TCIP

TECHNOLOGY COMPETITIVENESS & INDUSTRIAL POLICY CENTER

RECHARGING OUR FUTURE

CAN THE U.S. MANUFACTURE BATTERIES?

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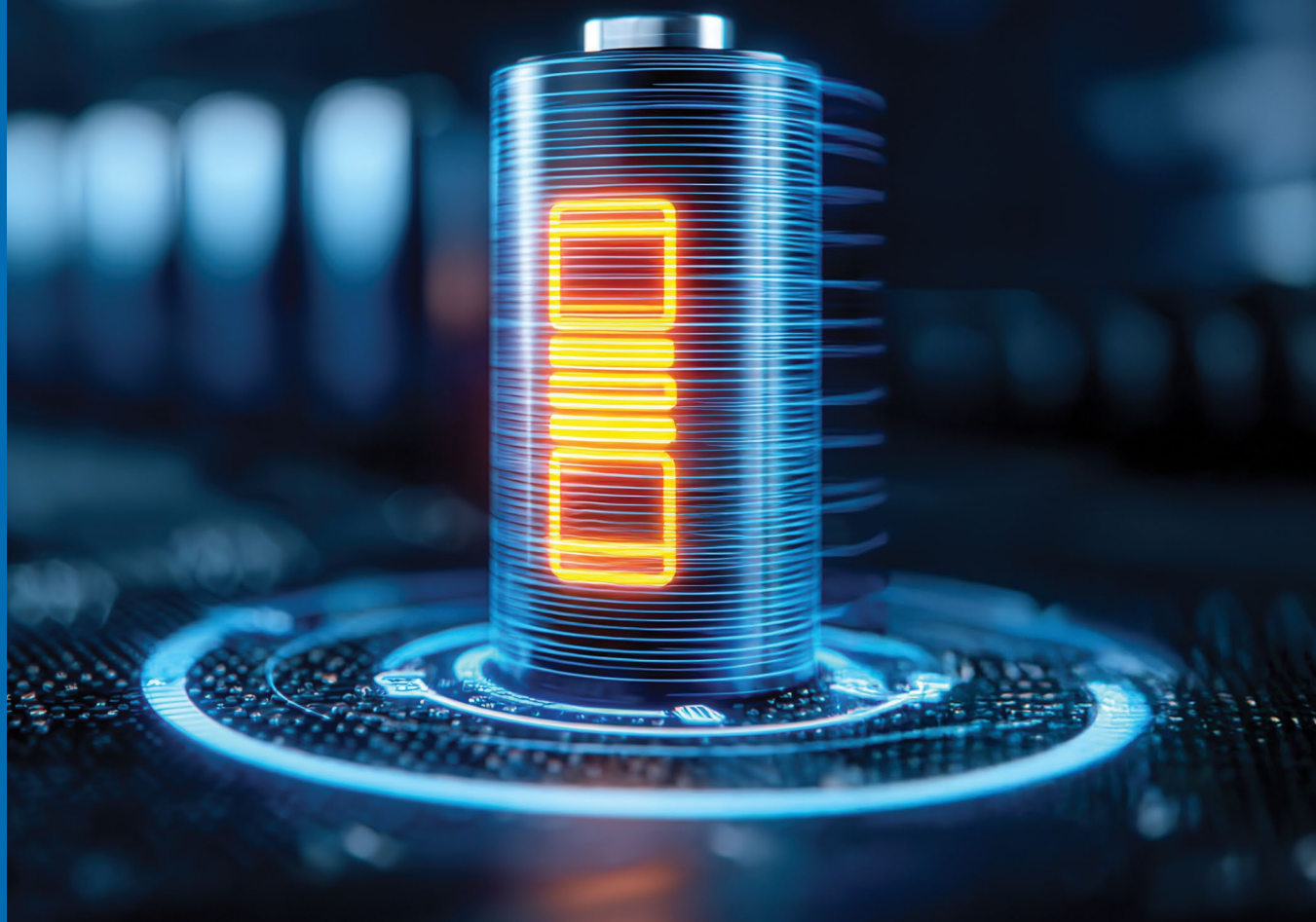

This report is the output of an assessment commissioned by the Technology Competitiveness and Industrial Policy Center (TCIP Center) at the University of California, Berkeley to understand the state of lithium-ion battery manufacturing in the United States. It is based on data analysis, insights from expert interviews, and a review of industrial policy choices and their effects. The study addresses U.S. dependence on China for battery imports, an appropriate and competitive strategy to build up domestic battery production capacity, and structural failings that led to offshoring of the production of U.S. battery innovations.

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China has rapidly risen to dominate global lithium-ion battery manufacturing despite the U.S. having invented the majority of foundational battery technologies. This outcome raises three critical questions:

1. Should the U.S. be concerned by its dependence on China for battery imports or should it consider producing batteries domestically?
2. If domestic manufacturing of batteries is indeed important for the U.S., what is an appropriate and competitive strategy to build up domestic production capacity?
3. Can the U.S. avoid a repetition of history by addressing the structural failings that led to offshoring of the production of its battery innovations to begin with?

This report examines these questions in turn. We begin by establishing that domestic battery manufacturing is indeed of economic and geostrategic importance. Continued dependance on China for battery technology puts the U.S. in a deeply unfavorable position from the perspectives of technology leadership and national security. However, through analysis of China's position in the battery sector, we also show that it will be extremely difficult for the U.S. to gain a significant foothold in manufacturing the current generation of lithium-ion (Li-ion) batteries.

Our research suggests that the U.S. needs to adopt a different approach. Rather than trying to catch up with China on lithium-ion production for the electric vehicle (EV) market - a technology that China already controls - the U.S. should focus on leading in novel rechargeable technologies for emerging downstream markets. Doing so changes the game in a way that plays to the U.S. strengths of innovation and entrepreneurship. In particular, we highlight the potential for U.S. competitiveness in grid-scale battery storage, the emerging electric aviation sector, and in the space economy. In all cases, novel battery concepts provide new modalities where the U.S. has competitive potential.

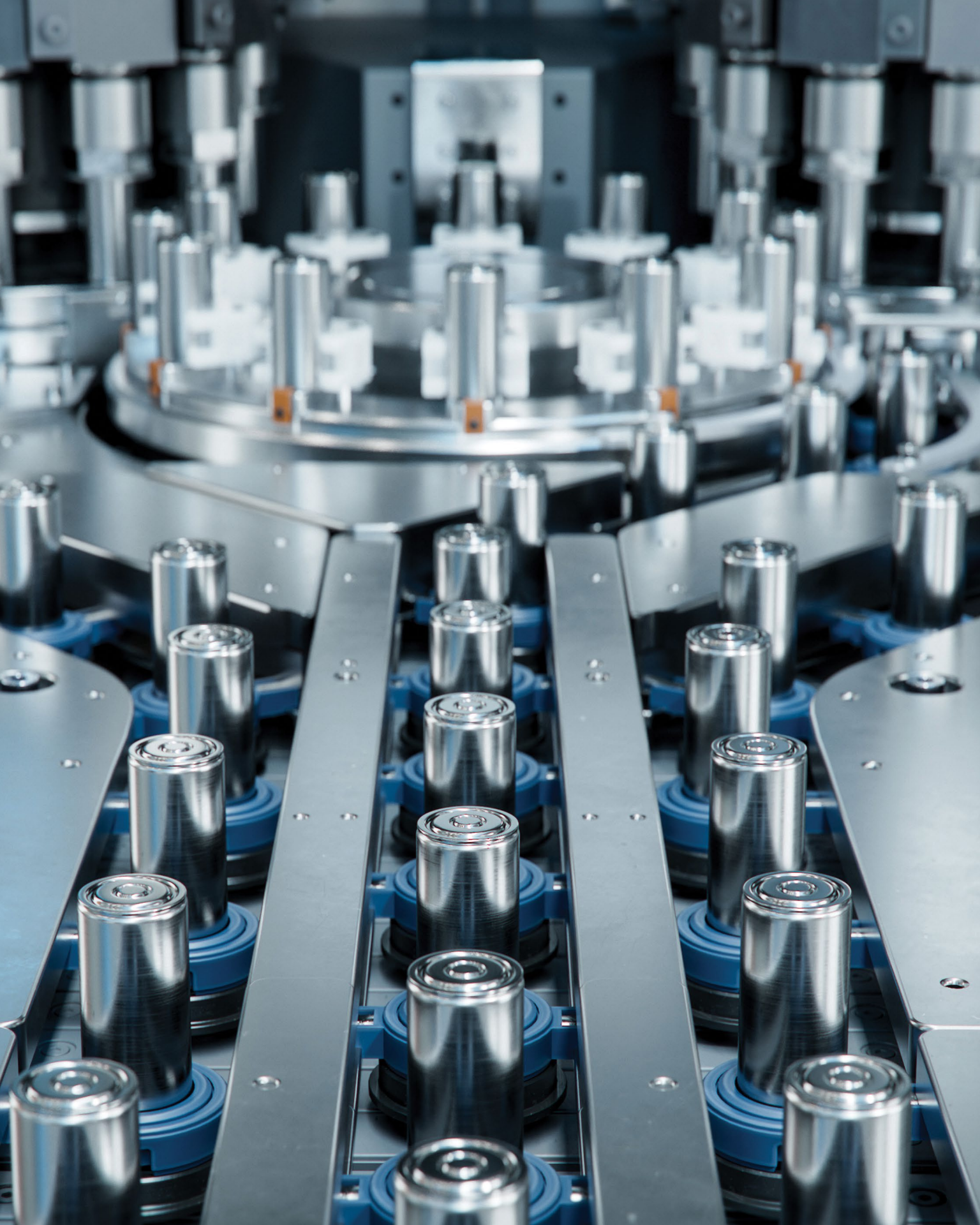
Opportunities to capitalize on new battery chemistries and products in these emerging sectors must be grounded on building U.S. competitiveness in scaling to high volume production. Simultaneously, the U.S. must foster the relevant end markets that provide a demand signal and accelerate adoption. From a policy perspective, coupling early-stage innovation and a scaled industrial base will require domestic investment and a strategy to attract established, foreign battery manufacturers to the U.S. This is because the industrial base required to scale battery technology currently does not exist domestically and will need to grow alongside the maturation of emerging battery chemistries from the U.S. innovation ecosystems. **Coupling innovation and scaled manufacturing by enabling both new startups and established industry creates the competitive playing field needed for the U.S. to lead in future battery innovations.**

Finally, we address the core systemic and historic weakness of the U.S.: **that inept or absent industrial policy has been the decisive factor in the U.S.'s inability to scale its innovations and sustain a resilient industrial base.** In the current period of geopolitical competition where

the means of production becomes a source of strength and bargaining power, this U.S. weakness outweighs all other advantages including its strong innovation ecosystems.

Without a commitment to industrial policy that emphasizes both innovation and its connection to manufacturing at scale, any strategy we might present for gaining leadership in rechargeable batteries will lead to the familiar outcome of China outpacing the U.S. in volume production and thus ultimately dominating U.S. technological innovations. This U.S. weakness stands in sharp contrast with China's coordinated and sustained industrial policies that, as we demonstrate, have been definitive in that nation's ability to scale up and capture the value of U.S. battery innovation among many other U.S. inventions. Recent efforts by the successive U.S. presidential administrations acknowledge the need for a robust industrial policy but are too recent to have had lasting impact on the sector.

We conclude by exploring what industrial policy choices are pragmatically available to the U.S. given that the U.S. is unlikely to compete successfully with China using China's industrial policy playbook. Rather than copy China, the U.S. must focus on playing to its strengths including its system of private sector ingenuity and entrepreneurialism, innovation ecosystems, and strong capital markets that could support all stages of innovation from idea to scaled industrial product.



ARE RECHARGEABLE BATTERIES A STRATEGIC INDUSTRY?

Batteries provide a powerful lens through which to examine the benefits of both economic growth and resilience of an important industrial sector that has strong foundations in continuous technological innovation.

