 24, 2022. https://www.energy.gov/policy/articles/americas-strategy-secure-supply-chain-robust-clean-energy-transition.
[32] Solar Energy Industry Association. "Solar Market Insight Report Q2 2024 – SEIA," August 29, 2024. https://seia.org/research-resources/solar-market-insight-report-q2-2024/.
[33] National Renewable Energy Laboratory. "Standard Scenarios," n.d. https://www.nrel.gov/analysis/standard-scenarios.html.
[34] Solar Energy Industry Association. "Solar Market Insight Report Q2 2024 – SEIA," August 29, 2024. https://seia.org/research-resources/solar-market-insight-report-q2-2024/.
[35] BloombergNEF. "New Energy Outlook 2024 | BloombergNEF | Bloomberg Finance LP," May 30, 2024. https://about.bnef.com/new-energy-outlook/.
[36] U.S. Department of Energy, Loan Programs Office, Energy.gov. "LPO Tech Talk: Solar Photovoltaics Supply Chain," n.d. https://www.energy.gov/lpo/articles/lpo-tech-talk-solar-photovoltaics-supply-chain.
[37] U.S. Department of Energy, Office of Manufacturing and Energy Supply Chains, internal analysis, December 2024.

the next few years.[38] These projects will lay the foundation for consistent long-term deployment, decarbonization, and economic benefit across the country. Longer term, offshore wind can deliver over 100 GW clean power by 2050. There is a clear path to scale, with ~50 GW-worth of U.S. seabed already leased to developers (more planned), and early project deployment advancing rapidly. Delivering over 100 GW by 2050 would require the industry to maintain a steady pace of 4–5 GW deployed per year.[39]

U.S. manufacturing capacity for offshore wind components is still scaling up, leaving a dependency on global sourcing. Like nuclear generation, the wind industry relies on large castings and forgings, specialized and engineered materials, and rare earth metals (e.g., neodymium, dysprosium) used in high-capacity magnets for nacelles. The Jones Act requires U.S.-flagged vessels to install wind turbines, and a shortage of U.S.-flagged installation vessels creates another challenge to rapid deployment. Despite these challenges, the wind industry has received substantial support from recent legislation and policy support. The IRA and BIL created funding opportunities to support offshore wind supply chains including the Qualifying Advanced Energy Project Credit (48C), the Advanced Energy Manufacturing and Recycling Grant program ($750 million),[40] and the Rare Earth Element Demonstration Facility grant program that provides up to $140 million from BIL.

Nuclear. Nuclear power provides a differentiated value proposition for a decarbonized grid; it generates carbon-free electricity, produces firm power that complements renewables, and lowers the need for new transmission and land-use relative to other generation sources. Nuclear power can deliver carbon-free electricity at scale while creating high-paying jobs with concentrated economic benefits for communities. The White House's domestic nuclear energy strategy, "Safely and Responsibly Expanding U.S. Nuclear Energy: Deployment Targets and a Framework for Action," established bold U.S. Government targets for safely and responsibly expanding U.S. nuclear energy, including tripling U.S.-installed nuclear energy capacity from ~100 GW in 2023 to ~300 GW by 2050.[41] The net new capacity gains are anticipated to come from multiple sources, including building new nuclear power plants, and by uprating existing reactors and restarting reactors that have retired for economic reasons. All reactor technologies and sizes will be needed including large, gigawatt-scale reactors, small modular reactors (SMRs), and microreactors.

The build-out of new nuclear power generation capacity in the U.S. would require an increase in capacity for its supporting fuel and component supply chains, as described in the White House domestic nuclear energy strategy, DOE's Pathway to Commercial Liftoff initiative,[42] and DOE's

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[38] U.S. Department of Energy, "Offshore Wind Deployment - Pathways to Commercial Liftoff." Pathways to Commercial Liftoff, August 22, 2024. https://liftoff.energy.gov/offshore-wind-liftoff/.

[39] *Ibid.*

[40] Small and medium-sized manufacturers producing or recycling OSW components—including but not limited to wind turbines, towers, floating offshore platforms, and related equipment—are eligible for up to $100 million to be used to build a new facility or retrofit an existing manufacturing or industrial facility to produce or recycle advanced energy products in communities where coal mines or coal power plants have closed.

[41] White House, "Safely and Responsibly Expanding U.S. Nuclear Energy: Deployment Targets and a Framework for Action." https://www.whitehouse.gov/wp-content/uploads/2024/11/US-Nuclear-Energy-Deployment-Framework.pdf

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

Nuclear Energy Supply Chain Deep Dive Assessment.[43] The U.S. lacks at-scale enrichment capacity for high-assay low-enriched uranium (HALEU), a key input for some nuclear reactor types, and which is largely concentrated in Russia. New DOE programs are investing in domestic enrichment capacity. Investments made possible by the HALEU Availability Program (Section 2001 of the Energy Act of 2020) and the Nuclear Fuel Security Initiative (Section 3131 of the FY2024 National Defense Authorization Act), funded by the IRA ($700 million for the HALEU Availability Program) and the FY2024 Consolidated Appropriations Act ($2.72 billion for the Nuclear Fuel Security Act of 2023), are scaling domestic HALEU and low-enriched uranium capacity. Current production capacity for specialized components—large castings and forgings for advanced reactor components, alloys, specialized equipment to produce reactor components—is also limited and under-developed relative to the forecasted demand. Future nuclear energy deployments must continue to adhere to the highest safety, security, nonproliferation, and labor and environmental protection standards. Efforts must also account for meaningful stakeholder engagement with the public (e.g., communities, intergovernmental, Tribal) to build and sustain the long-term public support of additional domestic nuclear energy.

Geothermal. Geothermal power technology has shown compelling advances—identification of substantial resources, transferability of technology from the oil and gas sector, and decreasing costs of deployment—that can enable it to become a key contributor to decarbonized, firm power generation for the U.S. energy system. Because geothermal leverages technologies developed by the oil and gas sector, particularly horizontal drilling from the U.S. shale boom, the U.S. is well-positioned to be a global leader. Next-generation geothermal technologies—including enhanced geothermal systems and closed-loop geothermal systems—vastly expand the total resource available for geothermal power generation beyond naturally occurring thermal sources and create a unique value proposition as a clean firm technology.[44] In a world where the U.S. grid will need 700–900 GW of additional clean firm capacity by 2050, next-gen geothermal could provide 90 GW by 2050.[45]

Geothermal has an advanced component supply chain, which leverages existing fossil energy networks. However, projects currently face challenges from high up-front costs and early-stage project risks. Technology-neutral tax credits such as the Clean Energy Production Tax Credit (PTC) and the Clean Energy Investment Tax Credit (ITC) can improve the economics of geothermal projects.

2. Clean Fuels

Hydrogen. By some estimates, low-carbon hydrogen can play a role in decarbonizing up to 25 percent of global energy-related CO2 emissions, particularly in industrial and chemicals use cases, as well as in heavy-duty transportation. Today, most of the hydrogen production (~99 percent) is through natural gas reformation (e.g., steam methane reforming or autothermal reforming), either with carbon capture and storage (<5 percent; known as "blue hydrogen") or without (~95 percent

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[43] U.S. Department of Energy, "Nuclear Energy Supply Chain Deep Dive Assessment." https://www.energy.gov/sites/default/files/2022-02/Nuclear%20Energy%20Supply%20Chain%20Report%20-%20Final.pdf.
[44] U.S. Department of Energy, "Next-Generation Geothermal Power - Pathways to Commercial Liftoff." Pathways to Commercial Liftoff, April 17, 2024. https://liftoff.energy.gov/next-generation-geothermal-power/.
[45] *Ibid.*

of total; known as "grey hydrogen")[46]. The U.S. clean hydrogen market is poised for rapid growth, accelerated by historic commitments to America's clean energy economy. Combined, incentives in the IRA and BIL can help make clean hydrogen cost-competitive with incumbent technologies in the next 3–5 years for numerous applications.[47] Clean hydrogen production for domestic demand has the potential to scale from <1 million metric tons per year (MMTpa) to ~10 MMTpa in 2030. Most near-term demand will come from transitioning existing end-uses away from the current ~10 MMTpa of carbon-intensive hydrogen production capacity. If water electrolysis dominates as the production method, up to 200 GW of new renewable power would be needed by 2030 to support clean hydrogen production. The opportunity for clean hydrogen in the U.S., aligned with the DOE National Clean Hydrogen Strategy and Roadmap, is 50 MMTpa by 2050.[48]

As the clean hydrogen economy scales up, domestic electrolyzer manufacturing and supply chains must grow from <1 GW to up to 20–25 GW/year by 2030. So far, $750 million in funding has been awarded across 52 projects to support clean hydrogen electrolysis, manufacturing, and recycling activities**.** Platinum group metals have broad applications across clean energy supply chains but are critical to electrolyzer membranes. Proton exchange membrane (PEM) electrolyzers are currently dependent on foreign supply chains (e.g., iridium—one of the rarest metals in the world—from South Africa; graphite from China for bipolar plates). The Hydrogen and Fuel Cell Technologies Office will administer $1 billion in funding through the Clean Hydrogen Electrolysis Program. The program will establish support for R&D, demonstration, commercialization, and deployment to improve cost and operational efficiency and increase durability of clean hydrogen production through electrolysis. Building CO2 transport and storage infrastructure for blue hydrogen produced with carbon capture, utilization, and storage (CCUS) also represents a sizeable task requiring substantial capital investments.

Sustainable Aviation Fuel. Sustainable aviation fuel (SAF)[49] is a family of synthetic- or biofuels that produce kerosene through pathways other than traditional fossil fuel refining. Because these production processes can have substantially lower carbon intensity and because few alternative fuel sources have sufficient power density to support aviation, SAF will be critical to reduce the 9–12 percent of U.S. transportation GHG emissions driven by air travel.

DOE's SAF Grand Challenge is a public–private program to reduce cost and expand domestic production of SAF, targeting production of 3 billion gallons per year by 2030 with a 50-percent-or-greater reduction in life cycle GHGs. By 2050, the program is targeting 35 billion gallons of annual production.[50] Limited availability of sustainable biofeedstocks, logistics and dedicated infrastructure

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[46] U.S. Department of Energy, "U.S. National Clean Hydrogen Strategy And Roadmap." U.S. National Clean Hydrogen Strategy And Roadmap, 2022. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf.
[47] U.S. Department of Energy, "Clean Hydrogen - Pathways to Commercial Liftoff," Pathways to Commercial Liftoff, December 19, 2023, https://liftoff.energy.gov/clean-hydrogen/.
[48] U.S. Department of Energy, "U.S. National Clean Hydrogen Strategy And Roadmap." U.S. National Clean Hydrogen Strategy And Roadmap, 2022. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf.
[49] U.S. Department of Energy, "Sustainable Aviation Fuel - Pathways to Commercial Liftoff." Pathways to Commercial Liftoff, November 2024. https://liftoff.energy.gov/sustainable-aviation-fuel/.
[50] U.S. Department of Energy, Prepared by the U.S. Department of Transportation, the U.S. Department of Agriculture, U.S. Department of Energy, U.S. Environmental Protection Agency, et al. "SAF Grand Challenge Roadmap." Report. SAF Grand Challenge Roadmap, n.d. https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf.

for collection, and high costs of hydrogen required for power-to-liquid fuel production create challenges to commercial viability today. Nevertheless, a relatively strong demand from airlines and corporate travelers has led to relatively strong demand for SAF-certificates, which supports the production of the more sustainable fuel.

3. Energy Storage

Advanced Batteries and Other Energy Storage Applications. Today, the transportation and power sectors together represent more than half of domestic emissions, and batteries are playing a key role in structural changes impacting both sectors. As a result, U.S. battery demand is expected to grow seven-fold from 2023 to 2030 for EV batteries and energy storage systems.[51]

For the electricity grid, batteries are increasingly critical for system and price stability as intermittent, renewable generation is added to the grid and distributed resources are more common. Lithium-ion batteries are likely to play a large role here for relatively short-term energy shifting. However, long-duration energy storage (LDES)[52] will also be critical to effectively firm intermittent power generation over longer periods of time. A range of technologies are being considered including electrochemical solutions like sodium-ion or flow batteries, mechanical solutions like pumped hydropower or compressed air energy storage, thermal solutions such as heat batteries, and even long-term hydrogen storage in salt caverns. For example, DOE awarded ~$150 million to construct a massive iron-air battery intended to help a strained pocket of the New England grid. DOE and DoD partnered together for the Long-Duration Energy Storage Joint Program to deploy LDES demonstrations at military installations to improve resilience. For transportation, the transition from internal combustion engines to battery electric vehicle powertrains will make battery production and innovation key sources of competitiveness for American auto manufacturers.

