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TECHNOLOGY COMPETITIVENESS
& INDUSTRIAL POLICY CENTER

AMERICA'S RETREAT IN ELECTRIC VEHICLES

ECONOMIC SECURITY, PROSPERITY, AND THE INDUSTRIAL FUTURE

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This report is the output of an assessment commissioned by the Technology Competitiveness and Industrial Policy Center (TCIP Center) at the University of California, Berkeley to address the global automotive industry's transformation from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs) and the ways in which it represents a fundamental reordering of global value chains, industrial capabilities, and strategic influence. Technologies core to EVs (batteries and their components, motors and magnets, semiconductors, software) have broad applications in other industries, including energy production and defense.

China has emerged as the undisputed leader in EVs and their key components—batteries, semiconductors, software, and rare earth minerals. Its success stems from sustained industrial policy, investment, and national vertical integration across the EV technology stack.

In contrast, the United States has remained tied to legacy ICEV technology. Once the global leader of automotive innovation in a petroleum era, the U.S. risks being left behind in the energy transition. Leadership in EV technology has broad implications for our national security, energy independence, and economic competitiveness. It is not simply an environmental goal.

This report calls for an urgent, coordinated dialogue and a corresponding series of actions to develop an industrial strategy to rebuild U.S. competitiveness and avoid becoming stranded on a shrinking ICE island. We must develop global-class capabilities to innovate and produce the key components of the EV technology stack, and ensure they are Competitive, Resilient, Sustainable, and Secure (CRSS). Coming from a trailing position, we must establish a forward-looking agenda that invests in American innovation, establishes alliances with trusted partners, and carefully manages relations with foreign producers, particularly China.

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The global automotive industry's transformation from internal combustion engine vehicles (ICEVs) to electric vehicles (EVs) is not only a technological transition. It is a fundamental reordering of global value chains, industrial capabilities, and strategic influence.

Technologies core to EVs (batteries and their components, motors and magnets, semiconductors, software) have broad applications in other industries, including energy production and defense. Follow-on innovations such as gigacasting and lightweighting have broad implications for much of the manufacturing sector. The auto industry is a driver of several waves of recent innovation, including sensors and communication technologies, the electric grid, connectivity, data and artificial intelligence, raw materials, manufacturing methods, and new interactions with roads. The auto industry continues to sustain demand for steel, aluminum, plastics, semiconductors, and advanced tooling while anchoring high-wage employment in manufacturing communities.

China has emerged as the undisputed leader in EVs and their key components: batteries, semiconductors, software, and rare earth minerals. The United States was once the global leader in automotive innovation in a petroleum era, but it risks being left behind in a changing energy system, isolated on a shrinking ICE island. The scale of EV production drives innovation and investment that promote learning-curve and other benefits to these other industries; without EV production, it will thus be difficult to be successful in areas such as energy independence and military technology.

CHINA'S RISE

China's success stems from **forward-looking industrial policies** that combine subsidies, local initiatives nurturing entrepreneurs, state-private collaboration, and long-term planning. Other factors include investment in developing university-industry partnerships, financial support for building entire value chains, encouraging experimentation that includes test market creation at the local levels and an ability for the central government to generalize experiments, thereby nurturing first mover advantages in an enormous market. The result is a vertically integrated EV supply chain spanning mining, batteries, electronics, and vehicle assembly.

In 2025, China produced roughly **two-thirds of all EV battery capacity** and exported over **2 million EVs annually**. It leads in low-cost production, innovation speed, and scale. Its EV and battery firms, including **BYD, CATL, and NIO**, are reshaping global markets and expanding into various markets globally. Many of these practices are ones that the U.S. should learn from, although the U.S. cannot adopt others such as low wages and unacceptable working conditions and violations of U.S. environmental regulations.

The lessons from the Chinese experience are that success comes from a long-term commitment that includes investment in developing university-industry partnerships, financial support for building an entire value chain, encouraging experimentation that includes test market creation at the local levels, and an ability for the central government to generalize experiments, thereby nurturing first mover advantages in an enormous market.

THE U.S. POSITION

Despite early leadership in battery innovation, incumbent U.S. ICE manufacturers now lag behind as they lack capabilities to commercialize new battery technology. Tesla remains competitive, but it is the exception. Legacy automakers remain tied to their more profitable ICE models and are struggling to find their footing in the new EV mobility technology. The U.S. transition is hindered by:

+ **POLICY VOLATILITY** (e.g., Inflation Reduction Act incentives and subsequent rollbacks)
+ **FRAGMENTED INDUSTRIAL POLICY** and insufficient EV infrastructure. Lower rate of consumer demand due in part to concerns about range, price, and charging times.
+ **HIGHER LABOR AND PRODUCTION COSTS**
+ **HALF-HEARTED EFFORTS** to do the all-important research in battery chemistries and electric mobility technologies

Technological competitiveness in EV technologies is necessary to capture a significant portion of this emerging global market. Losing leadership in these domains jeopardizes:

+ **NATIONAL SECURITY** - setting the U.S. up for reliance on foreign suppliers, especially China
+ **DEFENSE TECHNOLOGY** - falling behind on dual-use technologies that are critical for both civilian and military systems
+ **INDUSTRIAL EMPLOYMENT** - risking the long-term security of the auto industry, a key source of high-wage, unionized American jobs

- **ECONOMIC COMPETITIVENESS** – by impacting the automotive industry, subsequently threatening the critical end use of other key technologies (steel, semiconductors, lithium-ion batteries)

KEY LESSONS AND POLICY OPTIONS

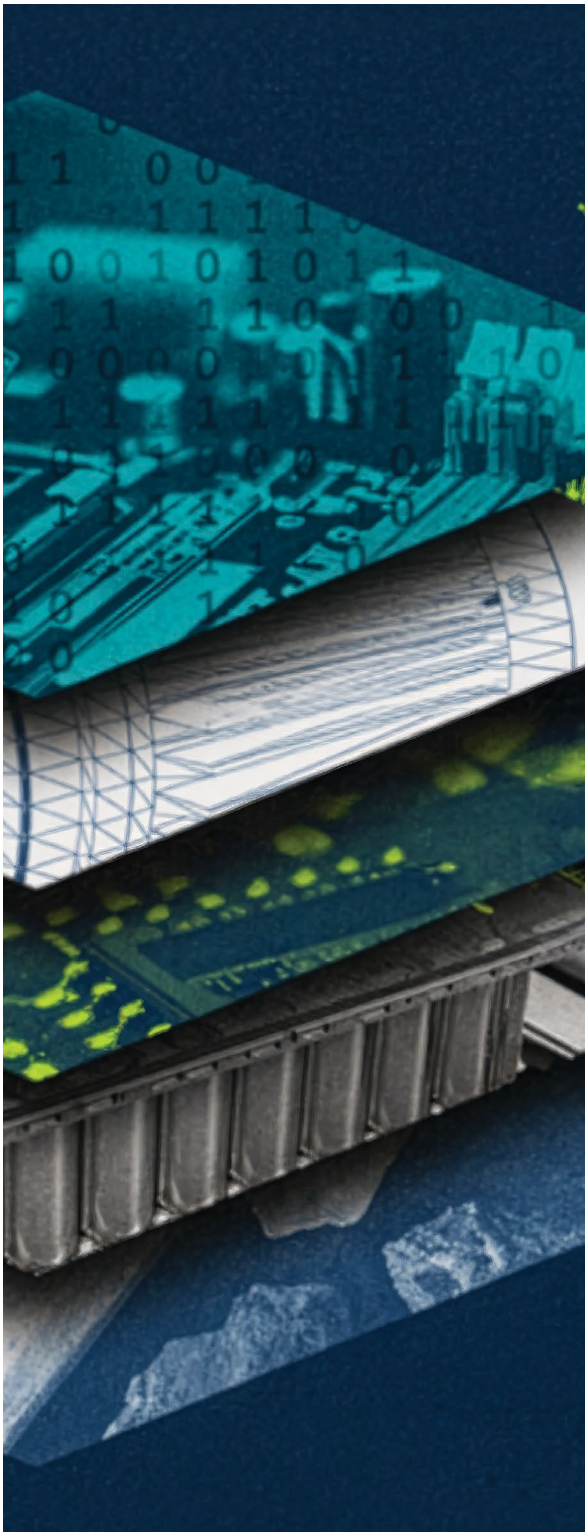
Time is short, as the industrial capabilities necessary to remain competitive in global mobility industries and ensure energy security are being solidified now. How the United States formulates policy will shape the role it plays in the rapidly changing electric economy. It must secure access to the components of the EV technology stack and ensure that the supply chains are **Competitive, Resilient**, **Sustainable, and Secure** (**CRSS**). Coming from a trailing position, the U.S. must establish a policy agenda with regard to foreign producers, particularly China. The report calls for an urgent, coordinated industrial strategy to rebuild U.S. competitiveness.

1. **WIN-WIN ALLIANCES** must be forged with trusted partners (Europe, Japan, Korea) to secure access to critical components and enormous markets.
2. **INVEST IN R&D** for next-generation battery chemistries and EV technologies through public–private partnerships.
3. **BUILD DOMESTIC SUPPLY CHAINS** for critical minerals to reduce vulnerability
4. **STABILIZE POLICY** to encourage long-term private investment in EV manufacturing and infrastructure.
5. **CONSIDER THE CONDITIONS UNDER WHICH JOINT VENTURES** with Chinese firms—modeled on the U.S. imposition of restraints on Japanese producers under President Reagan—could be set that would promote technology transfer and domestic production while maintaining security safeguards.

All these suggestions inherently entail taking risks, but time is short, and inaction is not a viable option.

CONCLUSIONS

The U.S. auto industry is at a strategic crossroads in which prioritizing short-term profitability will come at the cost of long-term obsolescence. Reclaiming leadership in EVs is not simply an environmental goal, nor does it solely impact the auto industry. Escaping the “shrinking island of ICEs” is critical to America’s long-term economic competitiveness and national security.



China has established a leading position in Battery Electric Vehicles (EVs) and many of the component domains, such as batteries. Indeed, it is increasingly acknowledged in popular discussion as well as expert analysis as the dominant force in the EV industry.[1]

As important as the production of the vehicles — where, by whom, and the employment involved — is the impact of the EV industry on the new sets of components facilitating and underpinning them. Some label this the "Electric Tech Stack," of batteries, semiconductors, software control systems, as well as the now controversial rare earth minerals.[2] The components are crucial not only for an array of manufactured consumer and industrial products but also for national security. Moreover, these components increasingly spin-on into national security applications from their consumer applications. Thus, a lack of capability in these consumer products would reduce U.S. prosperity and competitiveness, and threaten its position in security-relevant technologies.

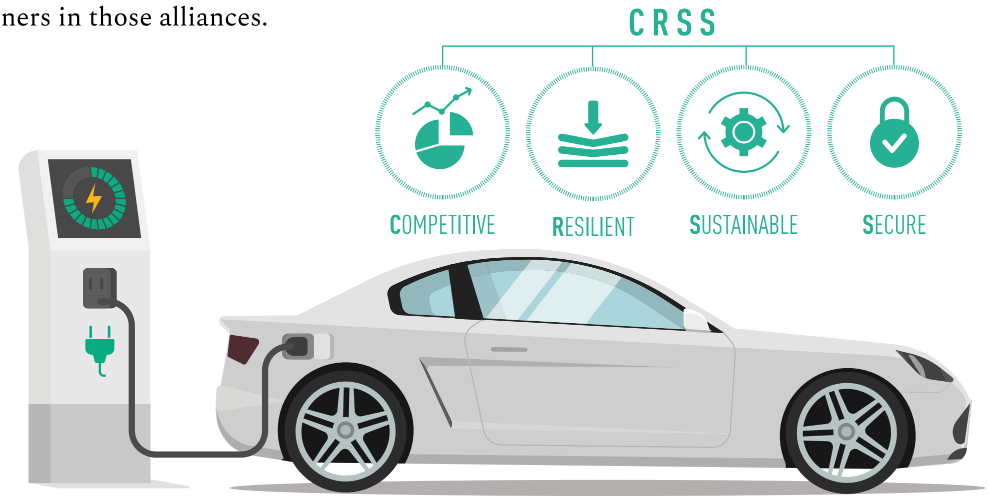
Indeed, the EV story has even broader implications. Part of the Chinese policy goal, along with other countries that are significant importers of fossil fuels for their energy needs, is to transition from a fossil fuel economy, dominated by incumbents with the United States in a central position, to an electric economy in which they can establish their own leadership. The issues for many are not strictly about climate, but about core economic and geopolitical positions. Both the specific case of EVs and the broader shift to electric energy generated from sources other than fossil fuels create real policy choices for the United States. The risk in the case at hand of EVs is whether the U.S. is left isolated on a shrinking island of ICEs, in which skills from the petroleum era do not enable us to build a position in a changing energy system.

Focusing on the EV case, the United States must formulate policy from a trailing rather than a leading position. A basic question is whether American producers and policy can recover from this trailing position to one of at least co-leadership. Or whether the U.S. has to accept and accommodate the consequences of a trailing position. If that trailing position is in the electric tech stack, not just in this single sector, the challenge is significantly more serious. The U.S.'s ability to compete will be compromised in those sectors that draw heavily on that stack. Policy must be forward-thinking. Simply protecting the past position in the era of fossil fuels without building for the future will leave the U.S. isolated and eventually impoverished, as it remains dependent on more expensive and polluting fuels.

First, the U.S. must build industrial alliances to assure access to products and innovation in the critical components. Laura Tyson and John Zysman have argued that there should be the goal of assuring access to crucial components, as **CRSS: Competitive, Resilient, Sustainable, and Secure.**[3] The U.S. must build alliances on those terms and provide concrete benefits to trustworthy partners in those alliances.

Second, what will be the U.S. policy toward foreign producers of vehicles and components, especially given China's dominant position? Do we exclude imports by Chinese firms? Do we allow China to produce in the U.S., in exchange for explicit technology transfer, joint ventures, upholding labor and environmental standards, and assured markets for American component producers? There are real difficulties with each of these paths. Alternatively, do we seek to rebuild American capacities by encouraging Japanese, Korean, and European producers to locate here?

The challenge for U.S. auto producers, headquartered in the U.S., and for the U.S. more generally, is how to respond. Developing a globally competitive American EV sector would require the U.S. to excel not only in vehicle assembly, but also in innovation in the supply chains and workforce systems that underpin global competitiveness. To address this question, we must distinguish between the competitiveness of the United States and that of U.S. auto companies headquartered in the U.S. But let us first turn to the core issues: the transformation of the global vehicle industry. We consider industrial policy issues in the conclusion.



The global automotive industry is undergoing a once-in-a-century transformation as internal combustion engine vehicles (ICEVs) give way to electric propulsion systems in much of the world. This shift represents not only a technological transition but also a fundamental reordering of global value chains, industrial capabilities, and strategic influence. For the United States, it is both an opportunity and a profound risk. EVs occupy a pivotal position in the 21st-century industrial landscape.[4] EVs sit at the intersection of multiple strategic domains: batteries, semiconductors, advanced manufacturing, vehicle software, including Artificial Intelligence (AI) software, and critical mineral supply chains.

Furthermore, EVs are central to decarbonization goals, and China is rapidly emerging as a leader in these technologies. Each of the EV domains consists of dual-use technologies that underpin both commercial competition and national security systems, from unmanned aerial vehicles to grid-scale energy storage. The EV domains encompass key areas of economic value that have commercial, strategic, and geopolitical significance.

The auto sector has long been a core manufacturing industry in all major industrial countries, including the United States, sustaining upstream demand for steel, aluminum, plastics, semiconductors, and advanced tooling while anchoring high-wage employment in manufacturing communities.[5] While the U.S. retains a deep manufacturing base, world-class research and development (R&D) institutions, and the second largest domestic market, U.S. auto companies are rapidly losing ground in EVs and their components. Policy volatility and fragmented production and infrastructure investment have constrained the pace of America's EV transition. The IRA legislation championed and signed by President Biden included consumer subsidies to boost demand for EVs and business incentives to invest in batteries and EVs over the next ten years. President Trump eliminated most of the IRA's clean energy provisions, including EV consumer incentives. Tesla retains a global presence in most markets and thus remains a global leader. Still, most U.S. legacy manufacturers are struggling to secure significant market share in the emerging EV market.

Meanwhile, China has become the dominant global player: it is now the largest exporter of cars, and almost half of its car exports are EVs. China's EV sector now leads in finished vehicles, battery manufacturing, and critical minerals. China is now the leader, and the U.S. is now the laggard in EVs and their components. As we discuss below, China's breathtaking success has been enabled by a variety of factors, including national and local industrial policies, encompassing demand-pull consumer subsidies and local content requirements for EVs and components; strong investment, innovation, and price competition from new private Chinese-based EV manufacturers; and lower wages and looser environmental regulations.

It is important to note that China's industrial policies in EVs and components have not been backward-looking to protect dying sectors from competition but forward-looking to foster competition and scale economies and create whole new products and sectors. China has built a vertically integrated EV supply chain, from critical minerals to batteries, electronics, and software, to support the EV industry. It has used a variety of demand-pull subsidies, along with local content requirements, to fuel domestic demand for EVs. These, in turn, have fostered enormous scale economies and learning-by-doing, resulting in lower costs and lower prices throughout the EV supply chain.

Over time, the allocation of EV subsidies has shifted from state-owned enterprises like BJEV (a major shareholder in Mercedes-Benz) to entrepreneurial firms such as BYD and other new entrants, as local governments have fostered their local EV companies. The resulting surge in production has led to sharp competition among Chinese producers, excess capacity, price-cutting, possible bankruptcies, and a rise in exports — a combination that President Xi has called "involution" — a cycle of destructive competition, overcapacity, and diminishing returns, which China hopes to counter through regulatory changes. While China confronts excess production of EVs and the rest of the world faces surges of cheap EV imports from China, U.S. auto producers are protected from imports of Chinese EVs by 100% tariffs, a ban on "connected vehicle technology" made in China, and a prohibition on incorporating software and hardware from Russia or China. The ban reflects the view of many policymakers and security experts that both imports and U.S. production of Chinese EVs pose several national security risks, including the collection of sensitive data, surveillance, and disruption of critical infrastructure. Together, tariffs and the ban keep Chinese EVs out of the U.S. market, while other foreign companies, like Hyundai, Kia, and Toyota, are both selling and producing EVs in the U.S.

With the removal of the IRA incentives that support EV demand and production, American auto companies find the production of ICEVs, including hybrid models, much more profitable than producing EVs. This may be a wise choice in the short run, but they may find themselves increasingly isolated on a shrinking island of ICEs. They might devote the next five to ten years to ICEV production while global demand shifts sharply to EVs, and Chinese and other global competitors increase their EV production both globally and in the U.S., when allowed. The strategy of the Big Three U.S. auto companies may deliver short-term stability and profits in the U.S. market but risks their long-term segregation from the technological paradigms and cost structures that will dominate global auto competition in the 2030s and beyond.

Moreover, the eroding competitiveness of U.S. auto companies in EVs threatens the broader U.S. industrial ecosystem and U.S. capabilities in multiple strategic industries. An array of crucial technologies, significant for both commercial products and military applications, is at risk from batteries, electric motors, semiconductors for auto system control, entertainment, and autonomous driving, as well as the software embedded in them. High-density batteries, lightweight composites, advanced power electronics, and autonomous navigation systems are equally applicable to unmanned aerial systems (drones), military ground vehicles, naval propulsion, and large-scale stationary energy storage for grid and critical infrastructure resilience. Rare-earth minerals are also crucial, not only to the production of batteries for EVs but also to a broad range of products, including consumer electronics.

Suppose the U.S. becomes structurally dependent on foreign sources for these dual-use products and technologies. In that case, its vulnerabilities will extend beyond commercial transportation to defense, energy security, and the security of critical infrastructure. In these products and technologies, the U.S. needs competitive, resilient, and secure supply chains that include both U.S. production and U.S. R&D to support learning-by-doing and scale economies. This does not mean autarky — it does not mean that the U.S. needs to produce everything in the EV supply chain alone. It does mean that the U.S. should work with its allies to build competitive, resilient, and secure supply chains for EVs, ensuring that China does not have an overwhelming market power and chokehold over key technologies like critical minerals and batteries.

Before turning to the full analysis, we must highlight the importance of "dual-use and spin-on technologies." Dual-use technologies are those products, both hardware and software, that can be used for both civilian and military purposes. The relationship steadily evolves, often reversing, between products emerging from commercial developments and applied to defense uses, and those emerging from defense R&D and applied to commercial uses. After World War II, massive American investments in science-based and advanced engineering technologies generated defense products that "spun off" into commercial applications. The list of "spin-off" technologies originating in defense is long and significant. It runs from semiconductors and jet aircrafts through GPS. The internet began as the ARPAnet. That reversed a process in which commercial developments, such as internal combustion automobiles, advanced military transport productions.

By the mid-1990s, the relation between defense and commercial production and technology had reversed again.[6] The exceptional scale of consumer electronics products and the remarkable investments in R&D from the companies making them meant that commercial products were being "spun-on" to defense applications. The range of products then extended from advanced computing to display technology for jet fighters. Today, of course, the long list of important commercial developments supporting defense would begin with machine learning and generative AI. EV production at scale would continue this trend — mastering production scale keeps costs down and is critical to defense.

The United States was an early pioneer in EV and battery technology, with breakthroughs in lithium-ion chemistry, battery management systems, and power electronics originating from U.S. laboratories and universities. Yet today, the most significant advances in high-energy-density chemistries, lithium iron phosphate (LFP) manufacturing, solid-state battery prototypes, and integrated battery-chassis designs are emerging from Chinese, Korean, and Japanese corporations.

R&D investment patterns have shifted accordingly. Chinese EV and battery manufacturers are channeling billions annually into advanced materials, battery-cell manufacturing processes, and vehicle operating systems—often backed by provincial and municipal governments. The Australian Strategic Policy Institute finds that China now invests more than the U.S. in R&D across 37 of 44 critical and emerging technology categories, including batteries, electric drivetrains, and advanced manufacturing.[7] U.S. private-sector automotive R&D, meanwhile, remains heavily concentrated in incremental improvements to ICE and hybrid platforms, with a smaller share devoted to EV architectures or next-generation chemistries.

This report analyzes the ICEV-to-EV transition, evaluates the current competitive position of U.S. companies and the U.S. as a production location in the global EV market and supply chain, and distills lessons from China's rapid ascent (see page 65 for a companion essay by Martin Kenney on the Chinese challenges for U.S. producers and policymakers). It concludes with policy recommendations that reflect both the strategic imperatives to ensure America's economic competitiveness and national security in one of the defining industrial transformations of our time.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THE INDUSTRY OF INDUSTRIES & THE MECHANICS OF THE EV TRANSITION

Countries that lack a large domestic legacy auto industry face lower political and economic barriers to shifting toward EVs. For those with national auto industries, the imperative is to transition to competence in the new technologies that underpin EVs.