Upon examining the buyout of U.S. battery startup A123 by Chinese auto parts giant Wanxiang in 2012, former Director of National Intelligence Dennis Blair wrote "There are many sensitive technologies that the United States should protect. The manufacture of lithium-ion batteries is not one of them."[1] This stance has never been endorsed as official U.S. policy (to our knowledge), but it has been adopted *de facto*. As a result, there has been inaction on the part of the U.S. government across multiple administrations to consistently promote the battery industry's growth.

The U.S. posture towards batteries stands in sharp contrast to China's evaluation of the rechargeable battery industry. As far back as 1987, the Chinese Communist Party (CCP) identified rechargeable batteries as a national-priority technology under Deng Xiaoping's "863 Program"[2] and has consistently reaffirmed that status in subsequent major national plans either directly or via support of battery-enabled sectors such as EVs. Examples include the National "863" Plan for Electric Vehicle Major Project in 2001,[3] the 2010 inclusion of new energy vehicles (NEV) as a national Strategic Emerging Industry (SEI),[4] priority
status in the Made in China 2025 program starting in 2015[5] and subsequent 13th and 14th Five Year Plans. More recently, the 2020 NEV Industrial Development Plan 2021-2035[6] highlighted batteries as a key area for technological advancement and industrial integration. It emphasized achieving breakthroughs in battery technology, particularly lithium-ion batteries, and accelerating the development and commercialization of solid-state batteries. The plan also focused on improving battery recycling, reuse, and disposal systems. Furthermore, it promoted the concept of "vehicle-to-grid" interaction and encouraged the integration of the NEV industry with the energy, transportation, and information communication industries.

Whether the U.S. or China were correct in their assessment of the strategic importance of the battery industry can now be analyzed through the lens of recent industrial history and importantly, in the light of today's great power competition. We consider different aspects of strategic competition relevant to sovereign nations and evaluate the role of the industry along two dimensions: economic growth and national resilience. While economic growth and competitiveness have traditionally been the driver of innovation policy and industrial strategy, in today's geopolitical era, a strong and innovative manufacturing base also provide much needed resilience and national security. Along both dimensions, maintaining technological advantage serves as the core starting point.

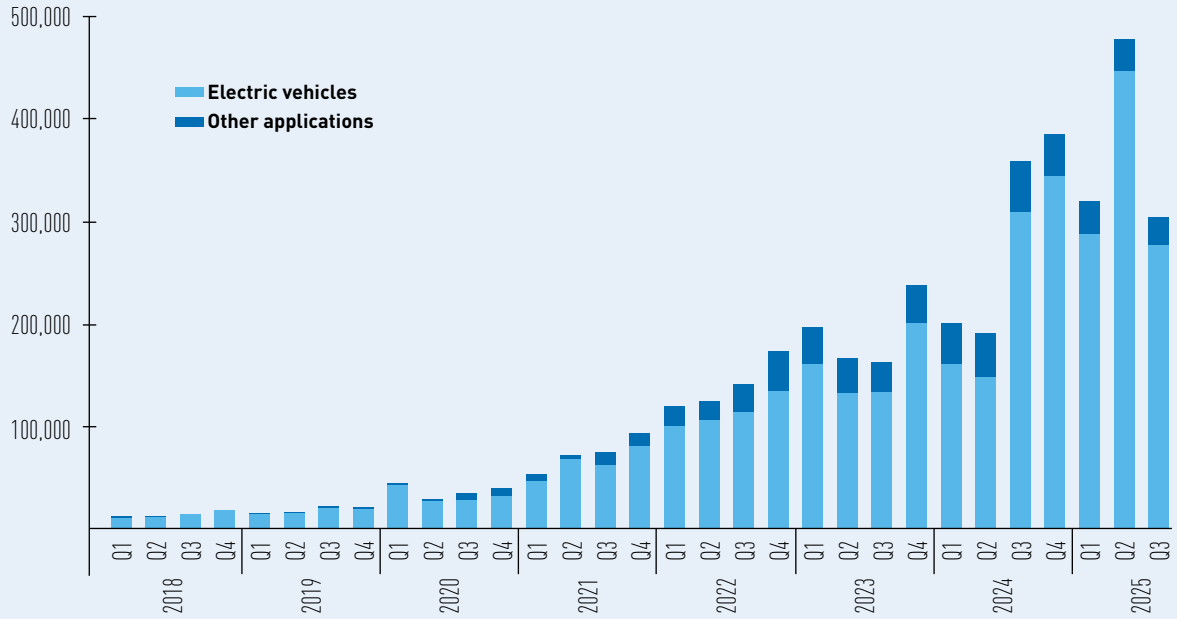
Batteries provide a powerful lens through which to examine the benefits of both economic growth and resilience of an important industrial sector that has strong foundations in continuous technological innovation. We consider six of these benefits in turn:

ECONOMIC GROWTH

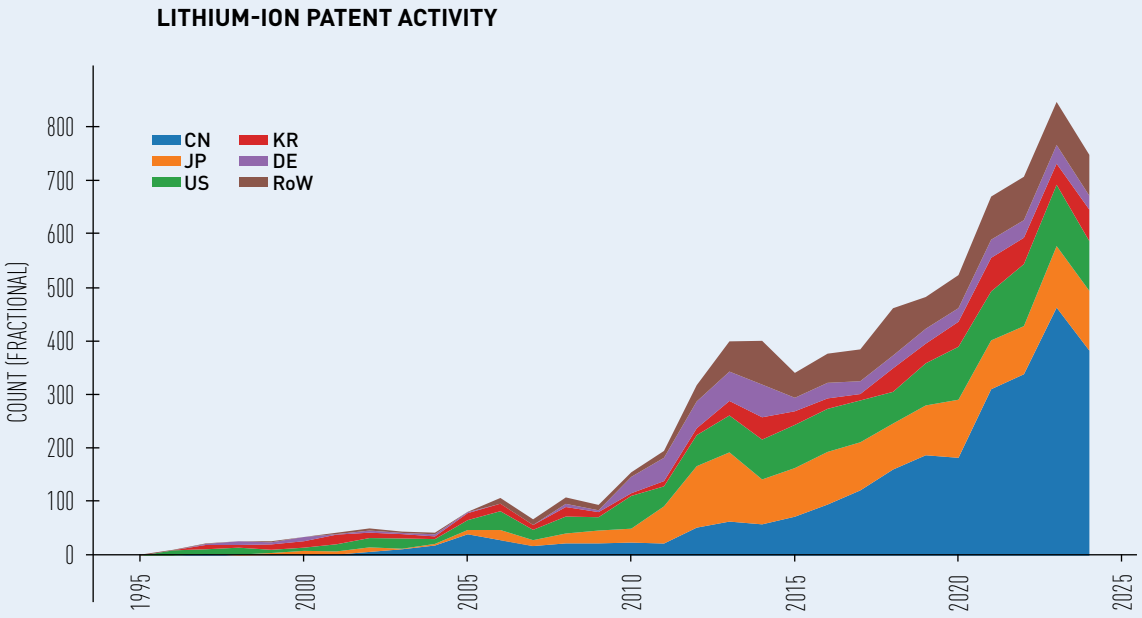
CAPTURING THE VALUE OF TODAY'S INDUSTRY

China has captured significant economic growth from prioritizing domestic battery manufacturing. Batteries combined with EVs and solar cells contributed 11.4tn yuan ($1.6 trillion) to China's economy in 2023 accounting for 40% of GDP expansion in that year alone.[7] Batteries similarly contribute to China's export strength accounting for 3.2% of exported goods in 2023.[8] By comparison, the U.S. has largely sat on the sidelines of battery manufacturing, failing to capture any meaningful economic growth or jobs growth from domestic production. Instead, the U.S. has developed increasing reliance on Chinese imports: between 2019 to 2023, imports of Chinese lithium-ion batteries to the U.S. grew from 53% of battery imports to 74%.[9] China is fast on its way to monopolizing rechargeable batteries[10] which would make the U.S. economy dependent on Chinese imports for all battery-enabled sectors.

QUARTERLY U.S. LITHIUM-ION BATTERY IMPORTS (METRIC TONS)



SOURCE: U.S. Census International Trade HS Code 8507.60



SOURCE: European Patent Office Worldwide Bibliographic Database (DOCDB)

TECHNOLOGY LEADERSHIP TO LAY THE FOUNDATION OF FUTURE INDUSTRIES.

The mix of battery-enabled technology sectors has only increased in recent years. Batteries are a form of general-purpose technology supporting many applications and have thus played a central role in consumer electronics, distributed computing, and cellular communication. They now play an increasingly important role in robotics and autonomous systems, medical devices, defense and aerospace, electric grid scale storage, and mobility including EVs. To stay at the leading edge of these technical sectors, capture economic growth, and avoid technology surprise, a country must be at the cutting edge of battery technology. The creation of new battery products and chemistries is tightly linked to their production due to needed advances in manufacturing processes. Manufacturing also provides the revenue and foundational jobs to support a high-tech workforce to advance research. CATL alone reported a research and development staff of over 20,000 experts backed by a RMB 18.36 billion (US $2.5 billion) research budget in 2023.[11]

POPULATION HEALTH AND LABOR PARTICIPATION

Adoption of electric vehicles has contributed significantly to improved air quality in major Chinese cities.[12] This contributes to overall enhancement of population health and quality of life which likely has positive impacts on labor participation.[13] The U.S. has not experienced similar air quality improvements in dense urban centers due to low levels of EV adoption. Of course, it is the adoption of batteries, not their manufacturing origin, that contributes to public health outcomes. However, China's provision of consumer incentives helped build a market for its domestic manufacturing sector enabling it to control both the supply and demand of batteries that has led to improved air quality.

RESILIENCE

ENERGY SECURITY

A primary reason driving China's move into the EV space was to bolster its energy security.[14] EVs enable China to decouple a significant part of its economy from oil import dependance. Estimates show that EVs have already displaced 1 million barrels per day of Chinese oil demand.[15] The U.S., by contrast, has ample domestic oil reserves and can potentially continue to rely on gasoline-powered vehicles. However, as battery technology improves, it will become an increasingly important means to store and distribute energy to a diversified range of downstream sectors unsuitable for fossil fuels (for example, supporting space-based systems). Some battery-enabled technologies will also likely outperform their gas-powered counterparts leading to better products and consumer outcomes. This is already proving to be true for EVs which have on average better acceleration and torque than internal combustion engine (ICE) vehicles,[16] lower maintenance costs,[17] and closing range gaps.[18] Batteries are therefore essential as part of a mix of technologies to ensure energy security.