The anticipated exponential growth in battery production will require a significant increase in raw and processed battery-grade metals. While domestic processing and refining capacity is coming online through federal investments, demand is forecast to outpace the current pipeline of future supply. Even with enough material, U.S. production faces challenges to produce competitively relative to global price benchmarks. This is driven in large part by low-cost Chinese production, which has substantial levels of policy support, including low-cost financing and access to cheap land and utilities, arising from decades of state-driven investment into battery manufacturing and upstream processing.

4. Electricity Grid System

Transmission and distribution network. Electricity is vital to modern life. The U.S. electric grid[53] is a remarkable feat of infrastructure—a network of wires carrying electricity from power plants

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[51] Gohlke, David, et al., Argonne National Laboratory. Energy Systems and Infrastructure Analysis Division, Nuclear Technologies and National Security Directorate, and Transportation and Power Systems Division. "Quantification of Commercially Planned Battery Component Supply in North America Through 2035," 2024. https://publications.anl.gov/anlpubs/2024/03/187735.pdf.

[52] U.S. Department of Energy, "Long Duration Energy Storage – Pathways to Commercial Liftoff." Pathways to Commercial Liftoff, March 2023, https://liftoff.energy.gov/long-duration-energy-storage/.

[53] U.S. Department of Energy, "Innovative Grid Deployment – Pathways to Commercial Liftoff." Pathways to Commercial Liftoff, April 2024, https://liftoff.energy.gov/innovative-grid-deployment/.

across the country into our homes. Assembled over a century by independent utilities, the grid is a vast, yet coordinated, machine. The National Renewable Energy Laboratory (NREL) estimates that transmission capacity would need to more than double in just over a decade to reach the Biden–Harris Administration's goal of 100 percent clean electricity generation by 2035.[54] Unfortunately, the transmission and distribution network that makes up the electric grid is becoming a bottleneck to greater economic development, decarbonization, and equity priorities. Customers are demanding more grid capacity as regional electricity demand grows substantially for the first time in decades to serve a rapid rise in data center buildout, manufacturing needs, and broader end-use electrification.[55] At the same time, heightened threats to the electric grid, often coming in the form of more extreme weather, and load growth driven by electrification increase the importance of making new grid infrastructure both resilient and reliable. Significant capital will be needed for grid modernization and expansion to meet net-zero goals. Regulatory barriers including permitting for approving new transmission lines remain major barriers to deployment.

Grid components. Transformers and grid equipment (e.g., switchgear, transmission circuit breakers) are critical components of a stable and resilient electric grid—the linchpin of U.S. infrastructure and economic vitality. During the COVID-19 pandemic, the grid component manufacturing industry was among those that experienced severe supply chain disruptions, with the electricity sector still reeling from the effects of the disruptions. Rising demand for grid components—driven by increasing electrification across the U.S. and global economies, the build-out of renewable electricity generation, and growth in large-load customers such as data centers—have further stressed supply chains, drawing out lead times and increasing prices. Across transmission and distribution (T&D) equipment, the lead time for components averaged 38 weeks in 2023, nearly double from the year prior, with costs escalating nearly 30 percent year-over-year.[56] Bottlenecks in the supply chains from upstream suppliers to manufacturers among key grid components risks system stability, deployment of clean energy generating assets, and the scale-up of new industrial production and technology facilities.[57] The grid components industrial base and supply chain is highly concentrated among a limited number of manufacturers operating in North America or in key trading partner countries. Vulnerabilities in the transformer and grid components supply chain are primarily driven by limited supply and increasing demand of key engineered materials including grain-oriented electrical steel (GOES), copper, and aluminum. Domestic capacity for distribution transformers is improving due to expansions, making headway on cutting down on lead times.

5. Industrials and Energy Infrastructure

Industrial Decarbonization. The U.S. industrial sector makes products and materials that Americans rely on and that will become increasingly important for the energy transition. Example

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[54] National Renewable Energy Laboratory. "100% Clean Electricity by 2035 Study," n.d. https://www.nrel.gov/analysis/100-percent-clean-electricity-by-2035-study.html.
[55] Wilson, John D., Zach Zimmerman, Rob Gramlich, and Grid Strategies. "Strategic Industries Surging: Driving US Power Demand," 2024. https://gridstrategiesllc.com/wp-content/uploads/National-Load-Growth-Report-2024.pdf.
[56] U.S. Department of Energy, Office of Electricity and Office of Manufacturing and Energy Supply Chains, internal analysis, December 2024.
[57] National Infrastructure Advisory Council. "Addressing the Critical Shortage of Power Transformers to Ensure Reliability of the U.S. Grid.", June 2024. https://www.cisa.gov/sites/default/files/2024-09/NIAC_Addressing%20the%20Critical%20Shortage%20of%20Power%20Transformers%20to%20Ensure%20Reliability%20of%20the%20U.S.%20Grid_Report_06112024_508c_pdf_0.pdf.

products include near-zero emissions steel and aluminum for automobiles and renewable energy generation, cement and concrete for buildings and infrastructure, pulp and paper for packaged goods, glass for windows and containers, and chemicals for fertilizers, pharmaceuticals, and certain plastics. Growing levels of these goods will be needed to satisfy growing demand and to build out infrastructure needed for the energy transition. At the same time, a decarbonized economy will require addressing the production emissions associated with industrial processes, which account for 30 percent of total U.S. emissions when considering both direct energy and electricity use.[58] Across key industrial sectors studied in the DOE's "Industrial Decarbonization" Pathways to Commercial Liftoff Report, ~27 percent of chemicals, ~14 percent of refining, and ~32 percent of cement emissions could be abated with decarbonization levers that have net-positive economics, representing billions of dollars of potential incremental value in the industrials sector.[59] Still, this means that substantial portions of emissions remain non-economical to address and will require further cost reductions through innovation or incentives to fully decarbonize this sector.

Relative to the power sector, industrial decarbonization faces relatively low supply chain risks today. The first wave of industrial decarbonization technologies like efficiency systems required limited process and supply chains. Many more technologies are in the demonstration phase which could create supply chain risks as industrial decarbonization accelerates. Potential supply chain bottlenecks include specialized capital equipment to replace fossil-based energy sources and underlying critical minerals (e.g., high-purity iron ore, material substitutes such as glass pozzolans for supplementary cementitious materials) that are used in this equipment. Electrolyzers, equipment used to produce green hydrogen necessary to decarbonize key processes in iron and chemicals production, are one such example of highly specialized equipment that may face shortages for key input materials including iridium, platinum group metals, and graphite.

Carbon management. Both carbon capture and carbon removal have the potential to eliminate hundreds of millions of tons of CO2 per year. Modeling studies suggest that in order to reach U.S. energy transition goals, 400 to 1,800 MT of carbon dioxide may need to be captured and stored annually by 2050, through both point-source CCUS and carbon dioxide removal (CDR).[60] Today, the U.S. has over 20 MTPA of carbon capture capacity, 1–5 percent of what could be needed by 2050. This scale-up represents a massive investment opportunity of up to ~$100 billion by 2030 and $600 billion by 2050.[61] An increase in the value of the 45Q tax credit—a federal tax credit provided for stored or utilized CO2—has provided a greater incentive to developers and investors for some types of carbon capture projects, though this remains variable by sector. Additionally, the U.S. has excellent geology for storing CO2, world-class engineering and professional talent, and relatively abundant low-cost zero-carbon energy resources that can power CDR projects to maximize net carbon removed. While carbon capture and removal should not supplant the deployment of clean energy or emissions-mitigating improvements across supply chains, these technologies can be part of the solution in achieving climate targets, especially for hard-to-abate sectors.

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[58] U.S. Environmental Protection Agency. "Sources of Greenhouse Gas Emissions | US EPA," October 22, 2024. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.
[59] U.S. Department of Energy, "Industrial Decarbonization Overview - Pathways to Commercial Liftoff," Pathways to Commercial Liftoff, May 22, 2024, https://liftoff.energy.gov/industrial-decarbonization/overview/.
[60] U.S. Department of Energy, "Carbon Management - Pathways to Commercial Liftoff," Pathways to Commercial Liftoff, February 6, 2024, https://liftoff.energy.gov/carbon-management/.
[61] *Ibid.*

The carbon management sector has lower supply chain risk associated with the common point-source amines and raw material inputs needed for scale-up. However, the U.S. has a limited number of suppliers able to complete the engineering and design of carbon management systems. Furthermore, high investment costs and capital investment are required to reach commercial viability. Demand for captured carbon is not yet sufficient to spur the scale of investments in CCUS and CDR that will be needed to reduce the cost of carbon management, reduce pollution, and meet climate targets.

PROGRESS TO DATE

One-year Review Priorities

In February 2022, DOE released "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition"—the first comprehensive plan to build the U.S. ESIB required to support a rapidly evolving energy system. The report was part of a whole of government approach to chart a course for revitalizing the U.S. economy and domestic manufacturing by securing the country's most critical supply chains.

The review found that without new domestic raw materials production and manufacturing capacity, the U.S. will continue to rely on clean energy imports, exposing the nation to supply chain vulnerabilities while simultaneously losing out on the enormous job opportunities associated with the energy transition. In short, there was ample whitespace and untapped potential in the U.S. to to support greater domestic production of energy technologies poised for exponential growth including solar, wind, nuclear, grid and battery storage, batteries, and hydrogen.

To position the U.S. for action, the report identified 60 actions across seven key areas where the U.S. Government could address risks and vulnerabilities in the energy industrial base that would maximize opportunities for economic growth and improve American quality of life:

- Increase domestic raw material availability
- Expand domestic manufacturing capabilities
- Invest and support the formation of diverse and reliable foreign supply chains to meet global climate ambitions
- Increase the adoption and deployment of clean energy
- Improve end-of-life waste management
- Attract and support a skilled U.S. workforce for the clean energy transition
- Augment supply chain knowledge and decision-making

Since the start of the Biden–Harris Administration, the U.S. Government has made significant progress against each of the seven key areas. Examples include over $77 billion[62] in historic investments in our ESIB manufacturing base along with creating millions of good paying, high-quality jobs for American workers; investments, tax credits, and policy changes that have strengthened our energy supply chains by making them more resilient, robust, diverse, and competitive and increasing access to clean and affordable energy for all Americans.

Progress from 2021 to Present

U.S. Energy Sector Investment: Government Enabled, Private Sector Led

The Bipartisan Infrastructure Law and Inflation Reduction Act have catalyzed historic growth of U.S. clean energy technologies, manufacturing, and the ESIB. Through a suite of public sector tools on both the supply and demand side—incentives for manufacturing across the clean energy supply

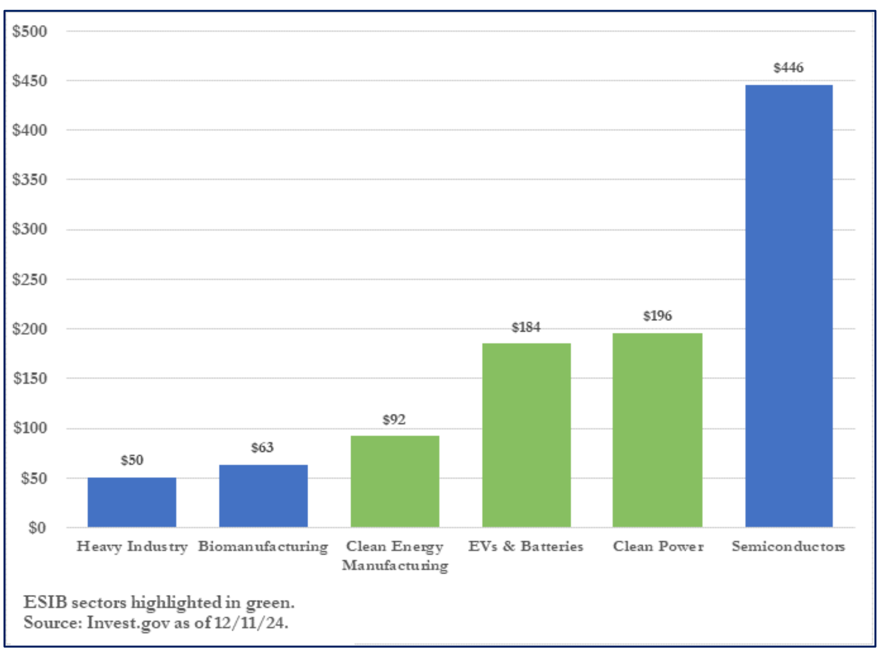
[62] U.S. Department of Energy. Office of Under Secretary for Infrastructure, Office of Manufacturing and Energy Supply Chains. Internal DOE award and project data. Accessed December, 6, 2024.

chain, investments in demonstration projects, loans and loan guarantees for a variety of clean energy technologies, production and investment tax credits for clean energy generation, and public procurement of clean technologies and materials such as through the Sustainability Executive Order, and the Buy Clean Initiative—the Biden–Harris Administration has initiated a government-enabled, private sector–led energy transition.

