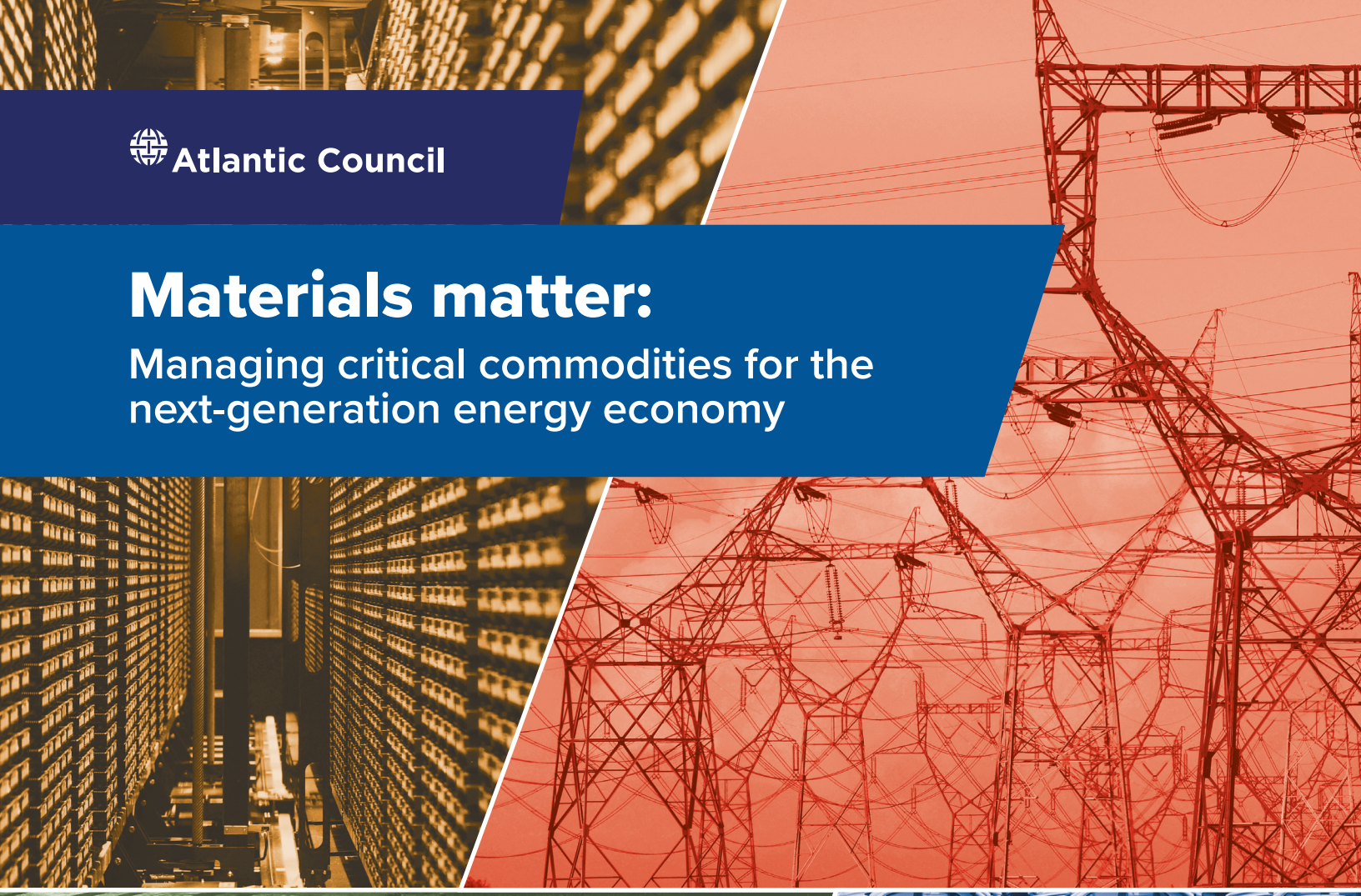


Atlantic Council

Materials matter:

Managing critical commodities for the next-generation energy economy





Reed Blakemore and Alexis Harmon



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The Atlantic Council Global Energy Center develops and promotes pragmatic and nonpartisan policy solutions designed to advance global energy security, drive economic opportunity, and foster a sustainable energy future.

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I. Executive summary

- **The energy transformation narrative has a blind spot: it largely focuses on electrons and critical minerals while overlooking the far larger material foundations beneath.** Copper, steel, and durable plastics are the physical backbone of the new energy economy, forming the basis of both renewable energy technologies and enabling infrastructure. Yet these foundational materials face supply challenges that could bottleneck the emergence of a new energy economy.
- **Material demand is growing as the world rapidly builds.** Constructing new electricity infrastructure and deploying renewable energy systems both require massive quantities of copper, steel, and advanced materials. Add surging power demand from data centers, growing infrastructure needs in emerging economies, and the reality that legacy energy systems persist even amid transition, and material demand is poised to accelerate dramatically.
- **Materials are essential to the new energy economy, but their value chains must navigate unique sustainability pressures.** Steel accounts for almost one-tenth of global emissions, yet transmission towers, wind turbine foundations, and grid infrastructure cannot be built without it. Plastics and composites are carbon based by definition, yet they enable the lightweighting, electrical insulation, and corrosion resistance that make renewable energy technologies viable. The new energy economy cannot succeed by avoiding these materials; rather, it requires transforming how they are produced and used.
- **Supply chains are struggling to keep pace in both quantity and quality.** Some materials face structural constraints in upstream or midstream capacity, while even well-supplied markets remain vulnerable to sudden disruptions, as the disruption to shipping through the Strait of Hormuz demonstrated. At the same time, producers seeking to meet higher environmental and labor standards can struggle to compete with lower-cost alternatives.
- **Policymakers face a three-way balance between climate ambition, economic growth, and supply security.** Reducing emissions in materials production is inseparable from long-term competitiveness and market access but cannot come at the cost of supply security or affordability. Success requires navigating these tensions rather than optimizing for any single objective.
- **Meeting this challenge requires rethinking industrial policy.** Securing supply means expanding access to reliable upstream resources, diversifying processing capacity, deploying trade policy strategically, maximizing circularity, and mobilizing unprecedented capital. The nations that get this right will build the infrastructure and deploy the technologies that define the next-generation energy economy. Those that do not will find themselves constrained by a basic reality: the next-generation energy economy cannot be built if it lacks the materials needed to construct it.

CASE STUDIES IN THIS REPORT

	**COPPER**	A metal foundational to the energy transition but with forecasted supply shortages.
	**PLASTICS AND COMPOSITE MATERIALS**	Widely used and versatile materials that highlight the complex evolution of legacy commodities as technologies shift.
	**STEEL**	An economically vital alloy with significant carbon abatement challenges.

II. Introduction

The story of the energy transformation is often limited to electrons, but it depends just as much on industrial materials such as copper, steel, and plastics that comprise the infrastructure that makes electrons flow. Building a new energy economy requires massive quantities of physical materials—copper for electrical systems, steel for infrastructure, advanced polymers for components—which are driving major new demand for the foundational materials that serve as the physical backbone of the modern world.

Rising energy demand and the proliferation of newly commercial-ready energy technologies are placing mounting pressure on supply chains still in development or undergoing significant reform to meet growing demand. Scaling these technologies is only the first layer of supply chain strain; success depends equally on expanding supporting infrastructure such as transmission lines, transformers, and storage—all of which have their own unique supply chains and material needs. Looking one step deeper, industrial materials underpin the new energy economy's basic building blocks: the power generation needed to unlock new manufacturing capacity, the polymers and lubricants that keep industrial processes running, and the built environment itself that houses new industries.

With demand soaring across key industrial materials, shortages are being forecast, prompting governments to step in to fill gaps and safeguard industrial competitiveness. However, this supply crunch also represents an opportunity. Policymakers and investors see the technological shift and market transformation as a rare opening for economic development, industrial growth, and possibly even new leadership on the global stage. Managing both the risks and opportunities requires a deliberate plan of action.

These pressures have brought industrial policy back to the forefront of economic strategy. After decades of market-led globalization, governments have emerged as the protagonist in boosting investment, building capacity, and securing supply chains. Yet, many of these efforts have so far focused narrowly on hot-button minerals such as lithium or rare earth elements. While such minerals are indeed critical, a minerals-only framing risks missing the broader reality: the world is entering an era in which the scale, complexity, and emissions profile of industrial materials—not just minerals—will define the pace and feasibility of the next-generation energy economy.

From grid expansion to wind farms and electric vehicles, the addition of new energy technologies is not simply about replacing legacy materials with new; it is about dramatically adding to overall consumption. Industrial materials remain central to both emerging technologies and the legacy industries with which they intersect, bolstering global emissions while contributing to economic growth. Industrial policy must, therefore, do more than secure high-profile critical minerals; it must navigate the enduring material intensity of progress itself by ensuring supply of the building blocks that are critical to the future economy.

This report takes up that challenge by reframing the conversation around critical supply chains to highlight industrial materials and arguing that any credible industrial strategy must confront the material reality of new industrial supply chains and the possible strains on those supply chains in the near future. It examines three key industrial materials—copper, plastics and composite materials, and steel—through the lens of expected demand growth, supply-side constraints, and industrial policy tools to support expansion in sustainable and strategic ways. Each material represents a distinct dimension of the material challenges embedded in the energy transition, be it industrial decarbonization, transforming legacy industries, or just dramatically scaling up supply. This report endeavors to set a path for an industrial policy that meets the moment—one that not only enables emissions-efficient technologies but also invests in the durable, materially intensive systems that support them.

These materials are economically indispensable, globally traded, and hard to both substitute and align with sustainability targets. They represent a wider category of inputs often overlooked in climate policy discourse that are too familiar to spark political urgency, yet far too fundamental to ignore. In a resource-constrained, geopolitically competitive world, securing consistent access to these inputs is increasingly a matter of strategic importance—a vulnerability brought into sharp relief by the crisis in the Strait of Hormuz.

The success of any national industrial strategy will hinge not just on speeding up and scaling innovation, but on managing the physical realities of industrial policy at scale. That means recognizing that the energy system of the future is not just a story of a transition to new technologies; it is a story of new and expanding physical systems built with legacy commodities.

Building a next-generation, sustainable energy system is functionally not a process of subtraction; it is a reordering of physical systems, many of which depend not just on minerals, but on heavy industrial materials produced at enormous scale using energy from hydocarbons and coal. It is also a process of energy addition: to meet rising demand in emerging economies, enable digital expansion, and achieve climate goals, we are not yet swapping one energy system for another. We are building on top of what already exists—and building means steel, copper, and composites.

Figure 1: Where future materials demand will come from

DRIVERS OF DEMAND

The structural economic, energy, and digital transitions increasing material demands for copper, steel, and plastics

BASELINE GLOBAL ECONOMIC GROWTH

Material demand scales with development.

KEY DEMAND CHANNELS

- Infrastructure buildout
- Industrialization
- Replacement and maintenance in mature economies
- Urbanization and income growth in emerging economies

MATERIAL IMPLICATIONS

COPPER: building wiring, urban power cables, appliances

PLASTICS: construction materials, consumer goods, manufacturing inputs

STEEL: buildings, bridges, rail, industrial facilities

ENERGY SYSTEM EXPANSION

Expanding energy systems requires expanding material inputs.

KEY DEMAND CHANNELS

- Electrification revolution
- Grid and transmission expansion and upgrading
- Renewable energy deployment
- Energy storage

MATERIAL IMPLICATIONS

COPPER: transmission lines, EV charging, renewable technologies

PLASTICS: cable insulation, wind blades, transportation lightweighting

STEEL: transmission towers, power plants, wind turbines, pipelines

INDUSTRIAL & DIGITAL TRANSFORMATION

Digital growth is underpinned by physical infrastructure.

KEY DEMAND CHANNELS

- AI and data centers
- Advanced manufacturing
- Connectivity and communications networks
- Rising performance, durability, and efficiency requirements

MATERIAL IMPLICATIONS

COPPER: data centers, 5G, advanced industrial equipment

PLASTICS: lightweighting, thermal management, electronics housings

STEEL: industrial capacity expansion, logistics infrastructure

III. Building the energy economy: Two major shifts in material supply chains

Two interconnected shifts are reshaping the foundations of the global energy economy. The first is physical: the steady emergence of a new energy system is driving sustained, large-scale demand for the industrial materials—steel, copper, durable plastics—that have underpinned modern economies for more than a century. The second is strategic: governments are rethinking their approaches to leadership of new energy technologies, the role of manufacturing in fostering economic prosperity, and the importance of policy in securing the materials needed to support their economies in an era of advanced and diversified energy resources. Together, these shifts are elevating industrial policy to the forefront of economic and national security planning, effectively rewriting the playbook for how nations build, power, and sustain their economies.

The material intensity of the energy transition

Material consumption is inseparable from the development process itself, both as developing economies grow and as developed economies evolve. Building modern infrastructure—whether roads, railways, power plants, or ports—has always required reshaping the physical landscape: tunneling through mountains, damming rivers, and digging up the earth.[1] Achieving a lower-emissions energy system will be no exception. In fact, achieving a lower emissions and more efficient energy system remains tightly bound to the use of massive volumes of physical materials, many of which still require material- and emissions-intensive supply chains.