THE IMPORTANCE OF THE U.S. AUTO INDUSTRY

The U.S. auto industry has long been an “industry of industries”—a sector whose vast and varied supply chain touches steelmaking, petrochemicals, glass production, electronics, and advanced manufacturing. The industry also pioneered mass production innovations, such as the moving assembly line, integrated automation, and robotics.[8] In the mid-20th century, the economic footprint of the “Big Three” U.S. automakers—Chrysler (today an American subsidiary of the multinational automotive company, Stellantis), Ford Motor Company, and General Motors (GM)—was unrivaled. Automobiles accounted for roughly a quarter of all U.S. manufacturing, provided a pathway to the middle-class for millions of American workers, and set collective bargaining standards through United Auto Workers (UAW) agreements that influenced labor markets nationwide.[9]

The U.S. auto industry’s dominance began to erode in the 1970s following the oil crisis, which created a new demand for fuel-efficient vehicles. Legacy automakers like GM, Ford, and Chrysler were slow to respond to Japanese upstarts—Toyota, Honda, and Nissan—who were already producing smaller, more reliable cars that rapidly captured market share. This shift was compounded in the 1980s when these Japanese firms began to invest directly in the U.S. market, strategically building “transplant” factories in non-unionized areas of the U.S. Midwest and South to avoid the high labor costs and rigid work rules of the UAW, leading the U.S. to be one of the very few countries with significant non-union production in auto assembly.[10] Evidence suggests that unionization was not the root cause of the Detroit Three’s decline (as the Japanese were unionized in their domestic market), but rather the American firms’ unwillingness to adopt the collaborative relationships with workers and suppliers that underlay the success of Honda and Toyota, in particular.[11] Instead, to cut costs, the Big Three began outsourcing component manufacturing to smaller, nonunion suppliers that generally paid less and were less innovative.[12] Together, these trends weakened the automotive union’s bargaining power and, with it, its historical role in expanding the American middle class.

The sector's resilience has been tested repeatedly in the 21st century. The Great Recession exacerbated preexisting weaknesses and decimated consumer demand, resulting in the 2008 automotive crisis and a federal financial bailout of automakers Chrysler and GM. The industry eventually recovered to its pre-crisis peak in 2015.[13] But in 2020, the COVID-19 pandemic again exposed U.S. automakers' failures of supply-chain management, halting production due to shortages of semiconductors and other components.[14] More recently, the return to typical interest rates have cooled auto demand. In this context, EVs represent both a disruptive threat and an opportunity to modernize the industrial base.

Although the American auto industry has weathered several shocks over the past decades, the industry remains a critical pillar of the American economy and political landscape. As we saw in the COVID-19 pandemic, problems in the auto supply chain may have economy-wide repercussions; the shortage of automotive chips reduced GDP growth by a full percentage point in 2021. Conversely, the vast capabilities of domestic automakers played an important role in making up the shortfall in domestic supplies of medical masks, and General Motors engineers figured out how to source the hundreds of parts of a ventilator. They set up a mass assembly line in just a few days. Thus, a strong domestic automotive supply chain may improve the health and resilience of other industries as well.

Having significant domestic production of critical goods also means that, in the event of a natural disaster or international conflict, U.S. firms are not existentially dependent on the policy choices of other countries.[15]

Furthermore, estimates indicate that American auto manufacturing boasts an eight-to-one employment multiplier—the highest in the private sector and higher than manufacturing overall.[16] The industry's geographic concentration in "Auto Alley," stretching from Canada to the Gulf of Mexico, also gives it outsized regional economic and electoral importance, making these areas particularly vulnerable to economic disruption as the transition to electric vehicles accelerates. At the same time, a poorly managed transition to battery electric vehicles could threaten the entire industry. We would also note that the sector continues to serve as a major source of well-compensated jobs: durable goods manufacturing has a higher rate of union members (7.8%) than the private sector overall (5.9%), with the automotive sector being a particularly strong unionized segment.[17] We discuss this point further below.

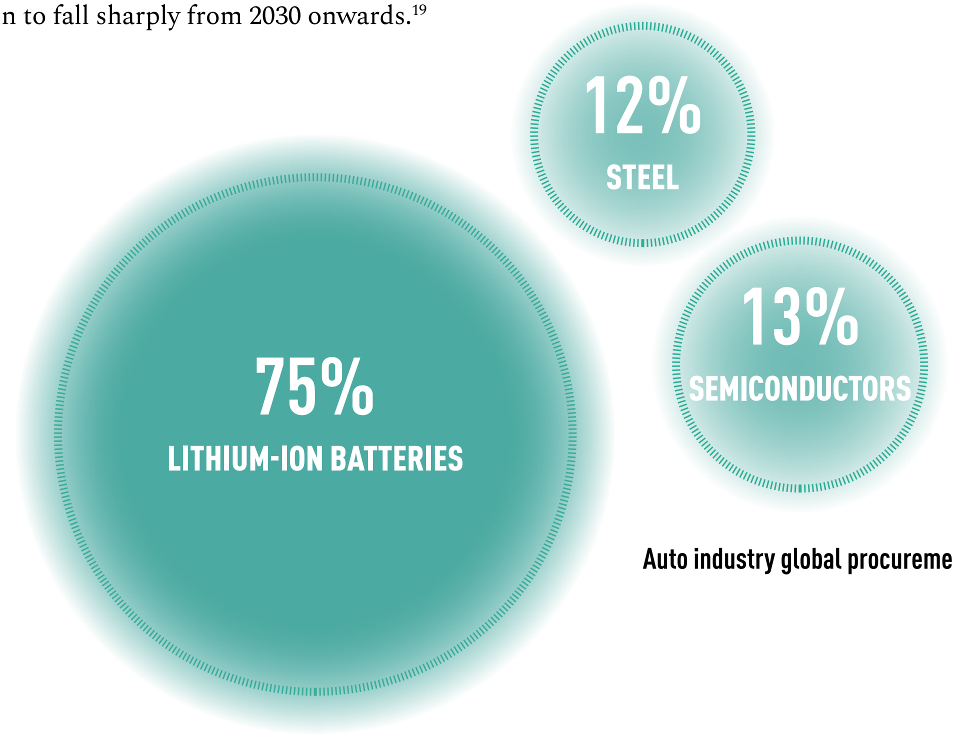
Of critical importance, the auto industry is also a linchpin of demand for strategic inputs. Globally, the auto industry procures 12% of steel (including 26% of steel produced in the United States), 13% of semiconductors, and approximately 75% of lithium-ion batteries.[18] The automotive industry will continue to be a critical end use for each of these technologies. For example, the current generation of cars can have between 1,000 and 3,500 semiconductors, a number expected to grow as consumers prioritize advancements in vehicle safety systems, connectivity, and electrification. Likewise, as EV sales increase, the automotive industry will strengthen its demand pull on battery technologies. Therefore, innovations in these components and EVs are likely to spur a positive feedback loop. Furthermore, EV production advances complementary capabilities in tooling, precision machining, and systems integration that are foundational to multiple advanced manufacturing sectors.

The auto industry's outsized demand for these technologies has significant benefits for other industries, such as those listed above. First, the "base load" demand provided by the industry provides economies of scale. Second, the experience gained by serving the auto industry drives faster progress down a learning curve. If a low-volume product such as military aircraft could not piggyback on these spillover benefits from autos, it would face dramatically higher prices and less innovation.

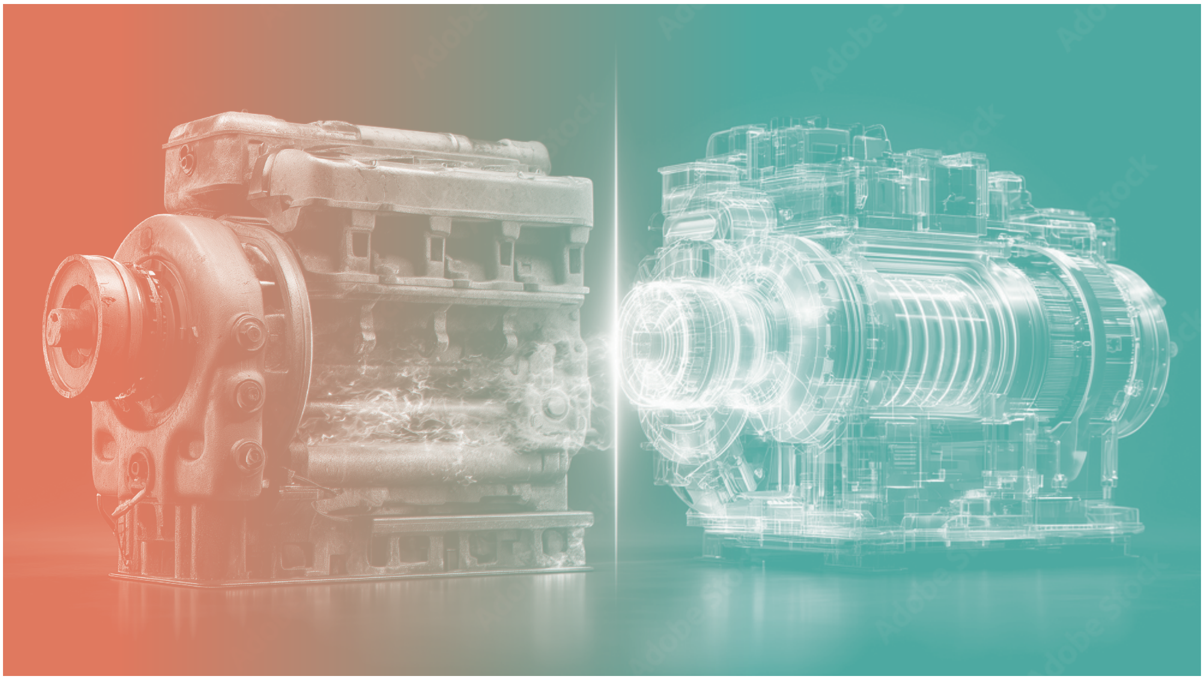
Road transport accounts for approximately 45% of global oil demand. The transition from ICEVs to EVs will continue to serve as a strong demand pull for energy, but the energy source will shift from gasoline to the electric grid. And that can be provided by renewables such as solar and wind, and possibly nuclear, natural gas, and coal. It is possible that the grid will need to be expanded for uses such as AI, which, if the ambitious estimates are correct, will make ever-increasing demands. As a result, global consumption of fossil fuels is expected to flatline over the coming years and then begin to fall sharply from 2030 onwards.[19]

By the end of 2026, the EV transition is projected to displace an incremental one million barrels of oil per day compared to 2024 levels. By 2030, that number is projected to rise to 5.3 million barrels displaced per day.[20] An electric age appears to be closer than many had imagined only five years ago.

Apart from reducing demand for fossil fuel and for many countries' fossil fuel imports, EVs have other real advantages. They are superior to ICE vehicles in many ways that are attractive to consumers: they accelerate faster, are quieter, and are easier to maintain. Of course, they produce fewer emissions of greenhouse gases and other pollutants. The main obstacles to EV adoption have been a) lack of places to charge and b) a higher initial purchase price, although the price premium is rapidly disappearing as prices by Chinese producers fall and the life-cycle costs of their products are already lower.[21]



Auto industry global procurement



THE MECHANICS OF THE ICE TO EV TRANSITION

The fundamental distinction, of course, between a traditional ICEV and a Battery Electric Vehicle (BEV) is rooted in the energy sources for their respective powertrains, i.e., the system of components in a vehicle that transform stored energy into torque (rotational force) at the wheels. Although the overall purpose is the same in both ICEVs and BEVs, the design of the system and the components it relies on are quite different. In an ICEV, fuel is combusted in an engine and transmitted through a multi-stage system to ultimately produce mechanical energy that turns the wheels of the vehicle. In contrast, a BEV stores energy in a battery and uses one or more electric motors to provide torque directly to the wheels. This fundamental difference in energy conversion leads to distinct component needs, vehicle designs, weight distribution, and efficiency profiles — factors that reshape supplier relationships, manufacturing processes, and more.

An ICE drivetrain may be composed of over 2,000 moving parts, including:[22]

- **PISTONS,** which move up and down when the fuel combusts, provide the motion that powers the car.
- **CRANKSHAFTS,** which take up-and-down piston movement and turn it into rotational motion.
- **VALVES,** which open and close to control the flow of air and fuel into the engine and the exhaust gases out of it.
- **TURBOCHARGERS,** which push more air into the engine to improve power output.

Each of these parts is manufactured with tight tolerances (precision manufacturing) and works together in perfect timing and requires lubricants and filters that must be changed regularly to significantly reduce friction and wear. The power produced by the engine is then sent to the variable-geared transmission, which manages the relationship between the engine and wheel speed. The transmission contains hundreds of additional parts, all of which must be manufactured and assembled at very high tolerances. Power then travels through a driveshaft—a rotating rod that carries torque to the wheels—and through a differential, which lets the left and right wheels spin at different speeds during a turn. ICEVs also require both an exhaust system (pipes, very expensive catalytic converters, mufflers) to manage combustion byproducts and reduce pollution, and a fuel system to deliver fuel from the gas tank to the engine. To prevent the machinery from overheating, ICEVs use a complex thermal management system with radiators, pumps, and hoses that circulate coolant to remove heat from the engine. Finally, an engine control unit is a small computer that manages fuel injection, ignition timing, and emissions compliance.

By contrast, an EV powertrain shifts the focus from the motor and its ancillary equipment to the battery, motors, and a battery management system. The battery pack becomes the dominant subsystem, requiring careful integration of thousands of cells, thermal management loops, and safety systems. Energy flows from the battery to an inverter and power electronics, which convert direct current into alternating current suitable for the motor. They regulate power flow depending on driving needs and shift the focus of engineering from metallurgy to battery chemistry, semiconductor reliability, and software optimization. The electric motor itself has far fewer moving parts compared to an engine; it produces torque directly from electricity and can instantly deliver power to the wheels. Because electric motors generate high torque across all speeds, EVs use a single-speed gearbox instead of a complex multi-gear transmission. Torque is then transmitted through driveshafts and differentials as in an ICEV. However, with an EV, it is possible to have two motors or even a motor for each wheel.

EVs also require thermal management systems, such as radiators, pumps, and hoses, which are somewhat similar, though far simpler than those in ICEVs. They also add new parts, such as passive cooling plates, to maintain safe, uniform operating temperatures for the battery packs and electronics. These thermal management systems are designed to keep the battery pack within a very narrow and safe temperature range, since overheating can degrade battery performance and create safety risks.[23] Similar to an ICEV engine control unit, EVs have a vehicle control unit and battery management system that monitors cell voltages, coordinates charging, and balances power delivery. Finally, where an ICEV has a fueling system (fuel tank, filler cap, gas pump infrastructure), an EV has a charging system (onboard charger and charging port, which is essentially a socket to the user) to charge from the grid. In sum, EVs have roughly half the parts and subsystems as ICE vehicles. However, EV subsystems require very sophisticated, high-quality, and challenging manufacturing, especially for batteries, where any anomaly can lead to failure, which can sometimes be catastrophic.[24]

In the shift from ICE to EV, the new “winners” are firms specializing in batteries, electric motors, and advanced power electronics. Meanwhile, traditional suppliers of ICE engine components face obsolescence, as much of the knowledge needed to produce them will become irrelevant. Components such as thermal control systems, suspension, and axles remain but are often redesigned with lighter or stronger materials.[25] The table below summarizes the similarities and differences between the parts within an EV and ICEV.

TABLE 1: IMPLICATIONS OF THE MECHANICS OF THE ICE TO EV TRANSITION

COMPONENT	ICEV FUNCTION	EV FUNCTION
Energy Source	Refined from crude oil that is stored in the fuel tank.	Electrical energy is derived from various sources, including renewable ones. It is stored in the battery pack, which is increasingly made of lithium-ion cells. These are the main drivers of EV cost and weight.
Primary Power Unit	An internal combustion engine that converts fuel into mechanical power via combustion.	An electric motor, which converts electrical energy into torque directly, has high efficiency, few moving parts.
Transmission	A multi-speed transmission that adjusts torque and speed to match driving conditions; a complex mechanical system.	A single-speed gearbox that provides fixed torque reduction; much simpler than a multi-gear ICE transmission.
Driveshaft & Differential	Transfers power from transmission to wheels; differential allows wheel speed differences.	Often retained in EVs, it serves the same function of torque distribution, but multiple electrical motors can be used.
Exhaust & Emission Systems	Manages pollutants through catalytic converters, filters, and mufflers.	Not required; EVs produce zero tailpipe emissions.
Cooling/Thermal Management (Radiator, Pump, Hoses)	Dissipates heat from engine combustion; prevents overheating.	Removes heat from battery, motor, and inverter; critical for efficiency and safety. In addition to radiators, pumps, and hoses, an EV thermal management system may also include cooling plates.
Control Unit	The engine control unit that manages fuel injection, ignition timing, emissions, and diagnostics.	The vehicle control unit and battery management system coordinate battery, inverter, motor torque, charging, and diagnostics.
Energy Replenishment	Fueling system (fuel filler cap, pump, fuel lines).	Onboard charger and plug interface replenish the battery from the grid or charging stations.
Braking System	Hydraulic brakes slow the vehicle.	Hydraulic brakes are still required, but supplemented by regenerative braking systems.
Vehicle Body & Frame	Steel-heavy body designed around engine bay, transmission tunnel, and exhaust routing.	Largely similar to an ICEV but with simpler architecture, increasing use of aluminum/gigacasting to offset battery weight.
Seats & Interior	Provides comfort, ergonomics, and safety for passengers.	Nearly identical across ICEV and EV platforms; manufactured by the same suppliers.
Suspension System	Springs, dampers, and control arms manage ride quality and handling.	Functionally the same; may be tuned for heavier EV battery packs, but uses similar components.
Safety Systems	Airbags, seatbelts, and crumple zones protect occupants in crashes.	Functionally identical; governed by the same crash standards and manufacturing processes.

🟥 **Components are completely redefined between ICEV to EV systems**
🟨 **Components share a functional role but require redesign**
🟩 **Components remain fundamentally similar**

SOURCE: Author's compilation

The mechanics of the shift from ICEVs to EVs carry profound implications for manufacturing processes, supply chain structures and components, workforce skills, and geopolitical dependencies. At its core, the transition involves moving from a production system optimized for ICEs and transmissions to one centered on batteries, electric motors, power electronics, and system integration.

For ICEVs, manufacturing has long emphasized precision machining, forging, and casting of engine blocks, pistons, crankshafts, and multi-gear transmissions. In EVs, the emphasis shifts toward battery cell fabrication, module and pack assembly, and high-voltage electronics integration. Also, some of the manufacturing equipment is different. ICE production depends on machine tools, casting foundries, stamping presses, and robotic welding systems. EV manufacturing uses these technologies as well but requires less stamping and machining. It also relies on cleanrooms for battery production, high-precision winding and coating equipment, and a greater use of leading-edge semiconductors.

This realignment has major consequences for workers and supplier firms: whereas ICEVs rely heavily on mechanical engineering, metallurgy, machining, and line assembly, EVs demand expertise in electrochemistry, materials science, automation engineering, and electronics assembly. While 200,000 jobs in engines, transmission, exhaust, and fuel systems are at risk from a transition to EVs, all 3 million jobs in the extended U.S. auto supply chain are at risk if the U.S. does not aggressively pursue the superior EV product technology. Often, shopfloor workers can be retrained to work in plants assembling EVs or making EV components. To illustrate, the main difference between an ICE and EV assembly plant is the presence of high-voltage parts and equipment, which experienced auto workers can be trained to handle in a few hours.[26] Many workers in engine plants are skilled and generally trained machinists, whose talents can be readily adapted to many jobs in battery plants. In contrast, U.S. automakers have felt it is not worth retraining their mechanical engineers to learn electrical and computer skills, so (whether an optimal strategy or not) have laid off thousands of them. Not all supplier firms will find work in the EV sector, because the engineering and design transition from stamped parts (which EVs have fewer of) to chemical and electronics parts (which EVs have more of) is not easy. However, opportunities exist for such firms in growing sectors, such as grid products, heat pumps, and advanced energy.[27]

The transition consequently reshapes global supply chain dependencies. The ICEV supply chain, developed over more than a century, is both robust and deeply entrenched across the United States and its allies. It is anchored in established suppliers of steel, aluminum, plastics, lubricants, and conventional components arranged in multiple tiers. By contrast, the EV supply chain is far more nascent and geographically concentrated outside the United States. Battery materials, in particular, are nearly entirely mined, processed and produced outside of the United States and, notably, in the case of LFP controlled mainly by Chinese firms.[28] While battery recycling offers a potential pathway to mitigate these vulnerabilities by recovering critical minerals, this recycling remains at an early stage in the United States and will need to be significantly scaled in the coming decades.[29]

Differences in manufacturing strategies have also created a competitive divide between legacy automakers and new entrants. Legacy firms such as Ford, GM, and Stellantis initially retrofitted existing ICE platforms for EV production, leveraging sunk capital but often producing suboptimal EV designs that retained unnecessary ICEV complexity. In contrast, new entrants such as Tesla and a growing cohort of Chinese manufacturers have pursued “clean sheet” design approaches, developing both vehicles and factories from the ground up. This has enabled them to pioneer innovations such as large-scale die-casting that confer a significant competitive advantage.[30] Tesla’s Italian-made “Giga Press,” for example, allows for the high-pressure casting of large vehicle sections—such as the front and rear underbodies—as single, integrated aluminum pieces. The Giga Press process drastically reduces the number of individual stamped parts from dozens to just a few, thereby minimizing welding, assembly steps, and labor costs. The simplified design translates to fewer workstations, fewer fasteners, and a faster assembly line. New entrants have also experimented with lighter-weight materials, such as aluminum alloys, over traditional steel structures, to improve efficiency and thereby increase battery range. By simplifying assembly, reducing labor, and securing their supply chains, new entrants have been able to achieve cost efficiencies and production scales that are challenging for legacy automakers to match.[31] Some incumbents are proposing production innovations that may allow them to catch up to entrants. For example, Ford has announced a “Universal EV Production System and Platform” that will produce a truck under $30,000 by 2027, using large castings and a tree-like assembly process.[32]

Managing the employment implications of the EV transition is thus an important task. As many of the production jobs displaced by the EV transition are high-quality, unionized jobs that anchor small communities, job quality as well as job quantity is key. We believe that this transition is both feasible and crucial; we offer policy suggestions below.

MOTIVATIONS FOR THE EV TRANSITION

Globally, the motivations for EV adoption are varied and mutually reinforcing. They include desire for energy independence, foreign exchange loss, technology competitiveness, local pollution reduction, and climate change concerns and commitments.[33] EV adoption carries important social and environmental co-benefits: e.g., reduced greenhouse gas emissions contribute to improved public health outcomes,[34] batteries can be recycled to meet future material needs and mitigate the long-term impacts of mining,[35] and EVs operate more quietly than ICEVs, decreasing urban noise pollution.[36]

Importantly, countries that are net importers of oil believe a transition to EVs (and solar) is a way to lessen their dependence on imported fossil fuels and the concomitant need to pay for energy imports. China, for example, is the world’s largest net oil importer, and Chinese officials have long feared that the U.S. and its allies could weaponize this dependence by choking off its oil

supply and hamstringing the Chinese economy. Xi Jinping, President of the People's Republic of China, has previously said, "the energy rice bowl must be held in our own hands." Through its rapid adoption of EVs, China is now beginning to curb its reliance on foreign oil, and national oil consumption is expected to peak by 2027 before falling.[37] Likewise, for European countries, the transition to EVs lessens exposure to volatile oil markets. This is an increasingly salient concern in the wake of the Russian invasion of Ukraine, which shifted Europe's dependency on fossil fuel imports to more expensive imported LNG and triggered a reevaluation of its energy strategy.[38]

Countries that lack a large domestic legacy auto industry face lower political and economic barriers to shifting toward EVs. Norway, a first mover and world leader in EV adoption, was, in part, enabled by the absence of a domestic auto industry lobby and enormous, inexpensive hydropower.[39] For those with national auto industries, the imperative is to transition to competence in the new technologies that underpin EVs.