SUPPLY CHAIN (IN)DEPENDENCE IN CRITICAL MINERALS AND BEYOND

China's focus on battery manufacturing has extended to include upstream supply chains, notably the mining and processing of critical minerals important to producing batteries. As a result of sustained investment, China now controls significant mineral processing of lithium, nickel, cobalt, and graphite giving it independence independence and control.[19] Consequently, even when these minerals are mined elsewhere, they are most often shipped to China for processing. Chinese companies have also heavily invested to gain controlling shares or full ownership of critical mineral mines around the world including 75% of Indonesia's nickel refining capacity,[20] 15 of the DR Congo's 19 best cobalt and copper sites,[21] and 7 of Argentina's 16 lithium mining operations.[22] Further down the value chain from critical minerals to batteries, nearly 90% of global installed cathode active material manufacturing capacity and over 97% of anode active material manufacturing capacity is located in China.[23] China's control of critical minerals extraction and processing has serious implications for the U.S. and the rest of the world given their ability to limit access[24] as has been demonstrated by recent sanctions. Specifically, China has implemented export restrictions, including tariffs and licensing requirements on certain critical minerals, particularly in response to U.S. trade policies. These actions, primarily targeting minerals like gallium, germanium, antimony, tungsten, tellurium, bismuth, and indium, are a strategic move by China to leverage its dominance in the global supply chain of these materials to impose its political will on other nations.[25]

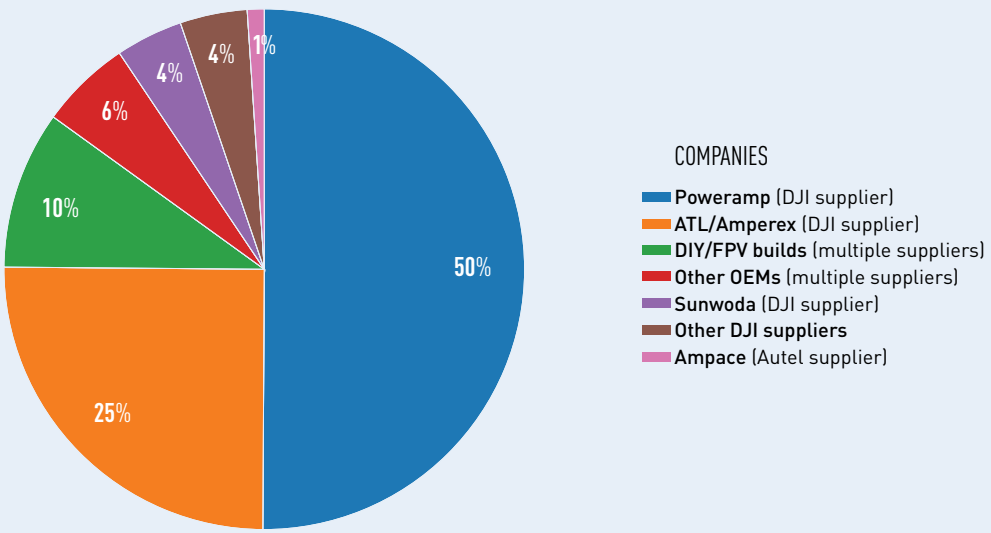
NATIONAL SECURITY

The introduction of new types of weapons and autonomous systems to the battlefield has more directly increased the strategic importance of battery technology to defense and national security. Unmanned aerial vehicles alone have transformed the battlefields in Ukraine and the Middle East in recent years.[26] The majority of these drones are

powered by lithium polymer batteries that are predominantly produced in China[27] giving the CCP strong control over this essential technology. Such monopoly control creates dependance upon China by the U.S. and other nations and is the source of significant national security concerns. This problem will only become more acute if not addressed. With the increasing importance of drones, robotic systems, and distributed intelligence systems, batteries are a foundational technology for future national security systems.

Taken together, China's leadership in batteries has provided that nation with strength in economic growth and national resilience along all six categories: value capture in the sector, advantage in future technologiesm and population health on the side of economic growth, along with energy security, supply chain independence, and national security on the side of resilience. Thus, by betting strongly on battery manufacturing, China has ended up in a stronger geostrategic position than the U.S. along the dimensions of economic growth and national resilience. This result indicates that battery innovation, manufacturing, and its associated value chain should indeed be treated as a strategic industry and it is not advisable for the U.S. to depend on China for provisioning this increasingly critical technology.

ESTIMATED LITHIUM-POLYMER DRONE BATTERY MARKET SHARE



SOURCE: UN38.3 Test Summaries and Battery Safety Data Sheets

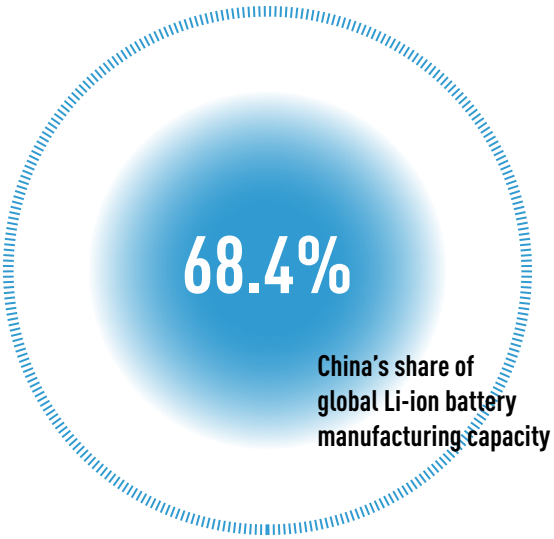
CHANGING THE GAME

A COMPETITIVE APPROACH FOR THE U.S. IN BATTERIES

The alternative way for the U.S. to compete is to change the game. This means the U.S. must focus on emerging battery-enabled sectors beyond electric vehicles which require new battery chemistries and business models.

The battery sector is clearly of strategic importance, but the question remains as to whether the U.S. can catch up in lithium-ion battery manufacturing. Six of the top ten global manufacturers of lithium-ion batteries are based in China: CATL, BYD subsidiary FDB, CALB, Gotion High-Tech, EVE Energy, and Svolt. **CATL and FDB alone account for a combined 55.5% of global manufacturing capacity.**[28] These companies hold a market position that will be difficult, if not impossible, to challenge due to the advantages in economies of scale and scope that in turn lower the cost of production year-on-year and which therefore provide opportunities for innovation.[29]

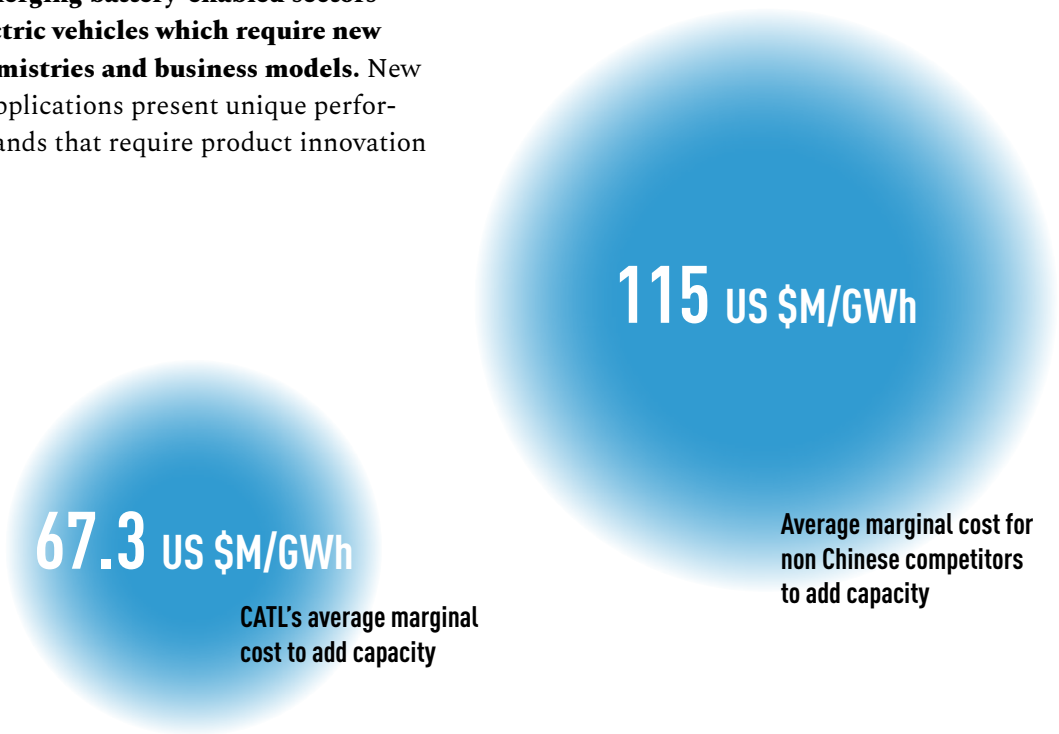
To put the economics of Chinese battery production into context, an estimate of the marginal cost for CATL to add manufacturing capacity in recent years is illustrative. Since 2023, CATL has announced several expansion projects including a 30 GWh capacity increase in Yibin, Sichuan, China for US $0.83 billion,[30] a 60 GWh capacity increase in Jining, Shandong, China for US $2.9 billion,[31] a 137 GWh capacity increase across 6 projects in Fujian, Zhejiang, and Guangdong, China for US $8.1 billion,[32] a 15 GWh capacity increase in West Java, Indonesia for US $1.18 billion,[33] a 100 GWh capacity increase in Debrecen, Hungary for US $8.6 billion,[34] and a 50 GWh capacity increase in Vigo, Spain for US $4.83 billion.[35] This accounts for a total additional capacity of 392 GWh for a total investment of US $26.4 billion which is an approximate **marginal cost of US $67.3 million per additional GWh. This is compared to the US $128 million/GWh that LG Energy will spend to build capacity in Queen Creek, Arizona,**[36] the US $82 million/GWh that Northvolt committed for its gigafactory in Heide, Germany[37] (now in doubt due to bankruptcy filing [38]), the US $133 million/GWh that Panasonic is spending on its factory in De Soto, Kansas,[39] and the US $118 million/GWh that SK On spent to build capacity in Commerce, Georgia.[40] These estimates exclude working capital and ramp-up expenses associated with operations.



These publically available data demonstrate that the marginal cost for industry leaders in China like CATL to add additional capacity is so low that other global competitors will have trouble keeping up, let alone catching up, if behind. This is largely because each doubling of cumulative capacity is accompanied by a predictable reduction of production cost due to a clear and ongoing learning curve. Specifically, today's battery technologies experience a 20% reduction in cost with each cumulative doubling of output,[41] meaning CATL's ability to add capacity at costs lower than its competitors will further accelerate its cost advantage and leadership position. **We conclude based on these numbers that competing on cost for producing existing lithium-ion batteries is likely a losing proposition for U.S. industry.**

The alternative way for the U.S. to compete is to change the game. This means the U.S. must focus on emerging battery-enabled sectors beyond electric vehicles which require new battery chemistries and business models. New industrial applications present unique performance demands that require product innovation in different battery chemistries and designs as well as new process innovation to achieve volume manufacturing. Cultivating innovation ecosystems to generate these breakthroughs — sufficiently differentiated from the lithium-ion batteries used for EVs — would enable the U.S. to leap-frog the current generation of rechargeable energy storage technologies and gain strategic advantage.

Building dominance with a new generation of technologies is a tried and tested approach to rebalancing strategic advantage. In assessing pathways to dominate the global automotive industry, China understood that it was too far behind on the learning curve to compete with established European and U.S. industry on ICE vehicles.[42] Instead, China focused on an entirely new technology approach — electric vehicles — thereby



eliminating the need to attempt to compete on the established technology. Critical to the success of China's strategy was its focus on innovating across the **entire value chain required for the EV industry to succeed.** CCP industrial policy spanned everything from the supply of critical minerals for battery active components to the networks of charging stations needed for consumers to keep their vehicles powered.

To be successful, **the U.S. must similarly focus on an end-to-end approach to dominate an emerging battery-enabled sector** rather than focusing on batteries-for-the-sake-of-batteries or critical-minerals-for-the-sake-of-critical-minerals. To do so requires a clear understanding of potential sectors where next generation battery technologies will be in strong demand. We examine four in particular: grid-scale energy storage, space exploration and satellites, electric aviation, and robotics.