These materials are not just passive inputs; they shape what is possible to build and how quickly it can be built. With demand drivers multiplying—from renewable energy construction to AI-driven data center expansion to the industrialization of emerging economies—material needs will likely remain high. However, while the share of certain transition minerals such as lithium and cobalt is set to surge, total mass of extracted ore could decline relative to today's energy system, which relies heavily on coal, oil, and gas. Every year, roughly 15 billion tonnes of coal, oil, and gas are extracted to be burned—an enormous flow of materials that disappear once combusted and must be continually replenished.[2] By contrast, many of the materials for new energy infrastructure—steel in wind towers, polymers in turbine blades, copper in transmission lines—remain embedded in the built environment for decades, reducing the frequency of replacement.

The world, however, is not hurtling toward an energy system that ends extractive pressures. The term "energy transition" often masks the reality that new sources are typically added to the energy mix without legacy sources declining in absolute terms. For example, although coal use has dramatically decreased compared to oil over time, total global consumption of coal has still increased in real terms and actually reached an all-time high in 2022.[3] Thus, the advent of renewable energy technologies does not necessarily produce a straightforward transition to a lower-emissions global energy system; instead, they may, for now, feed an ever-expanding machine.

Notably, hydrocarbons sit at the center of the energy transition picture in ways that are often overlooked in climate discussions. Oil and gas are not only burned directly as fuels, but are also embodied in materials, particularly plastics and composites. These polymer-based materials are critical for wind turbine blades, high-voltage transmission lines, insulation, and countless other components of energy infrastructure. In this way, oil and gas will continue to flow into the energy system, even if their role in electricity generation declines.

The challenge is to recognize and plan for the persistent, large-scale demand for industrial materials that will continue to define the energy economy. Sustainability targets and strategies to build and steward a new energy economy that ignore the scale, diversity, and durability of these material needs risk running aground on the realities of supply, cost, and manufacturing capacity.

Industrial policy surges to the forefront of national security strategy

If the material intensity of the energy transformation is the physical reality, the rise of industrial policy is the strategic res-

1. Maria Kaika, "Between the Frog and the Eagle: Claiming a 'Scholarship of Presence' for the Anthropocene," *European Planning Studies* 26, 9 (2018), 1714–1727, https://www.tandfonline.com/doi/full/10.1080/09654313.2018.1484893.
2. "International—World Data," US Energy Information Administration, last visited October 23, 2025, https://www.eia.gov/international/data/world.
3. Jean-Baptiste Fressoz, "Pour Une Histoire Désorientée de l'Energie," paper presented at *25èmes Journées Scientifiques de l'Environnement—l'Économie Verte en Question*, Créteil, France, February 2014, https://hal.science/hal-00956441/document; "The World's Coal Consumption Is Set to Reach a New High in 2022 as the Energy Crisis Shakes Markets," International Energy Agency, December 16, 2022, https://www.iea.org/news/the-worlds-coal-consumption-is-set-to-reach-a-new-high-in-2022-as-the-energy-crisis-shakes-markets.

DEGROWTH AND MATERIAL CONSTRAINTS

While green industrial policy debates largely focus on scaling production and securing materials to advance the new energy economy, degrowth thinkers challenge the premise that economic expansion and sustained material consumption can ever be compatible with environmental sustainability. Degrowthers contend that prevailing measures of progress capture only the "positive side of the ledger"—such as gross domestic product (GDP) gains, jobs, and industrial output—while externalizing the social and ecological costs. These debates are largely normative, centered on questions of environmental limits and distributive fairness. For policymakers, degrowth is therefore less a policy blueprint than a provocation: a challenge to confront the material and moral boundaries of growth itself, even as governments double down on strategies to accelerate it.

This report does not evaluate degrowth as a governing framework. Instead, it takes current demand trajectories as given based on three realities. First, even ambitious efficiency gains cannot substantially offset expected growth in demand driven by electrification, digitalization, and urbanization. Second, developing economies have legitimate claims to the material-intensive growth that wealthier nations historically enjoyed. Third, no major economy has adopted degrowth as an explicit industrial strategy. Whether this trajectory is desirable is a separate question from whether it is likely. Instead, this report holistically examines both demand- and supply-side industrial policy tools within the realities of today's political and economic systems, acknowledging environmental limits but without making them the central focus.

ponse. Robust supply chains are increasingly seen as assets necessary to secure a share of the global energy economy. Access to a steady, affordable flow of critical materials does not just keep industry humming along; it opens up opportunities for lucrative linkages and spillover effects that can lead to long-term economic growth.

Many of China's successes illustrate the point. Decades of targeted investment in lithium mining and processing have been foundational to the rise of its robust lithium-ion battery industry.[4] While this infrastructure was initially used to produce batteries for consumer electronics, the chemical engineering expertise gleaned from this industry spilled over to enable China's dominance in producing lithium-ion battery cathode production. As of 2025, China produced about 85 percent of the cathode active material used in lithium-ion batteries.[5]

Successes like these have driven a shift in policy thinking. Around the world, governments are reentering the industrial arena: actively pursuing new industrial policies and trying to catch up after years of effective Chinese policymaking on strategic minerals and materials.[6] In 2023 alone, more than sixteen hundred industrial policies were implemented around the world.[7]

This shift is reshaping the global economic landscape in several significant ways.

1. *The floodgates of market intervention are now open.* The days when integration with global markets was seen as a goal in itself are being replaced by a trade framework in which trade is increasingly conditional, with inefficiencies such as higher costs and supply chain redundancies becoming an accepted cost of pursuing strategic goals. With supply chains and security increasingly interconnected, there is a need to reduce reliance on competitors, secure inputs for frontier technologies, ensure sufficient material supply for the lower-emission energy systems, decarbonize heavy industries, and mitigate market volatility stemmi-

4. "Critical Minerals Market Review 2023," International Energy Agency July 2023, 8, https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/07/critical-minerals-market-review-2023_9dcfb1a7/9cdf8f39-en.pdf.
5. "Global EV Outlook 2026," International Energy Agency, May 20, 2026, https://www.iea.org/reports/global-ev-outlook-2026/manufacturing-and-trade.
6. Stew Magnuson, "China Maintains Dominance in Rare Earth Production," *National Defense*, September 8, 2021, https://www.nationaldefensemagazine.org/articles/2021/9/8/china-maintains-dominance-in-rare-earth-production.
7. Anna Ilyina, Ceyla Pazarbasioglu, and Michele Ruta, "Industrial Policy Is Back but the Bar to Get It Right Is High," International Monetary Fund, April 12, 2024, https://www.imf.org/en/Blogs/Articles/2024/04/12/industrial-policy-is-back-but-the-bar-to-get-it-right-is-high.

ng from both secular factors and nonmarket interventions—all at the same time.[8]

2. *The rewiring of globalization is rewiring trade relationships.* Protecting domestic industries often entails retreating from global integration, increasing the fragmentation of the global economy, and compromising supply chain efficiency for the sake of security. Protectionist trade measures have been a major part of this shift, from the global proliferation of subsidies and local content requirements to President Donald Trump's ever-evolving tariff regimes and the retaliatory measures they have prompted. This has caused governments to look to new partnerships, regional spheres of influence to increase in importance, and competition to unfold even between reliable geopolitical partners such as the United States and the European Union (EU).
3. *Domestic policy and international economic policy are converging.* Trade is no longer just a mechanism for economic optimization and specialization; it has become a battering ram to achieve broader domestic objectives, such as populist drives to revitalize manufacturing or secure national security interests. Politics play an increasingly central role in economic policymaking, and policymakers are increasingly willing to use a broader economic toolkit to achieve their goals.

The changing geopolitical and policy environment means countries are seeking new strategies to address old challenges. In this environment, securing access to the core materials of the energy economy, whether critical minerals or more traditional industrial commodities, is a necessary precursor to a successful industrial policy, whether targeted toward energy transition technologies, industrial manufacturing capacity, or national security.

8. Gordon H. Hanson, "Washington's New Trade Consensus: And What It Gets Wrong," *Foreign Affairs* 103, 1 (January/February 2024), https://www.foreignaffairs.com/reviews/washingtons-new-trade-consensus-hanson-lighthizer; Henry Farrell and Abraham Newman, "The New Economic Security State: How De-risking Will Remake Geopolitics," *Foreign Affairs* 102, 6 (November/December 202 3), https://www.foreignaffairs.com/united-states/economic-security-state-farrell-newman; Javier Blas, "China Has Broken the 'Critical Minerals' Market," Bloomberg, September 30, 2024, https://www.bloomberg.com/opinion/articles/2024-09-30/energy-transition-china-has-broken-the-critical-minerals-market.



A coil of copper rod sits on the production line for copper flat wire at a factory in Jiangxi province, China, August 14, 2025. REUTERS/Florence Lo

IV. Case study material 1: Copper

Copper, often referred to as the "metal of electrification," sits at the heart of the material intensity challenge in the new energy economy. Its exceptional conductivity and relative affordability make it essential for the generation, transmission, and storage of electricity. The metal is thus seminally important as the world enters the "Age of Electrification," in which industrial competitiveness is increasingly linked to the efficient use and abundance of electricity.[9] Given that electrification is part and parcel of climate-smart energy production, the sheer physical volume of copper required, not just its unique properties, has become a defining factor in the pace and cost of the transition.

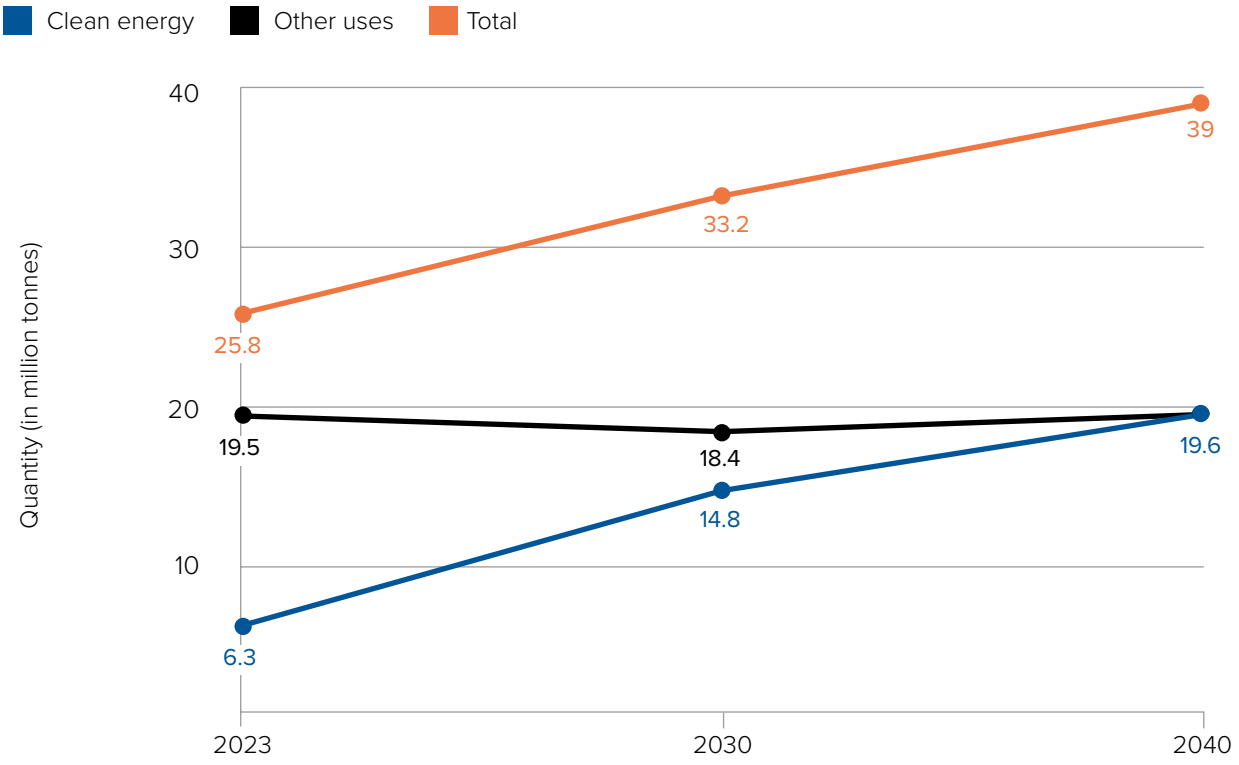
How demand is changing

Electrification will be a primary driver behind increasing copper demand, principally due to the need to expand electricity networks. To achieve net-zero emissions, the International Energy Agency (IEA) projects that electricity's share of final energy consumption must rise from roughly 20 percent to 50 percent.[10] Electricity networks will need to grow threefold to meet these goals—meaning there will be a need for vast amounts of copper. In fact, up to one-third of the growth in copper demand through 2050 will be derived from just the

9. "The World Is Moving at Speed into the Age of Electricity," International Energy Agency, last visited October 24, 2025, https://www.iea.org/spotlights/the-world-is-moving-at-speed-into-the-age-of-electricity.

10. "Net Zero by 2050: A Roadmap for the Global Energy Sector—Summary for Policy Makers," International Energy Agency, May 2021, https://iea.blob.core.windows.net/assets/7ebafc81-74ed-412b-9c60-5cc32c8396e4/NetZeroby2050-ARoadmapfortheGlobalEnergySector-SummaryforPolicyMakers_CORR.pdf.

Figure 2: Global copper demand in the net-zero scenario (2023–2040).



Source: "Global copper demand in the Net Zero Scenario, 2023-2040," International Energy Agency, updated 17 May 2024, https://www.iea.org/data-and-statistics/charts/global-copper-demand-in-the-net-zero-scenario-2023-2040-5856.

Note: While the IEA's net-zero scenario is highly ambitious, its copper demand trajectory reflects dynamics already emerging today, from rapid electrification to data center growth.

expansion of electricity grids.[11] Heightening demand further, modern energy infrastructure is becoming increasingly copper intensive because underground wiring is preferred in urban areas where demand is growing most and requires twice as much copper as traditional overhead lines.