By contrast, the U.S. faces weaker structural incentives for the ICEV to EV transition. While the U.S. has been a Paris Agreement signatory, federal commitments have fluctuated sharply across administrations. This has created uncertainty for automakers and investors and contributed to an overall uncertain federal investment landscape in the requisite infrastructure and demand-side incentives needed for an EV transition at scale. Additionally, the U.S. is a net exporter of petroleum products and has a robust oil and gas lobby, which reduces the geopolitical and economic urgency to displace oil imports compared to nations reliant on foreign energy imports. Third, the U.S. maintains a large and politically salient ICEV manufacturing and fossil fuel industry base, anchored by automakers with deep regional economic significance. The strength of this legacy sector—both economically and politically—creates incentives for delay by investors in legacy producers and biases investment toward extending ICEV production rather than accelerating the pivot to EVs.

THE EV TRANSITION: DOMESTICALLY AND GLOBALLY

Globally, the EV market is growing rapidly, both in adoption and production. The U.S. market is not only growing more slowly, for reasons specific to the American market, but also because of policy fluctuations that, in their most recent reversal, have sought to block EV production, adoption, and energy for the grid to support it. Today, there is an apparent conflict between the global direction and U.S. developments.

THE EV TRANSITION IN THE U.S.

The U.S. EV transition is slowing against a backdrop of rapid global adoption and intensifying competition to control and profit from it. The U.S. trajectory remains slower and less certain than that of any other country. Domestic automakers face a dual challenge: scaling EV production to meet rising demand while navigating policy volatility, supply chain constraints, and a legacy manufacturing base still oriented toward ICE platforms.

U.S. EV DEMAND

In the last two years, EV demand growth in the U.S. has been slower than initially projected. Today, EV sales represent approximately 10% of U.S. auto market.[40] Bloomberg NEF projects that EVs will comprise 27% of U.S. passenger sales by 2030, revised down from its previous outlook of 48% of passenger EV sales.[41] This revision is, in large part, driven by the Trump administration's rollback of federal policies supportive of EV infrastructure and consumer demand.

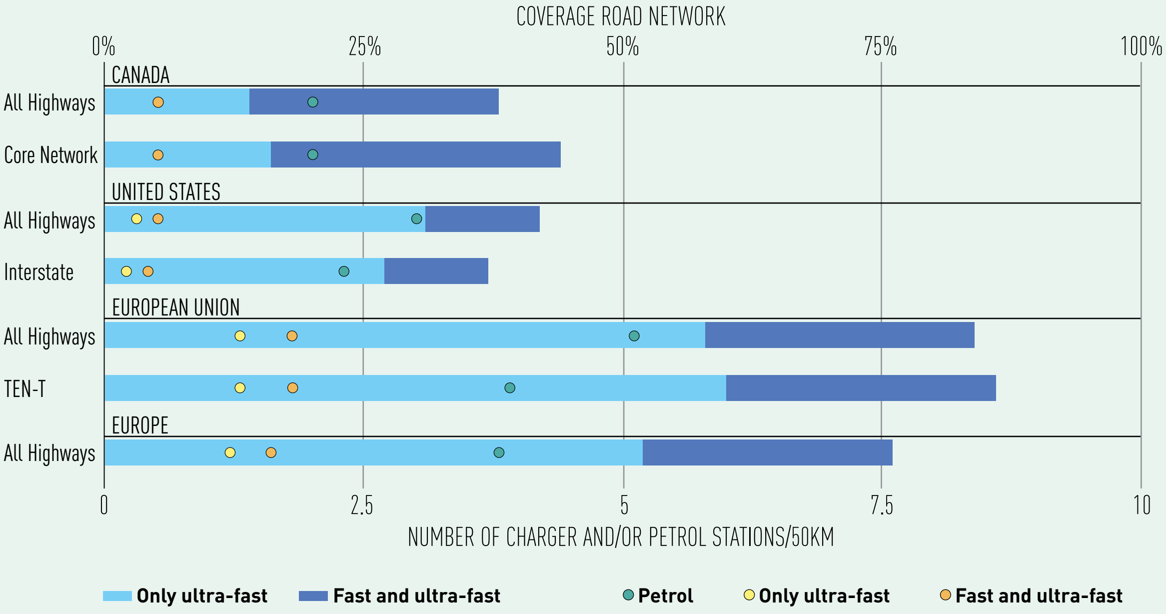
Furthermore, compared to global peers, American consumers have been reluctant to transition to EVs. A 2025 McKinsey consumer survey found that 32% of U.S. consumers have no intention to switch to EVs, and only 29% of U.S. consumers intend to purchase a PHEV or BEV as their next vehicle. In comparison, only 3% of Chinese and 19% of European consumers express no intention of switching to EVs, and 82% of Chinese and 50% of European consumers intend to purchase a PHEV or BEV vehicle next.[42]

Top concerns that U.S. consumers have identified as barriers to EV adoption include range, price, and charging infrastructure.[43] Survey respondents identified an average real driving range of 310 miles as the requirement to convince them to switch to an EV. Consumers generally consider edge cases, such as vacation trips, when estimating their needs. Notably, an increasing number of EV models coming onto the market today meet this objective.[44]

In the U.S. market, EVs continue to sell at a premium to ICEVs, and affordability remains a critical constraint to mass adoption.[45] In 2024, only 17% of BEVs were sold at a price less expensive than conventional ICEV equivalents, although this rate is an improvement over only 4% in 2021.[46] As of December 2024, the average transaction price of a new EV was US $55,000, or 12% more than that of an ICEV.[47] Note, however, that this number is partially inflated by the relative dominance of premium and luxury segments in the EV models available for sale. Automakers are beginning to address this gap with the Ford truck platform mentioned above, GM's new Bolt, and Tesla's cheaper Model 3 and Model Y.[48] Under the 2022 Inflation Reduction Act (IRA), the federal government sought to help address this EV premium and incentive adoption by providing a consumer tax credit of up to US $7,500 for qualifying new EVs and US $4,000 for qualifying used EVs.[49] However, the One Big Beautiful Bill, enacted in July 2025, terminated these tax credits effective September 30, 2025, introducing an additional headwind for EV affordability and adoption in the U.S.[50]

Infrastructure is another key bottleneck, particularly in the U.S. market. European highways have greater charger coverage than American highways, both for chargers overall and for high-speed DC fast chargers. Less than half of Americans live within 1 kilometer of a charging station, a much lower rate than in Europe. As of 2024, on American highways, gas stations continue to outnumber EV charging stations six-to-one and DC fast chargers ten-to-one.[51] This limits convenience and compounds consumer range anxiety. However, it is important to note that 86% of Americans live in homes where charging can take place on-site.[52] It would also be possible to install charging stations in multi-family dwellings or in streetlights (as Paris has done) — something that could be paired with requiring rooftop solar, thereby reducing the costs of charging. Asenio et al. show that charger availability has a significant positive effect on EV adoption.[53]

FIGURE 1: PERCENTAGE OF HIGHWAYS THAT ARE COVERED BY A FAST OR ULTRA-FAST CHARGER AND/OR PETROL STATIONS FOR SELECTED ROAD NETWORKS (2024)



The U.S. lags Canada and Europe in building out charging infrastructure on highways, and EV charger deployment lags far behind gas station coverage in the United States.

Source: International Energy Agency, “Percentage of Highways That Are Covered by a Fast or Ultra-Fast Charger and/or Petrol Stations for Selected Road Networks, 2024,” in *Global EV Outlook 2025* (Paris: IEA, 2025), https://www.iea.org/reports/global-ev-outlook-2025.

Finally, evidence shows that EV adoption in the U.S. is also highly partisan. Democratic voters are significantly more willing to adopt EVs than Republicans. Ideological differences, in part, may explain the lower willingness of Americans to adopt EVs relative to consumers in other major auto markets.[54]

Despite some headwinds in the U.S. EV market, such as range anxiety, affordability, infrastructure, and partisanship, EV adoption is increasing, albeit at a potentially slower rate than previously anticipated. Developments that will continue to advance the adoption of EVs in the U.S. market include:

- **THE EXPANSION OF THE CHARGING INFRASTRUCTURE.** The 2021 Bipartisan Infrastructure Law (BIL) allocates US $5 billion in funding to states to develop the country's EV charging infrastructure. These investments have been slow to materialize; by the end of 2024, only 31 charging stations funded by this program were operational, but now that initial planning processes have concluded and the Trump Administration has obeyed court orders to unfreeze the funding, the deployment of this funding will likely accelerate. Ultimately, the funding is expected to support up to 30,000 DC charging ports at 7,500 sites nationwide.[55] Additionally, private investment by charging providers, automakers, and retailers—in new public charging ports continues to be robust. As of July 2025, there are now over 225,000 public charging ports across the United States, compared to less than 100,000 in January 2021.[56] Past estimates of announced capacity indicate that the private sector intends to deploy an additional 164,000 DC fast chargers and 1.5 million Level 2 chargers at public locations and workplaces between 2023 to 2030.[57]
- **THE INCREASING COST COMPETITIVENESS OF EV MODELS IS NOTABLE.** EV costs are expected to decrease in the U.S. market in the coming years, driven primarily by falling battery prices, increased competition, and greater manufacturing efficiency. In the U.S. market, the upfront purchase price for new EVs is projected to reach parity with gas-powered cars within the next few years. To illustrate, a fully-loaded BYD SUV can now be purchased in Mexico for US $30,000, and prices are expected to drop even further.[58] Cox Automotive data shows that the price gap between both new and used EVs and ICEVs is continuing to narrow.[59] Furthermore, higher up-front sticker prices for EVs are more than offset by lower operating expenses, given EVs require less maintenance, and the cost of electricity for charging is significantly lower than the cost of fuel.[60]
- **EXPANDING MODEL VARIETY AND AVAILABILITY.** Limited model availability is a key factor restraining EV sales; Gillingham et al. found that in vehicle segments where an EV option is available, it performs well compared to its conventional ICEV counterpart, suggesting that greater product range is likely to induce greater EV market penetration.[61] Historically, EV model availability has grown from under 20 in 2012 to nearly 130 in 2024. Another 25 non-luxury and 25 luxury models are expected to launch between 2025 to 2028.[62]
- **IMPROVED EV PERFORMANCE.** Technological improvements in EVs, particularly increases in range, charging speed, and durability, have made EVs more attractive by directly addressing common consumer concerns. Already, there are EVs on the market with ranges of over 400 miles per charge, and charging times are increasingly shorter.[63] Finally, in terms of durability, EVs have already surpassed ICEVs.

The key point is that, although American consumers may lag the global market in EV adoption and new policies under the Trump Administration threaten to reduce domestic EV demand in the near-term, the EV revolution is still coming to the United States. Driven by new charging infrastructure, improved cost competitiveness, expanding variety, and enhanced EV technology performance, EVs will have an ever-stronger position in or perhaps eventually dominate the U.S. auto marketplace.[64]

U.S. EV PRODUCTION

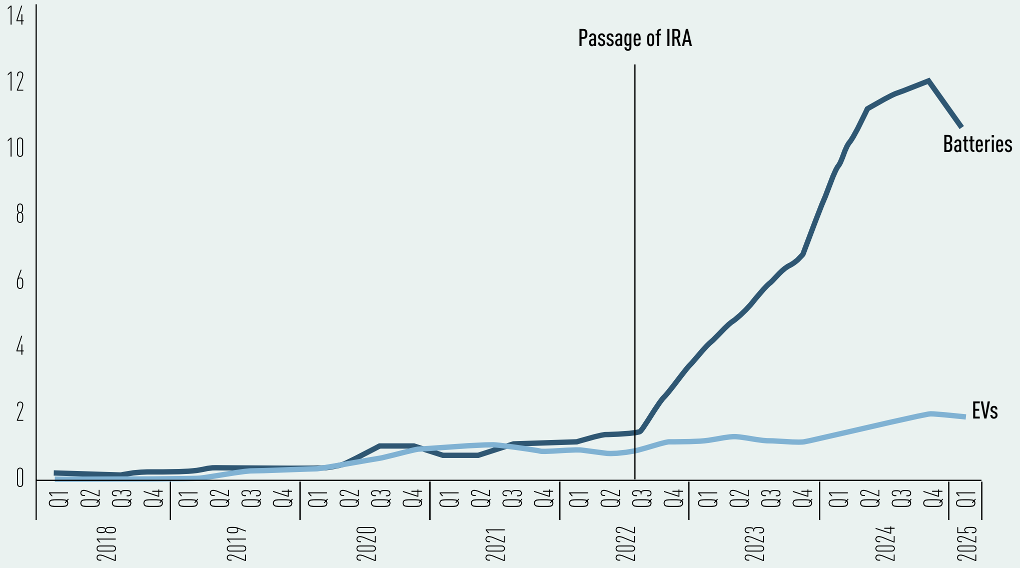
The modern revival of EV production in the U.S. began with two key events: the introduction of the Toyota Prius (which leveraged nickel metal hydride battery technology previously supported by the U.S. Department of Energy) and the establishment of Tesla Motors, the Silicon Valley-based entrant founded in 2003 and then acquired by Elon Musk. Tesla put the U.S. at the frontier of EV innovation. With support from a US $465 million low-interest loan through the U.S. Department of Energy's Advanced Technology Vehicles Manufacturing Loan Program, Tesla began mass producing vehicles in 2012 with the introduction of its Model S and quickly surged to the global EV leader.[65] Tesla's announcement and subsequent success spurred many major automakers to accelerate work on their own electric vehicles, such as GM, which announced its Chevy Volt in 2010.[66]

Aside from Tesla, however, the U.S. quickly came to lag Europe and especially China in EV production and adoption. The 2021 Bipartisan Infrastructure Law and 2022 Inflation Reduction Act attempted to address these trends through new grant and loan programs to support domestic EV supply chain manufacturing. These laws successfully catalyzed a surge in EV-related manufacturing investment, concentrated in a new "Battery Belt" stretching from Michigan to Georgia. In addition to federal policy incentives, this clustering of investments has been motivated by the presence of legacy auto manufacturing infrastructure and skilled labor availability. As of Q1 2025, the Clean Investment Monitor at the Rhodium Group tracked 123 operating battery manufacturing projects, plus an additional 65 facilities under construction and 44 announced but not yet under construction; if all these projects were to materialize, annual production capacity would reach 1,172 GWh for cells and 976 GWh for modules. With respect to EV manufacturing projects, the Clean Investment Monitor has tracked 79 operational projects, along with an additional 27 facilities under construction and 16 facilities announced with specific locations and construction timelines. Together, these announcements represent the capacity to produce 6.48 million EVs.[67] Yet, these gains are fragile. Policy rollbacks threaten planned investments, as realized manufacturing investment in these sectors has already slowed, and US $6 billion in battery manufacturing announcements were scrapped altogether in the first quarter of 2025. (See figure 2)

A unique feature of the U.S. EV market is that, in part, due to a fluctuating U.S. EV policy regime and unpredictable consumer preferences, the American manufacturing base remains structurally tied to multi-propulsion strategies rather than developing automobiles specifically designed for electric propulsion.[68] (See figure 3)

This inability to completely commit to EVs has meant that incumbent automakers have been unable to completely transition and thus must support multiple powertrains on the same assembly line. This results in lineside complexity, which requires additional tooling, broader worker

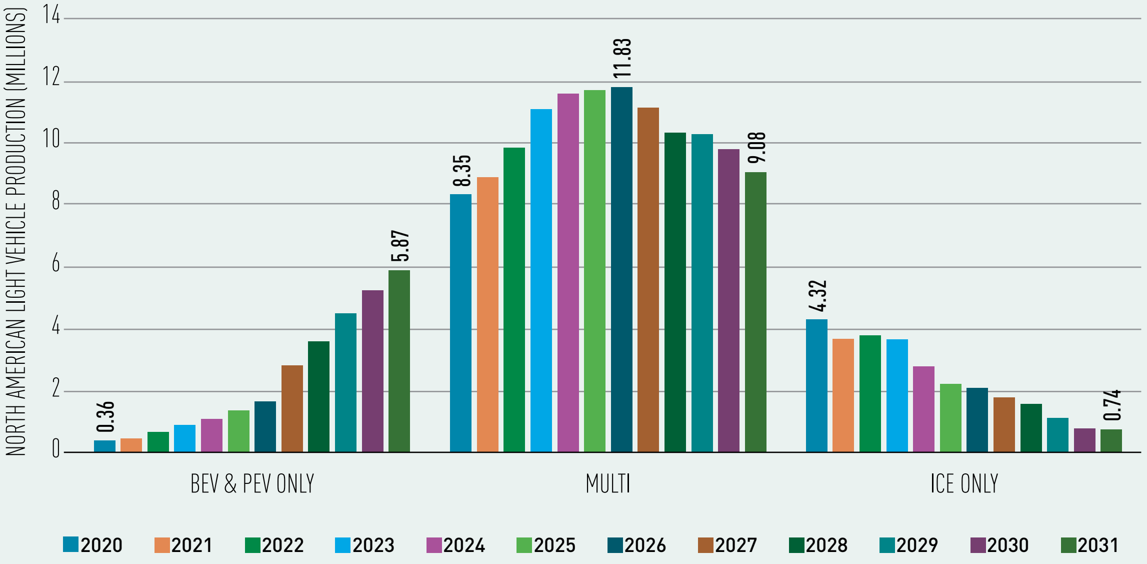
FIGURE 2: INVESTMENT IN EV SUPPLY CHAINS IN THE U.S. (BILLION 2023 USD)



The IRA catalyzed a new wave of battery manufacturing investment that has slowed beginning in 2025, likely in response to a changing federal policy landscape.

Source: Michael Delgado, Jessica Chan, Kate Larsen, et al., "FIGURE ES3: IRA supercharges US battery manufacturing investment, but US EV future now in doubt," in *Global Clean Investment Monitor: Electric Vehicles and Batteries* (Rhodium Group, 2025), 6.

FIGURE 3: NORTH AMERICAN PRODUCTION VOLUME PER PLATFORM CLASSIFICATION:
2020-2023, 2024E-2031E



North American automakers are hedging their bets with multi-propulsion systems.

Source: Kristin Dziczek, Susan Helper, and John Paul MacDuffie, "North American Production Volume per Platform Classification, 2020-2023, 2024E-2031E," in *Lightweighting and Vehicle Electrification: Balancing Efficiency and Performance* (unpublished working paper, Philadelphia: University of Pennsylvania, 2025).

training, and more frequent changeovers, all of which slow throughput. It also imposes design compromises: multi-propulsion platforms often retain ICE-oriented structural elements, which add weight, reduce aerodynamic efficiency, and undercut EV performance. These compromises dilute the advantages of clean-sheet EV architectures, which are optimized for battery placement, weight distribution, and energy efficiency.

Maintaining multiple powertrain programs stretches engineering resources and raises fixed costs, especially problematic when competitors like China's BYD or NIO focus exclusively on BEVs and achieve lower costs in significant part through scale. Moreover, this strategy slows the learning curve—the iterative design, manufacturing, and cost-reduction cycle that drives competitive advantage in emerging technologies. While multi-propulsion hedging may appear prudent amid policy uncertainty and uneven consumer demand, it risks delaying cost parity, blurring brand positioning, and ultimately ceding scale, innovation speed, and market share to pure-play EV rivals.

There is some indication that U.S. incumbent automakers may soon move away from the multi-propulsion platform approach. In August 2025, Ford announced a US $5 billion investment in its Louisville Assembly Plant to retool assembly lines for producing a "Ford Universal EV Platform" and "Ford Universal EV Production System" that will leverage one platform for multiple electric models. Compared to a typical vehicle, the new manufacturing model is designed to reduce parts by 20%, fasteners by 25%, workstations by 40%, and assembly time by 15%—ultimately driving manufacturing innovation and reducing vehicle costs.[69]

Notably, Ford's move to simplify its physical manufacturing footprint parallels its decision earlier in 2025 to postpone the FNV4 software project, an ambitious attempt to create a unified "electronic brain" for all software across both ICEV and EV models. The cancellation was attributed to ballooning costs and persistent integration delays, including roughly US $4.7 billion in software and EV-related losses in 2024.[70] The failure illustrates the structural disadvantage faced by legacy automakers: adapting software to existing multi-propulsion vehicle designs and integrating across a decentralized supplier network presents a coordination challenge. Achieving a centralized, software-first system across both EV and ICE models adds yet another layer of complexity. In comparison, Tesla's software-defined architecture—developed from a clean sheet with in-house control of both hardware and software — enables over-the-air updates, rapid iteration, and a unified operating system. While still early, together these shifts by Ford may signal a growing recognition among legacy U.S. automakers that despite having a shareholder base focused on short-term outcomes, clean-sheet EV systems in both hardware and software are critical to their viability.

While U.S. incumbent automakers have only had modest success in producing and selling EVs, Tesla was the global EV leader until 2024. Today, it has factories in the U.S., China (its largest), and Germany. These factories not only serve the domestic market but also export to other markets. In 2024, Tesla exported 420,000 vehicles from its U.S. plants and served the Asian market from its Chinese factory. Unfortunately, partly due to slow model refreshing and partly due to Elon Musk's involvement in the Trump Administration, the brand appears to have been damaged, especially in Europe. However, Tesla has undoubtedly contributed significantly to the growth of the EV industry in the U.S. and globally.

THE INTERACTION OF THE U.S. EV MARKET WITH THE POLICY LANDSCAPE

The U.S. EV policy environment has been marked by rapid shifts that complicate long-term investment decisions for manufacturers and suppliers. While the past several years saw unprecedented federal support for EV manufacturing, adoption, and supply chain development, recent rollbacks threaten to erode momentum even as global competitors are scaling up. The result is a U.S. policy landscape that alternates between strong incentives and sudden reversals—a "whiplash" that undermines investor confidence and slows domestic capacity growth.

Programs introduced under the 2021 Bipartisan Infrastructure Law and the 2022 Inflation Reduction Act aimed to address critical bottlenecks—from providing supply-side tax credits for domestic battery production, to including demand-side incentives such as an EV consumer tax credit, to laying the requisite infrastructure by building a nationwide charging network.

However, many of these investments were not fully operational before the transition to the Trump Administration and are now jeopardized due to the passage of the One Big Beautiful Bill Act and other actions taken by the Trump Administration. Many of the investments in the EV transition secured by the Biden Administration are now being curtailed or repealed, for example:

- The 30C charging credit expires June 30, 2026.
- Consumer and commercial EV tax credits (25E, 30D, 45W) expire October 1, 2025, as opposed to the initial schedule of December 31, 2032.
- The 48C credit phases down earlier for critical minerals, while domestic content requirements under 45X have tightened.
- Enforcement has been suspended for the Corporate Average Fuel Economy (CAFE) regulations, which set fuel economy standards for automakers.[71] This likely will be mitigated by the ability of states to impose their own CAFE standards, though even this is being challenged by the Trump Administration.