Public investments and tax incentives have been the catalyst for a complete reimagining of the energy sector: from the most significant expansion of the electrical grid in a century to development of a new clean hydrogen economy; the scaling up of a domestic battery supply chain to industrial decarbonization across heavy industry; carbon management at-scale and across industries; and the development of a U.S. fusion energy strategy with goal of commercialization by 2030. Charged with leading the strategy and implementation of the U.S. energy transition, DOE was allocated ~$90 billion in grant and rebate programs with more than $300 billion in loan and loan guarantee authority to invest in a range of clean energy projects and supply chains. Given the increase in funding and a mandate that stretches from basic research in a lab to funding giga-scale factories, DOE reorganized itself to define and implement this strategy—standing up the Office of the Undersecretary for Infrastructure—to steward public investment in the energy sector industrial base.

Complemented by long-term certainty of production and investment tax credits from the Department of the Treasury, the Biden–Harris Administration has provided the private sector with the necessary tools and foundations for investment. Indeed, the private-sector response has been historic. Since January 2021, private companies have announced more than $1 trillion in new investment, including over $471 billion in clean energy manufacturing, EVs and batteries, and power generation (Figure 3).

Figure 3. Announced U.S. industrial and energy sector industrial base investments since 2021, billions of dollars[63]



[63] The White House, "Investing in America | the White House," December 11, 2024, https://www.whitehouse.gov/invest/?utm_source=invest.gov. Data accessed on December 11, 2024.

Incentives and policy changes have spurred a resurgence of several key manufacturing activities critical to energy transition, such as critical material processing and refining, battery manufacturing, uranium enrichment, and other clean energy technology manufacturing. Evidence of onshoring and friendshoring is apparent in clean energy manufacturing investments and build-out in the United States over the past three years. The federal government has a suite of programs and vehicles for investment in the ESIB. A select subset of some major programs are highlighted below.

- **Investment Tax Credits:** The 48C Advanced Energy Property Credit provides a 30-percent tax credit to boost domestic manufacturing in clean energy supply chains and decarbonize industrial assets. The Treasury Department and IRS have announced nearly $4 billion in selections and are slated to announce another $6 billion by year-end.
- **Production Tax Credits:** Multiple tax credits have been developed to support clean energy manufacturing. The 45X production tax credit (PTC) provides substantial support for domestic clean energy manufacturing for critical materials, battery components, wind, and solar components. The 45X PTC makes U.S. production of battery cells at a lower cost of production than PRC.
- **Consumer Tax Credits:** Multiple tax credits are aimed at incentivizing the uptake of energy technologies to increase consumer adoption including the 30D Clean Vehicle Credit, the 25D Residential Clean Energy Credit, Energy Efficient Home Improvement Credit, among others. Each tax credit increases demand for manufactured energy products including batteries for EV and energy storage, heat pumps, and solar panels for residential or commercial use. Specifically, the 30D tax credit provides a credit for the purchase of electric vehicles subject to certain requirements that encourage resilient supply chains.
- **Capital Grants:** Multiple programs administered by DOE have provided billions in capital to support domestic manufacturing and industrial decarbonization. Notable examples include the Battery Materials Processing and Manufacturing Grants Program, which has committed $5 billion to support approximately 40 projects, the Advanced Energy Manufacturing and Recycling Grants Program, which has provided nearly $700 million in grants to small- and medium-sized manufacturers (SMMs) to build or retrofit manufacturing and industrial facilities in communities where coal mines or coal power plants have closed, and the Industrial Demonstration Program, which deployed $6 billion to large-scale demonstrations at industrial facilities.
- **Debt Financing:** DOE's Loan Program Office has several funding opportunities under the Title 17 Clean Energy Financing Program and the Advanced Technology Vehicles Manufacturing Loan Program (ATVM). $18.7 billion in loans have been committed through Title 17 and $20.6 billion have been committed through ATVM.[64] These programs are intended to deploy or manufacture new energy technologies (Section 1703), repurpose existing energy infrastructure to generate power or reduce emissions (Section 1706), or support the manufacture of advanced technology vehicles and their components.

One area in which these tools are being used to substantial effect is in securing upstream and critical materials supply in the United States and among key trading partners. Through the partnership between DOE and the Department of the Treasury, the U.S. Government has invested nearly $4 billion in projects from critical materials to final manufacturing through the 48C Advanced Energy Property Credit. Supply chain investments included copper and advanced conductor materials for grid components, polysilicon and recycled glass for solar panels, fuel for advanced nuclear reactors,

[64] Figures as of December 10, 2024 and includes conditional commitments.

electrolyzers for hydrogen and sustainable aviation fuel, permanent magnets and steel cable manufacturing for offshore wind, among other technology areas.[65]

Given the strategic importance of the automotive and electric power generation sectors to the U.S. economy, the battery supply chain has received considerable support. DOE, led by the Office of Manufacturing and Energy Supply Chains (MESC) and the Loan Programs Office (LPO), has funded and provided conditional commitments for more than $30 billion in battery supply chain projects for processing and refining from lithium, nickel, and graphite (natural and synthetic) to cathode active material and cell production. Lithium supply is a strategic advantage and an imperative for the country. The U.S. has substantial reserves of untapped lithium resources from hard rock, clays, and brines. For example, analysis funded by DOE through the Lawrence Berkeley National Laboratory found that with expected technology advances, total resources in the region could contain more than 3,400 kilotons (kt) of lithium, enough to support over 375 million batteries for electric vehicles (EVs)—more than the total number of vehicles currently on U.S. roads.[66] In addition, U.S. Geological Survey–led study estimated between 5 and 19 million tons of lithium may be present in brines in southwestern Arkansas—enough to meet projected 2030 world demand for lithium nine times over.[67] The DOE is taking an all-of-the-above investment approach to lithium—funding multiple extraction and processing projects for each geologic type of reserves—that are cost competitive and secure resources.

Domestic investments have been complemented by international coordination and strategy to build out raw material extraction where the materials are located and processing capacity away from its current geographic concentration. For example, U.S. leadership and partnership with allies through the Mineral Security Partnership (MSP)[68] have identified more than 30 projects for critical minerals and materials[69]—focused on extraction, processing and refining, and recycling—that serve as key natural resources for advanced batteries, grid components, electrolyzers, offshore wind, among other technologies.

MSP partners strive to elevate environmental, social, governance (ESG) practices and principles—including responsible stewardship of the natural environment; robust community engagement; fair, safe, and just economic benefits and internationally recognized labor rights for workers, among other necessary actions—in the mining, processing, and recycling sectors.[70] MSP commits to support and invest only in projects that meet high, internationally recognized principles, promote local value

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[65] U.S. Department of Energy. Energy.gov. "Applicant Self-Disclosed 48C Projects," n.d. https://www.energy.gov/mesc/applicant-self-disclosed-48c-projects.

[66] Dobson, P.; Araya, N.; Brounce, M.; Busse, M.; Camarillo, M.; English, L., et al. (2023). Characterizing the Geothermal Lithium Resource at the Salton Sea. UC Davis. Report #: LBNL-2001557. http://dx.doi.org/10.2172/2222403 Retrieved from https://escholarship.org/uc/item/4x8868mf.

[67] Knierim, Katherine J., et al. "Evaluation of the Lithium Resource in the Smackover Formation Brines of Southern Arkansas Using Machine Learning." *Science Advances*, vol. 10, no. 39, 2024, eadp8149. https://doi.org/10.1126/sciadv.adp8149.

[68] 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).

[69] This Review focuses on midstream processing and refining of critical minerals specifically for energy industrial base applications. Critical minerals are addressed in greater detail in a separate Review.

[70] United States Department of State. "Minerals Security Partnership - United States Department of State," September 30, 2024. https://www.state.gov/minerals-security-partnership/#:~:text=The%20MSP%20is%20a%20collaboration,powering%20the%20clean%20energy%20transition.

addition, and uplift communities, in recognition that all countries can benefit from the global clean energy transition. These principles distinguish the MSP from PRC efforts and give U.S. companies a competitive advantage in bidding for projects. The core investment principles enable resource-rich countries to diversify and stabilize global supply chains while elevating the standard for transparent, ethical business environments. National governments participating in the MSP, private investors representing over $30 trillion in assets under management, and critical mineral industry leaders gathered to launch the MSP Finance Network, advancing a commitment by all MSP partner nations' development finance institutions (DFIs) and export credit agencies (ECAs) to collaborate on investments in global mineral supplies.

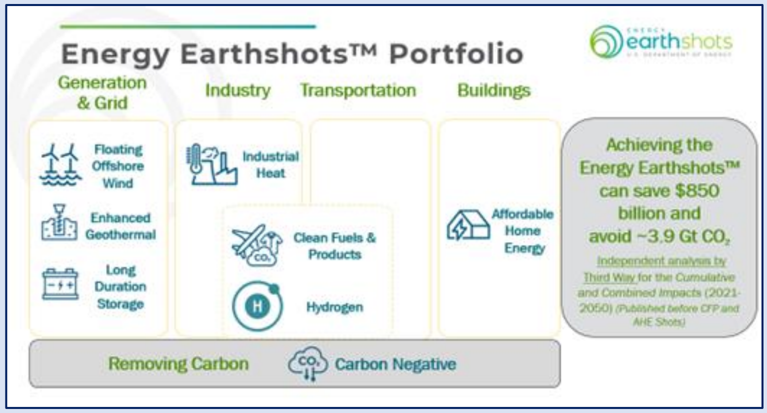
With a private sector–led, government-enabled approach to building strong and resilient ESIB supply chains, greater public and private sector collaboration remains an imperative. DOE recognizes that mobilizing and deploying the trillions of dollars in capital needed for the energy transition requires multiple approaches to scale an industrial base required to reach net-zero by 2050 and continue U.S. energy dominance. These initiatives span multiple focus areas including catalyzing investment to deploy private capital, demand-side initiatives to create a bridge to scale, shape future market activity through leading market analysis on key technologies, and workforce development projects for community-level impact.

Key DOE programs and initiatives

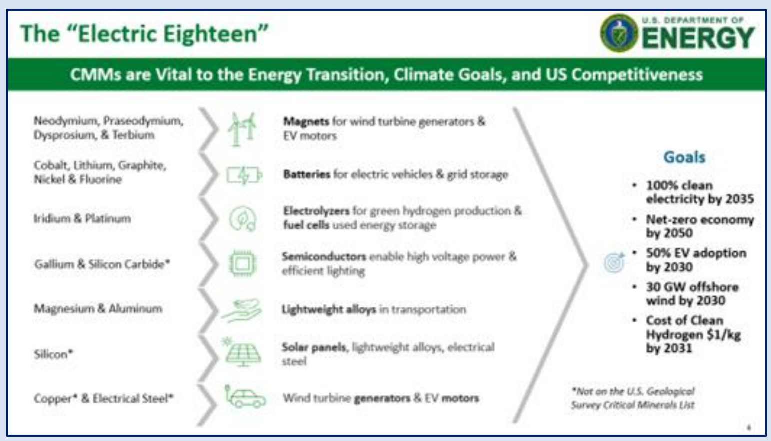
Leading the frontiers of energy innovation. In response to the urgency of the climate crisis, DOE has fast-tracked and expanded research, development, demonstration, and deployment (RDD&D) commercialization for the clean energy transition. From the Energy Earthshots™ Initiative to programs that focus on applied R&D for critical minerals to leading the U.S. strategy to commercialize nuclear fusion, the Office of Science is ensuring that RDD&D and accelerating commercialization of American innovation is a primary driver to not only meet U.S. climate goals and improve competitiveness, but also ensure future supply chains are resilient (Infographic). The electric eighteen are eighteen critical minerals, i.e., any non-fuel mineral, element, substance, or material that the Secretary of Energy determines (i) has high risk for supply chain disruption; and (ii) serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy. The minerals on this list have program support through 48C among other programs.