However, the surge in demand will not be driven by the energy transition alone. Even without net-zero emissions targets, global demand for electricity is rising sharply in nearly every corner of the globe. In advanced economies, this growth follows two decades of stagnated demand, driven in part by the soaring electricity needs of data centers that facilitate cloud storage and AI.[12] Copper demand from data centers could increase from 1 percent of total copper demand to 6 or 7 percent by 2050, according to copper producer BHP.[13] Although the processing chips that power data centers are becoming more energy efficient (e.g., NVIDIA has reportedly improved its graphics processing units' energy consumption efficiency by a factor of 45,000 in the past eight years), the energy usage of computing is increasingly driven by cooling systems rather than processing power.[14] Meanwhile, the growing need for residential and commercial cooling is expected to be nearly as

11. Nick Pickens and Alice Yu, "Red Metal, Green Demand: Copper's Critical Role in Achieving Net Zero," Wood Mackenzie, November 2, 2022, https://www.woodmac.com/horizons/red-metal-green-demand-coppers-critical-role-in-achieving-net-zero/; "Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach, International Energy Agency, 2023, https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-c-goal-in-reach.
12. "Electricity Demand Growth Resource Hub," US Department of Energy, last visited October 24, 2025, https://www.energy.gov/policy/electricity-demand-growth-resource-hub.
13. Colin Larkins, "BHP Warns AI Growth Will Worsen Copper Shortfall," *Financial Times*, September 15, 2024, https://www.ft.com/content/da407b47-4133-470a-9574-508cee43e107.
14. Lauren Leffer, "The AI Boom Could Use a Shocking Amount of Electricity," *Scientific American*, October 13, 2023, https://www.scientificamerican.com/article/the-ai-boom-could-use-a-shocking-amount-of-electricity/; Dion Harris, "How AI and Accelerated Computing Are Driving Energy Efficiency," NVIDIA, January 30, 2024, https://blogs.nvidia.com/blog/accelerated-ai-energy-efficiency/.

significant a driver for energy demand as the energy transition itself. The IEA forecasts that rising temperatures could boost electricity demand for home cooling by 280 percent by 2050.[15]

In emerging and developing economies, electricity demand is also growing in tandem with broader economic development, often without the same structural energy efficiency gains seen in the United States and Europe over the past twenty years.[16] Supplying enough copper to build out electricity infrastructure is equally necessary to support the economic growth ambitions of emerging and developing economies. These countries are projected to account for about 40 percent of demand growth through 2050.[17] In India alone, power-sector generation has grown by more than 8 percent a year since the COVID-19 pandemic.[18] With a population of more than 1 billion people gaining more access to electricity, demand is expected to grow fivefold over the next few decades.[19]

Despite copper demand related to the energy transition expanding more quickly than nonenergy transition demand, the latter is still a larger end market, expected to account for more than half the market in 2035.[20] The core role of copper in global economic productivity is best captured by what happens if there is insufficient supply: studies indicate that just a 10-percent shock in copper prices can increase the core consumer price index (CPI) by roughly 0.2 percent over a twelve-month period.[21]

Regardless, this confluence of structural shifts means copper demand is poised to grow significantly in the coming decade. Rystad Energy forecasts that in a scenario with 1.8 degrees Celsius of global warming, global copper supply will need to grow 2.5 times by 2050 in order to enable aggressive electrification.[22] This presents an extraordinary challenge for an industry that already produced a whopping 23 million (short) tons of copper in 2023 and is facing considerable obstacles in expanding supply.[23]

This is not just a story of faster growth; it is a story of cumulative scale. Copper use in grids, vehicles, and renewable installations will mean moving more physical material over the next three decades than at any previous point in history, creating pressures across mining, refining, and recycling systems.

Supply challenges

While many energy transition minerals are facing rising demand, the copper industry faces some of the most significant challenges in meeting projected needs, leading many governments to designate copper as a critical mineral. Achieving expected copper demand requires bringing one new major copper mine online each year, adding 1 percent to global supply annually.[24] Similarly, the smelting segment of the value chain will need to expand in the medium term.

However, meeting this demand is proving a significant challenge. The copper market is thousands of years old, and some sites have been mined for millennia. Discovering new, large, and high-quality copper deposits has become progressively more challenging, making it a relative rarity over the last decade.[25] This leaves industry increasingly dependent on existing but abandoned or underutilized mines, referred to as brownfield sites, as opposed to greenfield sites built from scratch in new areas. However, as brownfield mines continue to mature, ore grades decline, their output diminishes, and operational costs rise, exacerbating the growing supply shortfall. For instance, copper ore grades in Chile, the world's largest copper producer, declined by 56 percent from 1999 to 2016, making it progressively harder and more expensive

15. "World Energy Outlook 2024," International Energy Agency, October 16, 2024, https://www.iea.org/reports/world-energy-outlook-2024.
16. "Statistical Review of World Energy 2024," Energy Institute, June 2024, https://www.energyinst.org/statistical-review.
17. Ibid.
18. Sudarshan Varadhan, "India Expects Annual Power Output to Grow Fastest in Over a Decade," Reuters, April 26, 2024, https://www.reuters.com/world/india/india-expects-annual-power-output-grow-fastest-over-decade-2024-04-26/.
19. Sam Farrell and Laura Whitton, "How Copper Will Shape Our Future," BHP Insights, September 30, 2024, https://www.bhp.com/news/bhp-insights/2024/09/how-copper-will-shape-our-future.
20. "The Future of Copper: Will the Looming Supply Gap Short-Circuit the Energy Transition?" S&P Global, July 2022, https://cdn.ihsmarkit.com/www/pdf/0722/The-Future-of-Copper_Full-Report_14July2022.pdf.
21. Jorge Miranda-Pinto, et al., "Beyond Energy: Inflationary Effects of Metals Price Shocks," VoxEU, December 3, 2024, https://cepr.org/voxeu/columns/beyond-energy-inflationary-effects-metals-price-shocks.
22. "Power Grids Require US$3.1 Trillion of Grid Infrastructure Investments by 2030," Rystad Energy, February 15, 2024, https://www.rystadenergy.com/news/power-grids-investments-energy-transition-permitting-policies.
23. "Mineral Commodity Summaries 2024–Copper," US Geological Survey, 2024, https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-copper.pdf.
24. Rick Mills, "New Copper Supply Offset by Multiple Hits to Existing Operations," Mining.com, June 19, 2023, https://www.mining.com/new-copper-supply-offset-by-multiple-hits-to-existing-operations/.
25. Sean DeCoff, "Major Copper Discoveries," S&P Global, September 5, 2024, https://www.spglobal.com/market-intelligence/en/news-insights/research/major-copper-discoveries.

to extract copper from existing mines.[26] To offset this decline and produce enough copper concentrate, run-of-mine volumes—the total amount of raw ore extracted—are expected to increase by 36 percent through the end of this decade.[27] As a result, the IEA predicts that existing mines and mines under construction will only be able to produce 75 percent of the copper that the world will need in 2035 under its Stated Policies Scenario.[28]

Filling this supply gap poses a major concern. For most of the past decade, the industry has experienced underinvestment due to the trend toward reining in spending, with pressure on short-term returns over long-term expansion. This increased focus on capital discipline means funding for the exploration of new greenfield mines and the expansion of brownfield operations has been limited. Exploration spending, for example, dropped a staggering 42 percent between 2012 and 2022.[29]

In a survey of mining leaders, capital efficiency was highlighted as the central challenge in mining companies' decision-making process, with companies under pressure to meet shareholder expectations of short-term return on equity while also needing to invest in long-term projects to combat resource depletion. The conflict between these priorities—short-term returns vs. long-term resource development—compounds the difficulty of addressing copper supply shortfalls.[30]

Beyond mining, copper smelting costs are at a historic low due to Chinese overcapacity. China now accounts for around half of global copper smelting capacity, up from roughly 15 percent in 2005, and has accounted for more than 90 percent of global smelting capacity growth over that period.[31] The United States, by contrast, operates only two facilities, which likely amount to less than 1 percent of global capacity.[32] This geographic concentration highlights why policymakers are concerned: the challenge here is not an impending shortage in global ability to process copper ore, but getting preferred sources to invest in increased smelting capacity despite long development timelines and low profit margins. Tariffs are one tool governments have reached for, including recent US copper tariffs, but such measures often shift trade flows without addressing the underlying economic challenges constraining new copper mining and processing capacity.[33]

Socio-environmental challenges are among the most significant barriers to increasing copper production and meeting rising demand. These challenges are particularly pronounced in the upstream sector, in which mining operations intersect with local communities and ecosystems. Increased production at brownfield sites, where ore grades are declining, leads to greater extraction of low-grade ore. This results in more waste, which can contaminate nearby water sources and ecosystems, and more than 50 percent of copper production takes place in areas where water is already scarce.[34] Rising demand for water in mining operations exacerbates local water shortages, impacting communities that rely on these resources for drinking and agriculture.[35]

In addition to environmental concerns, copper mining often clashes with the rights of local communities. For example, more than half of Chile's copper reserves lie within indigenous territories, where communities have raised concerns about land disruption, water contamination, and the potential loss of their cultural heritage.[36] These issues frequently spark local opposition, making it harder for companies to obtain social license to operate. In some cases, such as with the Cobre Panamá mine in Panama, social and political disputes—often re-

26. Jorge Cantallopts, "Chilean Copper Mining Costs," Comisión Chilena del Cobre, December 2017, https://rcgi.cochilco.cl/Presentaciones%20Ingls/Chilean%20Copper%20Mining%20Costs.pdf.
27. Martyna Brychcy, Marta Dec, and Tom Thys, "Desalination Is Not the Only Answer to Chile's Water Problems," McKinsey & Company, September 3, 2020, https://www.mckinsey.com/industries/metals-and-mining/our-insights/desalination-is-not-the-only-answer-to-chiles-water-problems.
28. "Global Critical Minerals Outlook 2026," International Energy Agency, July 16, 2026, https://www.iea.org/reports/global-critical-minerals-outlook-2026/outlook.
29. "The Future of Copper."
30. "Capital Is King as Miners Respond to Energy Transition," Ernst & Young, October 1, 2024, https://www.ey.com/en_gl/newsroom/2024/10/capital-is-king-as-miners-respond-to-energy-transition.
31. "Global Critical Minerals Outlook."
32. "Shifting Away from China for Critical Minerals Would Increase Costs and Delay the Energy Transition, Warns Wood Mackenzie," Wood Mackenzie, press release, August 15, 2024, https://www.woodmac.com/press-releases/shifting-away-from-china-for-critical-minerals/.
33. Alexis Harmon and Reed Blakemore, "A Tale of Two Supply Chains: Comparing Trump's New Copper Tariffs and Rare Earth Investments," Atlantic Council, August 5, 2025, https://www.atlanticcouncil.org/blogs/new-atlanticist/a-tale-of-two-supply-chains-comparing-trumps-new-copper-tariffs-and-rare-earth-investments.
34. "The Role of Critical Minerals in Clean Energy Transitions."
35. "Scale of Conflict between Mineral Mines and Indigenous Peoples Revealed," Institute of Development Studies, August 9, 2023, https://www.ids.ac.uk/news/scale-of-conflict-between-mineral-mines-and-indigenous-peoples-revealed/; Brychcy, et al., "Desalination Is Not the Only Answer to Chile's Water Problems."
36. "Scale of Conflict between Mineral Mines and Indigenous Peoples Revealed."

volving around perceived injustice surrounding corrupt practices, labor rights, or environmental degradation—can lead to legal challenges, project delays, and even forced closures. In Chile, 80 percent of total investments submitted to Chile's environmental evaluation authority were contested by civil society between 1998 and 2022.[37]

Recommendations

Target diversification at vulnerable points in the copper value chain. Governments should focus interventions where geographic concentration creates the greatest supply risk rather than pursuing domestic capacity at every stage of the value chain. This means identifying specific vulnerabilities across mining, smelting and refining, fabrication, and recycling, and using fit-for-purpose tools to address them in collaboration with allies and partners. In segments where poor project economics inhibit diversification (particularly smelting and refining), governments may need to share risk with the private sector or look to partners abroad. Strategic reserves can buffer these investments, but cannot substitute for more resilient long-term supply.

Enhance collaboration with governments at all levels. There is a need for closer collaboration between the copper industry and governments at local, regional, and national levels. Governments should play a key role in the identification of projects, in order to promote a controlled and predictable process through which projects receive support. Projects should be launched using a co-development model that includes local communities from the very beginning, ensuring they have a voice in decision-making processes. This collaborative approach both fosters transparency and helps ensure that the long-term benefits of mining are shared with those living closest to extraction sites.

Address governance and legal challenges in high-risk areas. The copper industry faces significant governance and legal challenges in high-risk regions such as the "Copperbelt" in Zambia and the Democratic Republic of the Congo, where world-class ore grades are found. In these jurisdictions, Western mining firms often struggle with a lack of regulatory stability, widespread corruption in contract issuance, and an absence of effective legal recourse. Fostering rule of law and anti-corruption measures will reduce risks and make it easier for both investors and local communities to benefit from mining activities. A clear line of support from Western governments, including tailored contracts for large investments, might serve as a helpful measure in certain circumstances and promote transparency.