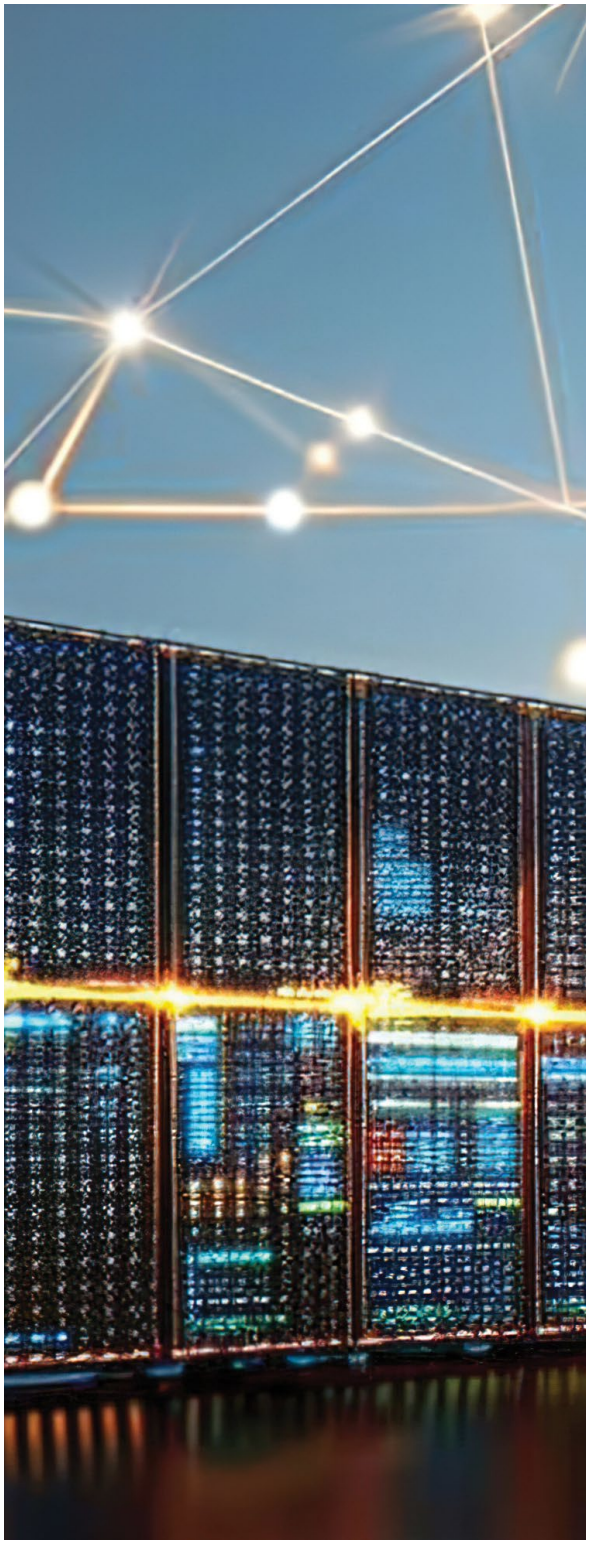
Table 1 illustrates some of the key technical requirements for batteries in each of these sectors including EVs and consumer electronics for comparison as areas where Chinese Li-ion battery expertise dominates. End-use applications such as defense or transportation that draw from from multiple of these sectors are not considered as a stand-alone category; defense, for example, will apply batteries for drones, robotics, and spacecraft in military technology.

For each battery-enabled sector, we assess whether the chemistries and processes involved are sufficiently distinct from Li-ion to represent a differentiated technical vector along which the U.S. can compete with China. We also assess the strength of the market opportunity in each industrial sector to determine the potential for economic and strategic returns as a result of focused innovation and market shaping.

PERFORMANCE METRICS DRIVING BATTERY INNOVATION

	Electric Vehicles	Grid Storage	Consumer Electronics	Electric Aviation & Drones	Robotics & Automation	Spacecraft & Satellite
High specific energy (Wh/kg)	+		+	+	+	+
High energy density (Wh/L)	+		+	+	+	+
High specific power (W/kg)				+	+	
Long cycle life		+				+
Wide operating temperature	+			+	+	+
Low cost ($/kWh)		+	+			
Radiation tolerance						+
Low self discharge		+				+

TABLE 1: Performance metrics driving the development of new battery technology across different sectors.



BATTERY-ENABLED SECTOR 1

GRID-SCALE ENERGY STORAGE

Batteries are a strong candidate for grid-scale energy storage used to balance the supply and demand of electricity generation, distribution, and consumption. Market-driven technical requirements for batteries supporting grid-scale storage include:

+ **LOW COST OF ENERGY CAPACITY**
  This is perhaps the defining requirement for grid-scale batteries to make them economically viable. The U.S. DOE calls for US $0.05 per kWh levelized cost for long-duration (>10 hour) storage by 2030.[43]
+ **LONG SERVICE LIFE**
  Grid-scale batteries are utilities assets with decade-plus service lifetimes. Long calendar life is needed, as is long cycle life for high throughput applications (e.g., daily cycling or shorter).
+ **LONG-TERM SAFETY AND RELIABILITY**[44]
  Safety features including thermal management solutions that serve to avoid fires in large-scale battery installations are essential.

The first two of these requirements stand in contrast to EV batteries that optimize for maximal energy and power density subject to weight and size reduction. EV batteries can tolerate somewhat higher costs and decreased longevity (cycle life) in exchange for lighter weight and higher discharge rates. Stationary batteries are not weight-constrained and can use safer, less energy-dense chemistries that are optimized for low cost per kWh, longevity, and reliability. Grid-storage batteries also operate in more controlled environmental conditions compared to

the wide temperature ranges, mechanical shock, and vibration experienced by vehicle batteries. These different drivers have led to the emergence of battery chemistries and systems that diverge from the dominant EV technologies including redox flow batteries and new long-lasting chemistries specifically metal-air batteries and sodium-based batteries. The advantages and opportunities for these dominant emerging vectors include:

REDOX FLOW BATTERIES

Since the 1970s, flow batteries have been explored for energy storage applications.[45] The assembly of flow batteries is very different from that of other rechargeable batteries. Two tanks are used to store two redox-active electrolytes that are separated by an ion-selective exchange membrane that is impermeable to the redox species. Many different redox couples have been explored for flow battery applications including inorganic species such as V/V, Zn/Br2, V/Br2, S/Br2,Ce/Zn, Fe/Cr, and Pb/Pb, as well as organic redox couples. The flow battery design enables an easy decoupling of the battery's energy capacity and power: the size of the electrolyte tanks determines the energy capacity of a flow battery whereas the size of the redox reactor stack determines the power.[46] Vanadium (V/V) redox flow batteries are the iconic flow battery chemistry and benefit from the fact that the vanadium species do not degrade over time and that the two electrolytes are compositionally identical, thereby negating the risk of cross-membrane contamination. Vanadium flow batteries have demonstrated tens of thousands of cycles of operation [47] making them well-suited for the grid. China's Rongke Power has completed several grid-scale vanadium flow battery installations including the 100 MW / 400 MWh Dalian project in 2022 and the 175 MW / 700 MWh Xinhua Ushi Energy Storage Project in Xinjiang in 2024.[48] These are among the world's largest vanadium redox flow battery systems. However, the hunt for alternative flow battery chemistries is still vibrant because vanadium is relatively expensive and potentially supply-constrained with China, Russia, and South Africa serving as the largest vanadium producers.[49]

METAL–AIR BATTERIES

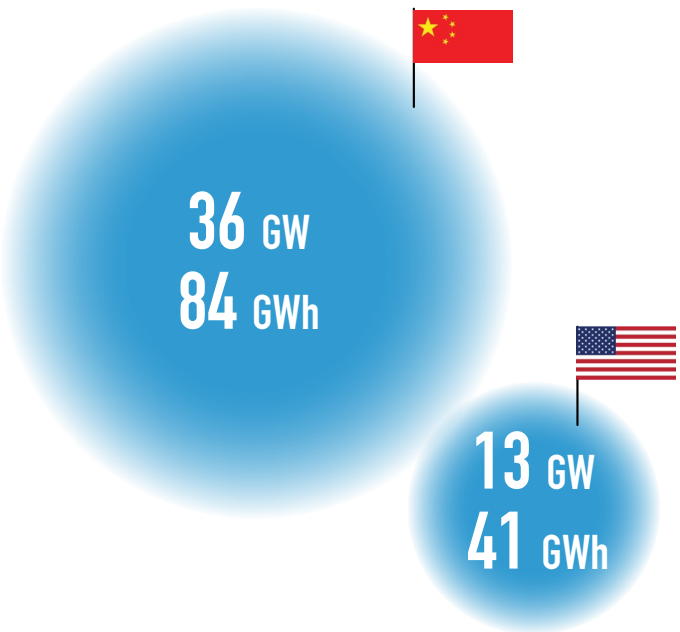
Rechargeable Iron-Air or Zinc-Air batteries use oxygen in the air as a reactant and offer high theoretical energy density at very low material cost compared to lithium-ion. The U.S. is a leader in Iron-Air battery development with startup Form Energy having several commercial projects in their pipeline including a 1.5 MW/150 MWh installation with Great River Energy in Minnesota[50] and a 15 MW/1,500 MWh installation with Georgia Power.[51] Nickel-hydrogen (NiH_2) is another metal-gas battery that has been around since the 1970s and was prominently used by NASA for space-based energy storage including the International Space Station. Cost-reducing innovations such as reduction in platinum catalyst could make them competitive for stationary terrestrial storage. U.S.-based startup EnerVenue is commercializing this technology for grid storage with an automated assembly line in California and a much larger factory planned in Kentucky.[52]

SODIUM-BASED BATTERIES

Sodium chemistries such as Sodium-Sulfur, Sodium-Metal Chloride, and Sodium-Ion, are receiving attention for grid applications due to the reduced cost and mitigated supply chain risk compared to lithium chemistries.

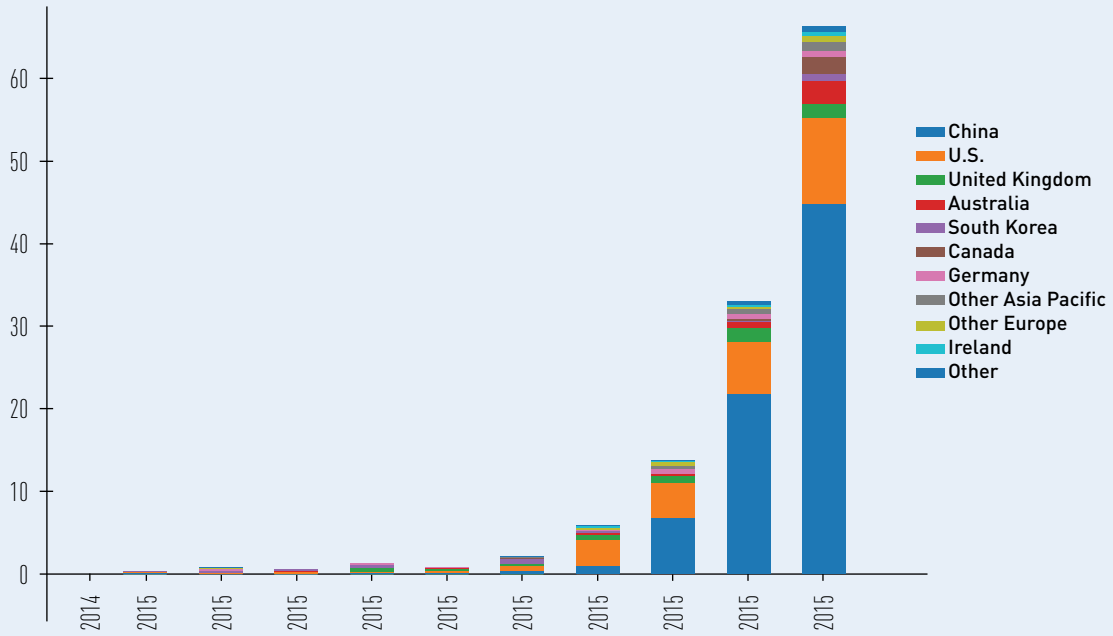
1. Sodium-Sulfur high temperature battery technology which uses molten sodium and sulfur along with solid electrolyte separators that conduct sodium ions. Its comparatively high cost, high operating temperature, and some safety incidents with deployed systems have slowed its adoption in recent years.
2. Sodium-Metal Chloride batteries likewise operate at an elevated temperature using sodium solid electrolytes and, while previously based on nickel as the metal, are now being developed using less expensive iron.[53]
3. Sodium-Ion technology is similar to Lithium-Ion batteries in cell design and manufacturing methods but uses anodes and cathodes specifically designed for sodium ion storage. Sodium-Ion has energy density and projected costs at scale close to that of LFP Lithium-Ion, while the lack of possible material supply bottlenecks especially in the U.S. may give it an advantage for grid-applications where energy density is not a critical factor. Nonetheless, China has taken the lead in commercializing Sodium-Ion technology with CATL launching its 175 Wh/kg Naxtra Sodium-Ion batteries in 2025.[54] BYD has similarly invested to build a 30 GWh capacity sodium-ion battery manufacturing facility in Xuzhou China,[55] and has also built what it claims to be the world's first high-performance sodium-ion, grid-scale battery electric storage system in 2024 in Qianjiang, Hubei province, China.[56] The main initial markets for Sodium-Ion batteries are expected to be in stationary and low-cost applications. As the technology improves, , especially in energy density, Sodium-Ion may encroach on the EV battery market. **CATL's CEO, Robin Zeng, has suggested that Sodium-Ion could replace up to 50% of Lithium Iron Phosphate (LFP) batteries in the future.**[57]