Infographic: Accelerating Climate Breakthroughs at the Department of Energy

DOE has launched a series of initiatives and cross-cutting programs to bolster RDD&D and expedite the pace of technology commercialization. DOE's Energy Earthshots™ Initiative—which sets technical and cost goals in key next-generation clean energy technologies—is accelerating RDD&D breakthroughs of more abundant, affordable, and reliable clean energy solutions by 2035 to address the climate crisis. Elsewhere within the Office of Science, basic and applied research is being conducted on critical materials supply chains aimed at developing new methods for processing materials, developing synthetic substitutes, and recycling, among other areas.

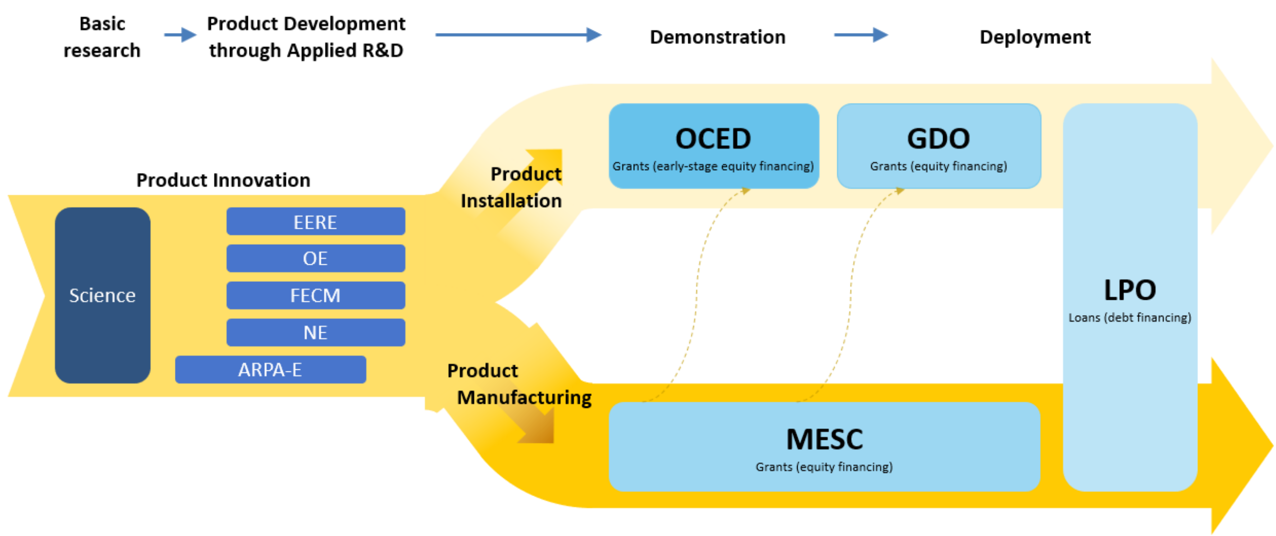


The "Electric Eighteen" critical materials and minerals are the building blocks of the ESIB, and vital to the energy transition to net-zero. DOE has granted funds across the National Lab system to develop the technology to detect and quantify rare-earth elements and critical minerals in unconventional and secondary sources, including five operational small-scale pilots to recover and upgrade to high purity mixed rare earth oxides. In addition, $32 million was awarded to support front-end engineering design to produce critical materials and rare earth elements from conventional coal-based resources, while $140 million was directed to a first-of-a-kind demonstration facility utilizing unconventional sources to extract, separate, and refine critical minerals.



Direct financial and capital support. DOE plays a critical role in funding energy technologies. With close to $90 billion in budget authority and over $300 billion in loan authority from BIL and the IRA, DOE invests in American clean energy innovation. DOE's mandate has expanded from the leading entity funding research and pre-commercialization to funding pilot and at-scale facilities for a range of technologies. Now, DOE is also focused on de-risking and scaling energy technologies and markets, with maximum potential for continued replicability and expansion across more geographies and industries. DOE offices and programs run the full lifecycle of a commercialization to enable American innovators to take an inspiration for a technology and turn it into a viable business. With programs that touch every corner of the economy, DOE has numerous tools to lever up private capital for the energy transition: basic research grants for laboratory exploration, funding to take bench-scale projects to pilot facilities, grants and cooperative agreements that act as non-diluted equity for demonstration projects, and first-of-a-kind (FOAK) investments. In addition to DOE, USDA, EPA, and DOT are providing billions of dollars in support for energy and industrial sector technology deployment.

Infographic: DOE's role in the U.S. energy technology commercialization lifecycle



Demand-side support. DOE has funded and partnered with a consortium of experts to develop demand-side support mechanisms to catalyze the development of key clean energy markets, specifically starting with demand-side support for Clean Hydrogen Hubs (H2Hubs).[71] As demand formation for new energy sources often lags the creation of new reliable supply, developing a hydrogen demand-side initiative is critical to enhancing the early commercial viability of the U.S. hydrogen economy. Demand-side support and other "demand pull" measures bridge the gap between producers, who need medium- to long-term offtake certainty for a significant portion of their projected output to secure financing to build a project, and buyers, who often prefer to buy on a short-term basis for energy inputs that are beginning to be produced at scale, like clean hydrogen.

[71] U.S. Department of Energy. Energy.gov. "DOE Selects Consortium to Bridge Early Demand for Clean Hydrogen, Providing Market Certainty and Unlocking Private Sector Investment," n.d. https://www.energy.gov/oced/articles/doe-selects-consortium-bridge-early-demand-clean-hydrogen-providing-market-certainty.

Catalyzation of private investment. The DOE has developed multiple tools to provide private-sector investors with clear signals about the investment viability of key clean energy technologies. The DOE's established the Pathways to Commercial Liftoff initiative provides public and private sector capital allocators with a perspective on both commercial viability and ultimate total addressable market size across various clean energy technologies.[72] Further, DOE has also taken steps to directly connect private-sector investors with clean energy projects through Office of Manufacturing Energy and Supply Chain's (MESC) Manufacturing Capital Connector (MCC), a financing platform that connects companies applying to DOE-administered clean energy manufacturing programs to a range of potential capital providers seeking high-quality projects.[73]

Supply chain analytics. Across the ESIB, industries and technologies face varying levels of supply chain risk. Multiple departments are undertaking efforts to better understand and gauge resilience within these supply chains. The Department of Commerce's recently launched SCALE tool assesses a broad range of supply chains to identify across more than 40 types of supply chain risk. DOE's MESC has also recently announced its Supply Chain Readiness Level framework intended to deep-dive within energy supply chains to identify key bottlenecks, inform project selection, and ultimately guide the broader policy process. These frameworks represent efforts to drive unprecedented view into these supply chains at granular levels, including risks within specific production steps, competitiveness of domestic manufacturing, and workforce readiness for U.S. projects.

Department of Energy's Supply Chain Readiness Levels

The Supply Chain Readiness Level (SCRL) is a data-driven, technology-agnostic approach to evaluate the resilience of clean energy technologies and their supply chains segments. SCRL assesses readiness at both the overall technology level and individual supply chain segment both today and in 2030.

	RISK FACTORS	ASSESSMENT QUESTION
Supply Reliability Factors	Deployment Viability	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
	Workforce Readiness	Availability of workers with sufficient skills
	Cost Competitiveness	US competitiveness relative to other global producers

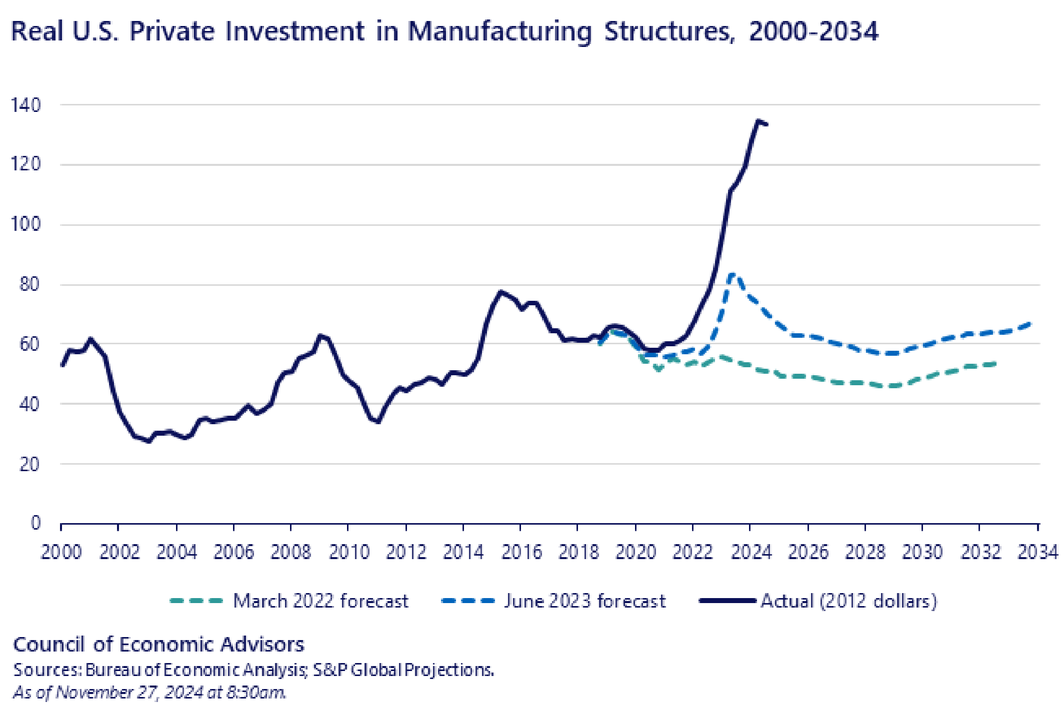
[72] U.S. Department of Energy. "About the Pathways Reports - Pathways to Commercial Liftoff." Pathways to Commercial Liftoff, November 13, 2024. https://liftoff.energy.gov/about-the-liftoff-reports/.
[73] U.S. Department of Energy. Office of Manufacturing and Energy Supply Chains. Energy.gov. "Manufacturing Capital Connector," n.d. https://www.energy.gov/mesc/manufacturing-capital-connector.

Impact of U.S. Energy Sector Industrial Base Investments

The investments made through BIL and IRA are dramatically accelerating demand for and deployment of clean energy technologies. By 2030, the share of electricity from clean sources is projected to reach 80 percent, significantly surpassing pre-IRA estimates. This domestic energy focus strengthens energy security, creates jobs, and reduces reliance on traditional fuel sources. DOE analysis also indicates that U.S. greenhouse gas emissions are projected to decline to 35–41 percent below 2005 levels by 2030, buoyed by the impacts of the IRA, compared to a 27-percent decline in a scenario without BIL and IRA.[74]

While achievement of U.S. climate commitments is laudable, it is equally important to look at the economic impact of not only deploying clean energy but also growing America's role in clean energy manufacturing. Since President Biden took office, inflation-adjusted spending on the construction of manufacturing facilities has more than doubled. This increase has exceeded forecasters' expectations, suggesting that the Investing in America agenda is catalyzing more private-sector funding than initially expected (Figure 6).[75]

Figure 6. Real U.S. private investment in manufacturing structures, 2000–2034

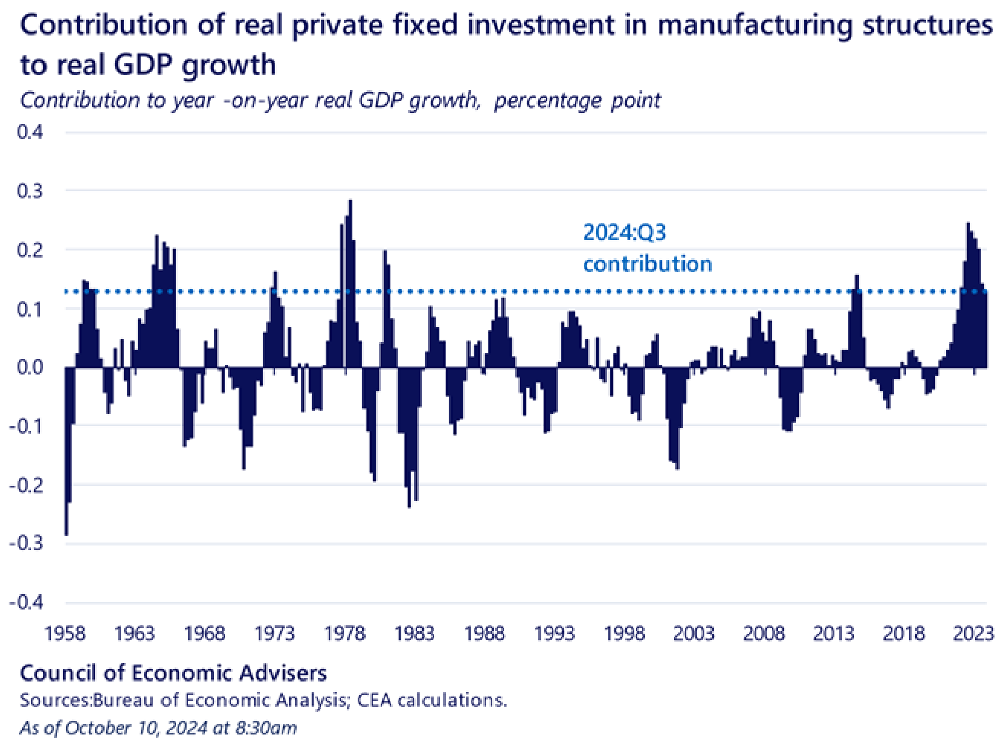


[74] U.S. Department of Energy. Office of Policy. "Investing in American Energy: Impacts of the Inflation Reduction Act and Bipartisan Infrastructure Law on the U.S. Energy Economy and Emissions Reductions." *Investing in American Energy: Impacts of the Inflation Reduction Act and Bipartisan Infrastructure Law on the U.S. Energy Economy and Emissions Reductions*, n.d. https://www.energy.gov/sites/default/files/2023-08/DOE%20OP%20Economy%20Wide%20Report_0.pdf.