Integrate sustainability into pricing. In addition to regulatory frameworks, sustainability-linked financing and pricing need to be utilized to ensure copper production that prioritizes environmental stewardship and standards for community engagement can remain economically competitive. Governments could introduce tax incentives or carbon credits for companies that achieve sustainability best practices, ensuring that companies are financially rewarded for pursuing higher standards of sustainability. At the same time, governments and financial institutions should integrate sustainability metrics into their investment criteria, steering capital toward projects that can demonstrate clear benefits to local communities and robust environmental stewardship.

Incorporate local supply chains. Copper projects should ensure linkages with local supply chains. One of the best ways to obtain the buy-in of local communities is to ensure that the project will enable sustainable economic development by fostering value-added commercial activities linked to mining operations. This can include everything from local procurement programs to enhancing infrastructure to providing training programs that empower local workers.

37. Anabel Marín, "Bringing Democracy to Governance of Mining for a Just Energy Transition," Institute of Development Studies, August 8, 2023, https://www.ids.ac.uk/publications/bringing-democracy-to-governance-of-mining-for-a-just-energy-transition/.



Vehicles sit in a storage yard at an industrial port in Yokohama, near Tokyo, Japan. July 23, 2025. REUTERS/Kim Kyung-Hoon

V. Case study material 2: Plastics & composite materials

Plastics and carbon polymer-based composite materials (henceforth "composites") are deeply integrated into virtually every sector of the global economy due to their remarkable versatility, durability, and cost-effectiveness. While commonly associated with textiles and packaging, plastics and composites are also ubiquitous in medicine, the automotive industry, renewable energy technologies, modern electronic equipment, aerospace technologies, and modern construction materials.

Few materials have shaped the twenty-first century as profoundly as plastics. Yet their very abundance has brought mounting costs: growing ocean pollution, toxic emissions from open burning in developing countries, and even the presence of microplastics in human bodies. The environmental imperative to curb plastic use and pollution has therefore focused largely on disposable applications, commonly referred to as single-use plastics or disposables.

But the story of plastics does not end with disposables. Long-lasting, durable plastics and composites ranging from polymers to lubricants form critical links in industrial value chains. These materials are frequently key precursors for advanced energy technologies and might, in fact, be key to propelling the energy transition by enabling material substitution and improving performance. From wind turbine blades and lightweight vehicle parts to insulation, coatings, and electronic components, plastics and composites help reduce weight, improve efficiency, and extend durability.

This creates an apparent paradox: plastics and composites reduce reliance on heavier, emissions-intensive inputs such as steel or aluminum and can help increase fuel efficiency of energy systems and transportation—yet they remain fundamentally dependent on oil and gas for their production and do little to ease the overall material demands of modern economies. In practice, they substitute one form of carbon intensity for another, embedding hydrocarbons not only as fuels for manufacturing plastics but as structural inputs into the very technology and infrastructure value chains meant to displace them.

KEY TERMS

Term	Definition
Plastics	A class of synthetic or semi-synthetic materials composed of polymers (includes both disposable and durable uses).
Polymers	Large molecules made of repeating chemical units.
Composites	Materials that combine polymers (typically carbon-based) with reinforcing fibers (e.g., carbon, glass) or fillers to enhance strength and durability.
Advanced materials	Engineered materials designed to outperform conventional materials in strength, weight, or sustainability (e.g., high-performance polymers, composites, and nanomaterials).

How demand is changing

Plastics demand is rapidly growing and deeply intertwined with rising incomes and industrial expansion worldwide. To meet demand, plastic production is expected to double by 2040.[38]

In 1980, Organisation for Economic Co-operation and Development (OECD) countries accounted for 87 percent of plastics use, reflecting the complexity of their economies and the high consumption of plastics in consumer goods, manufacturing, agriculture, medicine, and other sectors. This pattern is expected to nearly invert by 2060 as consumers' increased spending power in countries such as India and China drives non-OECD countries' share of global plastics use to 64 percent—though per capita plastics use will remain higher in OECD countries.[39]

Population growth alone is not the driver of rising plastics demand. Economic growth has the strongest correlation. As consumption rises, so does plastics use, in large part due to construction booms and increased vehicle purchases. Thus, as income levels continue to rise around the world, plastics demand will likely rise in lockstep. Within developed economies, the makeup of plastics use can vary and can be altered by demographic shifts (aging populations use fewer plastics) or the underlying structure of the economy (economies with higher shares of agricultural or manufacturing activity tend to use more plastics).[40] The bottom line is that changes in plastics demand are tangled with complex socioeconomic dynamics but plastics and polymer use is increasing, for one reason or another, almost everywhere in the world and higher use is difficult to parse from general growth.

Carbon-based polymers and composites represent some of the fastest-growing segments of the plastics industry and are expected to see substantial long-term growth. It is therefore critical to distinguish between the well-known challenges of single-use plastics and the durable plastics and composites that underpin advanced industrial activity and energy transition goals.

Advances in materials science have facilitated the proliferation of durable polymer-based materials that provide enhanced structural strength while offering lighter, more flexible alternatives to metals. These materials are key to the energy transition as they enable everything from making lighter vehicles with greater fuel efficiency or battery range to enabling more productive wind turbine blades. These advanced materials' unique properties, such as inflammability or temperature regulation, make them indispensable in applications ranging from transmission cabling (polyvinyl chloride to provide electrical wires) to solar panel architectures (polyethylene film to protect solar cells from environmental damage) to wind turbine towers, nacelles, and blades (epoxy resins and carbon fiber to provide a lightweight structural material)—all cases in which lowering carbon footprints actually depends on greater polymer throughput.

Through this incredible variety of applications, plastics and composites have become vital and often irreplaceable components of critical technologies, including the renewable energy technologies necessary to achieve a decarbonized world. According to the National Renewable Energy Laboratory, wind turbine architectures are often composed of between 11 and 16 percent fiberglass, resin, or plastic by mass, with carbon fiber-reinforced plastic commonly used in blades for its high strength-to-weight ratio.[41] Even more strikingly, plastics generally comprise more than 50 percent of a car's volume but only about 10 percent of its weight.[42] In fact, many electric vehicles (EVs) contain more plastic than any other material, as manufacturers use it to offset the added weight of batteries—consider

38. "Rethinking the Future of Plastics," International Organization for Standardization, March 31, 2022, https://www.iso.org/news/ref2792-1.html.
39. "Global Plastics Outlook: Policy Scenarios to 2060," Organisation for Economic Co-operation and Development, June 21, 2022, https://www.oecd.org/en/publications/global-plastics-outlook_aa1edf33-en/full-report.html#section-d1e4183.
40. "Global Plastics Outlook: Policy Scenarios to 2060," Organisation for Economic Co-operation and Development, June 2022, https://www.oecd.org/content/dam/oecd/en/publications/reports/2022/06/global-plastics-outlook_f065ef59/aa1edf33-en.pdf.
41. Donna Heimiller, et al., "2015 Cost of Wind Energy Review," National Renewable Energy Laboratory, May 2017, https://docs.nrel.gov/docs/fy17osti/66861.pdf.
42. "Chemistry and Automobiles: Driving the Future," American Chemistry Council, May 23, 2024, https://www.americanchemistry.com/better-policy-regulation/transportation-infrastructure/automotive-circularity/resources/chemistry-and-automobiles-2024.

the plastic battery casing, the wiring insulation, the dashboard, the bumper, and even the "vegan leather" interiors in a Tesla.

Composites also enable greater material and fuel efficiency in many aerospace and industrial applications. Aircraft fuselages, which comprise a significant portion of an airframe's weight and directly affect fuel efficiency, have benefited significantly from carbon fiber-reinforced polymer composites. The Boeing 787's composite fuselage made it the first major commercial airliner to rely predominantly on composites, resulting in a 20-percent increase in fuel efficiency compared to similar aircraft.[43] This is an incredible breakthrough in an industry where market participants often justify major capital expenditures that lead to just a 1-percent increase in fuel efficiency, given the compounding fuel savings over thousands of flights.[44]

Petrochemicals' overall demand growth is meant to slowly decrease over the next decade. But due to increasing demand for high-performance lightweight materials, certain industries, such as carbon fiber, are projected to steadily grow at about 6 percent a year through 2030.[45] As plastic demand continues to grow overall, especially for single-use plastics, so will plastic's share of demand for hydrocarbons. Because plastics and composites are produced from various petrochemical products that are primarily sourced from crude oil or natural gas, increased plastic consumption is expected to drive massive demand for petrochemical feedstocks such as naphtha and natural gas liquids. In fact, the IEA forecasts that the petrochemicals sector will be the largest overall driver of global oil demand growth; the sector will contribute to roughly one-third of overall growth through 2030 and nearly half by 2050 as oil demand from other sectors scales down, according to the IEA's Reference Technology Scenario.[46] This equates to 18.4 million barrels of oil used in petrochemical production per day in 2030, or more than one in six barrels.[47] Even so, advancements in recycling technologies and systems are expected to help moderate this trajectory by reducing the need for virgin plastic production and, by extension, petrochemical feedstocks.[48]

Supply challenges

The plastics industry was hit badly by the supply chain disruptions during the COVID-19 pandemic. Hurricane Ida closing many refineries on the Gulf Coast a year later only exacerbated the challenge, leading to some plastic resins tripling in price.[49] Those disruptions initially eased, but the 2026 war in Iran has demonstrated that abundant global production capacity does not eliminate supply chain vulnerability. Disruption to shipping through the Strait of Hormuz sharply constrained flows of petrochemical feedstocks and products from the Gulf, tightening supplies and pushing prices higher. The lesson here was similar to many other markets affected by the conflict: aggregate production capacity can be ample while geographic concentration, feedstock availability, and transportation chokepoints still create acute shortages. Over the longer term, the structural challenge remains overcapacity, as China's increasing petrochemical capacity continues to point to the possibility of oversupply.[50]

43. "Boeing 787 Dreamliner," International Aerospace Knowledge Centre, last visited October 24, 2025, https://www.sciencedirect.com/topics/engineering/boeing-787-dreamliner#:~:text=Each%20Boeing%20787%20aircraft%20contains,tail%2C%20doors%2C%20and%20interior; George Marsh, "Boeing's 787: Trials, Tribulations, and Restoring the Dream," *Renewable Energy Focus*, 2014, http://csmres.co.uk/cs.public.upd/article-downloads/boeing-final.pdf.
44. Ibid.
45. "Global Carbon Fiber Market Set to Reach $5 Billion by 2030, Driven by Demand for High-Performance Lightweight Materials—ResearchAndMarkets.com," *Business Wire*, April 24, 2024, https://www.businesswire.com/news/home/20240424645270/en/Global-Carbon-Fiber-Market-Set-to-Reach-5-Billion-by-2030-Driven-by-Demand-for-High-Performance-Lightweight-Materials---ResearchAndMarkets.com.
46. "The Future of Petrochemicals," International Energy Agency, October 4, 2018, https://www.iea.org/reports/the-future-of-petrochemicals.
47. "Oil 2025: Analysis and Forecast to 2030," International Energy Agency, June 17, 2025, https://www.iea.org/reports/oil-2025.
48. "World Energy Outlook 2022," International Energy Agency, October 27, 2022, https://www.iea.org/reports/world-energy-outlook-2022.
49. Karen Hanna, "Resin Shortages Put Strain on Processors," *Plastics Machinery & Manufacturing*, March 24, 2021, https://www.plasticsmachinerymanufacturing.com/injection-molding/article/21215638/resin-shortages-put-strain-on-processors.
50. "Sinopecs Half-year Profit Grew 19.3% on Year Despite Iran War, Falling Demand," Reuters, August 23, 2026, https://www.reuters.com/business/energy/sinopecs-half-year-profit-grew-193-year-despite-iran-war-falling-demand-2026-08-23.

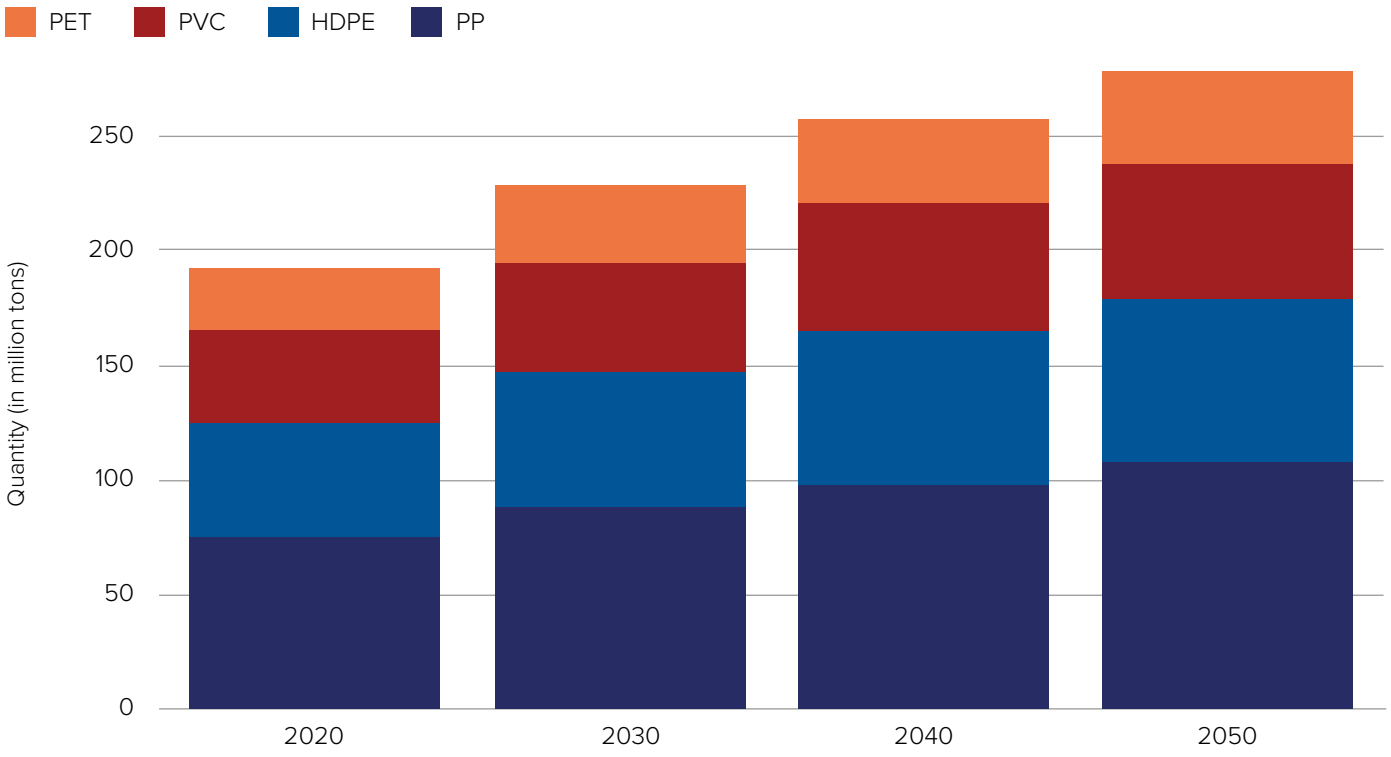
However, the supply of some specialized polymer-based composites such as carbon fiber faces constraints as demand surges across sectors. Carbon fiber production is energy intensive and concentrated in a few countries, with Japan, the United States, and China the largest producers. The reliance on limited suppliers and the high costs of production have led to price volatility. Furthermore, carbon fiber demand has surged faster than supply, pushing up prices.