Still, despite the different market drivers for EV and grid storage batteries, Li-Ion remains today's dominant battery technology for grid applications. The massive investment in Li-Ion batteries for EVs has drastically reduced the cost per kWh making Li-Ion the most cost-competitive for grid storage at shorter durations (frequent cycling, high utilization applications). LFP has been particularly successful for grid-scale storage accounting for 80% of new battery storage in 2023.[58] Notably, Tesla uses CATL's prismatic



Battery storage capacity added to the grid in 2024

GLOBAL ADDITIONS — GRID SCALE BESS (EI STATISTICAL REVIEW, DERIVED)



SOURCE: KPMG Energy Institute 2025 Statistical Review of World Energy

LFP technology for its Megapack energy storage batteries.[59] LFP is outcompeting nickel-based cathode Li-Ion batteries such as NMC and NCA in storage applications due to its lower cost resulting from the absence of nickel and cobalt, improved safety, and longer cycle life. Retired Li-Ion EV batteries are also recycled for battery storage applications, offering a lower-cost alternative to acquiring new batteries.[60]

That said, a few new technology vectors — notably redox flow and metal air — offer the U.S. an opportunity to change the battery competition by creating a new learning curve to climb. And, the market size and strategic nature of the electric grid make it an important sector for the U.S. to prioritize. Valued by some estimates at US $25.02 billion in 2024, the battery grid storage market is estimated to grow to US $114.05 billion by 2032, representing a compound annual growth rate (CAGR) approximately 20%.[61] Battery storage for data centers is also growing with the rising investment in artificial intelligence.[62] These global demand signals and the contribution of battery-enabled energy storage to electric grid stability and resilience means this sector is of high priority from both economic growth and national security perspectives. **Of course, China is also heavily invested in grid-technologies, and it is therefore not clear the U.S. has a nascent technology advantage upon which to build a competitive global industry.**

BATTERY-ENABLED SECTOR 2

SPACE EXPLORATION AND SATELLITES

Batteries are a critical enabling technology across a range of space systems, including satellites, rovers, landers, crewed spacecraft, and space habitats. They provide essential power for operation during periods when solar energy is unavailable, such as orbital eclipses, planetary nights, or emergency conditions. Space batteries must meet some of the most stringent technical requirements of any sector, shaped by the extreme environmental conditions of vacuum, radiation, temperature swings, and inaccessibility for repair. Key market-driven technical requirements include:

+ **ULTRA-LONG SERVICE LIFE**
  Batteries on satellites in geostationary earth orbit (GEO) must endure hundreds of cycles per year over 15 years; batteries on medium and lower earth (MEO and LEO) satellites often require greater than 5000 cycles per year.[63, 64, 65] To survive such a large number of charge/discharge cycles, batteries are often constrained to low depth-of-discharge. Battery end-of-life capacity must typically remain ≥ 80%.[66]
+ **HIGH SPECIFIC ENERGY (WH/KG) AND HIGH ENERGY DENSITY (WH/L)**
  Maximizing the amount of stored energy as a function of weight and as a function of volume is critical to reducing launch mass and volume while enabling more capable payloads.
+ **HIGH RELIABILITY**
  Space batteries must have extremely low failure rates and often have built-in redundancy so that failed cells can be isolated without mission loss.[67]

Today, the U.S. space industry is a global leader in commercialization of new space technologies, positioning it to lead in high-reliability, high-performance space batteries with new chemistries.

+ **LARGE OPERATIONAL TEMPERATURE RANGE**
  Batteries in space systems will experience extreme temperature swings, for example +120 °C to -130 °C in lunar environments[68] that have no counterpart in terrestrial applications.
+ **VACUUM COMPATIBLE**
  Cells must be properly sealed with extremely low outgassing and venting provisions. Crew-rated systems add toxicity constraints.[69]
+ **RADIATION TOLERANT**
  Batteries must be hardened against the radiation environments that will be encountered in space.

The requirements for batteries to operate successfully and safely in space are very different from those for EV batteries: Li-ion batteries suffer from aging with available capacity degrading over the course of operation; this make them problematic for satellite systems where no maintenance is available after initial deployment.[70] Additional radiation tolerance, vacuum compatibility, and the extremely large operational temperatures are also unique to space applications. These requirements open the door for new chemistries, including:

SOLID-STATE LITHIUM-METAL AND LITHIUM-SULFUR BATTERIES

The inherent non-flammability, broad operating temperature window, good radiation tolerance, and potentially high specific energy make solid state batteries highly attractive for spacecraft.[71] NASA's SABERS solid-state battery program[72] is developing lithium-sulfur cells[73] that, while focused on electric aviation, overlap with the same safety and thermal demands of crewed spacecraft, lunar rovers, and habitats.

RADIATION-HARDENED CHEMISTRIES AND IONIC LIQUIDS

Beyond Earth's magnetosphere, radiation damage becomes increasingly problematic to battery storage. Solid polymer electrolytes and ionic liquid electrolytes are considered prospective alternatives to the liquid organic electrolytes most common in Li-ion batteries due to their better radiation resilience.[74] These approaches are still well within the domain of "beyond-Li-ion" research[75] and have not to our knowledge been commercialized for space applications.

LI-ION SUPERCAPACITOR HYBRIDS

Certain space applications require short bursts of high power. Supercapacitors in tandem with batteries are being developed in lieu of oversizing batteries to supply these bursts. Candidate Li-ion capacitor hybrids reduce stress on primary cells and thereby extend overall system life.[76]

REGENERATIVE FUEL-CELL/BATTERY HYBRIDS

NASA has investigated regenerative fuel cells for lunar base concepts that combine daytime water electrolysis with nighttime fuel-cell discharge to provide reliable, long-duration power storage.[77] These systems act like a long-duration battery and can be coupled to conventional battery systems to store energy through 14-day lunar nights or during deep-space cruise.

While these alternatives all have potential, the dominance of Li-ion as an energy storage chemistry nonetheless makes it a natural candidate for space applications and indeed modern satellites increasingly use lithium-ion batteries with increased

energy density over legacy nickel-cadmium (NiCd) or nickel-hydrogen (NiH_2) chemistries.[78] The innovations here involve adapting Li-ion to space conditions and long cycle life e.g. using tailored electrolytes that can withstand radiation and vacuum outgassing, and robust separators to endure thousands of shallow cycles. These batteries (generally produced in China) have now replaced NiH_2 on the International Space Station[79] and are standard in many satellites.[80]

Today, nonetheless, the U.S. space industry is a global leader in commercialization of new space technologies, positioning it to lead in high-reliability, high-performance space batteries with new chemistries. NASA has a track record of successful partnership with industry through demand-side programs that have bolstered U.S. leadership. The sustained investment by NASA in energy storage systems for space and aviation such as SABERS and other next-generation Li-S and Li-metal programs provides domestic companies valuable intellectual property to commercialize.[81] The U.S. Space Force also requires radiation hardened batteries, providing an additional demand signal for industry.[82] As a result of investments for U.S. Space Force, and the growth of the space-based economy, the market for space batteries is rapidly expanding.[83] LEO mega-constellations such as Starlink, OneWeb, Amazon Kuiper, and China's GuoWang contribute to a CAGR of 25%,[84] and alone could require hundreds of MWh of space-qualified batteries per year this decade. NASA's Artemis program adds everything from rover packs to lunar-habitat banks,[85] translating into demand for advanced chemistries by the early 2030s. This is coupled to continued demand for Department of Defense procurement and growing commercial demand.

BATTERY-ENABLED SECTOR 3

ELECTRIC AVIATION AND DRONES

Electric aviation — spanning electric vertical-take-off-and-landing (eVTOL), air taxis, short-haul electric commuters, and autonomous unmanned aerial systems (drones) — are a third emerging sector for next generation battery innovation. Breakthroughs in energy and power are needed to advance this field: every kilogram dedicated to the battery subtracts directly from range or payload, yet those same cells must supply helicopter-class thrust for vertical takeoff and landing, accept rapid turn-around charging or battery swap, and meet the stringent reliability and abuse-tolerance standards of commercial aviation. The market-driven battery performance requirements are:

+ **HIGH SPECIFIC ENERGY (WH/KG)**
  Specific energy will determine a vehicle's range: the higher the specific energy, the longer the range of a vehicle will be at a given weight.
+ **HIGH SPECIFIC POWER (W/KG)**
  The high-power requirements of flight stages like take-off limit a vehicle's load capacity. The higher a battery's specific power the more weight the vehicle can carry.[86] Aviation batteries must sustain short and intense discharge bursts to support vertical take-off, climb, and hover.[87]
+ **FAST CHARGE OR OTHER RAPID TURN-AROUND MODELS**
  Commercial aircraft require rapid turnaround in service, which translates to high C-rate charging of rechargeable batteries or other "refueling" models including battery swap.
+ **REGULATORY COMPLIANCE**
  FAA approval has historically required many more years of effort than a typical product cycle

in other fields such as Automotive or Consumer Products, forcing a different time scale on aviation innovation.

These aviation-specific market pressures — ranging from high pack-level specific energy targets to burst-power demands and uncompromising aerospace safety rules — are pushing battery R&D onto paths that diverge sharply from EV batteries.[88] In response, developers are prioritizing chemistries and architectures that offer step-changes in specific energy, thermal robustness, and charge-rate tolerance:

LITHIUM-METAL AND SOLID-STATE BATTERIES

Li-metal anodes enable higher specific energy[89] and solid electrolytes promise better thermal behavior and specific energy.[90] One pathway to higher specific energy involves use of lithium metal anodes with liquid electrolytes, while the combined benefits of solid-state batteries are attractive but would represent a significant divergence from current design and manufacturing practice. Challenges that remain include achieving interface stability between electrodes and solid electrolytes, obtaining the high specific power needed for take-off and landing,[91] and developing cost-effective manufacturing methods.[92] U.S.-based startup QuantumScape is a prominent developer of solid-state batteries.[93]

SOLID-STATE LITHIUM-SULFUR

Li-S batteries have high theoretical energy density, and promise reduced cost compared to lithium-ion due to the replacement of metal oxide cathodes with highly abundant.[94] The potential weight advantage makes them particularly attractive for aviation, while they still face a number of challenges including low power, short lifetime due to the dissolution of polysulfide species in liquid electrolytes leading to irreversible sulfur loss, and dendrite formation on the lithium anode.[95] NASA's SABERS project focuses on solid state Li-S batteries, which may overcome these limitations.[96]

LIGHT METAL-AIR

Lithium-air batteries have amongst the highest specific energy among any battery chemistry.[97] Previous rechargeable Li-air batteries have used liquid electrolytes; however, emerging concepts also use solid ceramic polymer electrolytes.[98] Emerging metal-air fuel cells such as Na-air promise three times the specific energy of today's most advanced batteries[99] and could be a watershed for aviation.

STRUCTURAL BATTERIES

Structural batteries embed energy storage into the airframe to cut system mass, even if per-kg Wh is lower. Recent work has shown carbon-fiber laminate specific energy of 30 Wh/kg while matching the stiffness of aluminum at 70 GPa.[100] Although specific energy density is modest, embedding energy storage into load-bearing components could slash overall aircraft mass and wiring and represent an overall design win compared to discrete packaged high energy density batteries.