[75] White House, "Building a Thriving Clean Energy Economy in 2023 and Beyond: A Six-Month Update," The White House, July 1, 2024, https://www.whitehouse.gov/briefing-room/blog/2024/07/01/building-a-thriving-clean-energy-economy-in-2023-and-beyond-a-six-month-update/.

The rapid investment in domestic manufacturing of clean energy technologies, as well as in other critical supply chains, has spurred a manufacturing boom in the United States with tangible economic benefits. Manufacturing construction, spurred by these investments, has made substantial contributions to GDP growth in recent quarters, setting new records since data collection began in 1959 (Figure 7). In addition to propelling GDP growth, manufacturing projects create high-quality, enduring jobs, many of which are accessible without college degrees.

Figure 7. Contribution of private nonresidential investment in manufacturing construction as a share of real GDP, 1958 to 2024Q1



Investments in the ESIB are creating substantial benefits for communities that have been impacted by the energy transition. Investments have funneled to energy communities—areas historically reliant on fossil fuels for employment, wages, or tax revenue—demonstrating the economic impact of the energy transition in real time. Analysis shows that Energy Communities[76] have received a $2.4-billion-per-month increase in public and private investment, compared to $1 billion for the rest of the U.S. after the passage of the IRA.[77] According to the study, the investment in energy communities has additional benefits including the creation of high-quality jobs, health, and

[76] The IRA defines energy communities as: (1) A "brownfield site" (as defined in certain subparagraphs of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA)); (2) A "metropolitan statistical area" or "non-metropolitan statistical area" that has (or had at any time after 2009) 0.17 percent or greater direct employment or 25 percent or greater local tax revenues related to the extraction, processing, transport, or storage of coal, oil, or natural gas; and has an unemployment rate at or above the national average unemployment rate for the previous year; (3) A census tract (or directly adjoining census tract) in which a coal mine has closed after 1999; or in which a coal-fired electric generating unit has been retired after 2009.

[77] U.S. Department of the Treasury. "The Inflation Reduction Act: A Place-Based Analysis, Updates From Q3 and Q4 2023," November 19, 2024. https://home.treasury.gov/news/featured-stories/the-inflation-reduction-act-a-place-based-analysis-updates-from-q3-and-q4-2023.

environmental benefits. Prior to the Inflation Reduction Act, 68 percent of announced investments in clean technologies were in counties with median incomes below the U.S. aggregate median income. After the IRA, 75 percent of announced clean investments have been in counties with median incomes below the U.S. aggregate median.[78]

Further evidence beyond official U.S. Government data bolsters the case that public investment generates a positive return on investment. A recent analysis from the Clean Investment Monitor suggests that each dollar of federal funding—tax credits, grants, and loans—spurred at least $6 in private investment.[79] The combined pooling of public and private capital delivers outsized, long-term benefits including job creation and community development, lower electricity costs, and reduced carbon emissions. Such findings reinforce the notion that clean energy initiatives offer a compelling solution to environmental and energy challenges while simultaneously driving economic prosperity.

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[78] Ibid.

[79] Lily Bermel et al., "Clean Investment Monitor: Q4 2023 Update," January 29, 2024, https://assets-global.website-files.com/64e31ae6c5fd44b10ff405a7/65dfcaebd76fc56445fd7375_Clean%20Investment%20Monitor%20-%20Q4%202023%20Update.pdf.

RESILIENCE AND VULNERABILITY ASSESSMENT

Overview

Global supply chains for energy technologies have been under pressure since 2020 from the COVID-19 pandemic, the war in Ukraine, and other geopolitical conflicts. Now, the demand for energy technologies with their material and components necessary for final assembly and deployment adds an additional strain to already stretched supply networks. External macroeconomic pressures due to fluctuations in supply, volatility of raw material prices, changes in regulatory environments (e.g., export controls), and cost inflation add additional stress. A government-enabled, private sector–led investment has another crucial impact: it creates more secure and resilient supply chains. A resilient supply chain is one that proactively manages risks and recovers quickly from an unexpected event, or shock.

The long-standing U.S. approach to production, which for years, prioritized efficiency and low costs over security, sustainability and resilience, has resulted in increasing supply chain risk. The search for low-cost production has led to geographic concentrations of key supply chains in a few nations, most notably China, creating the risk of monopolistic behavior and increasing vulnerabilities for United States and its trading partners. Over the last decade, China's Belt and Road Initiative has synced foreign investments in raw material extraction to their domestic manufacturing build-up, making it difficult for U.S. companies to compete with China in global markets. Without a robust domestic manufacturing ecosystem, the U.S. will be reliant on value chains dominated by competitor nations, which poses a risk to national security and future economic prosperity.

As a result of decades of previous production and sourcing decisions, external risks to clean energy supply chains and the ESIB can be classified into two major categories: supply network constraints and sourcing concentration. Supply network constraints are largely a factor of commercial interests or macroeconomic conditions—sourcing investment decisions that focused on lowest cost of production, scarce or limited production of key input sources, price volatility that inhibits critical technology production and deployment, and significant ramp ups in demand outpacing supply. During the COVID-19 pandemic, the fragility of supply chains was laid bare: the lead times of 2 to 4 years for transformers and grid components that typically took weeks,[80] and thousands of pickup trucks sitting lifeless on manufacturers' parking lots without the necessary power electronics.[81] While the Biden–Harris Administration has made significant progress improving the strength and resilience of the ESIB, there are a set of remaining challenges to tackle in the coming years to continue technological progress and the momentum of energy supply chains in transition.

Transparency

Supply chain transparency is a challenge in multiple energy technologies, particularly those dominated by large, vertically integrated original equipment manufacturers (OEMs) (e.g., wind and grid components). In some sectors, high PRC market shares present a challenge to data transparency (e.g., battery and solar sectors). Notably, resources have been devoted to creating data transparency

[80] Postelwait, Jeff. T&D World. "No Easy Answers: Transformer Supply Crisis Deepens", February 23, 2023. https://www.tdworld.com/substations/article/21258955/no-easy-answers-transformer-supply-crisis-deepens.
[81] Hamblen, Matt. Fierce Electronics. "Covid and chip shortage hit GM pickup assembly", July 22, 2021. https://www.fierceelectronics.com/electronics/covid-and-chip-shortage-hit-gm-pickup-assembly.

in key sectors, led by efforts at U.S. National Laboratories and ongoing efforts by DOE. To inform the U.S. Government's understanding of supply chain risks, DOE's MESC has developed the SCRL framework. SCRL is designed to quantify the strength and resilience of each segment of key energy technology supply chains. As a complement to the Department of Commerce's SCALE tool, the SCRL framework is the product of rigorous, scalable, and data-driven analyses, creating a tool that can be applied consistently across energy technologies to gauge the ability of various supply chains to meet our energy needs.

The application of the tool allows the DOE to better understand impacts of external shocks, including whether supply chains can withstand anticompetitive practices, keep pace with rapid demand growth, demonstrate resilience in the face of geopolitical shocks, and prove durable and competitive over the long-term. Because this framework measures supply chain risk at both the overall technology level and for each individual supply chain segment, SCRL provides a critical diagnostic to inform where investment and policy support is required to address emerging bottlenecks and other energy supply chain risks. By providing a consistent measuring stick and a common language to evaluate supply chains, SCRL can enhance the prioritization and effectiveness of both public and private efforts to build more robust energy supply chains, enhancing U.S. energy independence, national security, and economic well-being.

Domestic capacity

Current and projected demand exceeds current manufacturing capacity for most energy technologies. While this is true for finished goods, shortfalls get more pronounced for upstream production steps. Upstream critical mineral extraction and processing creates a particular bottleneck for U.S. manufacturing across many key ESIB technologies. However, recent investment and policy have created substantial momentum in scaling domestic supply chains, including upstream production. However, it will be critical to ensure projects come to fruition and spur further investment. There are also areas in mature technologies where the United States still lacks manufacturing capabilities or is not competitive compared to other countries. In this case, deploying cutting-edge and innovative technologies could prove to be a viable path to building out supply chains.

As domestic supply chains for new technologies are developed, demand for materials and components often outpaces available supply. For example, large power transformer demand is expected to more than double, from 1,300 to 2,800 units from 2023 to 2030.[82] The limited production of U.S. GOES represents a key bottleneck for meeting required demand.[83] The scale of manufactured components can also add complexity. In the case of offshore wind, the components—blades, towers, and foundations—are large and must be assembled near ports. Building up domestic production takes time with the precise siting of facilities needed to make business cases viable. Supply chain constraints can be challenging when there is a confluence of factors lumped together. However, in most cases, they are market problems—solvable through additional capital or corrective measures taken between suppliers and customers.

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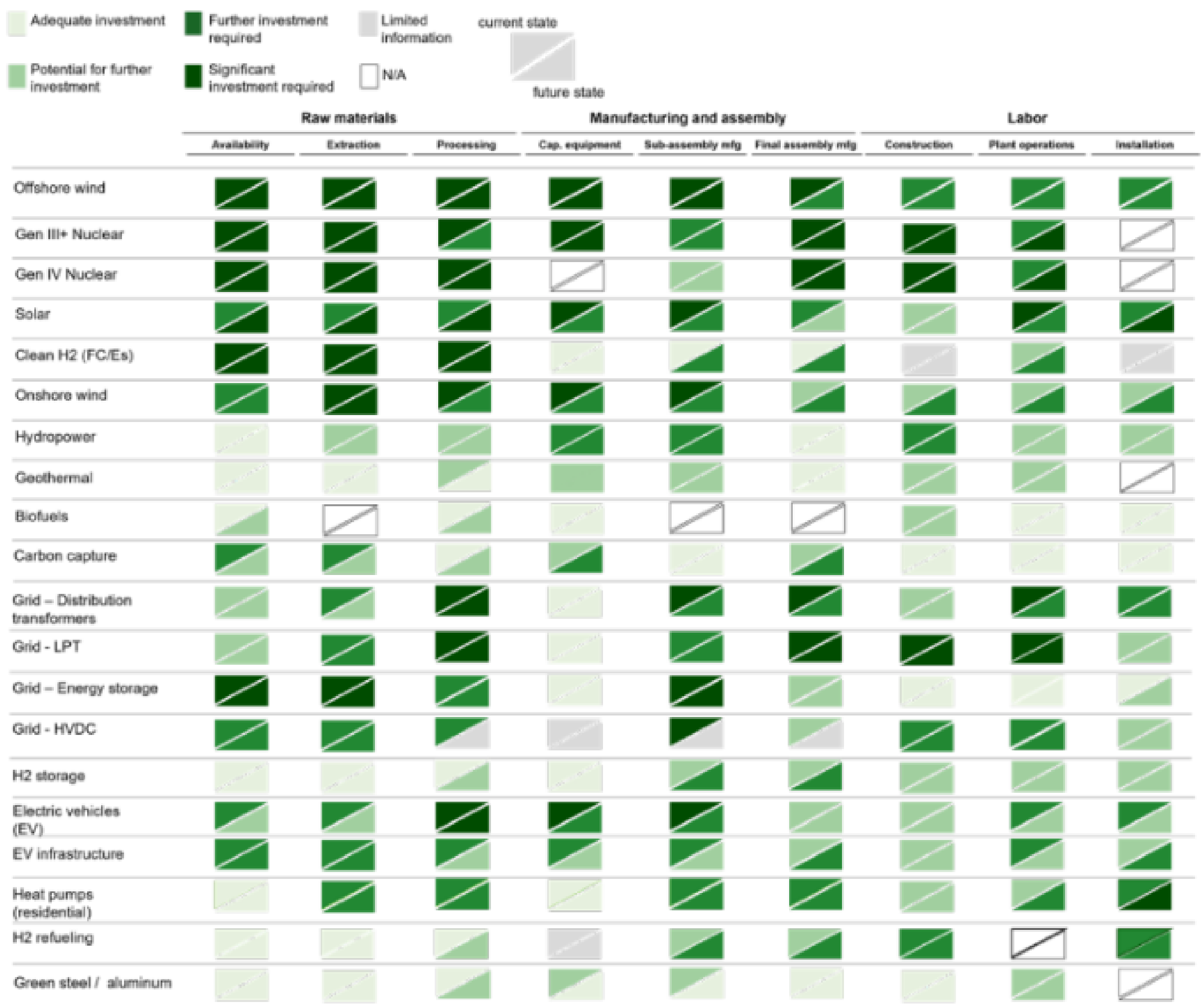
[82] Gonzalez, Eva. BloombergNEF. "Research Note: US Risks Power Transformer Supply Gap Becoming a Chasm". November 2023.