These shifts directly impact the economics of U.S. EV manufacturing. Automakers and suppliers plan investments on 5–10-year horizons; when incentives vanish mid-project, companies face stranded costs or delay scaling. Some domestic producers of battery manufacturing facilities that were announced but not yet operational have canceled their projects altogether, while others are reportedly switching to manufacturing batteries for other end-uses, such as long-duration energy storage (LDES). Domestic producers already struggling to achieve cost parity are further disadvantaged when Chinese or European rivals operate under more stable, long-term policy regimes.

Even so, certain positive signals remain, particularly concerning the battery materials supply chain. For example, under the One Big Beautiful Bill, the Department of Defense (DoD) was allocated US $7.5 billion in funding for critical minerals and streamlined permitting for mining projects. These targeted supports could help secure key parts of the EV supply chain. Much will depend on whether DoD funding effectively supports commercially competitive projects or aims at essentially gold-plated solutions of little use in the commercial sectors. Additionally, albeit with revised guidance, the Trump Administration has now unfrozen funding for the US $5 billion National Electric Vehicle Infrastructure Program created by BIL, which provides formula funding to U.S. states to build a nationwide network of EV chargers along designated highway corridors. However, without consistent, long-term consumer and manufacturing incentives, U.S. market share will stagnate and any chance at technological leadership will disappear.

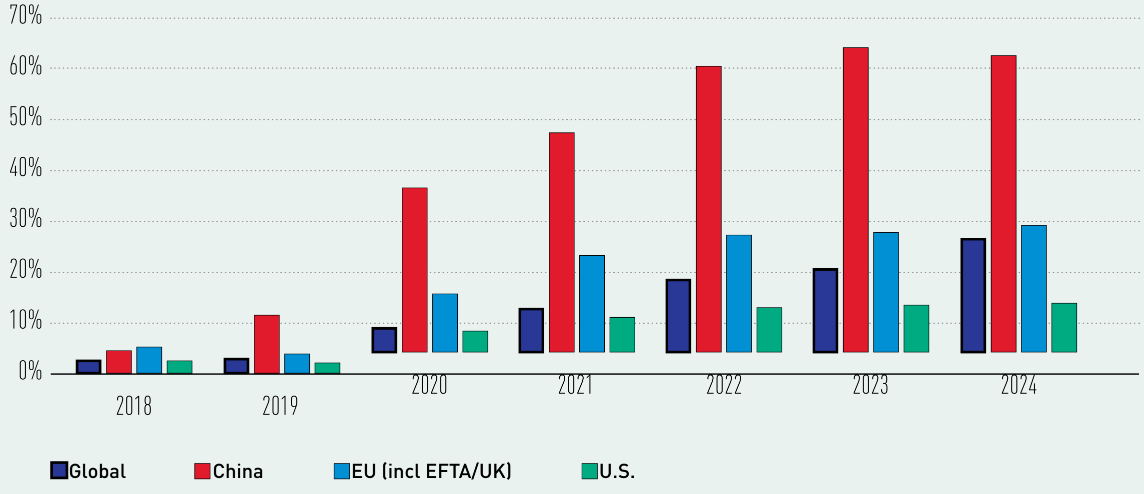
THE EV TRANSITION GLOBALLY

GLOBAL EV DEMAND

Global EV adoption is accelerating rapidly. In China, EVs now account for more than half of all new passenger car sales, creating a robust domestic market that reinforces manufacturing scale and cost competitiveness. The Chinese EV market is responsible for nearly 65% of global EV sales. The EU, buoyed by regulatory mandates and high fuel costs, is also on a steeper adoption curve than the U.S. and is responsible for 17% of global sales. The remaining 18% is composed of sales to the rest of the world. (See figure 4)

Global EV demand is expected to continue to climb over the coming decade, reaching the 50% mark in 2031. BEVs are expected to make up the lion's share of EV demand, whereas PHEVs are projected to hold steady at approximately 5% of the global light-duty market through the next several years.

FIGURE 4: EVS AS % OF NEW CAR SALES BY GLOBAL REGION: 2018-2024



China leads the world in EV adoption. The U.S. trails both China and EU peers.

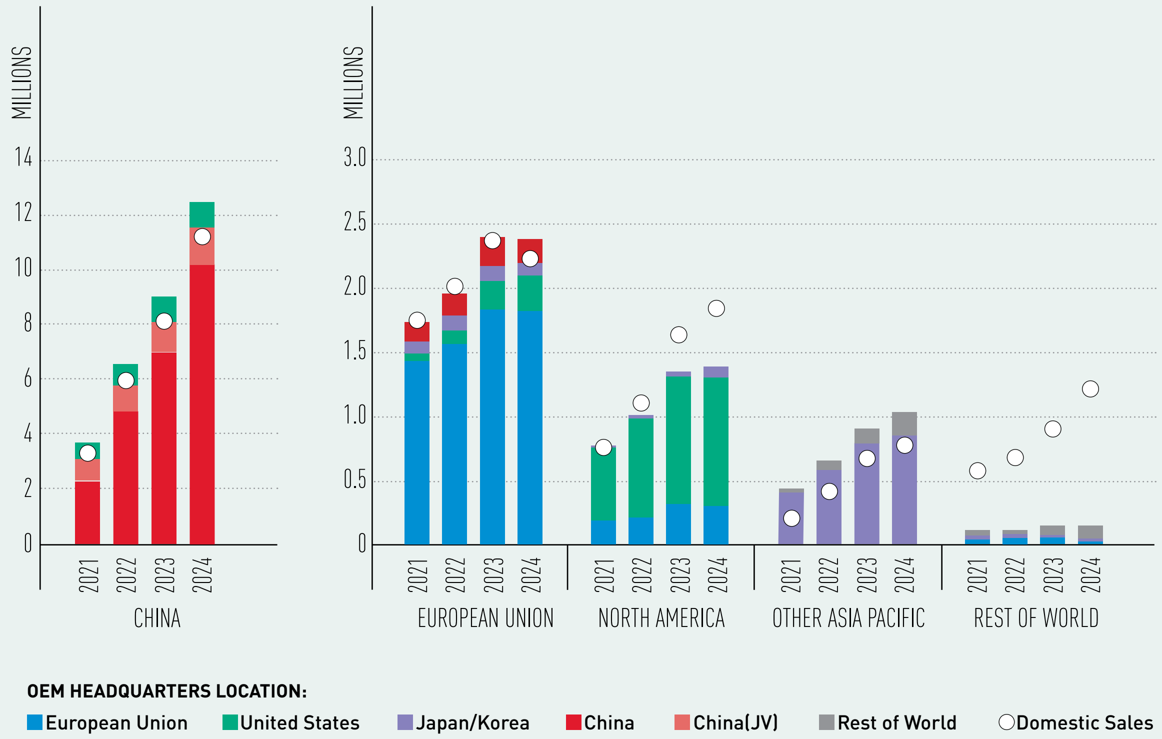
SOURCE: IEA

GLOBAL EV PRODUCTION

China dominates global EV production, with its firms leading at every stage in the supply chain—from mining and refining battery materials to final vehicle assembly and end-of-life recycling. Chinese-headquartered companies are complemented by global battery leaders such as CATL, which alone supplies more than one-third of the world's EV batteries.

This national vertical integration, combined with strong state support, aggressive R&D, loose regulation, and a dense supplier network, has resulted in China becoming the global leader in both cost and speed of innovation. (See figure 5)

FIGURE 5: GLOBAL EV PRODUCTION BY COUNTRY AND OEM HEADQUARTERS (2021-2024)



Note: OEM = original equipment manufacturer; JV = joint venture. Other Asia Pacific includes Australia, New Zealand, Japan, Korea, India and Southeast Asia. North America includes Canada, the United States and Mexico. Tesla is the only foreign OEM producing electric cars in China that is not part of a joint venture with a Chinese OEM.

China dominates in global EV production, and, in a break with historic ICEV manufacturing trends, the overwhelming majority of Chinese EV production is by Chinese headquartered firms.

Source: International Energy Agency, "Production of electric cars by region and location of car manufacturer headquarters, 2021-2024 International," in *Global EV Outlook 2025* (Paris: IEA, 2025), 32.

THE EV TRANSITION: CORE CHALLENGES TO U.S. INDUSTRY

The current EV market is the result of not only technology paradigm shifts but also the emergence of new business models, lower barriers to entry for production, and China's sustained and targeted industrial policy.

CHALLENGE 1

TECHNOLOGICAL PARADIGM SHIFTS

The powertrain swap from ICE to BEV represents a systemic transformation of business models, value chains, and innovation strategies. There is the potential that the vertically integrated, assembler-centric production pyramid will be undermined.[72] This shift parallels earlier ruptures in industries like information technology in the 1980s, where "Wintelism" redistributed value from an integrated IBM to component and platform providers like Intel and Microsoft through vertical disintegration, modularization, and "open-but-owned" standards. This ultimately enabled Intel and Microsoft to establish dominance by controlling key chokepoints in the supply chain.[73] In the EV context, the key points of value capture are migrating toward batteries, semiconductors that permit control of the entire car system, AI-driven software, and connectivity systems—domains where many U.S. automakers have weaker capabilities relative to specialist suppliers. It remains an open question whether new dominant integrators emerge to control suppliers or whether, as in "Wintelism," suppliers with a chokehold capture increasing value. Indeed, a new mixed model is likely.

Vertically integrated EV leaders such as BYD and Tesla are leveraging control over both hardware and software to accelerate innovation and manage supply chain shocks. In contrast, legacy automakers and many other startups in China and the U.S. (Rivian, Lucid, etc.) that depend on external suppliers for batteries, autonomous driving systems, or infotainment may be relegated to low-margin assembly roles. In China, where the EV industry is evolving rapidly, new entrants such as Huawei and Xiaomi are entering the EV industry, while purchasing rather than producing most of their key components such as batteries.[74]

Paradigm shifts often reconfigure industry control points. Apple successfully integrated hardware, proprietary software, and a captive ecosystem to capture a disproportionate share of value, create consumer lock-in, and control innovation trajectories. By contrast, pure assemblers such as Dell were squeezed. Will EVs follow this pattern with clean-sheet designs that integrate propulsion, energy management, connectivity, and user interface into unified platforms? The control point may shift from mechanical engineering to orchestrating entire technology stacks.

NVIDIA–Mercedes-Benz partnership offers a contrasting example. NVIDIA supplies the Drive platform, which defines much of the vehicle's autonomous and AI capability, while Mercedes handles vehicle integration.[75] This raises the question—echoing the Wintel era—of whether in the future EV market power will reside with the automakers that manage the brand and end-customer relationship, or with technology providers that own critical intellectual property and shape certain dimensions of performance and features.

However, there are significant differences between the auto industry and electronics. Scholars such as MacDuffie, Jacobides, and Tai (2023) and Calvo (2025) point to the outsized role that automakers play in systems integration and liability management. Thus, at least some auto assemblers (either entrants or legacy) may be able to leverage these capabilities to retain power in the value chain. Current electric vehicle designs, in fact, are more integral than are ICEV, as measured by the number of interactions across components.[76]

Whether a dominant business model will emerge is, at this point, unanswerable.

CHALLENGE 2

THE EMERGENCE OF NEW ENTRANTS

The EV transition has lowered some barriers to entry in vehicle manufacturing, particularly for firms with expertise in batteries, software, and electronics. Unlike ICE platforms—which now require decades of accumulated know-how in complex mechanical systems and expertise in both engine production and final assembly—BEV platforms can be developed more rapidly using modular battery packs, off-the-shelf power electronics, and contract manufacturing.[77] This shift has opened the door for startups, technology firms, and new global entrants to compete in the U.S. market.

Domestic newcomers like Rivian and Lucid are pursuing performance and premium niches.[78] Chinese new entrants and European incumbents are targeting all market segments. In parallel, consumer electronics giants like Xiaomi and telecommunications giants like Huawei are leveraging their software ecosystems, connectivity expertise, and design skills to begin EV production and sales. While some entrants like BYD and Tesla are highly integrated, others adopt asset-light strategies, outsourcing assembly while focusing on brand, customer experience, and technology differentiation.[79]

For incumbent U.S. automakers, this surge of competition compresses timelines for product launches, forces faster iteration on software and battery technology, and threatens market share in segments where they have historically been dominant. Without a decisive pivot toward EV-centric architectures, incumbents risk being undercut on cost, speed-to-market, and user experience.

CHALLENGE 3

CHINA[80]

China is the global leader in EV and battery technology, production, and sales. Chinese firms are rapidly expanding their international footprint, seizing market share by offering reasonable-quality EVs at extremely competitive prices. Their recent success is the result of a deliberate, multi-decade strategy that developed an entirely new EV sector alongside China's existing ICE industry. This industry was composed of state-owned enterprises (SOEs) that operated joint ventures with foreign auto firms (JVs) and benefited from targeted industrial policy.[81]

In the 1990s, Chinese SOEs established JVs with Western ICE manufacturers, but these arrangements brought two major problems: minimal technology transfer from foreign partners and a persistent cash outflow from China through profits extracted by the foreign JV partners. These SOEs had little incentive to invest in new EV technologies. Recognizing this, the Chinese government began funding small experimental EV projects in the early 2000s. By 2010, a more coherent national policy emerged to develop "new energy vehicles" (NEVs), with local governments providing direct support to entrepreneurial firms, promoting industry–university R&D partnerships, and fostering end-to-end supply chains from mining to recycling.[82]

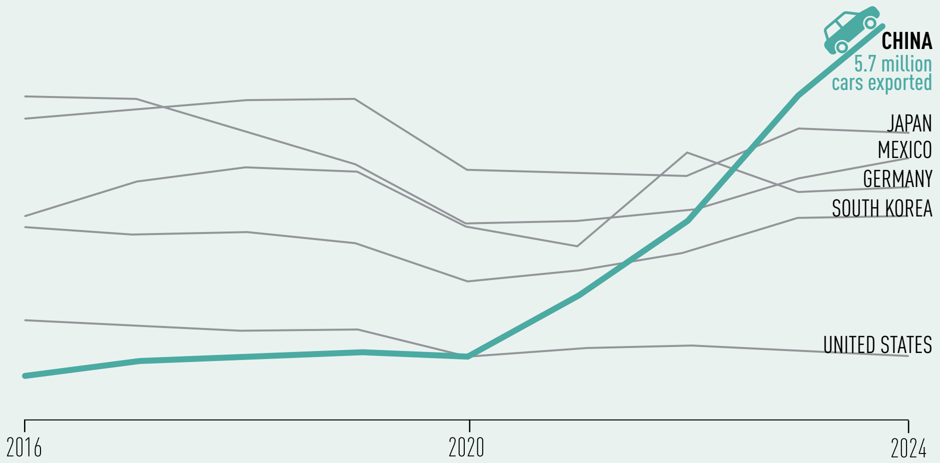
In 2013, the Chinese central and local governments began funding small-scale adoption programs and building out critical infrastructure using subsidies, government purchasing, license plate quotas, and other demand-side incentives to stimulate the market. Importantly, when corruption in subsidy programs surfaced, the government responded by introducing performance-based standards—such as minimum range requirements—that accelerated product-quality improvements. By 2022, the market had begun to "normalize" through gradual subsidy reductions and greater reliance on competitive forces, some of which had become so ferocious that by 2025, the government was trying to reduce the ruinous price competition.[83]

The results have been transformative. BYD and CATL—both originally battery makers—emerged as global leaders, joined by numerous automakers like NIO, XPeng, and Geely. The geography and proliferation of these new entrants resemble the early U.S. auto industry—a period marked by rapid innovation and overinvestment, which led to overcapacity.[84] In 2025, Chinese passenger car exports continued to grow rapidly, with Chinese firms controlling two-thirds of global EV battery capacity and leading in lithium iron phosphate (LFP) battery technology.[85] (See figures 6 and 7)

Chinese firms employ differing business models. BYD adopted a vertically integrated approach, designing and manufacturing nearly all core EV components in-house—from battery cells to final vehicle assembly—and even sourcing its battery materials. This maximizes control over quality, costs, and speed of innovation.[86] Potentially, this risks a lack of access to innovative or cheaper components if BYD loses its leadership. Indeed, BYD battery leadership is challenged by CATL. CATL, in contrast, is at the center of a modular production model, as it produces standardized battery packs (like the "Qilin" pack) that can be integrated into multiple OEM platforms. This broadens its customer base and leverages economies of scale.

Finally, it is critical to recognize that China is rapidly becoming the supplier of EVs, EV batteries, and battery components to much of the developing world. Chinese EVs are rapidly penetrating most of the rest of the world and, in the process,

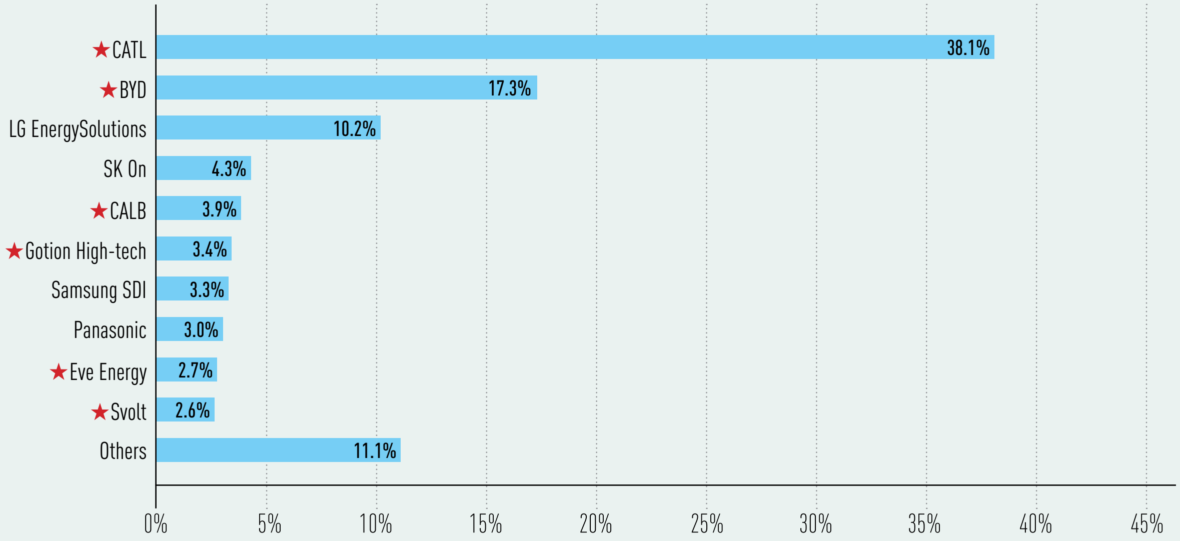
FIGURE 6: TOP CAR EXPORTERS IN THE WORLD



China has become the world's largest car exporter, moving rapidly since 2020 to overtake the United States, South Korea, Germany, Mexico, and Japan.

Source: Agnes Chang and Keith Bradsher, "How China Became the World's Largest Car Exporter," *New York Times,* 2024. Data source: Alix Partners.

FIGURE 7: MARKET SHARE OF WORLD'S TOP EV BATTERY MAKERS (JANUARY TO APRIL 2025)



★Starred producers are Chinese-headquartered firms.

Chinese players dominate the global battery sector, and none of the leading firms are U.S.-headquartered.

Source: Lei Kang, "Market share of the world's top EV battery makers (Jan-April 2025)," *CnEVPost,* 2025. Data source: SNE Research.

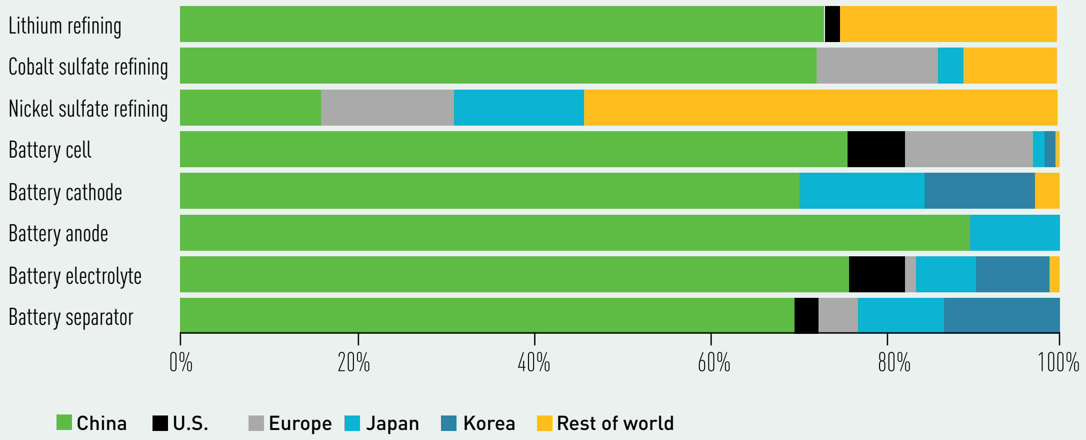
are eroding the European, Korean, and Japanese auto firms' market share, as consumers switch to the inexpensive Chinese EVs. To further cement their increasing hold on these markets, Chinese firms are building battery and assembly facilities in these countries. (See figure 8)

China's domestic tipping point is already here. Over 50% of its new passenger vehicle sales are EVs. Further, in addition to the new entrepreneurial firms that drove the early growth of the industry, the SOE joint ventures have now pivoted to EVs, and new entrants from the electronics industry, in particular, Huawei and Xiaomi, are also introducing EVs. As a result of competition, massive domestic overcapacity is pushing exports to markets outside the U.S., sparking fear and attempts to regulate Chinese penetration in countries with strong domestic firms. At the same time, Chinese firms are investing in NEV assembly and battery production facilities in third countries to circumvent tariffs and deepen global supply chain integration.

Technologically, Chinese EV and battery manufacturers are advancing rapidly. They use standardized parts and advanced software to reduce costs and iterate faster than global competitors, leveraging massive economies of scale and rapid iteration and improvement dynamics throughout the entire supply chain. The continuing development of Chinese manufacturing prowess rests on a powerful combination of central planning, setting objectives and goals, and providing resources, while also generating competition from rival regions and private sector players. Jean Pisani-Ferry, a leader in developing French economic strategies over the past decades, remarked at the ceremony awarding him the French Legion d'Honneur:

> *China's strength lies in combining planning and competition, something we are unable to do. That is the key to their success...Planning without competition generates unproductive rents. Competition without planning means running the risk of short-term thinking.*[87]

FIGURE 8: GLOBAL CONTROL OF THE BATTERY SUPPLY CHAIN (2023)
The country dominates much of the battery industry



Chinese players dominate the entire battery supply chain.