Lithium-ion also configures into the mix of possible eVTOL batteries, since energy density requirements are lower for urban mobility than for general regional aviation.[101] Replacing graphite anodes in Li-ion batteries with silicon anodes provides a more evolutionary, near-term pathway to higher specific energy and power that leverages known manufacturing.[102] As an anode material, silicon promises a much higher specific charge capacity than graphite, but suffers from challenges including volume expansion and

cycling stability[103] that may be addressed with nano-structured silicon. U.S.-based Amprius Technologies is one of several companies pursuing silicon anode-based Li-Ion for aviation.[104] High-nickel cathodes provide another pathway to enhance energy density of li-ion batteries that may approach levels relevant for aviation applications.[105] CATL recently announced a new 500 Wh/kg battery that they intend for the aviation sector.[106] It is unclear from public sources, but plausible, that CATL's batteries leverage high-nickel given their expertise in NMC cathode Li-ion manufacturing. CATL CEO, Robin Zeng stated recently: "Our condensed batteries, achieving up to 500 watt-hours per kilogram, are currently being tested in planes, allowing 4.0-ton aircraft to take off. We aim to support 8.8-ton aircraft next. By 2027 or 2028, we expect four-seater private jets to use these batteries, with a standardized range of 2,000 to 3,000 kilometers, making them feasible for private and business jets."[107]

The strength of the U.S. aerospace industry as well as the differentiation of many of the non-Li-ion chemistries from the established EV technologies give the U.S. the potential to leapfrog China. Aviation-grade batteries are also a growing market with Li-ion variants having an estimated US $1.6 billion market size in 2025 with a CAGR of about 10%.[108] Several key downstream players building aircraft in the U.S. include startups Joby, Archer, Beta, Eviation, Regent, and Electra Aero.[109] However, these firms are experiencing a contraction in available private capital in the U.S. with disclosed funding down 66% since 2021.[110] **The regulatory environment in the U.S. may also prove to be prohibitive due to restricted airspace and lengthy processes for airworthiness certification. China is looking to dominate the electric aviation sector[111] and will prove stiff competition.**

BATTERY-ENABLED SECTOR 4

ROBOTICS AND AUTOMATION

Robotics and autonomous systems are indispensable assets for the manufacturing, logistics, inspection, defense, and service industries. While the term robot applies to many different types of systems, we specifically looked at autonomous mobile robots (AMRs) that may be used in factory or warehouse settings and untethered bipedal or quadrupedal robots that may be used in human-assisted tasking. The market-drivers for onboard energy storage vary by application but largely include:

+ **HIGH SPECIFIC ENERGY (WH/KG):** The amount of energy carried by the robot per unit weight will limit how long the system will operate on a single charge.

+ **HIGH SPECIFIC POWER (W/KG):** The ability to deliver energy at a high discharge rate (C-rate) is important for robotic applications and functions such as pushing, lifting, jumping, or running.

+ **HIGH DUTY CYCLE:** Batteries supporting robotic systems will have to be continuously active for extensive periods of time to amortize the robot's cost. These batteries will need to survive more charge-discharge cycles and need higher recharge rate.

The gap between these requirements and those of EVs is highly dependent on the context in which the robot is used. In certain cases, the battery requirements of robotic systems will be sufficiently similar to those of EVs that technologies such as LFP or NMC may suffice.[112] In other cases, the requirements of the robotic system

may drive battery chemistries more similar to those required for electric aviation. Some emerging chemistries include:

LITHIUM-TITANATE (LTO) AND NIOBIUM-TITANATE (NTO)

LTO and NTO are anode chemistries typically used with LFP or NMC cathodes. The older LTO battery chemistry provides more rapid recharge capability, high power, wide operational temperature, and long cycle life compared to Li-ion chemistries that use graphite or silicon as the anode, but at the expense of energy density.[113] However, its lower commercial availability may make it less cost competitive. Toshiba has been a leader in LTO with products deployed in heavy duty applications.[114] The company recently announced a newer chemistry based on NTO that achieves an energy density similar to LFP batteries, but with superior ability to withstand repeated, faster charging.[115]

ADVANCED LITHIUM-ION AND LITHIUM-SULFUR

Similar to their application to electric aviation, high-silicon anode Li-ion batteries,[116] lithium metal, solid-state, and Li-S batteries[117] have higher specific energy than Li-Ion which would be advantageous in certain bi- or quadrupedal robotic applications that are weight limited like drones.

SODIUM-ION

Na-ion may be attractive for robotic applications where uptime and cost are more important considerations than absolute energy density, such as warehouse AMRs. Long cycle life along with fast charge, superior safety, and wide operating temperature range are other desirable attributes.

While these new chemistries may provide an advantage to robotics applications, our analysis indicates that battery requirements for robotics in aggregate are not sufficiently different from those of EVs so as to drive a clear need for differentiated chemistries. **This means that China's lead in EV batteries will translate into a lead in robotics batteries.** Indeed, China is surging ahead in robotics. One Shenzhen-based company recently announced a bipedal robot that could swap its own batteries without human intervention potentially leading to continuous operation.[118] The potential for robots to proliferate manufacturing, defense, human services, and logistics, means this sector will become increasingly important.[119] **While the U.S. may not expect to lead, it should figure out ways to enable industrial production of robots and their battery systems.**

CAPTURING THE VALUE OF THE MOST PROMISING BATTERY-ENABLE SECTORS

When taken together our results suggest that the U.S. has a particular advantage in pursuing and developing new innovations in battery chemistry focused on two sectors: grid-scale energy storage and space exploration and satellites. In grid-scale storage, the U.S. has a particular advantage in metal-air batteries and can still compete in redox flow batteries where optimal chemistries are still being developed. China's advantage in Li-ion and Na-ion means that new materials that are drop-ins will be readily adopted, but in turn may lock them into these established pathways as new technologies emerge. For the future space economy, battery development is at the starting line and will require novel battery chemistries and architectures, playing to the U.S.'s strengths.

Selecting new pathways for technological innovation is not a new approach to U.S. competitiveness. It is not enough to initiate innovation in order to lead in a particular sector. **It is also important to build and finance the industrial base necessary to manufacture at scale the new battery chemistries and products generated in innovation ecosystems.** History has shown that the U.S. repeatedly loses its leading innovations to China due to CCP government policy that supports what we have termed the "missing middle"[120] and enables a scaled domestic industrial base linked to its innovation ecosystems.

It is also important to build and finance the industrial base necessary to manufacture at scale the new battery chemistries and products generated in innovation ecosystems.

FOUR CASES OF U.S. BATTERY HISTORY

The U.S. has been the origin of many foundational battery breakthroughs and has serially failed to domestically commercialize and profit from any of them at a globally competitive scale.

The U.S. has been the origin of many foundational battery breakthroughs and has serially failed to domestically commercialize and profit from any of them at a globally competitive scale. Through four case studies, we explore the hypothesis that weak industrial policy has been the decisive factor in the U.S.'s inability to scale its innovations and sustain a resilient industrial base for batteries.

The U.S. has failed to commercialize at least four types of battery chemistry innovations across the past three decades as listed in Table 2: Li-ion, Li-Fe Phosphate, NMC Cathodes, and Vanadium redox flow batteries. Understanding the root cause of these consistent failures is essential to ensuring that history does not repeat itself. We unpack the ways in which the U.S. first gained the lead in innovating in these areas (the what) and then lost the lead in scaled industrialization to learn key policy lessons (the how). **These examples inform our approach not simply to "what" the U.S. should pursue from the perspective of particular technical pathways and innovation strategy to leap-frog China's current battery dominance, but "how" we should undertake our industrial strategy.**

BATTERY CHEMISTRY INNOVATION VERSUS COMMERCIALIZATION

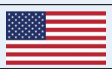
	Developed	Scaled
Lithium-Ion Batteries		
Lithium-Iron Phosphate Batteries		
Nickle Manganese Cobalt Cathods		
Vanadium Redox Flow Batteries		

TABLE 2: The U.S. has invented many new battery technologies that have all migrated to China for scaled manufacturing.

CASE STUDY 1

1972 — M.S. Whittingham prototypes first Li-ion battery at Exxon; Exxon begins battery production but quickly terminates

CASE STUDY 1

EXXON, SONY, ENERGIZER AND THE COMMERCIAL LAUNCH OF LITHIUM-ION BATTERIES

The first missed opportunity for the U.S. in the battery sector was failure to commercialize and profit from the first generation of Li-ion batteries. M. Stanley Whittingham and colleagues prototyped the rechargeable lithium battery in 1972 at Exxon Research in New Jersey using a titanium-disulfide cathode, a lithium metal anode, and a liquid electrolyte containing a dissolved lithium salt. Seeing promise, Exxon began producing coin-cell lithium batteries that a Swiss watchmaker, Ebauches, used in its solar-charging wrist watches. However, Exxon soon dropped battery production because the market was deemed too small. Exxon then licensed the technology to three firms, one each in the U.S., Europe, and Asia, all of whom failed to take advantage of the new battery.[121]

The next technical leap that replaced the titanium-disulfide cathode with lithium cobalt oxide was pioneered by John Goodenough at Oxford University in 1980. He courted corporate partners in the U.S., the UK, and Europe to commercialize the technology to no avail and ultimately let the UK's Atomic Energy Research Establishment (AERE) pick up and shelve the intellectual

1980 J. Goodenough pioneers lithium-cobalt oxide cathodes at Oxford

1987 Akira Yoshino of Asahi Chemical pioneers carbon-based anode; transfers technology to Sony

1991 Sony launches its first Li-ion battery

property (IP) when Oxford University refused to pay for the patent.[122]

In the 1980s, development proceeded in the hands of Akira Yoshino of Asahi Chemical in Japan who paired Goodenough's cathode with his carbon-based anode. Asahi Chemical, unfamiliar with the battery business, took the new battery technology to Sony in 1987. Sony, a vertically-integrated consumer electronics manufacturer and battery manufacturer, immediately saw the value of the new technology and from 1987 to 1989, its technical staff led, by Yoshino Nishi, turned Yoshino's prototype battery into a robust product. After licensing Goodenough's innovation from AERE, Sony successfully launched its Li-ion battery in 1991. Sony's success was soon followed by Matsushita (now Panasonic) whose batteries hit the market in 1994. Sanyo and other Japanese players likewise spun up production efforts to partake in the growing battery market as Li-ion technology rapidly spread to computers, cell phones, and other portable electronics.

U.S. companies were not blind to Sony's success. In the early 1990s, both Energizer (then Eveready) and Duracell began Li-Ion battery efforts with the aim to manufacture Li-ion cells. Energizer leveraged its experience with nickel-based rechargeable batteries at its Gainesville, FL facility to build a state-of- the-art Li-ion production plant in 1997. They licensed IP from Sony, built their own advantaged IP position in several areas, and established a sales and marketing group in Japan. Duracell embarked on a parallel development program. However, by 1998-1999, global Li-ion prices plunged due to intense competition and capacity expansion in Asia.[123] Faced with thin margins, Energizer abandoned Li-Ion manufacturing, idling its Gainesville plant and writing off all of its investments. The plant was sold off to Moltech and ultimately acquired by China-based Shanghai Tyre and Rubber Company (STARC) in 2002 for US $5.6 million.[124] Duracell, responding to the same market conditions, canceled its Li-ion program in the late 1990s. **Thus, by the year 2000, the U.S. had completely ceded the nascent industry to Asia, with Japan holding a dominant position of almost 95% of the global Li-ion battery market at that time.**[125]

The first industrial epoch of the Li-ion battery industry appears, at first sight, to be dominated by private sector competition. However, the competitive landscape for U.S. and Japanese companies was established in part by the respective governments' policy choices whose approaches to industrial policy into the 1980s and 1990s were starkly different.

+ The U.S. approach was dominated by *laissez-faire* thinking: it was assumed that if U.S. companies, universities, or national labs invented something useful, the market would handle commercialization.
+ In sharp contrast, Japan's approach, led by the Ministry of International Trade and Industry (MITI), architected an expansive industrial policy spanning targeted tariffs and trade controls,[126] export promotion including the five-company rule,[127] technology licensing, subsidized credit and lowered capital cost, anti-trust exemptions to promote inter-company collaboration,[128] and well-funded industrial R&D consortia.