As composite demand grows alongside the energy transition buildout, supply geographies are also shifting. China's major expansion of petrochemical production capacity has increasingly outpaced domestic demand growth, contributing to persistent global overcapacity and weak margins. Meanwhile, large oil and gas companies are increasingly transitioning into petrochemicals, intensifying competition and reshaping trade flows across an already oversupplied market. While traditional composite production has been concentrated in North America, Europe, and East Asia, emerging economies are beginning to play a more significant role in both the supply and demand for composites as some seize the opportunity to diversify their economies and build infrastructure.

However, the key challenge facing the plastics and composites supply chain is reducing production processes' emissions intensity and improving material efficiency in part by increasing circularity. This strengthens value chains, lowers production costs, and increases social license. It might also be the hallmark by which plastic-producing firms and nations will be able to distinguish themselves and remain competitive in a world where lifecycle emissions and production standards are increasingly an economic competitive advantage.

Even so, efforts to improve the sustainability of plastics and composite production confront an inherent contradiction, given that plastics are, by definition, polymer materials made of hydrocarbon chains tied to perpetuating oil and natural gas. Thus, the objective is not decarbonization in the sense of removing carbon from materials or technology value chains, but rather optimizing the carbon cycle: sourcing carbon efficiently, embedding it in durable products that provide decades of service, and recovering it at end of life for reuse. Given composites' critical role in the physical buildout of the energy transition and staying power in the global economy, improvements to sustainability remain critical. Plastics therefore sit at the heart of the paradox: indispensable to sustainability targets yet produced and consumed at massive scale through processes that remain heavily dependent on hydrocarbons.

Figure 3: Projected production of thermoplastics key to energy technologies (2020–2050).



Source: "Production of Key Thermoplastics, 1980-2050," International Energy Agency, updated September 25, 2018, https://www.iea.org/data-and-statistics/charts/production-of-key-thermoplastics-1980-2050.

Recommendations

Elevate plastics and composites as a strategic industrial input. Most policies frame plastics through the lens of recycling and waste reduction, but they are also a foundational industrial input for energy, mobility, and advanced manufacturing. As demand for EVs, grid infrastructure, and renewable energy technologies accelerates, plastics will become as central to industrial strategy as steel and copper. Governments should recognize plastics not exclusively as an environmental liability, but as a material system that underpins competitiveness, energy transition deployment, and economic resilience. This means incorporating plastics into industrial strategies and supply chain assessments alongside other core materials—all without shying away from attempts to reduce emissions intensity and improving sustainability wherever possible.

Invest in economic diversification to facilitate the transition from combustibles to composites. When oil rents are high, oil-producing countries should reinvest profits into research and development (R&D) and future-oriented infrastructure. Meeting rising demand for composite materials requires significant investment in new manufacturing facilities and technologies to scale production. The adoption of state-of-the-art manufacturing techniques, such as automated fiber placement and resin infusion systems, will be key to scaling production for sectors such as wind energy, electric vehicles, and aerospace. However, scaling up these technologies requires substantial investment and a supportive industrial policy framework to get the industry off the ground.

Link circularity with supply security. Circularity must be treated as a supply strategy, not a siloed environmental goal. Recycling and reuse provide a critical secondary source of plastics and composites, lowering pressure on petrochemical feedstocks while mitigating environmental impacts. While recycling alone will not meet surging demand, end-of-life solutions can extend lifecycles and strengthen supply resilience. Governments and industry should prioritize product designs that more intentionally enable recycling throughout plastics and composites value chains, better integrate recycling infrastructure, and form upstream partnerships to cut sorting costs.

PLASTICS, ADVANCED MATERIALS, AND SUSTAINABILITY

As global demand for advanced materials grows, reducing emissions in production is becoming a cornerstone of climate-aligned industrial policy. The challenge now is determining not only whether this can be achieved, but how quickly industry and governments can work together to bring these solutions to scale.

Three main strategies are emerging to reduce emissions in plastics and composites production.

1. Carbon capture, utilization, and storage (CCUS)

Plastic precursors, such as the polymers ethylene and propylene, are produced using high-temperature, emissions-intensive processes across refineries and petrochemical facilities. CCUS can be integrated into these processes, particularly at high-emission points such as steam methane reformers and fuel-fired heaters. In some cases, captured carbon dioxide (CO_2) can even be reused to create polymers such as polyurethanes or polypropylene carbonate, potentially turning a liability into a resource.

2. Electrification of process heat

Many key production steps in the composite manufacturing process rely on extreme heat. While not all operations can be electrified affordably, several key processes—including steam cracking, electric boilers for heat and steam generation, and electric drive turbines used in distillation and compression systems—show high potential for cost-effective emissions reduction and broader industrial decarbonization, especially when paired with abundant low-emissions electricity. Broad adoption of electric boilers, heat pumps, or electric cracking technologies will require continued investment in both technology development and power infrastructure.

3. Alternative feedstocks

Replacing hydrocarbon-based feedstocks with bio-based or synthetic alternatives offers another pathway. Ethanol from crops such as corn or sugarcane can be converted into plastic precursors, though bio-based feedstocks are not inherently more sustainable. Their lifecycle impact depends heavily on how and where they are produced; land-use change, fertilizer intensity, and irrigation needs can offset or even reverse potential emissions gains. Longer-term potential lies in synthetic hydrocarbons created from captured CO_2 and low-emissions hydrogen, though costs remain high. Continued innovation and scale will be critical for these options to compete.

Strategically integrate across value chains. As the plastics industry has matured, most producers have become less vertically integrated. However, forging strategic partnerships and increasing integration across value chains can add substantial value and a competitive advantage, especially when creating a closed-loop production system in which materials are reused and recycled.

Secure and support a sustainable feedstock supply. While plastics and composites are not combusted like fuels, their production still relies on emissions-intensive petrochemical feedstocks. Improving the sustainability of these supply chains through emissions reduction, carbon capture, and more efficient production offers a practical pathway to lower their climate impact while maintaining industrial competitiveness. Transitioning to alternative feedstocks—such as bio-based materials or carbon captured and synthesized into hydrocarbons—offers potential for long-term emissions reduction and greater supply chain resilience, though benefits similarly depend on sourcing, land use, and process efficiency. Near-term competitiveness of these alternatives is uncertain. However, as demand for eco-friendly single-use plastics grows and high-quality recycled inputs remain in short supply, interest in sustainable feedstocks is likely to rise, spurring innovation and helping drive down costs over time. Policy mechanisms focused on foreign pollution in trade could further strengthen the business case by penalizing emissions-intensive imports, creating incentives for producers to adopt lower-emission refining strategies to maintain global market access.

THE STRAIT OF HORMUZ: WHEN ENERGY DISRUPTIONS BECOME MATERIAL DISRUPTIONS

The 2026 war in Iran has provided a real-time stress test of the links between energy security and industrial material security. The Strait of Hormuz is normally discussed primarily as an oil and gas chokepoint, but the Gulf is also a major production and export hub for petrochemicals and their feedstocks. Disruption to shipping through the strait therefore reverberated well beyond fuel markets, constraining flows of polyethylene, polypropylene, and other petrochemical products and contributing to sharp increases in plastics prices.[1]

The disruption illustrates three broader lessons for industrial materials policy. First, aggregate global capacity is an incomplete measure of resilience. A market can be structurally oversupplied yet vulnerable when production or transportation is geographically concentrated. Second, feedstock security matters alongside manufacturing capacity. Petrochemical producers reliant on naphtha were exposed not only to physical supply disruptions but also to higher crude prices, while producers with access to relatively insulated gas-based feedstocks gained a competitive advantage. Third, inventories and strategic reserves can reshape how shocks propagate through downstream markets. For example, China's ample domestic petrochemical supply, excess production capacity, diversified feedstocks, and substantial crude reserves allowed its producers to maintain production and, in some cases, expand exports as competing producers faced feedstock shortages.[2]

1. Pooja Menon and Pranav Mathur, "Iran War Chokes Petrochemical Supply, Sends Plastic Prices Soaring," Reuters, March 26, 2026, https://www.reuters.com/business/energy/iran-war-chokes-petrochemical-supply-sends-plastic-prices-soaring-2026-03-26.
2. Clyde Russel, "China Kept Building Its Crude Stockpile in April Despite Iran Crisis," Reuters, May 21, 2026, https://www.reuters.com/commentary/reuters-open-interest/china-kept-building-its-crude-stockpile-april-despite-iran-crisis-2026-05-21; Yvonne Shi, "CHINAPLAS '26: Insight: China Petrochemical Industry Destocks Amid Unabated Capacity Expansion," Independent Commodity Intelligence Services, April 24, 2026, https://www.icis.com/explore/resources/news/2026/04/24/11201318/chinaplas-26-insight-china-petrochemical-industry-destocks-amid-unabated-capacity-expansion.



A steel worker stands amid sparks of raw iron coming from a blast furnace at a steel factory in Duisburg, Germany, November 5, 2025. REUTERS/Leon Kuegeler

VI. Case study material 3: Steel

Steel, the most commonly used metal in the world, is both literally and figuratively the backbone of the modern economy. It enables the construction of homes, workplaces, and the infrastructure that supports everything from transportation systems to the energy networks that power them. Few materials so directly capture the material intensity of modern life: the world cannot build, electrify, or urbanize without vast amounts of steel.

Steel's close association with industrial productivity and its symbolic link to economic growth have made it unusually politicized compared to other commodities. In the United States, it is bound up with narratives of industrial power and middle-class prosperity, while in many emerging economies it is treated as a foundational sector for early-stage economic development. As a result, governments frequently deploy tariffs, subsidies, and industrial policies to protect and expand domestic steel production, seeing it as both a national security asset and a lever for economic growth.

Steel's scale is staggering. In 2023, global crude steel production totaled 1.9 gigatonnes, and revenues are often estimated at around $900 billion, making it one of the largest industries in the world by both production volume and revenue.[51] Predictions for steel demand over the next few decades are highly varied and stratified by region, but many claim that global steel demand will increase by more than one-third by 2050.[52]

Exact future demand might not be clear, but what is increasingly apparent is that the world's future energy system will have a complex and multifaceted relationship with steel. On one hand, steel remains as indispensable as ever in building the modern world and will be in particularly high demand as new energy infrastructure is built. On the other hand, steel production is the most carbon intensive of all heavy industry,

51. "World Steel in Figures 2023," World Steel Association, June 7, 2023, https://worldsteel.org/data/world-steel-in-figures/world-steel-in-figures-2023/; Catherine Ngai and Joe Deaux, "Algos Keep Losing to Human Traders in $900 Billion Steel Market," Bloomberg, August 14, 2019, https://www.bloomberg.com/news/articles/2019-08-14/algos-keep-losing-to-human-traders-in-900-billion-steel-market.

52. "Iron and Steel Technology Roadmap: Towards More Sustainable Steelmaking," International Energy Agency, October 8 2020, https://www.iea.org/reports/iron-and-steel-technology-roadmap.

accounting for 7–9 percent of global emissions.[53] The result is a collision between the material intensity of decarbonization and the emissions intensity of steelmaking.

This tension is already reshaping markets. "Green steel"—steel produced with low-carbon processes such as hydrogen-based direct reduction or scrap recycling in electric arc furnaces—has emerged as a new axis of industrial competition. Traditional trade protections are increasingly intersecting with newer policy instruments, such as carbon tariffs and green procurement. The EU's Carbon Border Adjustment Mechanism entered its definitive enforcement phase in January 2026, directly exposing imported steel to carbon-related compliance and cost considerations. Meanwhile, differences in energy costs, ore quality, and demand forecasts are fragmenting the geography of production. The steel sector thus illustrates a core theme of this report: material intensity in the energy transition will require coordinated industrial policy to manage supply security, emissions, and trade dynamics simultaneously.