Source: Eric Olander, "Reality Check for U.S. and EU Policymakers Planning to Decouple from China's EV Battery Supply Chain," *The China-Global South Project,* April 3, 2023. Data Source: BloombergNEF

Certainly, China's success in developing a manufacturing powerhouse, which includes EVs, involved significant subsidies and questionable environmental and labor policies and practices. There is evidence that some of the low pricing of vehicles made in China is due to labor suppression and lax environmental standards. Importantly, these practices are not just relics of the past but are ongoing. Chinese dominance in auto parts has also had environmental costs, as more of China's energy has been generated from coal, unlike in the U.S. or Europe. For example, batteries in Europe are 37% less carbon-intensive than those made in China; In the case of Chinese steel, research suggests that Chinese blast-furnace steel is 10-20% more carbon-intensive than steel made in Western Europe.[88] Wages in the industry remain low and have fallen even further during the three-year price war engendered by the brutal competition among Chinese producers. A Reuters analysis in 2023 found wages that varied from US $1.93 to US $4.27 per hour, significantly below the average wage in China. In contrast, auto assembly wages in the U.S. range from US $18/ hour (for many suppliers and some non-union automakers) to US $35 (for a senior UAW autoworker). In sum, BYD and other Chinese automakers pay wages far below those of autoworkers in developed countries, leading to perhaps a 15-20% cost advantage, since direct labor costs account for about 20% of total costs in car production.[89] [90]

Toxic waste is another concern; lax treatment of such waste is one reason for China's dominance in the refining of rare-earth minerals. A July 2025 *New York Times* report detailed ongoing production of highly toxic waste because of China's rare-earth mining and refining, detailing (despite official repression) instances of human birth defects, sick animals, and clouds of poisonous dust.

> *"Achieving dominance in rare earths came with a heavy cost for China, which largely tolerated severe environmental damage for many years. The industrialized world, by contrast, had tighter regulations and stopped accepting even limited environmental harm from the industry as far back as the 1990s, when rare earth mines and processing centers closed elsewhere, as it outsourced this production to developing countries and then used these developing nations for recycling or dumping, as the case may be."* [91]

Reducing Chinese dominance by promoting rare-earth mining and refining in other locales may require a greater emphasis on recycling, asking consumers to pay more to avoid these environmental costs, or encouraging those living in the U.S. (likely in poorer areas like Native American reservations) to conduct such mining and processing on their lands.

For all these reasons (consistent policy, innovative management, and lower environmental and labor standards), the Chinese have built a formidable EV ecosystem. Our challenge is how to respond.

For U.S. automakers, the China challenge does not require just competing on cost—it also requires catching up to an ecosystem designed for speed, scale, and continuous innovation. There are some practices the U.S. should not imitate or facilitate access to the U.S. market for, such as the labor and environmental practices discussed above. There are signs that the low prices Chinese automakers are currently offering are not sustainable. This is because they depend on continued loans from municipalities that firms may not be able to repay, and lengthy payment terms that are likely to drive suppliers out of business. While the Chinese challenge is immense, all is not lost. And there is much to learn from China.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THE ECONOMIC AND NATIONAL SECURITY IMPLICATIONS OF THE TRANSITION TO EVS

The United States was an early pioneer in EV and battery technology. Yet today, most of the significant advances are emerging from Chinese firms.

The U.S. auto industry risks becoming a melting ICE island —sustaining internal combustion and hybrid production for the next 5–10 years while much of the rest of the world transitions toward BEVs. The position of American producers in global markets has already declined steadily and will weaken even further. In 1985, the largest auto market in the world was the United States. Today, the U.S. market is only about 60% of the Chinese market, and China is also the largest auto exporter in the world. In 2024, China exported roughly 1.25 million EVs—about 40% of global EV exports. Economies of scale and scope will likely accrue to China. As a result, China will likely dominate the international markets transformed by the transition of EVs.

In the near term, in the United States, the ICEV protection strategy may be viable as domestic demand for ICE-powered trucks and SUVs remains strong. U.S. automakers can continue to generate profits from legacy products. However, by the early to mid-2030s, the global market is expected to be dominated by cost-competitive, high-performance BEVs. At that point, the U.S. industry could face a sudden erosion of the domestic market as global EV producers enter with products refined over multiple design cycles and less expensive than ICE vehicles. Also, as the world moves away from internal combustion, the entire petroleum infrastructure will begin to degrade as firms no longer will invest in a dying industry.

The stakes extend beyond the auto sector itself. The technologies and skills underlying ICE vehicles will decline in importance globally. Moreover, the auto industry is a major source of demand for steel, aluminum, plastics, semiconductors, machine tools, and advanced manufacturing equipment. If the U.S. automotive base weakens, the ripple effects will undermine competitiveness in these upstream sectors, shrink economies of scale, reduce incentives for domestic innovation, and degrade capabilities that are also critical to defense and clean energy manufacturing. In effect, losing ground in EV manufacturing risks triggering a cascade of losses across the U.S. In sum, U.S. innovation capacities and leadership will be diminished.

This decline is crucial to the economic and social stability of the country, yet for auto communities and workers, it presents a compressed timeline: stability in the short run followed by the risk of steep employment losses. Communities that have relied for decades on North America-based supply networks could see high-value EV components—such as batteries, power electronics, and advanced drivetrains—produced abroad, hollowing out the economic base that sustains middle-class wages, supplier networks, and local tax revenues. Might this dismal trajectory be altered? We turn to that question in the conclusion. But first, let us consider the risks beyond EVs.

RISK TO U.S. INNOVATION IN FOUNDATIONAL EV TECHNOLOGIES

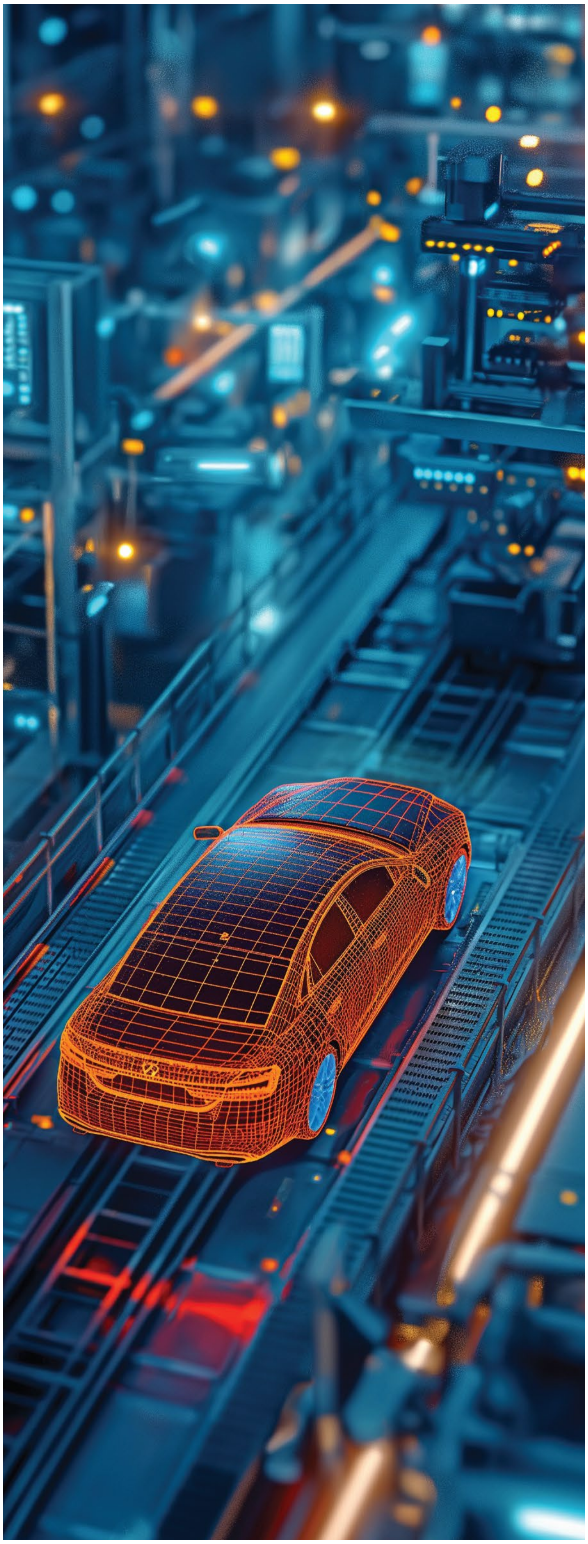
An array of crucial technologies, significant for both commercial products and military applications, from batteries to specific semiconductors for auto system control, entertainment, and autonomy, and software operating through chips and providing systems, are at risk from too weak positions in the EV sector. Indeed, the technologies and supply chains at the heart of EV production are of importance to an array of other sectors. Moreover, most of these technologies are inherently multi-use, i.e., they have both commercial and military applications. High-density batteries, lightweight composites, advanced power electronics, and autonomous navigation systems are equally applicable to unmanned aerial systems (drones), military ground vehicles, naval propulsion, and large-scale stationary energy storage for grid and critical infrastructure resilience. Certainly, rare earths are crucial not only to the production of batteries for EVs but also more generally for a range of products, including consumer electronics, green energy, defense, and medical equipment, and more. If the U.S. continues to be structurally dependent on foreign—especially Chinese—sources for these technologies, the vulnerabilities extend beyond commercial transportation to defense readiness, energy security, and the security of critical infrastructure.

Two issues are important to highlight: first, the importance of "spin-on" technologies from commercial to defense applications; and second, the place of constituent technologies in the business models of the EV companies.

THE IMPORTANCE OF DUAL-USE AND SPIN-ON TECHNOLOGIES:

Dual-use technologies are those products, both hardware and software, that can be used for both civilian and military purposes. The relationship steadily evolves, often reversing, between products emerging from commercial developments and applied to defense uses, and those emerging from defense R&D and applications that spin-off into commercial applications. After World War II, massive American investments in science-based and advanced engineering technologies generated defense products that "spun off" into commercial applications. The list of "spin-off" technologies originating in the defense sector is long and significant. By the mid-1990s, the relation between defense and commercial production and technology had reversed again. The exceptional scale of consumer electronics products and the remarkable investments in R&D from the companies making them meant that commercial products were being "spun-on" to defense applications. The range of products included advanced computing and display technology for jet fighters. Today, of course, the long list of important commercial developments supporting defense would begin with machine learning and generative AI. The point is that the massive scale of EV production means that financing the underlying R&D and mastering the production scale to keep costs down are critical for defense.

The United States was an early pioneer in EV and battery technology, with breakthroughs in lithium-ion chemistry, battery management systems, and power electronics originating from U.S. laboratories and universities. Yet today, most of the significant advances in high-energy-density chemistries, lithium iron phosphate (LFP) manufacturing, solid-state battery prototypes, and integrated battery-chassis designs are emerging



from Chinese firms like CATL, BYD, and CALB, as well as Korean and Japanese corporations, and Tesla.

R&D investment patterns have shifted accordingly. Chinese EV and battery manufacturers are channeling billions annually into advanced materials, cell manufacturing processes, and vehicle operating systems—often backed by provincial and municipal governments. The Australian Strategic Policy Institute finds that China now invests more than the U.S. in R&D across 37 of 44 critical and emerging technology categories, including batteries, electric drivetrains, and advanced manufacturing. U.S. private-sector automotive R&D, meanwhile, remains heavily concentrated in incremental improvements to ICE and hybrid platforms, with a smaller share devoted to EV architectures or next-generation chemistries.

The basic implications are concerning. At the same time, modern EVs can be seen as connected ICT platforms on wheels. Under the Commerce Department's ICTS authority, the U.S. is weaponizing these technologies by issuing rules prohibiting the sale or import of "connected vehicles" containing certain software, telematics, or vehicle-communication system (VCS) components from Chinese or Russian entities.[92] These rules reflect concrete security concerns: Chinese-supplied infotainment and cockpit systems—such as Huawei's HarmonyOS or Xiaomi's HyperOS—are already embedded in EVs abroad, even when the finished vehicle carries a non-Chinese brand. As Tesla has shown, such systems bring persistent risks of data harvesting (e.g., personal identifiers, in-cabin audio), continuous location tracking, and remote disablement through over-the-air (OTA) updates. Key issues, of course, are not only about data harvesting, but who has access to that data and the potential to use the data for intelligence purposes or, worse, for physical damage.

Even if the U.S. blocks direct imports of Chinese-brand EVs, other major markets will not. While the EU has applied tariffs to Chinese auto imports in reaction to what it considers unfair subsidies, the EU has not enacted any technology bans and instead opted for universal cybersecurity and data regimes that apply to all vehicles on its market. In 2024, China exported roughly 1.25 million EVs—about 40% of global EV exports—with the EU alone sourcing around 60% of its imported EVs from China. As these vehicles penetrate global markets outside the U.S., they will create massive economies of scale and scope, generating enormous profits that can be reinvested in further improving the technologies.

This generates significant geopolitical vulnerability. The EV transition is occurring within a broader global strategic dependence on Chinese materials, technologies, and manufacturing capacity. China dominates every stage of the EV value chain, from mining and processing critical minerals to producing battery cells, power electronics, and infotainment systems. This concentration creates systemic exposure: a disruption in Chinese production—whether due to market forces, industrial policy, or geopolitical tension—that ripples through the global auto sector.

WHAT BUSINESS MODEL? SYSTEM INTEGRATORS OR MODULE PRODUCERS?

Competing business models among the EV producers have implications for the evolution of the critical technologies discussed above. To what extent will system integrators, as has been the case with ICE vehicles, dominate the path of product development and capture the bulk of the value? Or will the value be captured by component producers who establish a distinctive position with unique intellectual property?

In the era of early personal computers, known as the "Wintellist" era, three critical components—the chips, Intel; the operating system, Microsoft Windows; and the screen technology —captured the bulk of value. They turned the integrators, such as Dell, into commodity providers, distinguishing themselves with branding like "-Intel Inside." By contrast, Apple, as an integrator, created its own operating system and purchased the microprocessor.

What will be the balance in the EV competition? There are, for now, only questions and prognostications.

Will integrators such as BYD dominate, given that BYD itself has a powerful position in the battery market? Tesla, as an integrator, has invested in battery production and development while adopting the giga-press approach.

Diverse component producers, conversely, are positioning themselves either as would-be integrators or to capture chunks of the value of the final good. CATL, a Chinese battery producer, is seeking to leverage its position to other parts of the drivetrain. Indeed, Nvidia has struck a deal with Mercedes to provide the tools for value-added services, and claimed, according to reports, 50% of the price to the customer, not just the net value.

European and American ICE companies have struggled both to integrate the electricity propulsion system into their more complex ICE structures and to begin, as the case of Ford, to develop dedicated designs for EVs.

We might speculate on the consequences for the development and control of critical components of several different business models. In any case, we anticipate ongoing investment, private and public, to establish controlling positions in integration and each of the defining components.


REGULATIONS
COMPLIANCE
POLICIES
RULES
STANDARDS

CONCLUSIONS AND POLICY ISSUES

When developing policies, we must recognize the scale and significance of the risk of ceding the EV production and technology development to China.

THE CHALLENGE

EVs are being rapidly adopted around the world as part of a basic shift away from fossil fuel vehicles. Battery-powered vehicles and energy storage batteries are a key artifact in this transition. The key components in this transition — electric motors, batteries, software, and semiconductors—constitute an electric stack that will be critical across many industries. EVs sit at the intersection of multiple strategic domains. Each component of the EV supply domains consists of dual-use technologies that underpin both commercial competition and national security systems, from unmanned aerial vehicles to grid-scale energy storage. In short, EVs and their components encompass key areas of economic value with commercial, strategic, and geopolitical significance.

The current trajectory will lead to the United States representing a shrinking, isolated ICE island. The U.S. position in the constituent technologies of EV vehicles is dwindling. The U.S. pioneered many of these technologies, but now China leads the world in use, production, and innovation, potentially establishing chokeholds on U.S. production. Leadership in the technologies of this transition is likely lost unless the U.S. can develop alternative superior (in performance and cost) batteries.

At the core is the fundamental transition in the global auto and mobility industries. They are undergoing a fundamental shift as batteries become increasingly capable in terms of energy density, and other components of EVs and the manufacturing of batteries are also improving. The manufacturing of batteries and EVs is benefiting from dynamic learning economies-of-scale and scope. Battery production will become even less expensive as home- and grid-level storage expands. Given that 25% of global auto sales were NEVs (BEVs and, to a lesser degree, PHEVs) and this percentage is only increasing, the tipping point is fast approaching. Moreover, as EVs become an increasing percentage of the existing fleet, the ICE service sector, including filling stations and repair shops, will begin to degrade, hastening the transition.

Recall the case of batteries. As discussed, battery technologies and products, for example, are already dominated by Chinese producers. The current situation and the trajectory suggest that as long as battery chemistries remain dependent upon lithium or, possibly, sodium, Chinese EV and battery firms are likely to become even more dominant due to their lead in manufacturing process knowledge and R&D. Importantly, Chinese firms are dominant in nearly every segment of the EV value chain and almost every major global automaker and component supplier have made China the location for their EV-related R&D. Not only the U.S., but also the traditional auto industry powers of Germany, Japan and Korea will have to develop strategies to adjust to this new reality. This will be further forced by the rapid increase in EV and battery exports from China, undertaken not only by Chinese but also foreign firms such as BMW, Mercedes-Benz, and Tesla. China's massive lead is reinforced by learning-by-doing dynamics that are becoming a virtuous feedback loop. This loop suggests that the longer it takes for the U.S. to respond, the more likely it is that the lag will be insurmountable.

There is a more *general challenge.* Nations left behind in this transition will become economically, politically, and militarily weaker and poorer than the leaders of the transition. The EV story reflects the reality that the United States is no longer the global manufacturing leader, nor is it the leader in many technological or scientific domains. Since World War II, for some 80 years, the United States had been the undoubted global technology leader. Indeed, leadership in manufacturing contributed to victory in that war with the mass production of planes and tanks. Japanese industrial introduction of lean production in the 1980s, and now the Chinese, highlight that we are no longer the manufacturing leaders.

More disturbing, China now challenges the core of our innovation leadership in both cutting-edge technologies, such as batteries, and advanced frontier foundational technologies. Indeed, China is contesting the innovative sectors in which the U.S. has long been the leader–aviation, telecommunications, microprocessors, robotics, and, more recently, AI and nuclear fusion. The Chinese challenge, at least in part, frames our options. Our policy approach, strategies, and tactics must account for both our lost leadership and the strategies of our competitors. Let us remind ourselves about the Chinese challenges.

THE CHINESE CHALLENGE

The Chinese, as we have argued, have established an ecosystem designed for speed, scale, and continuous innovation of EVs, batteries, and clean-energy production. Competition is no longer just about cost today, regardless of how the current Chinese cost advantages were achieved, but rather about sustaining a position in a rapidly changing industry. The Chinese achievements are formidable; our challenge is how to respond.

The current Chinese EV leadership results from an adaptive evolutionary process, involving significant interaction, adjustment, and learning by local governments and entrepreneurial firms.[93] Importantly, the Chinese government has encouraged local government experimentation, while providing resources and general directions. The U.S., as a federal system, has the inherent ability to enable the states to undertake experiments encouraging the EV industry. However, given the current political environment and divisions, this is unlikely to be effective. And, very unfortunately, the rapidity of development in the EV sector suggests that absent significant federal involvement, developing a cutting-edge, domestic-led EV and battery industry ecosystem in the U.S. is unlikely.

The lessons from the Chinese experience are that success comes from a long-term commitment that includes a variety of complementary tools: like subsidies to build consumer demand for scale; investment in developing university-industry partnerships; financial support for building an entire value chain; encouraging experimentation

that includes test-market creation; and competition at the local levels and an ability for the central government to generalize promising local experiments, thereby creating an enormous market. Overall, industrial policy in China has transitioned from top-down, command-economy planning to include bottom-up learning and competition derived from partnerships between various local governments and their private firms.

Given the current situation, one lesson from China may not come from the EV sector itself, but rather from the SOE-foreign partner joint ventures, particularly those in autos. The U.S. might open its market to Chinese firms on the proviso that they join joint ventures with U.S. automobile incumbents and, for batteries, perhaps with U.S. chemical firms. The other lesson is that China has invested enormous amounts into battery research. The U.S. joint-venture strategy could be combined with research funding for U.S. universities to investigate other battery chemistries that might leapfrog LFP and Sodium, where Chinese firms already have enormous leads. The U.S. could also draw on its experience with voluntary export restraints, which successfully promoted Japanese investment in the U.S. (although ideally without the features of immense state-level subsidies for new plants and union avoidance that unfairly disadvantaged incumbent producers).

WHAT IS TO BE DONE?

In formulating policy for EVs, we must recognize that the U.S. is starting from a trailing rather than a leading position. Can U.S. producers and policy-makers working together propel the U.S. to recover from its trailing position to establish a competitive position or even to a co-leadership position in the future? We must also realize that there are diverse and sometimes, in the short-term, conflicting goals, including maintaining production and production knowhow — and with that the skills and jobs on which they depend —along with sustaining innovative capacity to secure a viable position in the electric stack. For some, EV policy is also about climate goals. The overarching goal, however, must be sustaining U.S. competitiveness in EVs, other strategic sectors, and their component supply chains that are crucial to American prosperity—production and jobs — and national security.

There are domestic policy choices and trade policy choices. Whatever the details, a long-term stable policy is required for companies to make long-term investment and technology decisions.

DOMESTIC POLICIES setting aside the details, fall into four categories. We do not here sketch particular policies but identify the categories in which policies will need to be developed.

1. FOSTER A SUPPORTIVE AND ROBUST EV ECOSYSTEM

INVESTMENTS in research and technology to promote next-generation technologies in the electric stack and in advanced manufacturing. It is unlikely that the U.S. could match China's cost performance on existing technology given its learning-curve and other advantages. Leap-frogging the Chinese to introduce new technologies thus offers both prosperity and national security advantages. There are evident targets for such support such as:

- Increase investment in battery, magnet, and other chemistries and physical sciences, electric motors, automobile autonomy software, and lasers (LiDAR).
- Support startups and existing firms commercializing new battery and magnet chemistries. It is amazing to realize that the world's largest and most innovative producers of EV batteries and drone batteries as well are all Chinese startups, no more than 30 years old.
- Production technologies useful in manufacturing both autos and other products in a higher-quality, more productive manner, such as rebuilding U.S. capabilities in equipment manufacturing, applying additive manufacturing techniques to tooling, and development of lightweight materials and recycling techniques.[94]

REAL PROBLEMS must be noted. While investing in R&D for components and final production technologies is obviously necessary, there are real problems.[95] Critically, and foremost, many of these are principally spin-on technologies and products. Consequently, the scaling, production, and mastery of these technologies will depend on the market success of consumer products such as EVs. Investment in defense applications alone cannot address the challenge. Defense products tend to be gold-plated, and defense procurement makes goods expensive. Indeed, the defense sector is already dependent on the products emerging from the consumer sectors.

2. FACILITATE DEVELOPMENT AND ADOPTION OF EVS DIRECTLY

ASSURING A CHARGER SYSTEM NETWORK that can alleviate consumer fears about range limitations. Note, of course, that new battery approaches by both BYD and CATL promise ever greater range, sometimes as far as 500 miles. However, that does not relieve concerns about recharging. There are a variety of proposals. They include these.

- Continue existing incentives to deploy interoperable charging devices. Otherwise, it would be the equivalent of having separate fueling for Shell, Exxon, and Chevron.
- Make real-time data on EV charging locations available nationwide. Some contend that if charging stations were readily available nationwide, it could increase EV market share in the U.S. auto industry by eight percentage points by 2030.[96]
- Subsidies and incentives for user adoption have worked in many places, including the U.S. A discussion of which of these would be most effective should be initiated.