1994 Panasonic launches Li-ion battery

1997 Energizer begins commercialization

1999 Energizer drops all Li-ion efforts and sells off Gainesville FL plant to a Chinese-acquired entity

The result was a migration of the U.S.-led consumer electronics industry — established in the 1940s by U.S. firms such as RCA, Zenith, and GE — to Japan. By the 1980s, Japanese industrial giants including Sony and Panasonic dominated the global consumer electronics market. **This industrial-policy driven migration of consumer electronics production was critical to Japan's subsequent domination of Li-ion battery manufacturing.** U.S. battery manufacturers such as Energizer and Duracell were at a significant disadvantage to their vertically-integrated Japanese competition because of lack of proximity to the electronics device designers who determined new requirements for rechargeable batteries. Vertically-integrated Sony had both the vision and the structural advantage to dominate the early Li-ion market. U.S. industry simply could not stay ahead of new Li-ion battery requirements that were driven by product development in Japan and had no domestic consumer electronics champions to partner with.[129] **The erosion of U.S. consumer electronics manufacturing due to laissez faire industrial policy set the stage for U.S. industry to be structurally incapable of profiting from its battery innovations.**

MITI's legacy positively impacted the innovation ecosystems and wider supply chains and industrial base in Japan in additional ways. Policies that encouraged collaboration — e.g., antitrust exemptions and R&D consortia established a **culture of collaboration** between companies that enabled Japanese industry to climb technology learning curves faster than their more isolated U.S. competition. Japanese companies also had access to **long-term, low-cost capital** needed to build battery manufacturing plants: Japanese banks lent at favorable terms often with guidance from MITI as to what constituted a strategic investment. U.S. companies, by contrast, had to justify capital expenditures to shareholders focused on near-term return on investment. Japanese industry also benefited from the legacies of MITI's **export-oriented policies** coupled to the lack of any U.S. nationalist push to buy-American. Even when the Pentagon or NASA needed rechargeable batteries, they purchased from Japanese suppliers![130]

Finally, the lasting effect of MITI's decades-long focus on strategic industries was to create a business regulatory environment in Japan that structurally supported the goal of gaining **market share over the long-term.** This is in sharp contrast to the U.S. business environment that holds quarterly earnings and near-term stock prices as sacrosanct. Japanese companies who sought dominant global market share positions over the long-run were more willing to defer near-term profits in favor of investing for long-term success. This difference helps explain why corporate management at Exxon, Energizer, and Duracell were so quick to write-off their investments in Li-ion battery manufacturing.[131]

CASE STUDY 2

UT AUSTIN, A123, BYD AND HOW THE U.S. LOST OUT ON THE LFP REVOLUTION

China's commanding market share of Lithium iron phosphate (LFP) batteries represents another missed opportunity for the U.S. to profit from its tax-payer funded innovation. In 2024 alone, LFP batteries powered 74.6% of the EVs produced in China[132] and over half of global EVs.[133] These numbers are only expected to rise with enhanced LFP performance and wider EV adoption. China additionally holds over 95% of global production capacity for LFP, lithium manganese iron phosphate (LMFP), and other phosphate-based precursors.[134]

Once again, the original breakthrough to use LFP as a cathode material for rechargeable batteries was pioneered in the U.S., this time at UT Austin by John Goodenough and his research group in 1996.[135] As a safer, longer-lasting, and more affordable chemistry than nickel- and cobalt-based alternatives, LFP had promise to lower costs and derisk supply chains. Goodenough's LFP IP was licensed by the university to Hydro-Québec who partnered with the University of Montreal and France's Centre National de la Recherche Scientifique (CNRS) to further develop the material.[136] By the mid-2000s, Hydro-Québec, the University of Montreal, CNRS, and Süd-Chemie

2001 A123 founded to commercialize LFP

2003 BYD begins LFP commercialization for EVs

2009 A123 receives $249M DoE loan; U.S. EV market does not materialize

(via its subsidiary Phostech Lithium Inc. which was previously the exclusive sub-license holder) had clustered their LFP patents into a consortium designed to sublicense manufacturing rights to industry.[137]

Critically, UT Austin had not elected to file its patent in China, leaving Chinese industry free to exploit the invention. The university-industry IP consortium later chose not to attempt to enforce its other patents in China either.[138] [139] This effectively meant that Chinese firms like BYD and CATL could place big bets on LFP for domestic production at no additional cost, while U.S., Japanese, and Taiwanese manufacturers faced royalties on sales and found themselves entangled in costly patent litigation: Taiwan-based LFP maker Aleees reports that it paid about 10% of its sales in licensing fees.[140] And U.S. startups Valence Technology[141] and A123[142] that tried to commercialize LFP also found themselves entangled in extensive and costly patent litigation with the consortium, which in the case of A123 was settled with a cross-licensing agreement in 2011.[143] This patent landscape had the effect of freezing commercialization across much of the West and in particular disadvantaged U.S. companies compared to their Chinese counterparts. Subsequent divergent policy approaches of China and the U.S. further widened the gap in favor of Chinese industry to dominate LFP. This result is well-illustrated through the histories of U.S.-based A123 and China-based BYD.

A123 spun out of MIT in 2001 to commercialize its proprietary nano-phosphate LFP technology.[144] With initial venture capital raises totaling US $40 million, A123 had an 18-month runway to produce their battery product and the leadership team made the decision to take advantage of a Chinese-government low-tax economic zone outside Shanghai to build a cathode plant — betting on a favorable policy environment in China compared to the U.S., and keeping A123's costs down as it scaled enabling it to pursue customers including Black & Decker, Gillette, and Mattel. However, this move exposed A123 to intellectual property theft by Chinese competitors.[145] After significant engagement with the U.S. automotive industry, A123 was also positioned for the 2009 U.S. stimulus bill and received a US $249 million grant from the U.S. DoE to construct two manufacturing facilities in Michigan.[146] However, A123's bet on the electric vehicle sector in the U.S. fell through: its survival depended on the U.S. EV market taking off which did not happen at that time. A123's U.S. plant had vastly more capacity than its customers needed, and the absence of "buy American" industrial policy meant that GM was free to choose a foreign battery supplier, LG Chem, for its Chevy Volt PHEV. A costly product recall in 2012 due to manufacturing defects was a final problem.

In October 2012, A123 filed for Chapter 11 bankruptcy and all of its assets including IP and manufacturing plants were sold off to China's Wanxiang Group (even though others including

2012 A123 goes bankrupt and is acquired by China's Wanxiang Group with CFIU.S. approval

2025 China controls >95% of global LFP production

Siemens and NEC bid for the assets) with the approval of the Committee on Foreign Investment in the United States (CFIUS).[147] This was despite reservations on the part of members of Congress.[148] Thus, a U.S.-founded and government-funded LFP front-runner ended up under Chinese ownership after only a decade in business. And it has been noted that "all these years later...it is still unclear who has access to the spoils of the A123 IP or how widely they were shared. There are still traces of A123's technology inside of China's vast battery supply chain." [149]

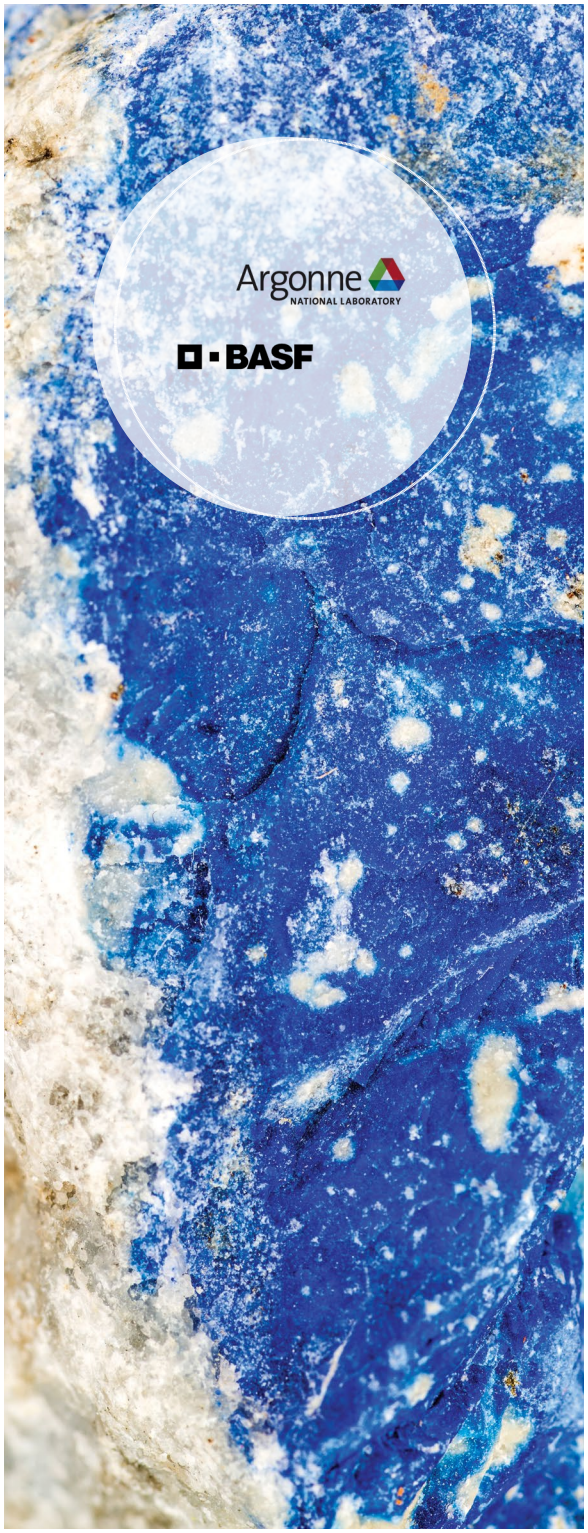
BYD, founded in 1995 with a focus on producing rechargeable batteries for consumer electronics, had already grown to be the largest Chinese manufacturer by 2001 when A123 was founded. Its domestic competition was fierce: over 200 Chinese companies had entered the market to produce rechargeable batteries between 1995-2002.[150] To increase competitiveness, BYD expanded into the EV market after acquiring Qinchuan Auto in 2003. National initiatives under the "863 Program" encouraged R&D in advanced batteries for EVs and BYD invested heavily in developing in-house LFP batteries. The company soon began manufacturing LFP batteries for its electric models, such as the F3DM plug-in hybrid launched 2008 and the e6 EV launched in 2009. Shenzhen, BYD's home city, began transitioning its public bus fleet to electric buses, providing a guaranteed early market for BYD's LFP batteries. After BYD successfully used LFP in electric buses for the 2008 Beijing Olympics, China's government made LFP a national priority.[151] In 2009, China launched large-scale demand subsidies and pilot programs for EVs. The "Ten Cities, Thousand Vehicles" program rolled out electric buses and cars in pilot cities, often using batteries from BYD and other local firms. Generous consumer subsidies for EV purchases begin in 2010, alongside R&D programs and tax breaks for battery makers.[152] Today, BYD is the second largest global supplier of rechargeable batteries with 17.4% of the global market,[153] behind only CATL which benefited from the same Chinese government policies.

Policy shortcomings on the part of the U.S. contributed significantly to the lost LFP opportunity. The U.S. gave up control of the original taxpayer-funded IP at UT Austin when it was licensed to a Canadian entity, did not create a competitive manufacturing and industrial base in the U.S. to keep U.S. companies on-shore, provided one-off debt financing to U.S. companies rather than the Chinese approach of sustained capital injection totaling US $230 billion from 2009 to 2023,[154] failed to create incentives for long-term capital to support a strategic industry, failed to prevent Chinese acquisition of critical IP and assets via CFIU.S., and failed to stimulate the demand-side either through government purchasing of batteries and EVs or consumer incentives. Had U.S. policies been more competitive, it is plausible that U.S. companies would be significant players today.