[83] U.S. Department of Commerce. U.S. Bureau of Industry and Security. "The Effect of Imports of Transformers and Transformer Components on the National Security", October 15, 2020. https://www.bis.doc.gov/index.php/documents/section-232-investigations/2790-redacted-goes-report-20210723-ab-redacted/file.

In the near term, the U.S. has sizable investment gaps across a variety of energy technologies from upstream materials to final products. Across twenty major technologies, the U.S. has adequate levels of investment for only 3 out of 20 major energy technologies. The gap is further pronounced as supply chains move upstream to critical minerals and materials (Figure 8).

Figure 8. U.S. energy technology and supply chain investment matrix[84]

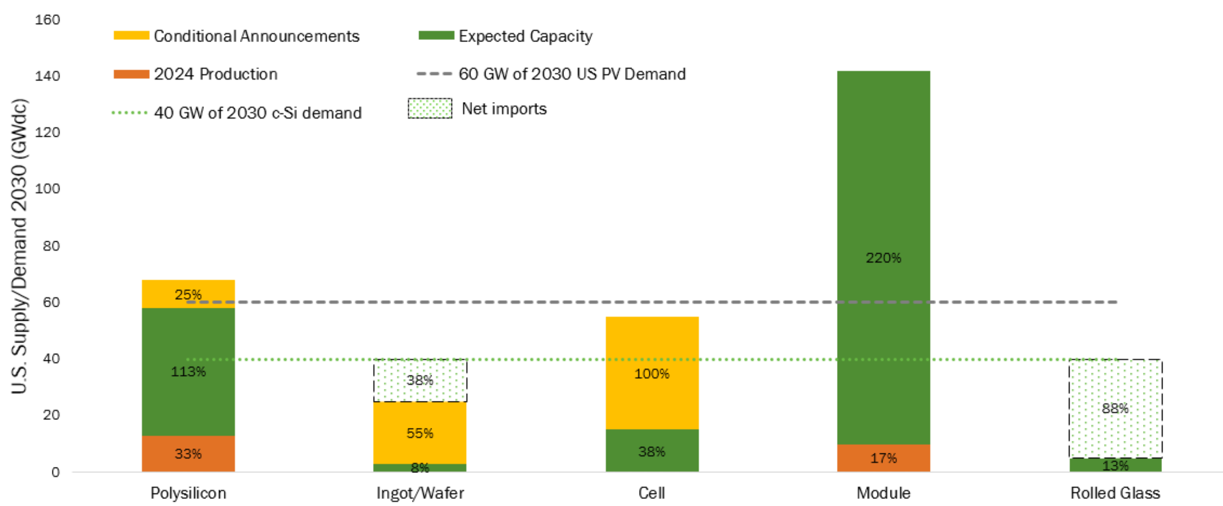


Tax credits for production (e.g., Advanced Manufacturing Production Tax Credit – 45X), investment (e.g., domestic content bonus adders for Clean Electricity Investment Tax Credit – 48E), and consumption (e.g., mineral and component sourcing requirements for Clean Vehicle Credit – 30D) have made a meaningful dent against the PRC's cost advantages in certain areas (e.g., battery cell and pack manufacturing, solar modules). However, sustained, long-term certainty and additional capital is needed to make progress against the cost gap. Support for multiple cost levers—lowering cost of capital, incentives to improve learning rates, additional capital expenditure support, and

[84] Tsisilile Barlock et al., U.S. Department of Energy, Office of Manufacturing and Energy Supply Chains. "Supply Chains Progress Report," *Supply Chains Progress Report*, 2023, https://www.energy.gov/sites/default/files/2023-08/Supply%20Chain%20Progress%20Report%20-%20August%202023.pdf.

additional demand-side support, coupled with targeted tariffs—should be up for consideration. While there has been sizable investment in the overall U.S. ESIB since 2021, the allocation of projects has been uneven across supply chain segments and technologies. Private investments in production across clean energy supply chains have initially focused on downstream production and final assembly (e.g., battery cells and solar modules), leaving gaps in upstream and midstream materials (Figure 9).

Figure 9. U.S. supply and demand by solar component, 2024–2030[85]



The PRC has established considerable structural advantages in building out advantages in energy supply chains across batteries, electrolyzers, solar, wind components, and others. Sustained commitment in the form of additional and lower-cost capital, policy incentives to stimulate investment, advancing commercial relationships with trading partners, and partnership among all levels of government and industry are needed to build at-scale facilities. In the near term, it may not be feasible or economical to onshore all segments of energy supply chains, particularly on the timeframe necessary to meet clean energy and climate goals. In this case, diversifying U.S. import sources by friendshoring to U.S. allies with a comparative advantage to manufacture the needed critical components or nearshoring to countries near the United States is seen as another option to strengthen supply chain resilience by both industry and government. The U.S. will need to further align its foreign policy and international finance tools with both domestic policy and with allies to achieve significant friendshoring.

Trade concentration

Trade concentration varies by energy technologies. However, in some key clean energy technologies China plays an outsized role in supply chains, creating potential bottlenecks. For example, these conditions are most pronounced in solar and batteries, though similar risks exist in other sectors including electrolyzers and key upstream inputs such as NOES and GOES. Sourcing concentration represents a structural market problem and a national security risk: low-cost, often subsidized

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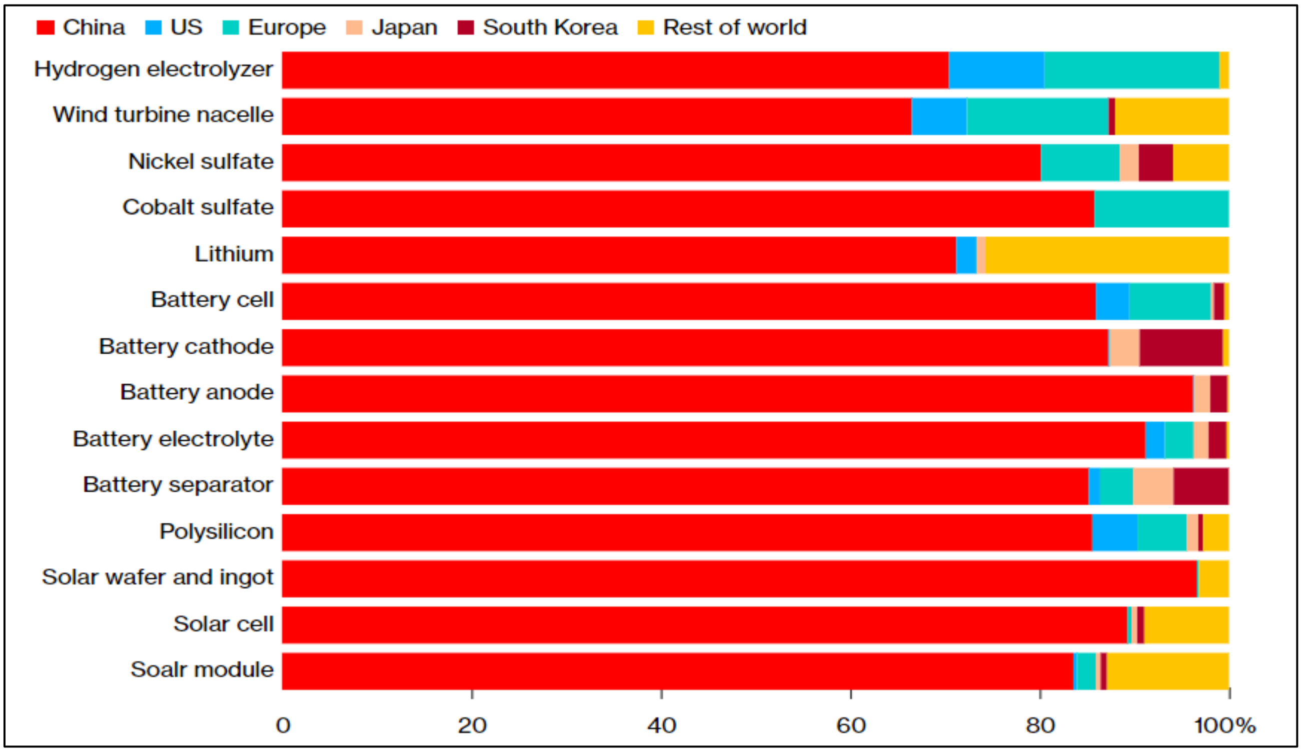
[85] Internal analysis from the National Renewable Energy Laboratory and U.S. Department of Energy Internal Analysis. December 2024.

production from FEOCs creates sourcing concentration and other associated risks (e.g., cybersecurity for connected grid equipment). U.S. clean energy manufactured products face challenging market conditions due to FEOC-concentrated production and associated supply chains. U.S. and global clean energy supply chains rely on majority of critical upstream materials refined and processed and manufactured components assembled in FEOC countries. Across a survey of clean energy production segments—ranging from raw materials to components, the PRC controls more than 80 percent of raw material processing and manufacturing capacity (Figure 10).

Figure 10. Global manufacturing capacity of energy supply chains by country or region, 2024[86]



While the U.S. and trading partners have made considerable progress towards standing up energy supply chains independent from the PRC, future investments should consider the structural advantages built up over the last decade. The PRC has structurally invested in upstream clean energy critical materials capacity through subsidies and state-controlled finance, which has shifted the supply chains of U.S. innovations to China.

Solar technology was invented in the U.S., but global solar PV manufacturing capacity has increasingly moved to PRC over the last decade. As a result, the PRC's market share across the key production steps (e.g., polysilicon, ingots / wafers, cells, and modules) exceeds ~80 percent.[87] China controls 97 percent of global silicon wafer production, creating sourcing risks in event of trade disruption. The level of geographical concentration of global supply chains presents sizable risks for

[86] BloombergNEF. "China Extends Control of Global Clean Energy Supply Chain", September 10, 2024. https://www.bnef.com/shorts/sje1z4dwx2ps00
[87] International Energy Agency. "Executive Summary – Solar PV Global Supply Chains – Analysis - IEA," IEA, n.d., https://www.iea.org/reports/solar-pv-global-supply-chains/executive-summary.

the U.S. and trading partners. Since the passage of the IRA, U.S. announced solar module assembly projects—nearly 50 GWdc of annual manufacturing capacity—enough to satisfy 80 percent of demand with domestically produced modules.[88] While the U.S. solar manufacturing sector made sizable gains in building out a domestic solar supply chain, there are outstanding resilience challenges ahead that may challenge the longevity of raw material and component production of the U.S. solar industry.

Current PRC production and planned investment—from upstream materials to downstream products—exceed global demand across solar—which will make business cases for investments in the U.S. and allied countries challenging to prove out. This reality is consistent across technologies including batteries and electric vehicles, where PRC has looked to export markets to sell excess supply and right size imbalances within its economy. The risk of dumping of cheap materials and components due to overproduction challenges efforts to build competing U.S. and trading partner production capacity.

Oversupply in the global economy makes cost competitiveness a key challenge for the U.S. and major developed trading partners. Due to both at-scale concentration of production value chains, low environmental standards, protections, or compliance, inadequate enforcement of absence of labor standards, and publicly funded support for these industries, the PRC holds a structural advantage on cost competitiveness. Key U.S. upstream materials (e.g., solar-grade polysilicon for solar) and manufactured products (e.g., crystalline silicon solar modules) are not cost-competitive with PRC production.