How demand is changing

Steel demand has been notoriously difficult to predict against the backdrop of global economic cycles, urbanization, industrial development, shifting geoeconomic dynamics, and now energy transition goals. While global steel demand is expected to remain positive in the near term, its trajectory is highly stratified by region and sector.

In Western Europe and North America, steel demand is expected to decrease gradually over the next decade. This is due primarily to slower than anticipated construction growth and shifts toward more resource-efficient technologies in sectors such as automotives and manufacturing. However, the scale of construction needed to enable the energy transition might reverse or abate this trend.[54] By 2050, steel demand from solar, wind, and energy storage could exceed the steel demand from the coal, oil, and natural gas sectors at their 2010 levels.

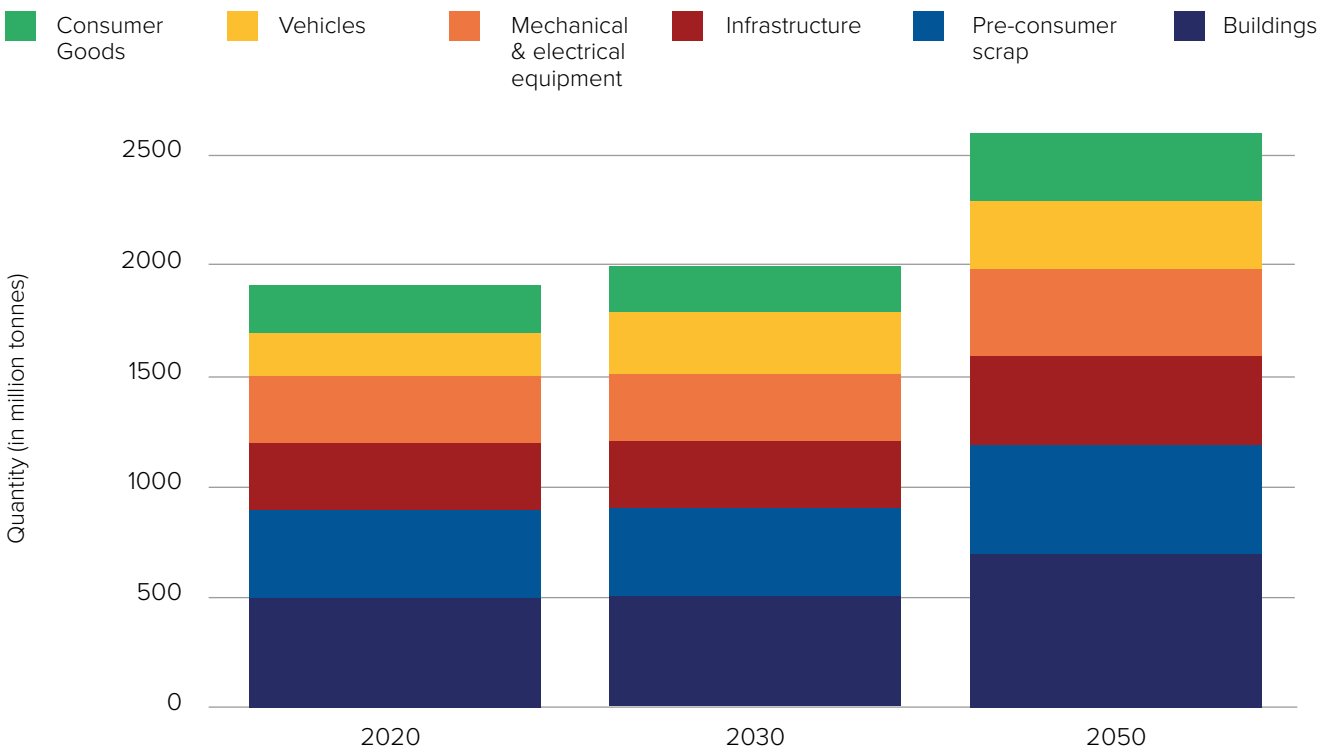
China, the world's largest producer and consumer of steel, has seen demand slow since 2020, driven by a struggling property sector and underwhelming infrastructure development that indicate generally slower economic growth. China accounts for almost half of global steel consumption, so these dynamics are among the most influential factors in global demand. Regardless, steel demand in China is expected to remain high relative to other regions, albeit at a slower growth rate than in the country's 2010s steel frenzy.[55]

Emerging economies are the primary drivers of near- and medium-term steel demand. India has been the largest driver of steel demand since 2021, a trend likely to continue as its rapid economic growth, urbanization, and construction boom continue to create significant steel requirements.[56] While the 2026 war in Iran has interrupted previously strong growth expectations for the Middle East, Southeast Asia and Africa remain important sources of longer-term demand growth.

The wild card in demand is energy transition-driven policy and corresponding public infrastructure investments. Today, most steel is produced using the coal-intensive blast furnace-basic oxygen furnace (BF-BOF) process, which generates extraordinarily high emissions.[57] Emerging technologies—hydrogen-based direct reduction (H2-DRI), molten oxide electrolysis (MOE), CCUS, and expanded electric arc furnace (EAF) scrap recycling—offer pathways to lower emissions. However, these technologies face hurdles: high capital costs, energy requirements, technological maturity, and the need for significant infrastructure investments. Despite billions of dollars of investment into green steel and hopes for commercialization, less than 1 percent of steel is currently produced this way.[58] Global demand for low-emissions steel is expected to grow dramatically, increasing tenfold to comprise 10 percent of total demand by 2030 and 25 percent of demand by 2040—though only time will tell if these expectations come true.[59]

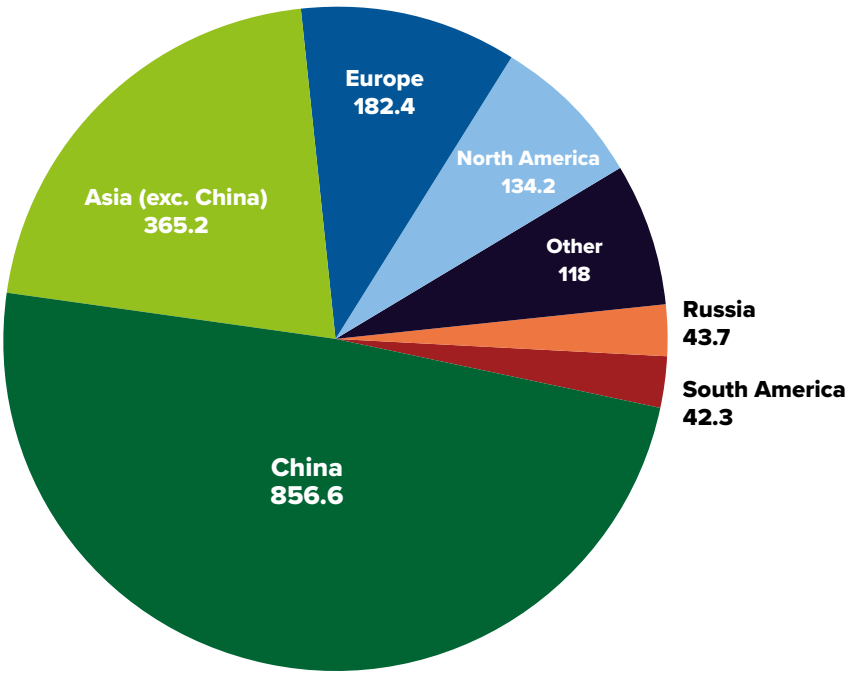
53. "Steel and Aluminum: Net Zero Emissions Guide," International Energy Agency, September 26, 2023, https://www.iea.org/reports/steel-and-aluminium.
54. "Short Range Outlook October 2024," World Steel Association, press release, October 14, 2024, https://worldsteel.org/media/press-releases/2024/worldsteel-short-range-outlook-october-2024.
55. Serene Cheong, "China's Steel Demand Has Shrunk to Less than Half Global Total," Bloomberg, October 21, 2024, https://www.mining.com/web/chinas-steel-demand-has-shrunk-to-less-than-half-global-total/; "Short Range Outlook October 2024."
56. Kunwar Vijayant Singh, et al., "Evolving with Steel: Future Growth and Opportunities," McKinsey & Company, September 4, 2024,https://www.mckinsey.com/in/our-insights/evolving-with-steel-future-growth-and-opportunities; "Short Range Outlook October 2024."
57. "Basic Oxygen Furnace," Science Direct Topics, last visited October 24, 2025, https://www.sciencedirect.com/topics/engineering/basic-oxygen-furnace.
58. "Net-Zero Industry Tracker 2023: Steel Industry Net-Zero Tracker," World Economic Forum and Accenture, November 2023, https://www.weforum.org/publications/net-zero-industry-tracker-2023/in-full/steel-industry-net-zero-tracker/.
59. Oleksandr Kravchenko, et al., "The Resilience of Steel: Navigating the Crossroads," McKinsey & Company, April 18, 2023,https://www.mckinsey.com/industries/metals-and-mining/our-insights/the-resilience-of-steel-navigating-the-crossroads.

Figure 4: Projected steel demand by sector (2020–2050).



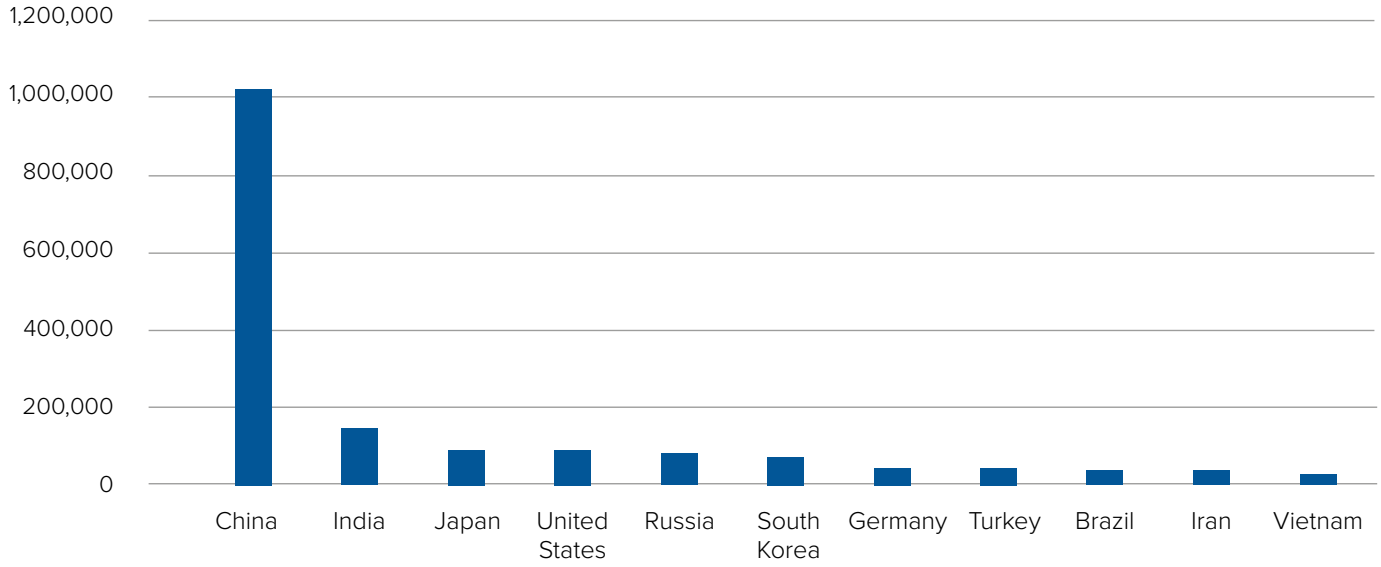
Source: "Global End-use Steel Demand and In-use Steel Stock by Scenario, 2000-2050," International Energy Agency, Stated Policies Scenario data used for 2030 and 2050, last updated October 5, 2020, https://www.iea.org/data-and-statistics/charts/global-end-use-steel-demand-and-in-use-steel-stock-by-scenario-2000-2050.

Figure 5: Finished steel consumption by region in 2024 (million tonnes).



Source: "Apparent Steel Use 2020 to 2024, Million Tonnes, Finished Steel Products," *World Steel in Figures 2025*, World Steel Association, last visited December 21, 2025, https://worldsteel.org/data/world-steel-in-figures/world-steel-in-figures-2025/.

Figure 6: Crude steel production by country in 2024 (1,000 tonnes).



Source: "Major Steel-Producing Countries, 2023 and 2024," *World Steel in Figures 2025*, World Steel Association, last visited December 21, 2025, https://worldsteel.org/data/world-steel-in-figures/world-steel-in-figures-2025.

Supply challenges

The global steel industry is currently contending with a significant oversupply of steel. Since 2000, global crude steel production has doubled, with 85 percent of growth in China, where capacity expansion has outpaced global demand growth.[60] This surplus of steel exacerbates market volatility and poses challenges for producers attempting to justify the cost of transitioning to low-carbon production methods. With excess supply and limited price differentiation for green steel, producers face difficulties in securing market share for lower-emission products.

Moreover, the rapid increase in steel supply has been accompanied by a proliferation of production infrastructure such as blast furnaces, which typically have a lifespan of fifty years. With the global blast furnace fleet averaging just thirteen years of age, transitioning to lower-emissions production technologies means creating a substantial number of stranded assets.[61]

Demand for green steel, meanwhile, is expected to outpace supply. Retrofitting existing steel production facilities with low-emission technologies is generally considered too difficult or costly. As a result, enthusiasm for green steel as a market advantage will be largely dependent on further technological advancements or policies such as carbon pricing or green procurement commitments. The quid pro quo of these policies, however, might only further pronounce the geographic stratification of steel production, as the greatest uptake for green steel will be in markets that are willing to adopt a premium for that steel due to security, competitiveness, or emission reduction priorities.