3. BUILD A COLLABORATIVE AND RESILIENT EV SUPPLY CHAIN AND PROMOTE GOOD JOBS

Policies include:

- Goal setting (e.g., by 2035, 5 million EVs produced and sold year in the U.S.); joint grants to automakers and their suppliers (to provide demand certainty for suppliers).
- Assistance to suppliers and workers in transitioning to new jobs both in the auto industry and in related industries (such as products for the electric grid or heat pumps). These policies could be adopted nationally and/or by auto-producing states such as Michigan and Ohio.[97]

4. EXPLORE THE OPTION OF DIRECT GOVERNMENT SUPPORT for taking equity stakes in EV firms and their component supplier companies is an option. The Trump administration is taking stakes in particular firms, which broadly raises the question of whom to support, how to make decisions about support, the form of support, and the terms of that support.

- The U.S. government lent Tesla 465 million dollars, which was roughly one quarter of its capitalization. If the government had taken a stake of perhaps 25%, we might view matters of state support differently.
- Should the U.S. establish a politically insulated national investment authority, operating as a VC investment fund to support early-stage startups, or, perhaps, a private equity fund for more mature firms? Political insulation and skilled expertise will be required in any such institutions.

TRADE POLICIES

To begin, protection alone will not create a competitive EV industry or provide development space for component producers such as battery manufacturers. Indeed, a protection-only strategy is likely to generate an inefficient autarchy rooted in ICE vehicles and an inefficient and expensive EV sector. However, tariffs may be necessary to give time for U.S. manufacturers to attempt to catch up, and to seek to offset less-desirable aspects of Chinese production (such as labor suppression and environmental degradation).

We need to address two sets of questions.

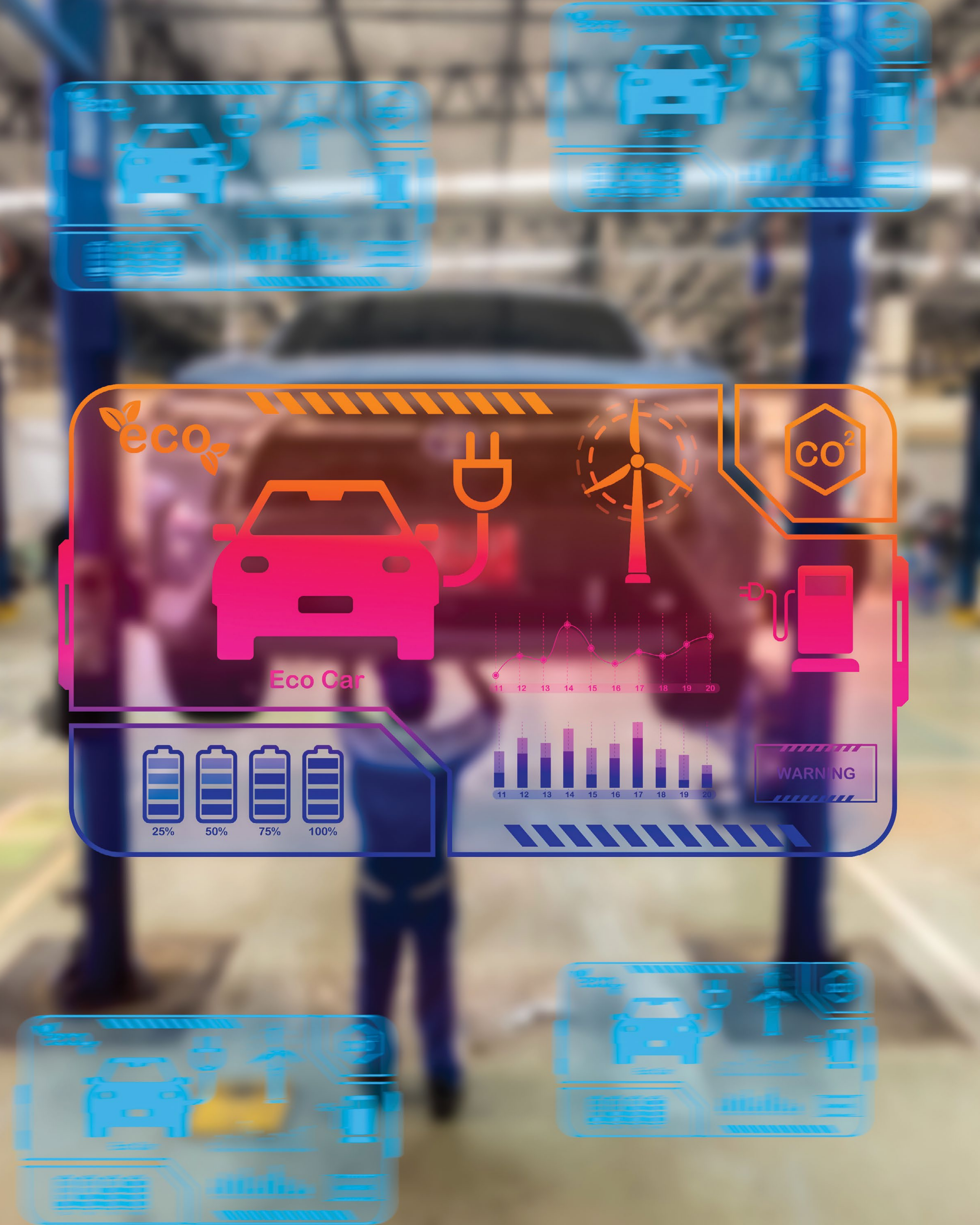
1. The first, evidently, is whether and on what terms to allow Chinese firms to export to the United States market, or, alternatively, whether to permit and encourage their production investment in the United States. We must decide whether to simply ban Chinese imports and investment in the U.S. or to carefully invite them to produce in the U.S., taking into account concerns about cyber security, technology transfer, and job quality/union rights. Here, we have much to learn from China's own policies regarding international joint ventures and technology. These are difficult issues that will not be usefully resolved by ideological posturing.

2. Encouraging "transplants" of any nationality to produce here that are willing or forced to share know-how and intellectual property would be difficult. Many questions arise:

- Since building leading-edge plants is difficult at best, the transplants will want, at least initially to bring their own workforce to get things started. Given the recent immigration raid on Hyundai, would such arrangements even be possible? What is the right balance between requiring these firms to transfer technology to the U.S. in exchange for U.S. government support, and allowing them to start up (and/or operate) with their own skilled workers?
- Would the transplants simply dominate the market for vehicles and components in the U.S.?
- What cyber and data security questions are opened? We should consider whether it is feasible to preserve privacy and cybersecurity with EVs, and indeed, policy should apply to all firms, domestic and foreign.
- What labor rules and arrangements would apply?

Since we share with our industrial allies in Europe and East Asia the challenge of China's current dominant position in EVs, we should negotiate with them about how to create mutually beneficial relationships in EVs and their constituent components. Our goal must be, as Tyson and Zysman have argued, a Competitive, Resilient, Sustainable, and Secure ecosystem for EVs and the constituent elements among our allies, CRSS.[98] Competitive markets, more generally, would mean no chokeholds and would stimulate innovation through competition.

In conclusion, when developing policies, we must recognize the scale and significance of the risk of ceding the EV production and technology development to China. We must begin a serious, unemotional discussion about why the U.S. economy failed to nurture and generate a vital EV market, despite Tesla's then-world leadership being evident. And we must develop strategies to assure America's competitiveness in EVs and in other sectors crucial to American prosperity and national security. Only that competitiveness can generate and sustain the good jobs and security that emanates from technology leadership.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ADDENDUM

GLOBAL SHIFT?

THE CHINESE EV/BATTERY CHALLENGE

Martin Kenney

In less than two decades, China evolved from an automotive follower dependent on foreign joint ventures to the global leader in the transition to electric vehicles (EVs), both battery powered battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). This transition will be a bridge to what some have termed an "Electric Age."

China's rise was the result of long-term central government planning, aggressive local experimentation, and entrepreneurial dynamism. China's powerful domestic market, its emerging leadership in BEVs, battery technology, and lithium-ion supply chain sets it up for dominance in the larger clean-energy transition. Given the current trajectory, the rapid growth and improvement in the Chinese EV industry poses a fundamental threat to incumbent automakers whose business models are dependent upon the internal-combustion engine.

THE EVOLUTION OF THE EV INDUSTRY IN CHINA

Facing severe urban air pollution, dependence on imported oil, vulnerability to global price shocks, and a recognition that it was likely to remain backward in internal combustion engine technology, China began experimentation with new energy vehicles, but by the 2010s began to emphasize the development and commercialization of BEVs. Within a decade, China emerged as the global center for BEV innovation and production, and by 2024 China was building over 60% of all EVs globally.

The Chinese government was critical in the development of the EV industry—not only at the national but also at the local level. We divide their efforts into four stages and describe some of the most important policies in each stage:

1. TECHNOLOGY DEVELOPMENT (2001–2009): Government-funded R&D partnerships between automakers and universities established core NEV (New Energy Vehicle) capabilities.

2. PILOT PRODUCTION (2009–2013): "Ten Cities, Thousand Vehicles" programs tested adoption in municipal fleets, with limited private take-up.

3. LARGE-SCALE ADOPTION (2013–2018): Expanding subsidies, tax exemptions, and licensing advantages spurred mass consumer adoption; by 2015, China became the world's largest EV market.

4. MARKET COMPETITION (2018–PRESENT): Gradual subsidy withdrawal and rising technical standards fostered competition. One signal of confidence in Chinese competitiveness was giving permission to Tesla to build a wholly owned Shanghai factory—the first wholly foreign-owned automobile factory in China.

5. LOCAL GOVERNMENTS reinforced central policy by offering land, loans, infrastructure, and preferential licensing. This multi-level governance model produced a vast industrial base, though one with overcapacity and fierce price wars.

THE CHINESE EV INDUSTRY

In China, 59% of all sales are now new energy vehicles (NEVs and predominantly BEVs). In 2024, the Chinese NEV market was 12.87 million (and increasing rapidly), compared to U.S. NEV sales that are expected to be about 1.6 million in 2025, while sales in the EU were marginally larger, but some of these were imported from China. There are substantially no foreign EVs imported, though foreign automakers and Tesla do produce and sell BEVs in China. More important, today China is the largest automobile and EV exporter in the world.

Interestingly, the leading BEV and battery manufacturers are not the state-owned enterprises (SOEs), but rather are founder-led entrepreneurial firms and, more recently, entrepreneurial firms from the electronics industry such as Huawei and Xiaomi have entered the industry.

+ **SUPPLY CHAINS:** China now controls roughly 75–85% of the global lithium-ion battery supply chain, from raw-material mining (lithium, graphite) to cell manufacturing and recycling.

+ **BATTERIES:** China's early bet on lithium iron phosphate (LFP) chemistry meant that it would have a significant cost advantage over Japan and Korea's more costly nickelcobalt based technologies.

+ **ELECTRIC MOTORS:** China is also a leader in automobile electric motor production. Though it is not yet clear whether the electric motor industry will be integrated by the automobile assemblers, the battery producers, or independent motor producers (BYD currently produces not only its own batteries but also electric motors).

+ **SEMICONDUCTORS:** China has recently implemented policies to replace foreign semiconductors with Chinese products—an area that has recently been politicized by the Netherlands seizure of Nexperia.

+ **CHARGING INFRASTRUCTURE:** By 2022, China had installed nearly 50% of global EV charging stations, and 90% of fast chargers.

GLOBALIZATION

Facing domestic oversupply and margin compression, Chinese firms began exporting EVs. Since 2022, exports have surged making China the world's largest auto exporter by 2023.

Leading Chinese EV and battery producers are rapidly building overseas factories across Southeast Asia, Europe, and Latin America. This will continue to raise trade tensions, especially with the U.S. and EU, whose domestic producers are laggard in terms of competitiveness and technology.

While the impact of labor abuses and government subsidies should not be ignored, China has been able to take advantage of the disruption caused by the transition to BEVs to reclaim the domestic market from the SOE-foreign ICE-based joint ventures and rapidly and decisively enter the global market.

CONCLUSIONS

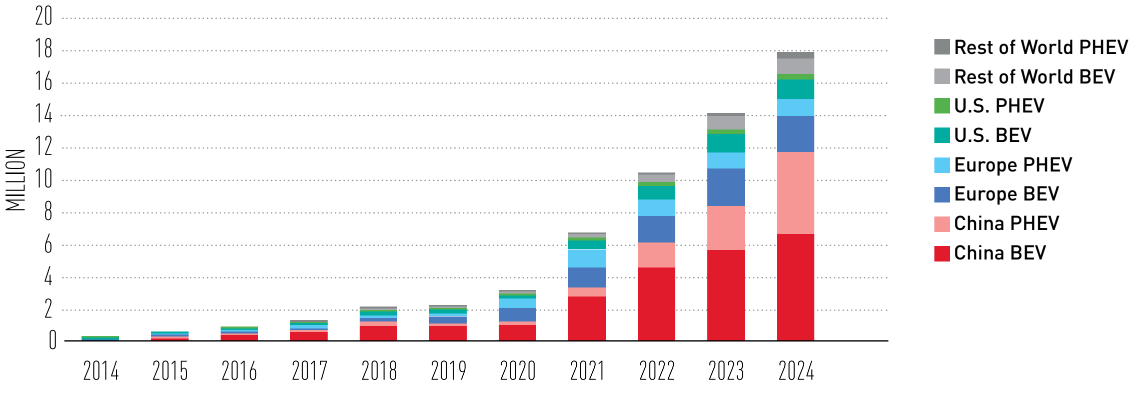
While the future is uncertain, today Chinese firms dominate the global EV market and, increasingly technology. This dominance includes battery production and, it will be the first large economy to transition to an electricity-centric economy and society.

For other nations, if the current trajectory of Chinese EV and battery development continues, their domestic industrial and environmental policies will have to be made, while recognizing that China will, almost certainly, be the central actor in the dawning electric-centric energy era.

The revolution in transportation created by the transition to battery-powered vehicles (BEVs) is being led by China, as the adoption of battery-powered electric vehicles and plug-in hybrid electric vehicles (PHEV) or, collectively, electric vehicles (EV) has grown from a curiosity to a transition from internal combustion engine–powered vehicles (ICEV). This transition will be centered on EVs, batteries, and renewable energy increasingly generated by wind and solar energy. China is already the world's leading producer and consumer of automobiles because of the size of its domestic market. Based on its emerging leadership in BEVs and batteries, Chinese firms are becoming the dominant global manufacturers and innovators.[1] The EV industry is also vitally important because it is an enormous consumer of batteries and thus will drive the battery production and the rise of what some call an "electric age," in much the same way as the ICEV drove the development of what might be termed the "petrochemical age". For this reason, BEVs are critical for the transition to a more sustainable electric age that will reinforce Chinese dominance in photovoltaics and clean energy. The entrance of Chinese EV makers to the global auto industry, combined with the transition to BEVs, is a profound threat to the success of incumbent automakers in the rest of the world as well as their survival as global firms, as they might end up being confined to protected domestic markets.

Of course, the BEV industry has a long history. At the beginning of the automobile era in the early twentieth century, BEVs might have been the direction taken but, at that time, batteries were quite rudimentary, hence, that became the road *not* taken. In the 1990s, incumbent ICEV producers created some experimental vehicles, but only in the 2000s were new entrants introduced, in particular by Tesla, and U.S. government investment, incentives, and policies employed to initiate mass production and sales of BEVs. Unnoticed by the rest of the world, the Chinese government and entrepreneurs also were experimenting, and, in the 2010s, BEVs began to be commercialized in China. By the end of the decade, China had emerged as the global center of BEV and vehicle battery technologies and production, and by 2024 China had become the global center for BEV consumption, as over 60 percent of all EVs were bought there, as shown in figure 1.

FIGURE 1: GLOBAL EV SALES BY COUNTRY (2014-2024)



Source: International Energy Agency, "Global electric car sales, 2014-2024," in *Global EV Outlook 2025* (Paris: IEA, 2025), 15.

The current Chinese dominance is due to a confluence of government policy and entrepreneurial activity as well as, in part, the result of early decisions by Chinese entrepreneurs to focus on the chemistry of lithium iron phosphate (LFP) batteries, which they were already producing for consumer electronics. This success was built on prior experience in other modes of transportation, such as e-bikes and e-scooters, which helped accumulate volume and LFP experience. LFP proved to be cheaper than existing EV battery chemistry based on nickel and cobalt that was used in non–plug-in hybrid vehicles (e.g., Toyota Prius). Chinese success was achieved through trial and error subsidized by the government but undertaken by entrepreneurial firms that were intent on competing with the nickel/cobalt-based solutions used by Japanese and Korean manufacturers in their hybrid vehicles. The LFP development trajectory has been steep, in part, driven by the massive, across-the-board research investment made at the national and local levels at universities and research institutes and subsidized similarly large corporate investment.

Chinese EV and battery producers are now the global leaders, the most potent demonstration of their success. In the following discussion, we show that China not only built the entire supply chain for LFP batteries but also dominates it, capturing market shares in excess of 75 percent at most nodes in the supply chain. If the current Chinese lead continues, then other countries and their automotive industries will have to develop strategies for competing in an environment formed by Chinese firms and technologies. This paper explores the development, government policies, and current state of the Chinese BEV industry.

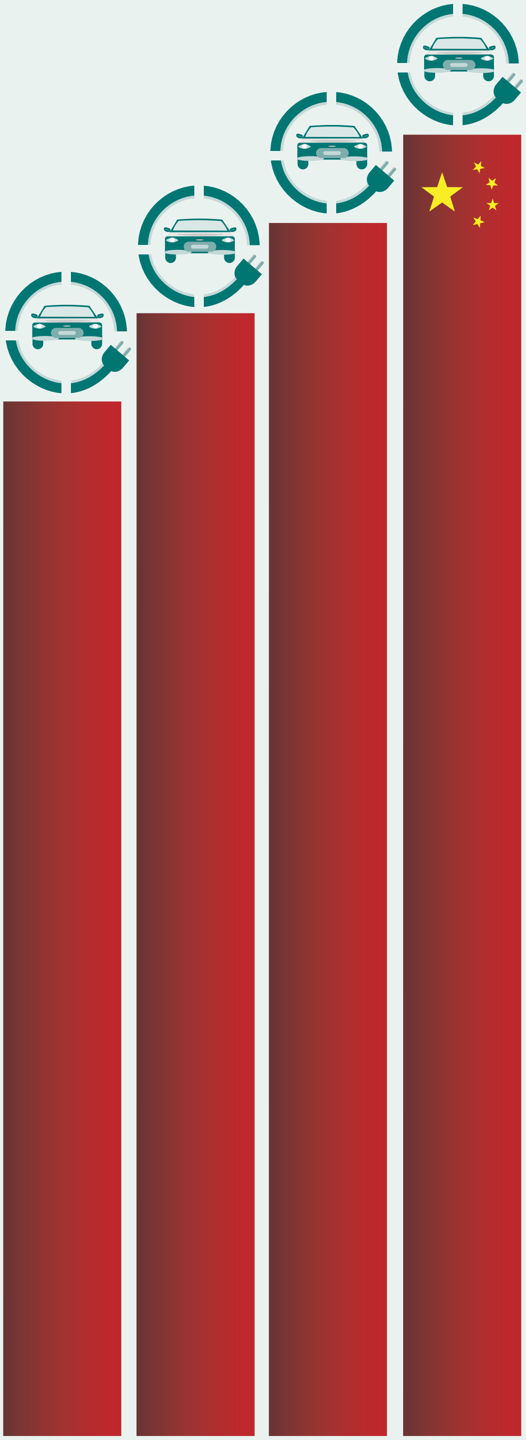
WHY EVS IN CHINA?

In the 1990s, as the Chinese economy boomed, purchases of passenger vehicles expanded, creating increasingly serious air pollution in large Chinese cities. Moreover, China is a petroleum-poor country and thus was forced to import ever-larger amounts of oil as it grew, leading to outflows of foreign exchange, a matter of great concern at the time.[2] In other words, China was on an inescapable treadmill and constantly at risk of an oil price shock from the U.S.-controlled global oil economy. Chinese leaders faced pressure due to worsening air pollution at home and global climate change turbocharged by Chinese growth, the latter of which was acknowledged in discussions related to the Kyoto Protocol.[3] They realized that the pressure would only grow, as China's growth would lead to ever higher bills for oil imports.

Roughly contemporaneously, China initiated a concerted effort to develop a photovoltaic industry[4] — the other part of a clean energy revolution. In the 1990s, the Chinese auto industry began to grow rapidly, as Chinese state-owned vehicle enterprises formed joint ventures (JVs) with foreign firms, which were immensely profitable for the foreign firms.[5] For example, for many years, Volkswagen's largest and most profitable market was China, which accounted for 37 percent of the company's total profits in 2020.[6] For China, these JVs were intended to transfer technology and liberate it from dependence on foreign technology; but, understandably, the foreign firms resisted technology transfer. However, a transition to EVs was seen not only as a solution to pollution and foreign exchange problems but also as a new industry that would not have many incumbents. Finally, China already had a consumer-electronics battery industry that used lithium-ion batteries, which was the battery chemistry used by Chinese firms to scale up and rapidly dominate, whereas Korean and Japanese firms dominated nickel batteries. From a larger perspective, EVs are only a part of the sustainability transition that includes solar/wind/nuclear energy production, battery storage, and battery-powered EVs (not only automobiles, but also buses, trucks, motorcycles, lawn mowers, leaf blowers, e-bikes, ships, and perhaps even aircraft—basically anything with an internal combustion engine [ICE]).

The foregoing suggests that China is driving a "sustainability" transition to electrification. The current success of the Chinese EV industry is the result of a strategy that China developed in its catch-up phase but, more recently, has been adapted for cutting-edge industries.[7] Moreover, pursuing further growth and development of a global-class auto industry would allow China to deepen its manufacturing infrastructure using a path similar to that taken by Korea and Japan earlier, as they became exporters.

Until recently, Chinese production of ICE was in JVs with foreign partners that had little interest in exporting from China to markets that they already controlled. China came to understand that the ICE industry would be very difficult to master, at home and, even more so, abroad.



EVOLVING POLICIES TO CREATE A BEV INDUSTRY[8]

As in every other country developing a new infrastructural technology, China has relied on the critical role of government in creating its EV industry, but the way in which this role was played was nuanced and evolved with technological progress and maturation of the market (e.g., regarding plug-in hybrid EVs [PEV] in China, see Helveston et al. [2019]).[9] The early Chinese government activities are best seen as aspirational and exploratory. Chinese government officials closely followed developments in developed countries and were highly motivated to find solutions to the multiple problems as the industry developed. Moreover, focusing simply on central government policies overlooks the role of local governments—many of which were critical in supporting startups, such as BYD, Nio, and Xpeng. Following and drawing on Kenney et al. (2025), we divide the Chinese central government efforts to nurture new energy vehicles (NEV), of which BEVs predominate, development into four stages. Further, because of the importance of local governments, we add a final section briefly highlighting a few of their many policies to encourage NEVs, in particular, BEVs.