Supplier diversity

Supplier diversity varies dramatically by technology, though many sectors experience concentration among a small number of suppliers. The most prominent supplier concentration risks exist in upstream processed and engineered materials such as refined natural graphite for battery anodes, GOES, and production and enrichment for nuclear fuel.

Agility

Responding to supply chain shocks remains a challenge for several key portions of the ESIB due to trade and/or supplier concentration. While these supply chains will always be complex and take time to rewire following shocks, increasing domestic capacity will likely help on this front. However, additional waves of investment will be required to create enduring agility across the ESIB.

Security

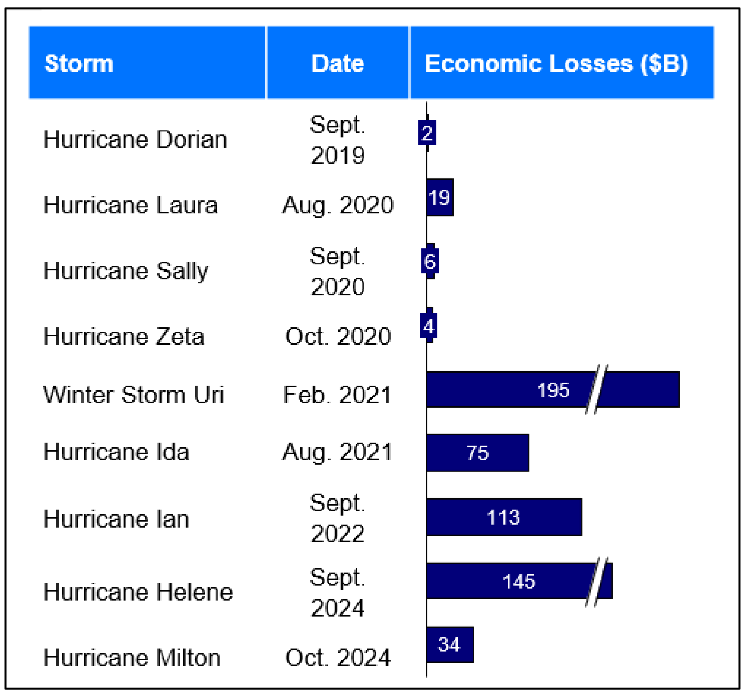
As the energy sector has become more globalized and increasingly complex, digitized, and even virtualized, its supply chain risk for digital components—the software, virtual platforms and services, and data—in energy systems has evolved and expanded. All digital components in U.S. energy sector systems are vulnerable and may be subject to cyber supply chain risks stemming from a variety of threats, vulnerabilities, and impacts. This includes digital components in all systems within the ESIB, namely those systems operated by asset owners across different energy subsectors

[88] U.S. Department of Energy, Loan Programs Office, Energy.gov. "LPO Tech Talk: Solar Photovoltaics Supply Chain," n.d. https://www.energy.gov/lpo/articles/lpo-tech-talk-solar-photovoltaics-supply-

(e.g., electricity, oil and natural gas, and renewables) and the systems operated by a worldwide industrial complex with capabilities to perform research and development and design, produce, operate, and maintain energy sector systems, subsystems, components, or parts to meet U.S. energy requirements. Supply chain risks for digital components including software, virtual platforms and services, and data have grown in recent years as increasingly sophisticated cyber adversaries have targeted exploiting vulnerabilities in these digital assets. Supply chain risks for digital components in energy sector systems will continue to evolve and likely increase as these systems are increasingly interconnected, digitized, and remotely operated.

Extreme weather and natural hazards are weakening U.S. energy supply chains and supporting infrastructure. Hurricanes, floods, wildfires, severe convective storms and other natural events routinely inflict widespread property damage. Less well publicized and understood are the cascading (negative) effects of such events on the systems that underpin society, including energy, water and transport infrastructure (Figure 11).

Figure 11. Select U.S. extreme weather events and economic losses, 2019–2024[89]



As storms increase in frequency and strength this amount of damage will only further widen the gap between supply and demand and slow down economic development of projects related to manufacturing, housing, technology and infrastructure. Storm damage is increasingly resulting in full-system and substation replacements for investor-owned utilities, cooperatives, and municipal-owned utilities. In the aftermath of Hurricane Ida—utilities estimated $2.6 billion in grid damage and reported nearly 6,000 transformers damaged.[90]

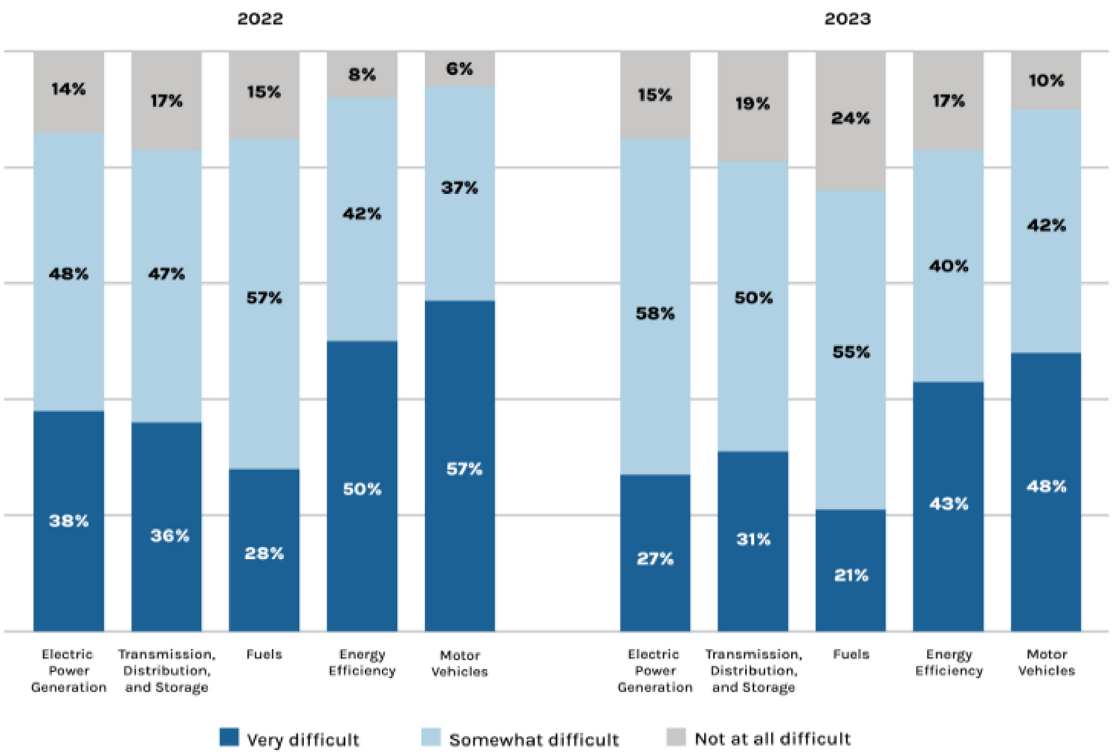
[89] U.S. Department of Commerce. National Oceanic and Atmospheric Administration. National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2024). https://www.ncei.noaa.gov/access/billions/, DOI: 10.25921/stkw-7w73

[90] Entergy Newsroom. "Entergy Provides Update on Hurricane Ida," n.d. https://www.entergynewsroom.com/news/entergy-provides-update-on-hurricane-ida/.

Economic health and compliance

Scaling of supply chains and final assembly requires a sufficient workforce to assemble materials and operate facilities. Data from the 2024 U.S. Energy & Employment Jobs Report (USEER) suggest that ESIB continues to face near term challenges including hiring difficulty, high demand for construction workers to build new production facilities, and specialized skills across the sector (e.g., electricians, welders, heavy equipment operators, and pipefitters). The challenges are particularly acute due to significant competition among energy technologies for the same labor pool and limited specialized knowledge in the U.S. market (Figure 12).

Figure 12. Hiring difficulty by energy sector technology



Targeted investments in education, training, certification, and apprenticeship programs can create pipelines that equip and connect workers with the skills needed to fill high-quality clean energy jobs, while simultaneously reducing constraints on the clean energy manufacturing sector. Additional research is required to identify target models for this training, considering the role of both private and public entities.

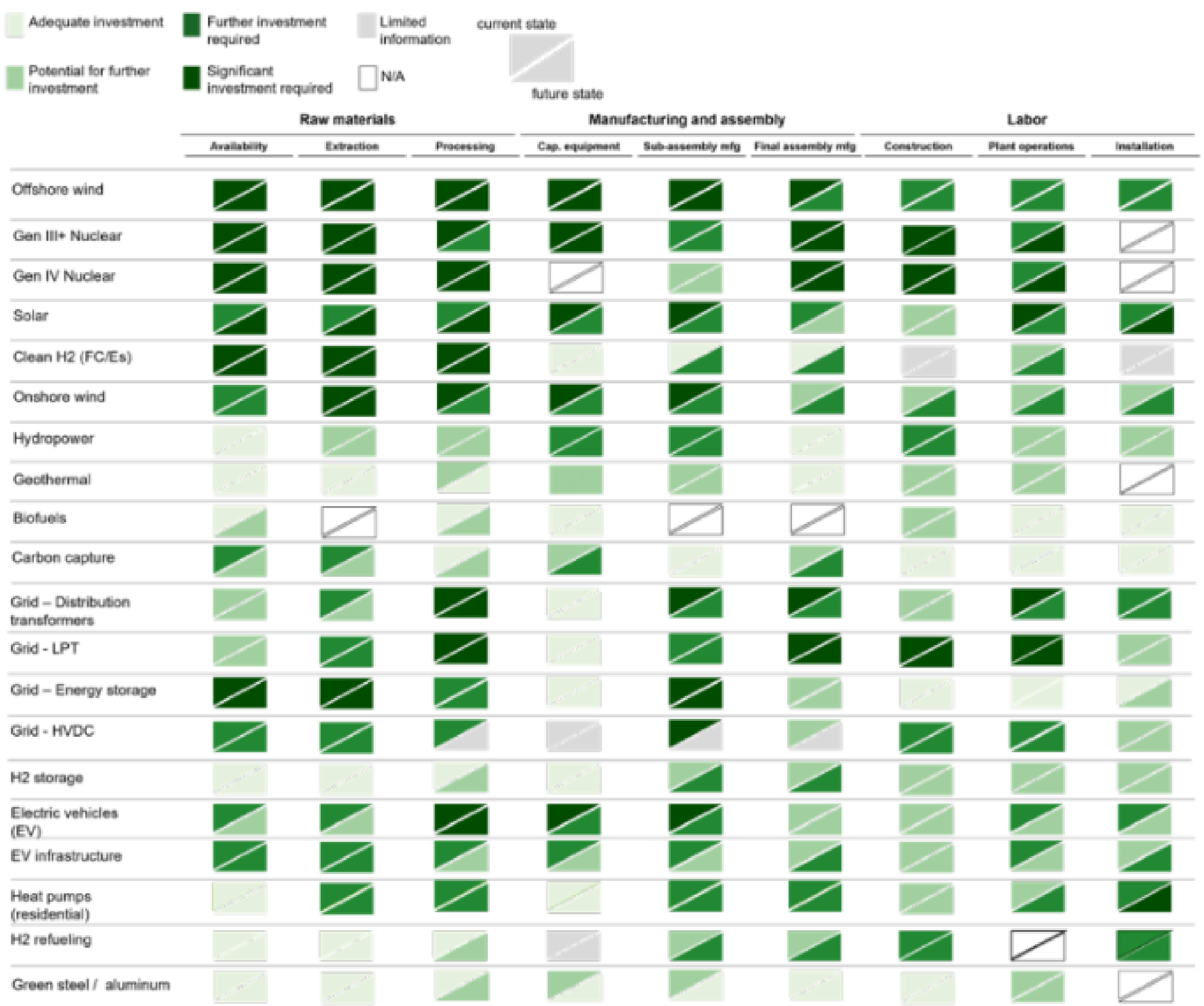
In some supply chain areas, foreign incumbents are in a strong position given strong market share, expertise and IP leading to lower cost operations, enabled by strong policy support. In these areas, robust U.S. policy is needed. U.S. production generally has high standards for labor and environmental compliance relative to global competitors. Requiring trade partners to operate with similar standards may help create a more level economic playing field.