As markets become more dominated by green steel, supply chains will evolve in ways that differ fundamentally from the traditional blast furnace-basic oxygen furnace model. Three dynamics stand out.

- **Ore quality constraints and shifting iron markets:** Hydrogen-based direct reduced iron (DRI), one of the leading pathways for green steel, requires high-grade iron ore of at least 67 percent.[62] Based on these technological requirements (which might evolve), the geography of iron ore exports might shift to favor regions that have higher-grade deposits, such as Brazil and Sweden. Australia, today's dominant exporter, relies heavily on medium-grade ore (typically 56–62 percent iron), which is less suitable for

60. "Iron and Steel Technology Roadmap."

61. Ibid.

62. Simon Nicholas and Soroush Basirat, "More High Grade Iron Ore Needed to Accelerate Steel Decarbonisation," Institute for Energy Economics and Financial Analysis, June 28, 2022, https://ieefa.org/articles/more-high-grade-iron-ore-needed-accelerate-steel-decarbonisation.

hydrogen-based DRI.[63] Australian producers might be able to protect their market share given their investments in beneficiation technologies to upgrade ore quality and in new reduction methods that can process lower grades. However, these approaches come with higher costs, and competitive advantages could reshape markets faster than Australia can catch up.[64]

- **Energy-driven competitiveness:** Regions with abundant, low-cost, and low-emissions electricity will be advantaged in green steel production, whether through direct power for EAFs or as feedstock for green hydrogen. By contrast, regions with limited access to affordable, low-emissions energy might rely more heavily on CCUS. However, CCUS for steel is generating far less investment than DRI and EAF projects—partly due to high costs with mediocre returns, because CCUS's carbon capture rate generally only hits about 19–26 percent.[65]
- **Emergence of green steel corridors:** These shifting fundamentals could also encourage a new geography of production. Despite the global fragmentation of most production processes in recent decades, steelmaking has remained concentrated in vertically integrated facilities that craft both iron and steel. With ore and energy demands evolving, green steel production might be unbundled across borders into green iron corridors where high-grade ore is shipped to regions with cheap, low-emissions energy, then exported as green iron or semi-finished steel.[66] While transport adds cost, the savings from ore quality and energy input optimization could yield competitive pig iron prices that are comparable to traditional prices at less than $400 per ton.

In a process already substantially more expensive than traditional steelmaking, efficiencies must be capitalized on whenever possible. Together, these shifts suggest that future steel supply will be defined as much by ore quality and electricity costs as by traditional cost and scale advantages, with new trade patterns emerging to connect them.

Recommendations

Steel production is simultaneously a material security issue, a trade and competitiveness issue, and a climate challenge. Because it is so foundational to the world economy, policy interventions must carefully navigate today's political and economic realities without ever losing sight of transition imperatives.

Manage oversupply and market distortions. Global steel markets are plagued by chronic overcapacity, which depresses prices and undermines investment in lower-carbon capacity elsewhere. A stronger response requires both defensive and proactive measures. On the defensive side, governments must coordinate with allies to enforce trade remedies against dumping, improve monitoring of embedded carbon and subsidies in imported steel, and ensure that border adjustments focused on emissions and carbon close loopholes rather than simply shifting trade flows. On the proactive side, advanced economies could pursue plurilateral agreements or green steel clubs that both align standards for emissions intensity and provide preferential market access for compliant producers. This would create protected demand signals that allow allied firms to invest in upgrading capacity without being undercut by artificially cheap imports.

Elevate green steel as a competitiveness strategy, not just a climate goal. It is neither realistic nor productive to frame the future of steel as a binary choice between blast furnaces and lower-emissions production methods. Many regions will continue to rely on coal-based steelmaking for decades. However, demand for low-carbon steel from automakers, construction firms, and public procurement programs is rising and will continue to expand as buyers and broader carbon adjustments converge on emissions intensity. Governments that prepare today will be better positioned as markets shift and can broaden the coalition of support beyond climate advocates. Ultimately, approaching green steel as an industrial advantage will protect exporters from carbon-based trade barriers, capture premium markets, and reduce long-term stranded asset risks for blast furnace capacity. Two key policy interventions are critical here. First, there is an urgent need to lower the production cost of hydrogen, CCUS technologies, and other key technological enablers of green steel production. This can be done through investments in R&D, tax credits, or preferential

63. Daisy Summerfield, "Australian Resource Reviews: Iron Ore 2019," Geoscience Australia, 2020, https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/iron-ore.
64. Simon Nicholas, "In 2025, Australia Needs to Accept that Its Iron Ore and Coal Markets Are Changing Permanently . . . and Gas Is Not a Solution," Institute for Energy Economics and Financial Analysis, January 22, 2025, https://ieefa.org/resources/2025-australia-needs-accept-its-iron-ore-and-coal-markets-are-changing-permanently-and; Taylor Kuykendall, "FRETS over High-Grade Iron Ore Ease as Tech Mines Open New Paths to Green Steel," S&P Global, February 2024, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/frets-over-high-grade-iron-ore-ease-as-tech-mines-open-new-paths-to-green-steel-80602431.
65. Simon Nicholas and Soroush Basirat, "CCUS Will Not Play a Major Role in Steel Decarbonisation," Institute for Energy Economics and Financial Analysis, April 17, 2024, https://ieefa.org/articles/ccus-will-not-play-major-role-steel-decarbonisation.
66. Rachel Wilmoth, et al., "Green Iron Corridors: A New Way to Transform the Steel Business," Rocky Mountain Institute, April 23, 2024, https://rmi.org/green-iron-corridors-a-new-way-to-transform-the-steel-business.

access to government contracts. Second, carbon accounting needs to be standardized to create clearer market signals. Coordinated frameworks for emissions reporting at the product and facility level, such as the e-liability framework, can reduce distortions, improve transparency, and help make lower-emissions steel competitive.

Leverage circularity as a core supply-side tool to ease material intensity. Steel's material intensity cannot be reduced through substitution, only through better reuse. Economies could integrate circular economy principles into industry regulations by expanding scrap recovery, mandating minimum recycled content in new products, and requiring designs that allow easier disassembly and recycling. They could also promote collaboration across the value chain to encourage direct coordination between producers, recyclers, and manufacturers on recycling. An impactful example is the partnership between steel producer SSAB and recycling company Stena Metall. The two Swedish companies brokered a strategic cooperation agreement ensuring SSAB's EAFs receive regular deliveries of Stena Metall's high-quality scrap steel. This domestic collaboration strengthens Sweden's supply chain for scrap steel, advances its decarbonization goals, and also ensures economic benefits stay within the country.

VII. Overarching considerations for policymakers to manage the material intensity of a new energy economy

As the above case studies show, a growing global economy, surging electricity demand, and rising infrastructure needs in the developing world all point toward dramatically increasing consumption of foundational materials. Copper, durable plastics and composites, and steel remain the backbone of industrial economies, and their role in the energy system of the future only amplifies their importance.

Yet conversations about material value chain management have centered predominantly on critical minerals. While important, these debates must expand to encompass the evolving dynamics of fundamental commodities. Managing these materials effectively is not a side story. These materials are central to achieving a resilient, low-emissions economy and warrant equal consideration in industrial policy frameworks.

The immediate challenge is managing intensifying demand while building resilient, secure, sustainable, and economically viable supply chains. This requires policy frameworks that simultaneously build supply capacity, diversify processing infrastructure, navigate complex trade dynamics, incentivize sustainable production, accelerate innovation, and mobilize unprecedented levels of capital—all while maintaining the cost competitiveness that industrial customers require.

To manage these complexities, the following strategic considerations are essential.

Ensuring security of supply

As industrial transformation unfolds, maintaining robust, diverse, and reliable sources of key commodities is fundamental to economic resilience. This is, first and foremost, an exercise in global capacity building and strategic diversification. Industrial materials such as copper, plastics, and steel face different risks than niche critical minerals. They are not constrained by narrow deposit concentrations or specialized extraction technologies, but they nonetheless remain vulnerable to supply concentration, political risk, and market manipulation.

Material intensity amplifies these vulnerabilities: even marginal disruptions in supply can ripple through markets when demand is rising steeply and alternative sources cannot quickly scale. Nearly half of the world's raw copper production originates from Latin America, while China refines and smelts about half of the global copper supply.[67] Plastic production has historically been geographically diverse, but the war in Iran exposed vulnerabilities beneath that apparent diversification, as disruptions to Gulf petrochemical feedstocks and trade through the Strait of Hormuz reverberated across global plastics markets. Steel illustrates how supply chain exposure can also be indirect. While the United States imports minimal Chinese steel, China's oversupply significantly influences global steel markets, distorting prices and affecting competitiveness worldwide. Building resilience in this context is less about national self-sufficiency and more about ensuring sufficient global capacity, addressing midstream bottlenecks, and coordinating among allies to counter market manipulation and avoid overreliance on single suppliers.

Diversification of processing infrastructure. Sustained policy focus on critical minerals has increasingly highlighted the strategic importance of smelting and refining capacity, including for copper, while the war in Iran has exposed parallel vulnerabilities in petrochemical processing and trade through the Strait of Hormuz. Policymakers should build on this momentum by incentivizing processing capacity across a wider range of geographies, while addressing the fundamental economics that have driven consolidation. Offtake agreements, long-term contracts, and other risk-sharing mechanisms can help de-risk these capital intensive projects.

Choke point and transit resilience. Material security frameworks built around production concentration risk missing the transit layer entirely. The disruption of Strait of Hormuz shipping demonstrated how quickly maritime risk can outpace production risk as the binding constraint. Governments and industry should map choke point exposure into the same resilience planning applied to mine and smelter concentration, and build routing and insurance-backstop contingencies accordingly.

Allied coordination frameworks. Partnerships among like-minded nations can help diversify markets while creating the scale and collective leverage needed to support more resilient and sustainable production. This could include joint investment, coordinated offtake, or mutual assistance during supply disruptions. FORGE provides an emerging model for this type of coordination in critical minerals, but similar approaches could be extended to traditional industrial materials where fragmented

67. Gracelin Baskaran and Paula Reynal, "Latin America: The World's Copper Stronghold," Center for Strategic and International Studies, November 2024, https://features.csis.org/copper-in-latin-america/index.html; "Shifting Away from China for Critical Minerals Would Increase Costs and Delay the Energy Transition, Warns Wood Mackenzie."

demand and competition from lower-cost producers can undermine investment in diversified, higher-standard supply.[68]

Strategic stockpiling and buffer mechanisms. Governments should consider establishing or expanding strategic reserves for key industrial materials, particularly copper. Similar to the US government's new Project Vault stockpiling initiative, these reserves could be designed for short-term economic stabilization rather than controlling the market, releasing material during supply shocks and purchasing during periods of oversupply to support market stability.[69] Coordination among allied nations on stockpiling strategies could amplify effectiveness.

Trade policy as a tool for value chain management

Trade policies are increasingly playing a bigger role in the global economy, positioning domestic industries to compete more effectively against foreign goods. They serve both economic and broader geopolitical objectives, and tariffs have become one of the clearest expressions of this shift. While tariff use has been rising for decades, this has accelerated sharply during Trump's second administration. His return to office has brought an assertive use of tariffs as a foreign policy tool, framed around restoring fair trade for the United States and advancing opportunities for a domestic prosperity agenda through planned reshoring of manufacturing.

The United States is not alone. Other major economies have also turned to tariffs to shield producers from perceived unfair competition, particularly from China. The EU, India, and Mexico have all imposed duties on Chinese steel. Indonesia has targeted imported copper wire rods, and South Africa has introduced duties on polymers to stabilize local markets amid oversupply and price swings.

Tariffs and trade barriers can serve legitimate policy objectives: protecting domestic industries from dumping and market distortions created by state subsidies, preserving production capacity that has national security implications, and providing breathing room for industries to modernize and become more efficient. However, long-term effectiveness depends on design and context. Without complementary strategies such as investment promotion, targeted exemptions, or coordinated diplomacy, trade barriers risk creating new vulnerabilities by raising input costs and limiting access to key commodities, rather than improving access to needed short-term capacity.

Strategic tariffs and complementary investment policy. When foreign competitors benefit from state subsidies, lax environmental standards, or unfair labor practices, tariffs can help level the playing field and prevent the erosion of domestic capacity. However, tariffs alone are not a growth strategy. Pairing them with targeted domestic investment—such as tax incentives for modernization, R&D support, or concessional financing—can turn short-term protection into long-term competitiveness. Still, the reality is that few countries can fully meet their material needs domestically, and overly restrictive trade regimes risk inflating input costs, limiting access to key commodities, and undermining broader economic resilience. Trade policy must be flexible and calibrated to avoid excessive costs for downstream industries. The most effective approach combines trade shields with proactive industrial tools, ensuring tariffs buy time for domestic firms to innovate rather than locking them into permanent protection.

Sectoral agreements as alternative architectures. FORGE and the Global Arrangement on Sustainable Steel and Aluminum represent potentially valuable models, creating clubs of nations committed to high standards while addressing overcapacity and market distortions collectively. Such arrangements can achieve trade policy objectives while maintaining market access among participants. Extending this approach to other materials or deepening existing arrangements could provide a middle ground between pure protectionism and fully open markets. However, these frameworks require significant diplomatic investment and work best among nations with shared interests and comparable production standards.

Moving toward adaptive trade frameworks. Overall, the trajectory of trade policy should move toward greater sophistication rather than simply higher barriers. This means dynamic responses calibrated to market conditions, rather than static tariff rates and trade frameworks that differentiate based on production standards (emissions intensity, labor practices, etc.).