STAGE 1

INDUSTRIAL POLICIES FOR DEVELOPING THE TECHNOLOGY, 2001–2009

The Chinese government began to experiment with developing NEVs as early as the 1990s. In 2001, the tenth five-year plan (FYP) called for “the development of economical cars, the improvement of the manufacturing level of automobiles and key components, and the active development of high-efficiency, energy-saving and low-emission automobile engines and hybrid power systems."[10] During this period, the idea of developing an "NEV industry" appeared in various industry-specific initiatives, but the ideas about what that would mean and how to do it remained vague—and were largely confined to some publicly funded research projects.

In 2001, the State Economic and Trade Commission issued the tenth FYP for the automobile industry, calling for the promotion of R&D on alternative-fuel vehicles. The goal was to develop NEVs, including BEVs as well as fuel cells, and hybrids. This policy was intended to nurture not only the development of the basic technologies but also the associated supply chains.

The central government's investment during the tenth FYP was mainly to support technology-development partnerships between existing automobile manufacturers and universities.[11] In the period of the eleventh FYP (2006-2011), the government funded 270 science and technology projects, which covered key components, power systems, vehicle integration, test platforms, demonstration, and promotion, as well as standards and policies. The financial investment available through the projects totaled RMB 7.5 billion (US $1 billion). The main emphasis was on technology development across all NEV technologies. (Tesla was formed in Silicon Valley to develop EVs in 2003). Contemporaneously, though largely unsupervised or unsupported by the government, Chinese entrepreneurs began to introduce battery-powered motorcycles, which became popular with consumers.[12] As this stage ended, perhaps, inspired in part by Tesla's growing success, the central government began to consider the demonstration stage.

STAGE 2:

INDUSTRIAL POLICY FOR PILOT PRODUCTION, 2009–2013

Beginning in 2009, the government introduced policies to create a market for new energy vehicles. First, it designated pilot cities that would be charged with creating. In early 2009, the State Council advocated the large-scale development of NEVs and initiated the "Ten Cities and One Thousand Vehicles Demonstration and Application Project for Energy-Saving and New Energy Vehicles." This policy provided financial subsidies to 10 cities that were each meant to purchase and use 1,000 NEVs. The ambitious goal was to have NEVs account for 10 percent of all vehicles sold by 2012. However, in 2012, only 27,432 pilot vehicles were in use in the now 25 NEV demonstration cities—of which 23,032 were in the public service sector and 4,400 were purchased by private individuals.[13] This policy largely failed to spur NEV purchases.

In 2010, the State Council introduced policies to target the core technologies including batteries, drive motors, and electronic control for PHEV and BEV."[14] In addition to these policies, subsidies for BEV purchases were introduced. In 2012, the State Council issued policies that showed that BEVs were becoming the focus of government policies. Hybrids such as the Prius and energy-efficient ICE vehicles that already had significant market share no longer benefited from government policies.

The Chinese government had identified EV and PHEV as the goal of its NEV policy by 2012, though research on fuel cells continued. Interest in EVs was growing rapidly, as new firms were being formed in the United States, and Tesla, in particular, was growing rapidly. Further, Chinese air pollution problems continued to worsen, due to rapid growth in automobile ownership.

STAGE 3

INDUSTRIAL POLICY FOR LARGE-SCALE ADOPTION, 2013–2018

In the third stage, the government's goal was to encourage the large-scale adoption of EVs. In 2013 and 2014, the Ten Cities and One Thousand Vehicles Policy was extended to most large and medium-size cities. By September 2015, 180,945 EVs were operating in 39 cities. Moreover, in 2015, 379,000 NEVs were sold, outpacing U.S. EV sales After 2015, China became the world's largest EV market.[15] Industrial policies now focused on incentives to encourage large-scale adoption. For example, in 2014 purchases of EVs became tax exempt.

Also, EV manufacturers reduced prices by deducting the subsidies for them, as the central government reimbursed manufacturers directly.[16] This policy set the subsidy standard in 2016 for various types of EVs, but it was gradually reduced over time.[17]

As a result, consumer sales increased from a few thousand in the public transportation sector at the end of 2013 to more than 60,000 at the end of 2017, of which more than 60 percent were privately owned.[18] This growth slowed in 2016 because of a scandal involving subsidies in which some EV manufacturers sold cars to car rental firms that they owned yet received over RMB 1 billion (approximately US $150 million) in public subsidies.[19] In response, the government not only decreased fiscal incentives but also mandated that, to qualify for subsidies, EVs would have to be graded by government inspectors, and EVs with advanced technologies would receive preference for subsidies. This enabled government officials to test and certify EVs[20] as well as to set quality standards, which were tightened every year. By the end of this period, China had a small but growing consumer market for EVs, whose technological sophistication was rising.

STAGE 4

INDUSTRIAL POLICY TO ENCOURAGE MARKET COMPETITION, 2018–PRESENT

In the fourth stage, which began in 2018, the central government gradually decreased the subsidies[21] and promoted marketization. In February 2018, new policies were introduced to increase the technical threshold requirements to qualify for subsidies. Subsidy policies would now be updated annually and gradually applied to fewer vehicles; according to one estimate, total EV subsidies declined from US $13,860 in 2018 to US $4,500 in 2023.[22] Perhaps most surprising is that the government was so confident that it allowed the then–global leader, Tesla, to build a wholly owned factory in Shanghai that was intended to produce 500,000 EVs a year.

The central government increased support for building charging infrastructure and deploying batteries, and so forth, while encouraging further technological innovation, such as developing intelligent, connected vehicles. The Circular of the General Office of the State Council on the Issuance of the New Energy Vehicle Industry Development Plan (2021–2035) issued by the State Council focuses the development agenda on R&D. With respect to the "three vertical" trajectories, it stresses pure EVs, plug-in hybrid (including programmable) vehicles, and fuel cell vehicles. In addition, the industrial policy emphasizes improving EV infrastructure by subsidizing the construction of charging networks, coordinating and promoting the construction of intelligent road networks and facilities, and orderly creation of a hydrogen fuel supply system.[23]

As the foregoing lays out, China's industrial policy evolved in four stages. The initial technology-development strategy was intended to develop the technology for building a domestic EV industry. The targets of these industrial policies evolved from the supply side to the demand side. Initially, the demand-side industrial policies were aimed at vehicles for public transportation, such as buses and taxis, in designated cities. This was followed by attempts at large-scale marketization of EVs in the nationwide consumer market for passenger cars. This stage was driven by production and sales subsidies. Supply-side industrial policies continued with large subsidies for R&D. The synergies between the supply-side and demand-side industrial policies accelerated the evolution of EVs by increasing market size and encouraging rapid improvement in batteries and other components. When technological capabilities (e.g., battery technological innovations by CATL and BYD), production levels, and the scale (e.g., large sales) of BYD, CATL, and others expanded, the competitive advantages of China's EV industry became more obvious.

All aspects of EV adoption were considered, and applicable industrial policies were introduced. Throughout this period, safety was a policy and regulatory goal, as the government established safety standards for EV batteries. In 2025, it introduced the world's most stringent EV battery standard, aimed at preventing fires and explosions.[24] Because of the growth and increasing dominance of the Chinese industry and markets, increasing exportation of automobiles, and building of factories globally, these and other Chinese-developed standards will probably become the de facto and de jure global standards adopted by regulators in other countries. In many respects, the size of the Chinese EV market and its increasing dominance in much of the world suggest that it will increasingly dominate in all but the most protected markets.

LOCAL GOVERNMENT INITIATIVES

China has developed a national innovation system in which the central government is responsible for setting the goals for developing industries and technology, but, in many industries, local entrepreneurs and local government officials manage the implementation of these goals. For example, the central government's desire to establish industry-university partnerships was almost invariably realized by building relationships between regionally proximate actors. For example, when the central government mandated that pioneering local governments should purchase EVs—some cities, such as Shenzhen, mandated that its municipal bus and taxi firms, which are state-owned enterprises (SOEs), purchase BYD EVs, thereby creating a market for EVs.[25] As local government officials were judged by their adoption of EVs, they became responsible for building charging networks. Local governments also innovated local industrial policies, such as preferential license quotas, traffic control exemptions, and infrastructure support for EVs. In addition, some cities reduced costs for vehicle owners by reducing annual inspection and parking fees, among other initiatives. For example, in 2014 the Beijing government greatly reduced the quotas for new ICE vehicles, while increasing those for EVs. These quotas are important because larger Chinese cities are crowded with cars already, so it is difficult to obtain permission to buy them. These nonpecuniary (dis)incentives can be as powerful as prices.

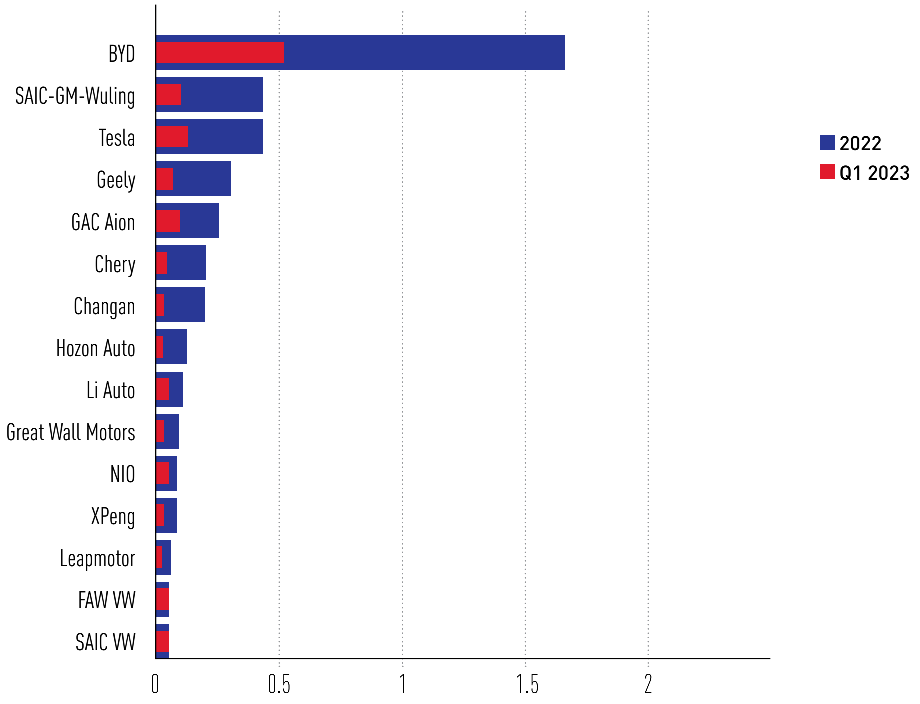
In addition to offering demand-side incentives, local governments also extended supplyside incentives to local entrepreneurs launching EV startups. For example, local governments gave factories building permits and low-cost land, helped arrange and fund cooperation with local research institutions, and even went so far as to offer key employees residence permits to live in particular cities. Local governments also offer loans to entrepreneurs. This support was critical in the early success of many entrepreneurial EV firms and had a positive effect on their growth. However, it has a downside, as the support can lead to excess capacity, ruinous subsidized competition, regionalism, and duplication, which can result in ferocious price wars— as the industry experienced in 2025. This situation has also contributed to a massive export boom, as manufacturers seek to circumvent domestic market competition by entering foreign markets and offering very aggressive pricing.[26]

THE CHINESE EV INDUSTRY

In China, more than 50 percent of all sales are now for NEVs, predominantly BEVs. As discussed earlier, government policy was critical for the development of the BEV industry. However, contrary to what one might believe about a country in which government policy is so important, the leading BEV and battery manufacturers are not SOEs but, rather, are founder-led startups and, more recently, those in the electronics industry, such as Huawei, the Chinese electronics giant, and Xiaomi, the mobile phone giant. Only after 2020 did the SOEs with their JVs with foreign firms begin a large-scale pivot to BEVs as well.

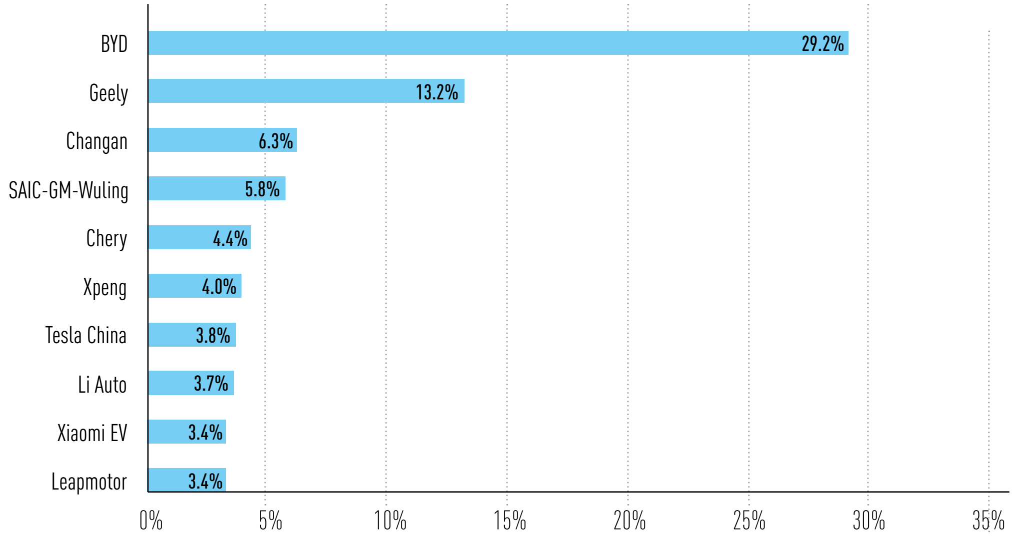
The Chinese automobile market is by far the largest in the world, with sales of 31.4 million vehicles in 2024, compared with the entire market in the European Union (EU) of nearly 11 million and the North American market of 11.5 million (the Indian and Japanese markets each total approximately 4.5 million). In particular, in 2024 the Chinese EV market totaled 12.87 million vehicles; the NEV share of total sales increased monthly, and 2025 will certainly set a new record. In contrast, EV sales in the U.S. were expected to be about 1.6 million and sales in the EU marginally higher. This is the competitive environment in which the more than 50 Chinese and foreign EV firms, including Tesla China, are operating. When it was first introduced in large volume in China in 2019, Tesla was very successful: In 2022, it was the third-largest NEV producer in China, but by February 2025 it had ceased to be among the top five brands and continued to decline because it lagged in technology and design. At the same time, Wuling, the SAIC–General Motors joint venture, rose to become one of the top five brands (see figures 2 and 3). China imports essentially no foreign EVs, whereas, as mentioned earlier, it exports a large number of Chinese EVs.[27]

FIGURE 2: TOP 15 COMPANIES: CHINA ELECTRIC VEHICLE SALES (MILLIONS)



Source: The China Project, “China’s top 15 electric vehicle companies,” *The China Project*, 2023. Data Source: China Passenger Car Association (CPCA)

FIGURE 3: AUTOMAKERS SHARE OF CHINA NEV MARKET (FEBRUARY 205 RETAIL)



Source: Lei Kang, “Automakers’ share of China NEV market in Feb: BYD tops with 29.2%, Tesla 7th with 3.8%,” *CnEVPost*, 2025. Data source: CPCA

The number of EV producers in China has been counted in various ways. As of 2025 the broadly accepted total seems to be 50 discrete firms, which represents a decline from the high of approximately 90 firms in 2024. Some firms have exited the market, but many new ones have entered it, including SOE-foreign JVs and, most recently, Huawei and Xiaomi. These new entrants have engaged in ferocious price cutting, dubbed "involution." Even the strongest firms, such as BYD and Xpeng, have experienced shrinking profit margins, and the central government has cautioned firms to temper their price reductions.[28] Their fierce "race-to-the-bottom" price wars are destructive of capital and can destabilize entire sectors, but ultimately the survivors become extremely competitive, though with enormous and destructive pressure on their suppliers and workers.

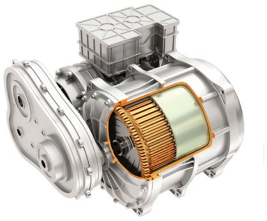
At this early stage, it is still difficult to determine how EV supply chains will be organized. For example, at present CATL is purely a battery producer that supplies batteries to Chinese and global manufacturers, including Toyota, VW, Nissan, and GM. Other Chinese battery makers also supply various EV producers. In contrast, BYD, the world's largest EV manufacturer, has integrated battery, electric motor, and vehicle production, and it also sells batteries to other EV manufacturers. Almost all incumbent ICE vehicle producers that had built engines and transmissions in-house now purchase batteries and electrical motors from suppliers. Given the scale and sophisticated knowledge required for battery production, backward integration into battery production might be difficult, though the two early entrants, BYD and, to a smaller degree, Tesla, continue to be battery producers (though Tesla participates in a JV factory with a dedicated battery manufacturer). Thus, no dominant design has emerged yet, and it is possible that BYD, like Apple, will become more integrated, and other EV producers will purchase batteries. However, BYD's integration strategy might be threatened by CATL's announcement in October 2025 of a sodium-ion battery that could make LFP largely obsolete, which would weaken BYD's strong position in it.

China has become the center of the global market by dint of the sheer volume of its EVs produced and sold, the number of its competing firms, and its technological advancements, and firms such as BYD, Xpeng, and CATL have developed world-class technology. Chinese firms benefit not just from lower labor costs than in many other countries but from proximity to world class suppliers and multidimensional economies of scale, scope, and know-how. These advantages are amplified by the ability of Chinese EV makers to develop and introduce new models every 18 months—far outpacing their European and Asian competitors.[29]

SUPPLY CHAINS

One of the keys to understanding China's dominance is the early decision, driven in part by success in producing lithium-ion batteries for consumer electronics, to emphasize lithium, which has become the dominant battery chemistry, in large measure due to Chinese success.[30] The rapid growth in the Chinese EV industry created enormous demand for components from batteries to suspension systems optimized for BEVs and materials, such as lithium and graphite, that are necessary for producing lithium-ion batteries. Although some components, such as tires and shock absorbers, are largely the same in ICEVs and EVs, the drivetrain-related components are completely different (See figure 4).

FIGURE 4: INTERNAL COMBUSTION ENGINES VS ELECTRIC VEHICLE MOTORS



	INTERNAL COMBUSTION ENGINE (ICE)	ELECTRIC VEHICLE MOTOR (EV)
WEIGHT	300-500+ lbs.	100-200+ lbs.
POWER	180-400+ HP	180-400+ HP
MAX SPEED	6,000-7,000 RPM	15,000-21,000 RPM
Efficiency	30-35%	90-95%
MOVING PARTS	1 Crankshaft 3-12 Pistons 3-12 Connecting Rods 6-48 Valves 6-48 Valve Springs 6-48 Rockers/followers 6-45 Lifters & Pushrods 1-4 Cam Drivers & Chains/belts 1 Oil Pump 1-2 Balance Shafts 1 Flywheel	1 Rotor
MAINTENANCE REQUIRED	Oil & Filter changes 5-12 K Miles Spark Plugs change at 100K Timing & Drive Belts change at 100K miles Coolant changes at 50-100K Miles Emission Inspections 1-2 years	No Oil Changes No Spark Plugs No Timimg & Driver Belts Coolant Changes maybe 50K+ Mil No Emission Inspection

Precise comparison of the number of components in EVs and ICEVs is difficult, but certainly an EV has far fewer discrete components, considering the large number of subsystems and components in ICEVs. For example, a battery consists of many identical cells. In contrast, an ICEV requires a complex fuel system with a pump, an exhaust and timing system, and a complex cooling system (an EV also requires a cooling system but inherently has less heat that needs to be dispersed).

The lower number of components in an EV drivetrain means that it has less need for parts makers as well, overall. Unsurprisingly, given the domination of the Chinese market and the government's focus on creating an entire supply chain, Chinese suppliers dominate EV and battery production (and, increasingly, R&D). However, they are not alone, as they face global parts suppliers, such as Bosch and Magna (a giant premier Canadian automotive supplier), that have opened global EV R&D centers in China.

BATTERIES

Chinese firms dominate production at every stage of the EV battery supply chain, beginning with control over 80 percent of the lithium mines. In heavy industry and other infrastructure, SOEs were important investors in building mines, transportation networks, and so on around the world, particularly for lithium, rare earth extraction, and so forth. However, component suppliers are often either existing firms that extended their product lines (e.g., graphite producers) or new entrants. Component production is highly concentrated in a few firms globally, and, just as important, Chinese producers have become even more important. In 2024, China had nearly three-quarters of the production capacity for battery cell, specialized cathode, and anode materials, 70 percent for global cathode, and 85 percent for anode materials, and more than 50 percent of the global raw material processing of lithium, cobalt, and graphite. China dominates the entire graphite anode supply chain end to end, as it has 80 percent of the global graphite mining.[31]

The highest value-added component in EVs is the battery. In less than a decade, China went from being relatively backward and an unimportant actor in the vehicle battery industry to the global leader in production and usage. Although Chinese firms had lagged behind Asian competitors in patenting,[32] in 2025 BYD surpassed Toyota in EV patents,[33] and its dominance seems likely to accelerate. Similarly, China and, particularly, CATL, the world's largest battery producer, gained leadership in battery patenting, though Japanese and U.S. patents still appear to be the most influential.[34] Together, as of 2025, CATL and BYD produced approximately 55 percent of the world's batteries (predominantly LFP batteries) and six of the top ten battery producers were Chinese, three were Korean (only one of which, LG Energy Solution, had a 10% market share, and one was Japanese (Panasonic, essentially for Toyota's Prius, had a 3% market share). Most importantly, the Korean and Japanese manufacturers are concentrated in the now-declining nickel hydride batteries. The U.S. and the EU have no significant EV battery producers and, most likely, will remain dependent on Chinese battery producers if a new battery chemistry does not emerge. As with EVs, battery technology development also currently appears to be concentrated in China. Most significantly, in 2026 CATL is expected to mass produce sodium ion–based batteries, whose cost will be significantly lower than LFP batteries, but whose energy density appears to be only slightly less than that of LFP batteries. Sodium-based batteries have some advantages, such as higher safety, the ability to operate in extremely cold temperatures, and charging speed.[35] Some estimates show that the cost of sodium ion–based batteries might drop to US $10/kWh—compared to LFP, which cost approximately US $80/kWh.[36] If these estimates are borne out, then battery and vehicle costs will drop dramatically. Chinese producers are even more dominant in the supply chain for raw materials and components for LFP batteries, at least in part because of Chinese government policy. Over the past two decades, Chinese firms consolidated the production of components, such as anodes, cathodes, and cell materials, attaining a market share of 80 percent in most nodes in the LFP supply chain.[37] The sources of capital goods for the manufacture of batteries are more difficult to identify, but Chinese capital goods producers are likely to be dominant, at least, with regard to LFP chemistries.

ELECTRIC MOTORS

Not surprisingly, electric motors are also a high-technology input. Motor production can be vertically integrated, and motors can be produced by auto assemblers or purchased from component suppliers. For example, BYD produces not only its own batteries but also electric motors. Although not many EV assemblers appear to follow its example, according to a McKinsey report[38], those that make more than 100,000 vehicles per year are expected to move powertrain production in-house.[39] EV motor producers are numerous and include Western Tier-One automobile parts suppliers, such as Bosch, Denso, Nidec, Magna, and Valeo, as well as several startups. Chinese assemblers and various parts suppliers (including battery firms, e.g., CATL) produce EV motors.