PRIORITIES AHEAD

Four-year Outlook

As the U.S. and other countries around the world strive to diversify the energy industrial base, the extent to which global materials and component supply chains can keep up with new and accelerating sources of demand will be a critical determinant of reaching net-zero targets. While the U.S. has made substantial progress in investments to build out new production capacity, there is more work to do. Estimates on the degree of public and private investment required to establish industry-leading U.S. energy supply chains show five- and ten-year investment ramps fall short across many energy technologies (Figure 12).

Figure 13. U.S. energy technology and supply chain investment matrix[91]



[91] Tsisilile Barlock et al., U.S. Department of Energy, Office of Manufacturing and Energy Supply Chains. "Supply Chains Progress Report," *Supply Chains Progress Report*, 2023, https://www.energy.gov/sites/default/files/2023-08/Supply%20Chain%20Progress%20Report%20-%20August%202023.pdf.

Goal 1. Increase investment in upstream supply chains

The extensive use of processed minerals and materials creates complexity for domestic production of most ESIB outputs including batteries, grid components, electricity generation, industrial decarbonization technologies, among other technologies. Lack of at-scale production and current timelines to production (e.g., 2026–2030 to be operational) for facilities under construction creates risks, including the inability to respond to market developments (e.g., cost declines), technology obsolescence, outdated production techniques, among other areas.

While recent investment and policy have created momentum in scaling domestic supply chains, further investment and support is needed. DOE-led analytical efforts including Supply Chain Readiness Levels and the Critical Minerals Report have identified areas in urgent need of action. The Department of the Interior, through the U.S. Geological Survey's National Minerals Information Center, developed a whole-of-government List of Critical Minerals using a data-driven methodology in 2022. Since publication, the List of Critical Minerals has been used to identify supply risks and work collaboratively to develop solutions to strengthen specific supply chains including where to focus government investments. In parallel, secure trade partnerships will be another critical approach to building resilience and filling supply chain gaps.

Goal 2. Continue to expand manufacturing and production capacity for key components in value chain with focus on systemic vulnerabilities

As demand for ESIB technologies ramps up, there will be a continued focus on increasing the sources and quantity of reliable suppliers domestically and among trading partners. Currently, the U.S. has supplier concentration risk in key technology areas (e.g., grid components) or in some cases sole source suppliers (e.g., grain-oriented electrical steel and amorphous metal for distribution transformers) for upstream materials on several manufactured products essential for ESIB and the clean energy transition. Among other critical materials and metals for clean energy technologies, the U.S. has limited smelting, refining, and recycling capacity for copper, aluminum, and silver, among others, amidst increasing demand. The U.S. needs an additional 400 kt of copper by 2030 with over 50 percent for end-uses in direct support of the energy transition.[92]

Copper smelting is a significant bottleneck (e.g., only two domestic smelters are operational) with unfavorable operating costs (e.g., U.S. producers operate in the fourth quartile of global producers).[93] Moreover, idle production capacity across the value chain for several technologies (e.g., polysilicon and large power transformers) is due to a lack of cost competitiveness with global production. For example, U.S. capacity for producing large power transformers is underutilized at about 40–50 percent of current production line operations despite projections for increasing electrical load growth.[94] Policy supporting the domestic grid supply chain can alleviate these risks. For example, additional targeted funding to bolster manufacturing capacity, as well as potential demand-side support to give suppliers confidence to make investments in expanding production capacity for equipment necessary for grid expansion. In addition, distributed energy resources such

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[92] Crooks, Scott, Jonathan Lindley, Dawid Lipus, Richard Sellschop, Eugéne Smit, and Stephan Van Zyl. "Bridging the Copper Supply Gap." McKinsey & Company, February 17, 2023. https://www.mckinsey.com/industries/metals-and-mining/our-insights/bridging-the-copper-supply-gap.
[93] U.S. Department of Energy. Office of Manufacturing and Energy Supply Chains. Internal analysis. December 2024.
[94] Gonzalez, Eva. BloombergNEF. "Research Note: US Risks Power Transformer Supply Gap Becoming a Chasm". November 2023.

as rooftop solar and storage and expansion of technologies such as geothermal for behind-the-meter generation can reduce dependence on grid infrastructure

Goal 3. Improve resilience for specialized materials and capital equipment by increasing domestic production and through trading partners

The challenge of onshoring or friendshoring of key supply chains extends to specialized materials and components along with the capital equipment needed to produce them. Increasing production capacity for specialized components remains a critical gap to close for the ESIB.[95] For example, the U.S. does not have large-scale domestic castings and forgings capabilities to meet demand in offshore wind. Global supply chains may have bandwidth for many sub-components (e.g., bearings), but many will be in high demand with a limited pool of suppliers (e.g., flanges for offshore wind have about seven global suppliers and only 2–3 with the capacity to meet current specifications).[96]

Supply chain challenges have slowed the deployment of offshore wind farms, in addition to other factors. The U.S. also faces limited domestic sourcing of leading- and current-generation capital equipment, tooling, and specialized machinery needed to produce clean energy technologies. The majority of leading-edge solar PV equipment is developed in the PRC or Southeast Asia (e.g., ingot/wafer pullers and diamond wire saws). The increasing size of components—from wind blades to modules—also may make current specs and installation of capital equipment obsolete in the next 2–5 years. Certain technologies require higher-grade equipment than others (e.g., nuclear), which creates potential risk if the necessary components are unavailable. These bottlenecks can be addressed through targeted investment and diplomatic engagement, including strategic trade partnerships with reliable trade partners.

Goal 4. Increased federal investment and program support for workforce development

The U.S. energy workforce overall added over 250,000 jobs in 2023—59 percent of the total share attributed to clean energy and growing 4.9 percent year over year.[97] And for the first time ever, unionization rates in clean energy, at 12.4 percent, surpassed the average rate in the energy sector of 11 percent, driven by rapid growth in unionized construction and utility industries.[98] While the U.S. ESIB workforce has shown promising developments, long-term structural factors may lead to a shortfall in the necessary workers and skills required for U.S. clean energy manufacturing.

Factors including geographic variations in the labor force, a lack of investment in worker skill development, an aging workforce, and changes in workforce preferences all shape the underlying foundations of the labor market.

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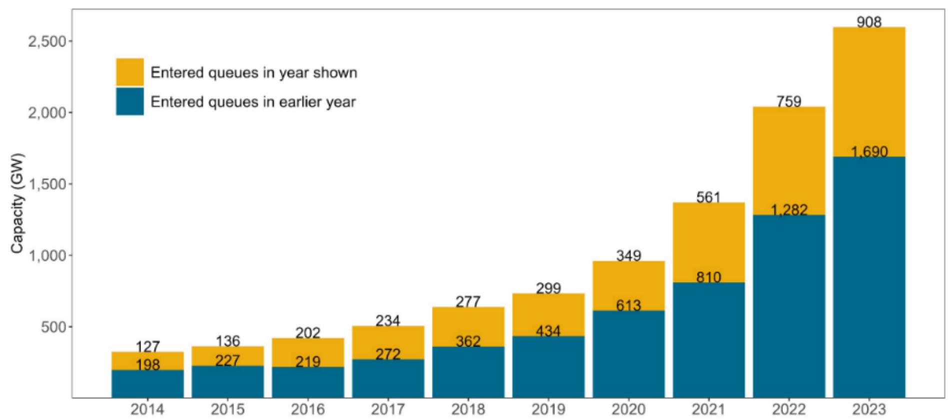
[95] U.S. Department of Energy. "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition," U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains", February 24, 2022. https://www.energy.gov/policy/articles/americas-strategy-secure-supply-chain-robust-clean-energy-transition.
[96] Ruth Baranowski et al., "Wind Energy Supply Chain Deep Dive Assessment," February 24, 2022, https://www.energy.gov/sites/default/files/2022-02/Wind%20Supply%20Chain%20Report%20-%20Final%202.25.22.pdf.
[97] U.S. Department of Energy et al., "United States Energy & Employment Report 2024," U.S. Department of Energy, 2024, https://www.energy.gov/sites/default/files/2024-10/USEER%202024_COMPLETE_1002.pdf.
[98] Ibid.

Goal 5. Modernize infrastructure to alleviate bottlenecks for downstream demand.

While financial incentives can drive investment, the physical realities of connecting clean energy systems and infrastructure necessary create a risk that could limit deployment. For example, grid interconnection queues increased 27 percent to 2,600 GW—twice as much as the existing U.S. generation capacity—in 2023 (Figure 14).

Figure 14. Total active capacity in interconnection queues, 2023[99]



The increasing backlog of connecting into the grid is exacerbated by the pace of modernization and expansion. DOE released the National Transmission Needs Study, which found the U.S. will need to more than double intra-regional transmission capacity and quadruple interregional transmission capacity by 2035.[100] Estimates have found that large transmission projects can take 20 years to complete. Lack of transparency in the ISO/RTO interconnection backlog and low completion rates for transmission create mixed signals for manufacturers and investors.

While the U.S. needs to clear hurdles to deploy more clean generating assets, there are current investments that can be added to the existing grid network to alleviate current bottlenecks. Deploying advanced grid solutions available today can cost effectively increase the capacity of the existing grid to support 20–100 GW of incremental peak demand when installed individually, while improving grid reliability, resilience, affordability, and sustainability.[101] For consumers, one of the top barriers that prevent them from buying or leasing an EV is charging logistics (61 percent),[102] with evidence showing positive feedback loops with respect to both EV demand and EV charger

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[99] Rand, Joseph, Nick Manderlink, Will Gorman, Ryan H Wiser, Joachim Seel, Julie Mulvaney Kemp, Seongeun Jeong, and Fritz Kahrl "Queued Up: 2024 Edition, Characteristics of Power Plants Seeking Transmission Interconnection As of the End of 2023." (2024). https://emp.lbl.gov/sites/default/files/2024-04/Queued%20Up%202024%20Edition_R2.pdf

[100] U.S. Department of Energy. Energy.gov. "National Transmission Needs Study," n.d. https://www.energy.gov/gdo/national-transmission-needs-study.

[101] U.S. Department of Energy, "Innovative Grid Deployment - Pathways to Commercial Liftoff," Pathways to Commercial Liftoff, May 14, 2024, https://liftoff.energy.gov/innovative-grid-deployment/.

[102] Consumer Reports. "CR Report: Charging the Future—The Role of Retail in Our EV Transition - CR Advocacy," CR Advocacy, March 4, 2024, https://advocacy.consumerreports.org/research/cr-report-charging-the-future-the-role-of-retail-in-our-ev-transition/.

investment.[103] Meaningful progress has been made for EV charging infrastructure build out, with greater expansion needed to make charging ubiquitous and frictionless.[104]

Long-term Resilience Goals

The energy sector industrial base is undergoing rapid transition and will continue to over the coming decades. The United States is poised to emerge from this transition as a leader, maintaining energy independence and its status as an energy superpower. However, a holistic strategy is required to chart this transition as sources of advantage shift to extraction of new minerals and rely on the maintenance of complex supply chains for specialized materials and components.

While the U.S. has driven historical investment through the Inflation Reduction Act and Bipartisan Infrastructure Law, ongoing policy support will be needed to close investment gaps and build the necessary capacity in clean energy supply chains. These efforts must focus on three critical areas:

- **Continuing momentum to build out U.S. energy manufacturing.** This will require ongoing public support in key portions of the supply chain, including both production and recycling capacity, as well as the articulation of a long-term policy orientation to ensure U.S. manufacturing can compete with low-cost production in PRC driven by states support.
- **Building international partnerships to enhance supply chain resilience.** Clean energy supply chains will inevitably have to rely on productive capacity in other nations, due to both resource availability and existing IP. Pursuing an international engagement strategy that considers the competitiveness of U.S. vs. partner production and positions clean energy security prominently within the international agenda will be critical.
- **Activating the U.S. innovation ecosystem to build advantage in emerging technologies.** The competition in energy technologies will continue to grow in the coming decades. The U.S. Government must continue to deploy resources to innovate to improve existing technologies and accelerate the development of next generation solutions. The U.S. has long been a leader in early-stage R&D, and it will need to ensure IP is grown and commercialized within the U.S. ecosystem in the future.

Conclusion

The path to build enduring resilience in clean energy supply chains will be a long one, but the United States has the resources required to take on this challenge. Additional public capital will likely be required to unlock the trillions available in private capital markets in the U.S., and a clear and sustained policy agenda will be required to show investors that the long-term, hard investments in producing clean energy technologies will pay off. Recent actions funded by the Inflation Reduction Act and Bipartisan Infrastructure Law represent a critical step in this direction, and the task ahead is to ensure that the momentum to secure supply chains and preserve American energy independence is maintained.

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