Sustainability frameworks and market differentiation

Emerging frameworks that account for production standards (e.g., emissions intensity, labor practices, governance quality) are becoming increasingly important to market access and industrial competitiveness. Policymakers seeking to shape the global future of emissions-intensive materials are increasingly turning to mechanisms to account for emissions throughout value chains and sectoral arrangements like the Global Arrangement on Sustainable Steel and Aluminum. These frameworks aspire to serve multiple strategic objectives beyond environmental goals: they protect domestic industries from competitors operating under lax standards or with state subsidies; they create incentives for process innovation and efficiency improvements; and they potentially command price premiums in markets where buyers value sustainability and security of supply from aligned partners.

68. Reed Blakemore and Alexis Harmon, "US Critical Minerals Policy Goes Collaborative With Forge," Atlantic Council, February 12, 2026, https://www.atlanticcouncil.org/dispatches/us-critical-minerals-policy-goes-collaborative-with-forge.

69. Landon Derentz, "The Export-Import Bank Is Spending Big To Secure Our Economic Future," *The Hill*, February 5, 2026, https://thehill.com/opinion/energy-environment/5722625-trump-project-vault-investment.

Yet implementation challenges remain significant. Even where carbon accounting frameworks exist, enforcing price premiums or preferential market access has proven difficult. Buyers often lack incentives to choose low-emission products, and producers face competitive pressure from imports produced under less stringent standards, limiting the effectiveness of these policies and the durability of the partnerships underpinning them.

In this context, copper and steel producers are struggling to justify investment in more sustainable and secure production when prices are volatile, and competition is not always fair. These challenges underscore the need for policy frameworks that level the playing field while supporting investment in lower-emissions production.

Price discovery and premium support mechanisms. Producers investing billions in less emissions-intensive production need confidence that markets will reward those investments. Public procurement mandating specified production standards, formalized green premiums through commodity exchanges or industry consortia, government offtake agreements, and production tax credits can provide the revenue certainty that justifies major capital deployment. Recent critical minerals interventions have gone further, experimenting with price floors and other mechanisms to insulate strategic producers from artificially low or volatile global prices, offering potential models for other industrial materials.[70] These mechanisms must be underpinned by standardized carbon measurement, transparent pricing, and international coordination to achieve sufficient scale without becoming opaque subsidies.

Navigating differentiation without fragmentation. Market differentiation based on carbon intensity carries a fundamental tension: it can incentivize lower-emissions production while simultaneously fracturing global markets into incompatible blocs. Overcapacity and low-cost exports from countries like China already undermine producers meeting higher production standards, and divergent sustainability frameworks could worsen this dynamic by creating protected markets that discourage necessary restructuring. To prevent market isolation, policymakers should prioritize interoperability among production standard frameworks. This requires explicitly grappling with tradeoffs: sustainability, competitiveness, and supply security often pull in different directions, and policies designed in isolation—climate policy ignoring supply realities, industrial policy ignoring environmental constraints, or trade policy ignoring both—produce the worst outcomes.

Embracing circularity and substitutability

As demand rises and supply remains constrained due to long lead times for new production, growing trade fragmentation, and the fluctuating prioritization of scale of the energy transition goals, circularity and substitution are among the most immediately actionable tools for mitigating supply pressure. While substitution options exist for some applications, many core materials have few viable alternatives. In many cases, the focus should be on managing both supply and demand through improving material efficiency and recycling rather than wholesale replacement.

Each of the materials examined in this paper presents unique opportunities in this space.

Copper

Copper has limited substitutability due to its unmatched conductivity and cost-effectiveness. Only silver is a better electrical conductor, but its cost and scarcity make it impractical for most industrial applications. Aluminum is a possible alternative, though it is a less efficient conductor.

The greatest near-term opportunity lies in circularity. Copper is theoretically infinitely recyclable, retaining its properties through repeated reuse. In fact, about two-thirds of the copper mined since 1900 is still in use today, yet only about 30 percent of copper demand is met using recycled copper.[71] This is a remarkably high recycling rate compared to other metals, but is still insufficient to meet projected supply gaps.[72]

Policymakers can support circularity through a combination of incentives and regulatory measures, such as extended producer responsibility schemes that fund collection and design for recovery, deposit-return systems for high-copper-content products, and landfill restrictions that can force material into recovery streams. These investments have high capital barriers, but demand-side measures can give companies the confidence to overcome them, such as through tax incentives for recycling infrastructure, minimum recycled content standards, and public procurement preferences.

Plastics

Durable carbon-based materials, including certain plastics and polymers, are more often substituted in than out. While their current use as substitutes is concentrated in lightweighting for aerospace and automotive applications, materials science increasingly shows the promise of carbon-based materials as competitive, durable options that can compete with a range of other materials used in industrial activity, manufacturing, and construction, including concrete. Carbon-based composites

70. Blakemore and Harmon, “US Critical Minerals Policy.”
71. “Copper Demand and Long-Term Availability,” International Copper Association, last visited October 24, 2025, https://internationalcopper.org/sustainable-copper/about-copper/cu-demand-long-term-availability/.
72. Kijune Kim, “Mining’s New Frontier: Recycling Metal for a More Sustainable Future,” World Economic Forum, December 12, 2024, https://www.weforum.org/stories/2024/12/mining-s-new-frontier-developing-copper-recycling-for-a-more-sustainable-future/.

are becoming even more lightweight over time, possibly reducing some components' weight by 50–75 percent compared to metal alternatives, with corresponding benefits for energy efficiency in transportation applications.

Beyond their structural strength and flexibility, these materials can offer lower emissions intensity than traditional alternatives, though the climate case for plastic substitution depends entirely on improving circularity and feedstock sustainability. For example, durable plastics generally require less energy to produce than blast furnace steel, and they can reduce transport emissions due to lower weight. The average carbon footprint of polypropylene and polyethylene production ranges from 2–3 kilograms (kg) of CO_2 per kg of plastic, compared to 1.8–2.5 kg for primary steel. However, the lower weight of plastics often offsets this difference in embodied carbon, especially over the product lifecycle.[73]

Recycling plastics can save 90 percent of the emissions from new production, but technical and economic barriers make certain plastics and composites a challenge to recycle.[74] Many high-performance polymers used in durable applications are thermosets that cannot be easily remelted and reformed like thermoplastics. Advanced composites are particularly difficult to separate and recover economically. Even for more readily recyclable plastics, contamination, degradation of properties over multiple cycles, and the low cost of virgin plastics from petrochemical feedstocks undermine recycling economics.

Achieving meaningful circularity requires multiple interventions: extended producer responsibility to incentivize design for recyclability, minimum recycled content mandates to stabilize demand for recycling infrastructure, standards that simplify material composition and enable disassembly, and investment in advanced recycling techniques to expand the suite of downstream customers for recycled products. Policymakers should also address economic distortions that make virgin plastic artificially cheap through carbon pricing, virgin material taxes, or differentiated value-added tax (VAT) rates favoring recycled content. As demand for advanced materials grows, enabling greater recyclability will be essential to reduce lifecycle emissions and mitigate supply chain strain.

Steel

Steel faces limited substitution pressure in most applications, though lightweighting in vehicles and other sectors might reduce demand in specific contexts. For example, steel currently comprises 67 percent of passenger vehicle weight but is projected to drop to 31 percent in EVs to increase range. Over the longer term, substitution of steel could come from durable composites and plastics given the opportunities mentioned above. In the immediate future, however, aluminum might be a substitute for steel when lightweighting—though at a higher cost and with higher emissions. For every 100 kg of steel, thirty-five kg of aluminum would be needed but, despite a lower material footprint, emissions would go up 116 percent.

Circularity remains the most immediate and scalable opportunity. Like copper, steel is theoretically infinitely recyclable. Nearly 85 percent of end-of-life steel is already collected for recycling, largely due to its magnetic properties that make it easy to separate from waste products. However, only 30 percent of this is used to produce new steel, and all available steel scrap can only meet about one-quarter of steel demand. Notably, recycled steel has a carbon intensity about 30 percent lower than that of primary steel.[75]

The rise of EAFs, which use scrap rather than iron ore and can operate with dramatically lower emissions, has made circularity increasingly important. Although a global surplus of steel scrap exists today (about 9 million tonnes), a deficit of about 15 million tonnes is projected by 2030 as EAF capacity expands. Scrap supply is inherently limited by the volume of steel reaching end of life, making collection, sorting, and quality improvement critical. Policies such as scrap quality standards, advanced sorting technologies, design for disassembly, production tax credits, carbon pricing, and low-carbon procurement can all enhance usable supply and emissions reductions.

However, even with maximized circularity, scrap cannot meet total demand growth. Primary steel production remains necessary to meet supply, making it essential to simultaneously pursue both circularity and lower-emissions primary production methods such as hydrogen-based DRI. Maximizing circularity buys time and reduces emissions while breakthrough technologies mature. Policy should support both strategies simultaneously rather than treating them as alternatives.

Meeting the demands of the future: Innovation, capital deployment, and workforce development

Meeting intensifying demand securely, sustainably, and competitively requires breakthrough innovation that can eventually reduce material intensity, unprecedented capital mobilization to build adequate supply capacity, and workforce transformation to deploy new technologies and scale production. These three enablers are interdependent: innovation without capital deployment remains theoretical, capital without skilled workers cannot build projects, and workforce development without technological direction trains for outdated industries.

73. Material Economics, "The Circular Economy—A Powerful Force for Climate Mitigation," European Union, June 2018, https://circulareconomy.europa.eu/platform/en/knowledge/circular-economy-powerful-force-climate-mitigation.

74. Ibid.

75. David Stanway, "New Green Steel Firms Could Reap Rewards as EU Carbon Tariffs Loom," Reuters, November 8, 2024, https://www.reuters.com/markets/commodities/new-green-steel-firms-could-reap-rewards-eu-carbon-tariffs-loom-2024-11-08/.

Accelerate innovation from laboratory to deployment. Governments should increase materials research funding focused on breakthrough recycling technologies, low-emissions primary production methods, and sustainable management of feedstocks. This research must span basic science through commercialization, with explicit technology transfer strategies. The valley of death between a promising technology and its deployment is particularly deep for materials innovations. Demonstration projects, loan guarantees, offtake agreements, and production tax credits can bridge this gap by proving viability and de-risking first-mover investments.

Mobilize capital at scale. Meeting supply requires trillions in new investment globally; neither the public nor private sector can provide this alone. Public institutions, such as development finance institutions and export credit agencies, can provide patient, risk-tolerant capital that commercial lenders cannot. Furthermore, public procurement can aggregate demand and signal market opportunities, helping to justify private investment. Blended finance structures that pair concessional public capital with commercial funds can unlock strategically important projects in developing economies. Overall, financial frameworks should explicitly include low-emission materials production, while avoiding rigid rules that ignore the need for primary production or set infeasible carbon thresholds.

Build workforce capacity. Meeting growing demand for materials requires a workforce with skills tailored to new technologies such as EAFs, chemical recycling, and advanced composites. Training should be modernized through industry partnerships and apprenticeships; transition support for workers affected by changes in industrial production is vital for both economic efficiency and public legitimacy. Finally, immigration policies should enable the movement of specialized talent, while educational partnerships across primary and secondary schools, universities, and industry can strengthen long-term pipelines, modernize perceptions of materials careers, and expand the talent pool.

VIII. Conclusion

The future of the global energy system is often framed as a race for critical minerals or a process of doing more with less. Developments in 2026 have underscored the limits of that framing. Disruptions to petrochemical trade through the Strait of Hormuz, continued overcapacity in Chinese industrial sectors, and rapid shifts in trade policy have demonstrated that supply chain vulnerabilities extend well beyond minerals. These fixations risk obscuring a more fundamental reality: future energy technologies are built not only on lithium, cobalt, and rare earths but on the far larger foundation of steel, copper, and plastics. These bulk industrial materials might lack the political cachet of strategic minerals, but they represent the true scale of the challenge to build a sustainable and competitive economy

Steel underpins every turbine, transmission tower, and EV chassis. Copper conducts the electrons on which electrification depends. Plastics and composites make systems lighter, more durable, and more efficient. Together, these materials define the material intensity of the new energy economy and reveal a sobering paradox: even as the world shifts toward a more diverse fuel mix, the energy system remains profoundly material intensive.

Policymakers must recognize that meeting material demand is an enabling condition for the success of the energy transition, and it requires a strategy built for a world in which supply disruptions, market distortions, and policy shifts are features rather than exceptions. That means tackling three imperatives at once: securing reliable supply chains in a geopolitically fractured world, scaling low-emissions production at speed, and ensuring that material availability supports sustainable economic growth by keeping industries and infrastructure development well supplied.

To meet this moment, governments must move beyond ad hoc interventions and embrace a more integrated approach to supply chain governance. This includes building domestic capacity where feasible, deepening cooperation with trusted partners, and designing regulatory frameworks that incentivize sustainability without compromising scalability. Material substitution, circularity, and technological innovation all offer opportunities to reduce the pressure on primary inputs, but they will not be sufficient on their own. Policy must address the full lifecycle of these materials—from upstream extraction to midstream processing to downstream deployment—while remaining agile in response to market signals and technological shifts.

Ultimately, critical materials are strategic assets that shape the direction of national development and international influence. The recommendations provided herein offer a roadmap for aligning material policy with broader goals of economic security, environmental responsibility, and industrial competitiveness. Getting this right is the first step toward a strategy that matches the scale of the challenge and secures the material foundations of a sustainable, competitive energy future.

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