Foreign EV drivetrain manufacturers, including major European auto assemblers and Tesla, have invested in both production and R&D operations in China. For example, in 2017, Magna established a JV with Huayu Automotive Systems to support Magna's first edrivetrain business in China, which is intended to supply a German automaker.[40] Similarly, Punch Powertrain, a Belgian company purchased by the Yinyi Group in China, built significant Chinese production capacity and R&D facilities.

Because of the size and diversity of the Chinese market for electric motors to power not only automobiles but also all kinds of vehicles, from long-haul trucks to buses to bicycles, China has become the center of electric motor R&D. It is not yet clear whether a large independent electric motor industry will exist in the long term or the industry will be absorbed by auto assemblers, such as BYD, or battery producers, such as CATL, as they might be able to exploit synergies between battery packs and electric motors.

SEMICONDUCTORS

More and more-sophisticated semiconductors are required for all vehicles, especially EVs.[41] Although these semiconductors may not be extremely sophisticated compared to those in computers and smartphones, some are high value added and, until recently, have been designed and produced by U.S. and European manufacturers.

Because of increasing trade tensions between the U.S./Europe and China and the volume of Chinese EV production and its importance to the Chinese economy, it is not surprising that China has implemented policies to replace foreign semiconductors with Chinese products.

INFRASTRUCTURE: CHARGING STATIONS

The transition to EVs will require a charging infrastructure. But, unlike the infrastructure necessary for fueling ICE vehicles when they were first introduced, the infrastructure for charging EVs—that is, the electrical grid—largely already exists. Thus, only the final node, the charging station, has to be built.[42] Very early on, the Chinese government recognized the need for this infrastructure and charged local governments with installing it. As a result, by 2022 nearly 50 percent of the EV charging stations in the world had been installed in China. But, more important, 90 percent of the fast chargers were in China, which had an installed base of 760,000, compared with 70,000 across all of Europe.[43] As a result, China has so many charging locations that "range anxiety" is far less problematic there than in the U.S. or the EU.

The infrastructure economics are different for EVs than for ICEV, in the sense that fuel for ICEV could be accessed only at gas stations, which were eventually built in large numbers throughout a country to ensure wide availability of fuel. Moreover, ICEV required an entire supply chain, from oil drilling and refining to delivery to the end user. The transition to EVs presented fewer issues than the adoption of ICEV, as the electrical grid had already been built— that is, the problem of energy delivery had already been solved.

The charging infrastructure creates some conundrums. For example, as the range of an EV increases, demand for charging away from home will decline. Mandates that multifamily dwellings have charging points will exacerbate that problem. Further, utility and road maintenance economics will be changed dramatically by residential charging powered using residential solar panels (perhaps with home electricity storage). Finally, because Chinese firms have the largest and earliest market for widespread charging infrastructure, they are global technological leaders and have begun building charging infrastructure elsewhere, such as Mexico and countries in Southeast Asia. In many of these countries, Chinese charging standards are likely to be adopted de facto and, possibly, de jure. This expansion will almost certainly enable Chinese charging infrastructure firms to further increase their exports.[44]

SUMMARY

China has the largest EV market by far and, unsurprisingly, given the early attention the Chinese government paid to the entire value chain and its deliberate effort to build ecosystems, a robust value chain. Chinese firms are also global leaders in many components. Non-Chinese manufacturers that already had electric motor–related skills (Nidec, Bosch, etc.) in some of them or in components (e.g., tires, shock absorbers, and steering components) remained competitive. However, even these non-Chinese firms have had to establish R&D facilities in China both to remain competitive and to learn from the market (presumably to export that knowledge to their home markets). The EV industry is most likely to be experiencing what David Harvey called a “spatial fix” that makes one place, such as Detroit for automobiles early on, the center of a particular industry.

GLOBALIZATION

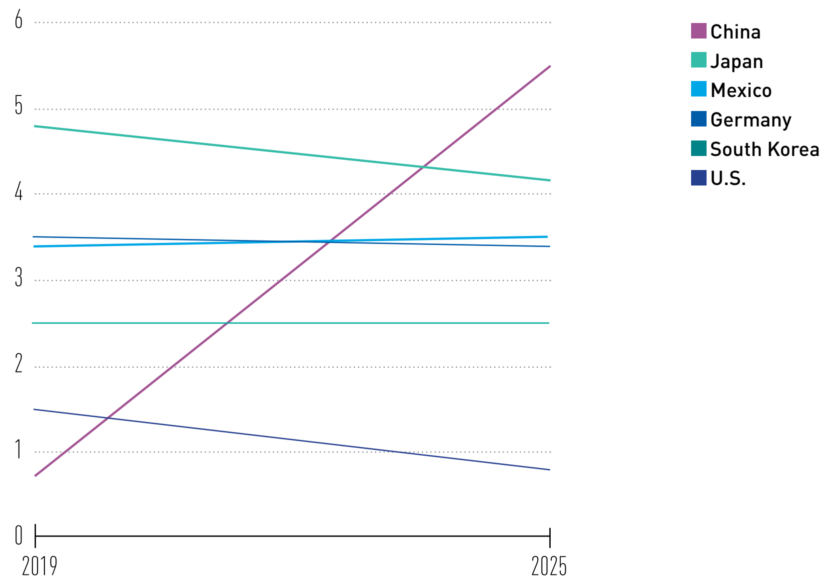
Only a decade ago, globalization and the Chinese automobile industry meant foreign direct investment (FDI) in the Chinese auto industry. But this has been reversed since approximately 2021. In 2025, an increasing number of foreign automakers shuttered their Chinese JVs, as the market for their ICEVs declined rapidly. Moreover, the Chinese government granted Tesla the right to build a factory in Shanghai as a wholly owned subsidiary. At least some of these JVs are producing EVs not only for the Chinese market but also for export to the foreign partner’s home market or to third-country markets.[45] Finally, as discussed below, Chinese EV and battery makers are rapidly initiating manufacturing operations overseas. In the 1990s, China had only limited auto production expertise and embarked on a policy of encouraging FDI in JVs with Chinese SOEs. These were intended to accelerate technology transfer to the Chinese JV partners—a policy that was somewhat successful, though less so in key drivetrain technologies. The disruption caused by the emergence of EVs as competitive with ICEVs meant that new competitors, such as Tesla and the Chinese EV startups, could enter a market and not need a long period in which to catch up to global-class levels—and even become leaders. Thus, when Chinese EV producers enter foreign markets, they do not face deeply embedded EV incumbents—of course, there are embedded ICEV incumbents—using technology that is rapidly becoming obsolete. If unhindered, Chinese EV firms might become dominant in many foreign markets—a catastrophic outcome for incumbent transplants from, in particular, Korea, Japan, and Europe.

The growth in Chinese ICEV, EV, and battery exports has been remarkably rapid. Until 2020, China imported far more vehicles than it exported. Chinese exports began to increase at the end of 2020 and then grew enormously in 2022—just when auto manufacturers in the G7 countries abandoned the Russian market. Most of the vehicles going to the Russian market were ICEVs.

However, after 2022, NEVs began to dominate Chinese exports, as internal competition heated up, and capacity was recklessly expanded. Figure 5 illustrates the speed of the expansion, as auto exports from China exceeded those from Japan in 2023 and continued to grow in 2025, widening the distance between its exports and those from other exporting countries. According to one estimate, auto exports from China are expected to reach 10 million by 2030 compared to approximately 5 million in 2025.[46]

These Chinese car exports include ICEVs and PHEVs but increasingly consist of NEVs. Their growth created trade tension with many of the importing countries, even though the domestic manufacturers in developing countries often originated in the G7 countries in Europe, Japan, and Korea—which would be displaced by this growth in Chinese imports. Although BYD already had e-bus assembly facilities in several countries, after 2022, Chinese firms began to build assembly facilities and battery factories abroad, as a result of the tensions with these importing countries. Table 1 shows that these facilities were concentrated in Southeast Asia, Brazil, Spain, and Morocco. Little investment was made in North America (other than two operations in the U.S.), Africa (with the exception of Morocco and Egypt), and Russia. In the EU, Germany and

FIGURE 5: GLOBAL CAR EXPORTS BY REGION IN MILLIONS OF VEHICLES



Source: McKinsey & Company, “China Drives to the Top,” *Week in Charts,* 2025, https://www.mckinsey.com/featured-insights/week-in-charts/china-drives-to-the-top/. Data Source: General Administration of Customs of the People’s Republic of China; German Federal Statistical Office; INEGI; Japan Automobile Manufacturers Association; KAMA; US Census Bureau

TABLE 1: CHINESE OVERSEAS FACTORIES, PRODUCT, OWNERSHIP, AND YEAR OF OPENING

CHINESE FIRM	LOCATION	PRODUCT	OWNERSHIP	YEAR OF OPENING
BTR	Morocco	Battery materials	Wholly owned	2026
BYD	Brazil	Buses	Wholly owned	2015
BYD	Brazil	Batteries	Wholly owned	2020
BYD	Brazil	Autos	Wholly owned	2025
BYD	Hungary	Buses	Wholly owned	2018
BYD	Hungary	Autos	Wholly owned	2026
BYD	France	Buses	Wholly owned	Closed
BYD	U.S.	Buses	Wholly owned	2014
BYD	Canada	Buses	Wholly owned	2019
BYD	Thailand	Autos	JV	2024
BYD	Thailand	Seats	JV	2024
BYD	Indonesia	Autos	JV	2026
BYD	Brazil	Autos	Wholly owned	2026
BYD	Brazil	Buses	Wholly owned	2015
BYD	Türkiye	Autos	JV	2026
BYD	Malaysia	EV CKD	Wholly owned	2025
BYD	Uzbekistan	EVs CKD	Wholly owned	2024
CATL	Germany	Battery	Wholly owned	2018
CATL	Hungary	Battery	Wholly owned	Under construction
CATL	Spain	Battery	JV Stellantis	Under construction
CATL	Indonesia	Integrated	JV	2026
CATL	Morocco	Battery materials	Wholly owned	2026
CATL	U.S.	Battery	Tech ties w/Ford	2025
CATL	U.S.	Battery	JV Tesla	2025
CATL	Thailand	Battery	JV Arun	2024
Chery	Russia	EV CKD	Wholly owned	2024
Chery	Spain	EV	JV	2025
Chery	Brazil	EVs CKD	JV	2024
Chery	Türkiye	EVs CKD	Wholly owned	Under construction
Chery	Kazakhstan	EVs CKD	Wholly owned	2024
Chery	Egypt	EVs CKD	Wholly owned	2024
Chery	Malaysia	EVs CKD	Wholly owned	2024
Envision	France	Battery	Wholly owned	2025
Eve Energy	Thailand	Battery	JV	2023
Geely	Malaysia	EV	Proton acquired	2025
Gotion	Thailand	Battery	JV	2023
Gotion	U.S.	Battery (Storage)	Wholly owned	2023
Great Wall	Brazil	Autos (ICE)	Wholly owned	2025
Great Wall	Brazil	EV	Wholly owned	2025
Hailiang	Morocco	Materials	Wholly owned	2026
SAIC (SOE)	Thailand	Batteries	JV	2023
SAIC (SOE)	Indonesia	Autos (ICE)	Wholly	2015
SAIC (SOE)	Indonesia	Batteries	JV	2025
SAIC (SOE)	India	Autos (ICE)	JV	2019
Sunwoda	Morocco	Battery	Wholly owned	2026
Tinci	Morocco	Battery materials	Wholly owned	2026
Zhongde	Morocco	Anode materials	Wholly owned	2026

SOURCE: Author compilation from various sources. SOE = state-owned enterprise. ICE = internal combustion engine. JV = joint venture.

Hungary have some factories, but it appears that Spain and Morocco might become the European hub for Chinese EV production.

The speed of expansion in Chinese exports, followed by the establishment of EVs and battery production facilities is unprecedented, and it exceeds that of, for example, Japanese auto manufacturers in the 1980s and 1990s.[47] Chinese EVs are likely to most directly affect the offshore operations of Japan, Korea, and Germany, among the developed countries. The new Chinese battery factories might prove to be potent competitors to European automakers that have had little success in developing competitive battery makers thus far. Because of Chinese production for its domestic market and exports to its capacity added in various countries, China seems certain to benefit enormously from economies of scale and learning that come with higher volume, and it is possible that a significant proportion of global demand for EVs will be satisfied by Chinese firms.

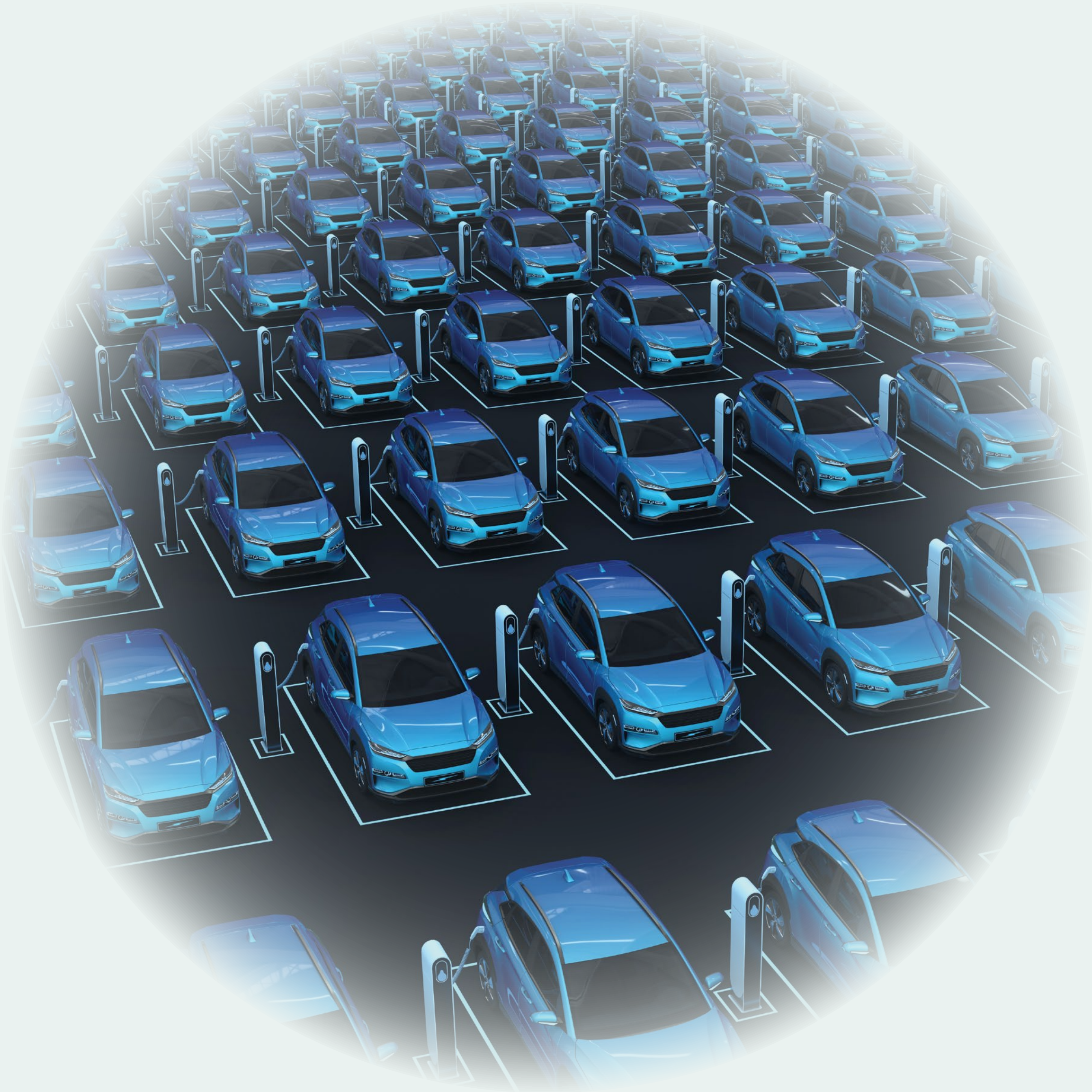
CONCLUSION

Chinese success in EVs and batteries resulted from a unique model that combines evolving goal setting and support by the central government, grassroots entrepreneurial initiatives, and local government experimentation with a large variety of initiatives aimed at supporting local entrepreneurs. It is based, in part, on the early adoption and massive investment in the improvement of LFP batteries, which enabled firms that use them to outflank Chinese and Korean competitors that relied on more expensive battery chemistries. The extent of this success and the current dominance of LFP batteries is illustrated by the fact that CATL and BYD together provide more than 55 percent of all EV batteries. Moreover, Chinese battery firms, in particular CATL, are investing in potential replacement chemistries, such as sodium. This success is the evolutionary result of more than 25 years of research, development, demonstration, and commercial production. Not only has China built a supply chain for EVs and LFP batteries encompassing their entire life cycle, from mining minerals to recycling, but it is dominant in many of the nodes of this supply chain. Extension of this trendline, especially if seen as part of a larger cleantech transition comprising solar- and wind-generated energy, could have profound implications.

Yet the Chinese development model also has some contradictions that are important to acknowledge. Ample evidence shows that Chinese workers receive low wages and have been widely documented to suffer abuse. Moreover, during the recent price wars, auto assemblers have delayed paying suppliers to such an extent that the central government has stepped in to demand prompt payment for deliveries. Finally, government subsidies, particularly at the local level, have contributed significantly to the excess capacity and ongoing ruinous price wars, which not only affect profitability in China but also incentivize the current tsunami of exports. These Chinese exports are so inexpensive that they are rapidly gaining market share from incumbents in the importing countries. Some of these exports are going to Russia, one of China's largest overseas markets, from which European and Japanese firms withdrew due to sanctions imposed because of the military actions in Ukraine. Another rapidly growing market and offshore production base from which the Chinese auto and battery producers will also export to third countries consists of the member countries of the Association of Southeast Asian Nations (ASEAN). Moreover, an increasingly large number of Chinese-made automobiles and EVs are sold to countries in Latin America, especially Brazil and Mexico (though Mexico is under tremendous pressure to halt Chinese imports), and in Africa. If the current trajectory continues, Chinese EV producers might become dominant globally, catering not only to their home market but capturing much of the market in the rest of the world other than North America, Western Europe, Japan, Korea, and a few countries, such as India, that have significant political differences with China. And in many of these other countries, Chinese firms might provide the batteries and drivetrains (e.g., Toyota purchases batteries from CATL and BYD). The massive export push has also come to include the building of factories overseas.

At present, China and the LFP battery technology have the upper hand in global EVs. However, the industry is still in flux, with new entrants, particularly in batteries, that could develop and introduce new batteries that upend the industrial order. Further, governments in Europe and/or the U.S. might erect barriers to Chinese imports or investment so as to protect their domestic producers until they can develop sufficient scale, business models, and technology to become globally competitive.

The future is difficult to predict, but the disruption caused by BEVs has created an opportunity for Chinese automakers to reclaim their domestic market from the JVs between SOEs and foreign automakers, as they rapidly and apparently decisively enter the global market. Dominance in EVs will, almost certainly, result in dominance in batteries and determine which country will benefit the most in the transition to an electricity-centric economy and society. If the current trajectory of Chinese EV and battery development continues, the domestic industrial and environmental policies of other countries will be shaped by a recognition of China's vital role in the dawning electric-centric energy paradigm.



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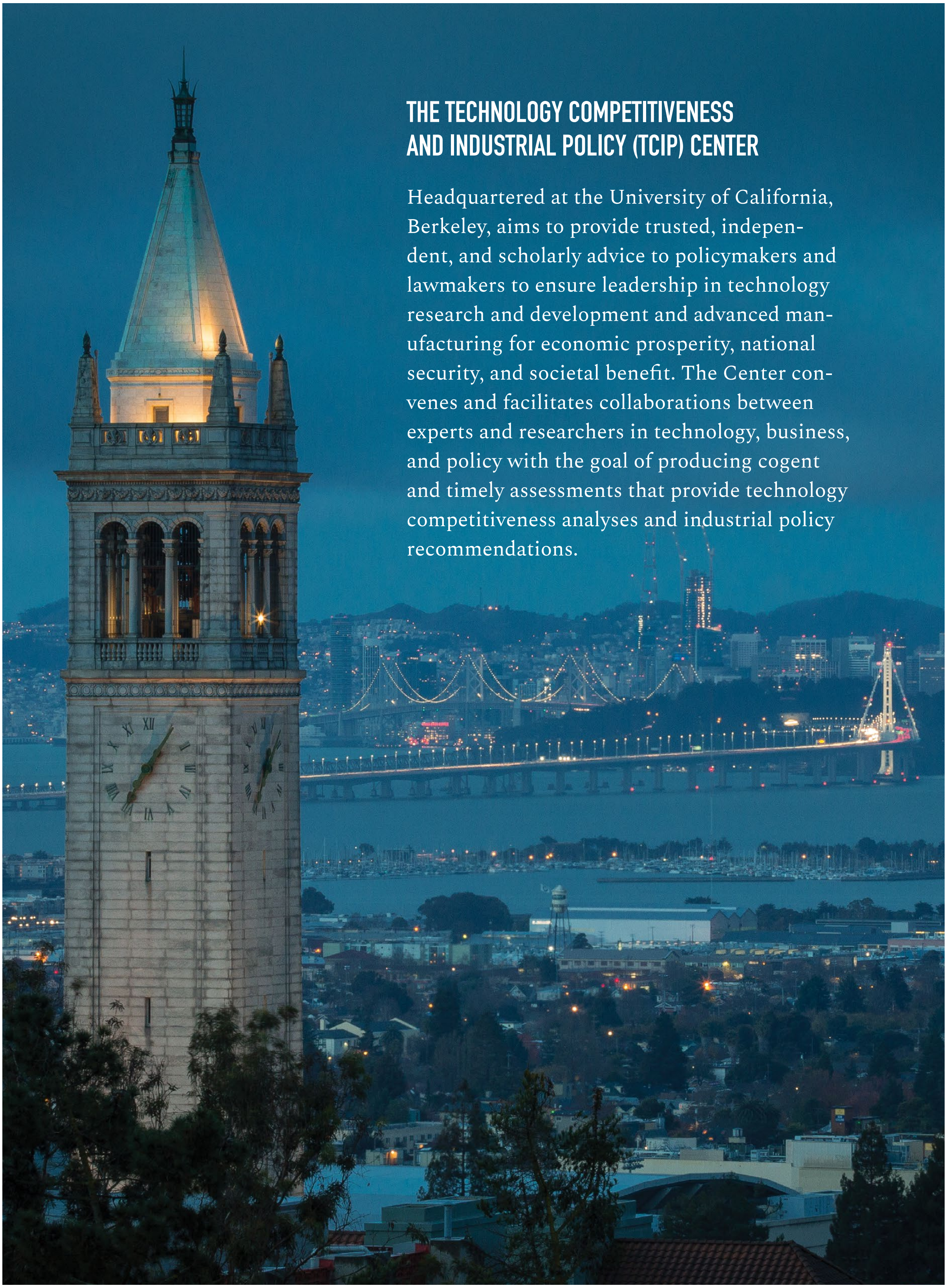

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