CASE STUDY 3

2001 ANL/Dalhousie patents filed for layered cathodes

2009 BASF global licensing agreement for NMC cathodes



CASE STUDY 3

ARGONNE, BASF, AND THE MIGRATION OF NMC CATHODE PRODUCTION TO ASIA

The migration of NMC cathodes to Asia presents another story of failed invention to industrialization in the U.S. In 2001, Michael Thackeray and colleagues at Argonne National Laboratory (ANL) in Illinois filed two patents for a new class of layered cathodes consisting of nickel, manganese, and cobalt.[155] Nearly simultaneously, a patent was filed by Jeff Dahn and co-workers at Dalhousie University in Canada on essentially the same material, with the rights to the IP belonging to an American company, 3M, who had supported the Dalhousie research.[156] Today, major manufactures of Li-ion batteries using these nickel, manganese, cobalt (NMC) cathodes are Chinese and South Korean,[157] and major producers of the NMC cathode active materials are Chinese.[158]

This is not the outcome that U.S. Energy Secretary Steven Chu had hoped for when he lauded a 2011 partnership between Argonne and GM to license the technology for EV batteries as "an important return on the American investment in innovative vehicle and battery research [that] will also spur the renewal of the American battery industry, creating hundreds of new jobs where they are needed most."[159] The U.S. DoE funded the development of this new battery chemistry, but U.S. taxpayers lost out profiting from the breakthrough for the familiar industrial policy failings that led to prior technology migration.

By the early 2000s, the market value of rechargeable batteries was clear. With its newly discovered NMC cathode technology, ANL pursued an open licensing model. An early industry partner was

2011 LG Chem subsidiary secures license to produce ANL NMC-based cathode for battery cells

2022 China produces 54k metric tons of NMC cathode precursor materials and 16.8 GWh of NMC batteries

2025 China is home to 70% of production capacity for cathodes and 85% for anodes

BASF, the European chemicals giant, who in June 2009 signed a global licensing agreement for NMC cathodes.[160] BASF planned on building a large cathode materials production facility in Elyria, Ohio contingent upon winning a DOE grant via the Electric Drive Vehicle Battery and Component Manufacturing Initiative under President Obama's American Recovery and Reinvestment Act of 2009 (Recovery Act).[161] A small plant was ultimately built in Ohio, but NMC production did not scale in the U.S. nearly as rapidly as in Asia. At the same time, companies in South Korea, Japan, and China also jumped on the new technology. LG Chem Michigan, Inc., a U.S. entity and wholly owned subsidiary of LG Chem, secured a license to produce Argonne's NMC-based cathode for its battery cells. The company committed to manufacture Li-ion battery cells for the Chevy Volt at a US $303 million production facility they promised to build in Holland, Michigan[162] with US $150 million in Recovery Act funding.[163] GM simultaneously reached a worldwide licensing agreement announced by the DOE.[164]

However, it was BASF's license agreement that proved definitive in global dissemination of the technology, especially to China. BASF was the only licensee of ANL's NMC cathode active materials patents with the ability to grant sub-licenses.[165] The sublicensing strategy pursued by BASF included transfer of the chemistry to many Chinese companies[166] including an indirect transfer to CATL through a sublicense to CATL's subsidiary, Brunp Recycling.[167] The result was two-fold: first, access to all the cathode-active IP was legally in the hands of Chinese battery competitors, and second, China ramped production to over 54,000 metric tons of NMC cathode precursor materials[168] and 16.8 GWh of NMC batteries[169] by 2022. Today, China is home to 70% of production capacity for cathodes (and 85% for anodes).[170]

The revolutionary battery chemistry developed by leading U.S. researchers was a clear leapfrog in capabilities and its early development a measure of the strength of U.S. innovation ecosystems. And yet the failure to win at an industrial scale reflects multiple structural failings of U.S. public and private sector decisions.

- First, giving up control of tax-payer funded IP to a European entity and allowing sublicensing to Chinese companies is a repeat of the same policy short-coming that lost the U.S. its leadership in LFP (via Canada).
- Second, while the U.S. federal government was, by the time of NMCs, interested in supporting manufacturing and had committed US $2.4 billion in funding for the Vehicle Technologies Program under the Recovery Act,[171] the US $29 million to BASF's Elyria Ohio plant[172] and US $150 million to LG Chem's Michigan plant were one-off grants that paled in comparison to China's sustained injection of capital totaling US $230 billion from 2009 to 2023.[173] The U.S. was not seriously competing with China to dominate this industry.
- Finally, by this point, the U.S. did not have a competitive industrial base in which to scale battery manufacturing as compared to Asia. The workforce, regulatory environment, low cost of capital, infrastructure, and rapid construction available to Chinese, South Korean, and Japanese competitors meant they could build manufacturing facilities much more quickly than in the U.S.

Three years after receiving its Recovery Act funds, LG Chem Michigan had failed to manufacture battery cells that could be used in electric vehicles. An investigation into the use of U.S. taxpayer funding found that employees spent time volunteering at local non-profit organizations, playing games, and watching movies during regular working hours on the taxpayer's dime.[174]

CASE STUDY 4

1988 VRB technology patented in Australia

2011 PNNL improvements widen operational temperature and increase energy density of VRBs

CASE STUDY 4

HOW CHINA LED COMMERCIALIZATION OF U.S.-DEVELOPED VANADIUM REDOX BATTERIES

Vanadium redox batteries (VRBs) are one of the new technologies identified for grid-scale energy storage as an area of potential U.S. competition with China. However, the U.S. has already fallen behind China in commercializing this new technology despite having had a significant head-start in VRB development.

VRBs were originally patented by Maria Skyllas-Kazacos at the University of New South Wales in Sydney, Australia in 1988.[175] Two decades later, researchers under Gary Yang at Pacific Northwest National Laboratories (PNNL) advanced the VRB chemistry with mixed sulfate-chloride and later sulfate-phosphate electrolytes to widen operational temperature and increase energy density.[176, 177] These improvements took six years and more than US $15 million in public funding.[178] They served to make VRBs a viable option for grid storage and were patented in both the U.S. and China by Battelle Memorial Institute, the DoE contractor who manages PNNL.[179]

Yang launched Washington-based UniEnergy Technologies to commercialize VRBs in 2012 and was granted a semi-exclusive license by the Battelle to manufacture and sell the batteries.[180] However, UniEnergy ran into difficulties raising private capital in the U.S. and turned to the Chinse company Dalian Rongke Power Co. Ltd. to invest in and help manufacture the batteries. By 2017, much of the battery manufacturing and assembly had transition to Rongke Power, and

2012 PNNL improvements widen operational temperature and increase energy density of VRBs

2017 Rongke Power transitions VRB production to China

2025 Chinese-owned companies are leaders in manufacturing VRBs

UniEnergy granted the company a sublicense to officially produce in China. This action was taken despite the original Battelle license requiring UniEnergy to sell a certain number of batteries in the U.S. that were substantially manufactured in the U.S. According to UniEnergy, the U.S. did not have the supply chain required, whereas China had the supply chain and the advanced manufacturing ecosystems needed to productize and produce utility-scale batteries.[181] In 2021, UniEnergy transferred the full VRB license to Vanadis Power, a Netherlands-based company that had Chinese ownership with plans to continue manufacturing the batteries in China.[182] Because Vanadis Power is a foreign entity, the U.S. lost jurisdiction over the technology once the license was transferred.

Today, China is the global leader in the manufacturing of VRB batteries with Rongke Power as a major contributor[183] and Vanadis Power a close partner.[184] The Chinese government has emphasized VRBs as a national priority and has invested significantly in scaling new, large-scale vanadium flow battery energy storage power stations and national demonstration projects, as well as upstream control of vanadium active precursor development.[185] This includes the largest VRB installation in the world, a 200 MW/1 GWh system in Jimusar, Xinjiang costing US $520 million.[186]

This fourth case study is by now familiar: Short-termism in U.S. capital markets likely contributed to UniEnergy's difficulty in raising the capital it needed to scale manufacturing domestically. There was also no industrial demand locally, so no market existed to supply locally. The cost of capital in the U.S. was likely also much higher than that in China for high capex manufacturing. In addition, by the 2010s, chronic underinvestment in battery manufacturing in the U.S. meant that the industrial base needed to support rapid scaling of a new technology like VRBs was simply non-competitive to non-existent in the U.S. when compared to China, making Chinese partnership an inevitable choice. The subsequent loss of U.S. jurisdiction due to licensing to a foreign entity perpetuated the problem. A 2024 Government Accountability Office investigation found that DoE lacked the metrics and processes to properly monitor its licenses for compliance with government regulations and to ensure manufacturing do not move overseas without prior government approval.[187] In this case, the sublicense to Vanadis Power was explicitly approved which further speaks to a lapse in appropriate metrics to evaluate approvals.

HOW TO AVOID A REPETITION OF HISTORY

Taken together, these four case studies suggest that a strategic plan to develop novel technologies for next-generation battery-enabled sectors is — while necessary — not sufficient to solve the problem of U.S. industrial competitiveness in the strategic battery sector. Focusing on R&D alone will certainly lead to further strengthening of early-stage innovation ecosystems. However, a repeat of these prior cases will occur leading to a failure on the part of the U.S. to profit from its innovations and build out dynamic and resilient manufacturing ecosystems. This suggests a second part of the strategic puzzle: beyond the "what" of new technology vectors must be the "how" to commercialize and scale them. **Thus, the U.S. must not only change the game by identifying leap-frog technologies, it must also create the playing field to build a robust domestic industrial base for producing next generation battery technology at scale.**

CREATING THE PLAYING FIELD

A WINNING POLICY IMPLEMENTATION

The U.S. will not compete successfully with China using China's industrial policy playbook. Rather, the U.S. must focus on playing to its strengths.

Creating the playing field requires focusing resources from both the public and private sectors on new battery-enabled sectors in ways that support early-stage innovation coupled to a dynamic domestic manufacturing base. It is only when this connection is made that **the twin engines of innovation and scaled industrialization can drive economic growth, technology leadership, and national security and resilience.**

Well-crafted industrial policy is needed to aggregate the resources necessary for U.S. industry to participate in—let alone lead—any of these emerging, battery-enabled sectors at scale. And, to be most effective, these policies should be focused on specific end-market sectors where the U.S. has comparative advantage, rather than hoping that their retrospective application to the wider battery industry is likely to be successful. We identify two sectors with particular potential for policy action: grid-scale storage and the electric aviation/space sectors. Both are large and growing, place demands on batteries that render current Li-ion solutions inadequate and have the potential for U.S. innovation and large-scale industrialization. **At least six policy elements are essential to support competitiveness in these emerging sectors - each in turn supports and amplifies the others.** Our approach highlights that either a virtuous cycle can be established with consistent, aligned policies, or a downward spiral and loss of opportunity quickly materializes. In turn these six policies include:

SECURE THE SUPPLY OF INTELLECTUAL PROPERTY

First, IP and sublicensing must be carefully managed. Ideas funded by tax-payers should ideally be developed by U.S. startups and established U.S. corporations, and at the very least remain under U.S. jurisdiction. To this end, IP protection is necessary, but not sufficient. Licensing jurisdiction, focusing on controlling the entities that are licensing the technology, is equally necessary to consider. IP protection refers to patents filed in the jurisdictions in which a company intends to litigate in order to protect its IP portfolio. IP filings should span the locations of manufacturing and of the end use markets. This requires that the U.S. provide resources for strategic foreign filings for U.S.-funded IP in countries like China. Licensing jurisdiction refers to which governments have jurisdiction over the corporate entities that license the IP.

The U.S. government should restrict licensing of U.S.-funded IP to non-U.S. entities because legal controls, including export controls and CFIU.S. rulings, apply only if the licensing entities are U.S. entities. Foreign entities should be required to create U.S. subsidiaries to gain licensing access to U.S.-funded IP. This would keep technology under U.S. jurisdiction and would also require the subsidiary to pay U.S. taxes, thereby supporting the very ecosystem that funded the creation of the IP being licensed.

CREATE DEMAND-SIDE INNOVATION

Second, it is essential to match supply-side support for innovation with demand-side signals. Specifically, government agencies should create markets for new battery solutions by leveraging their procurement programs. This is possible through large departments such as the Department of Defense with significant demand where contracts and preference to U.S.-based sources of innovation can be emphasized to support broader strategic signals. These policies derisk the demand-side adoption of new battery tech, while enabling companies to focus on retiring technical risk. The Inflation Reduction Act (IRA) is an example of policy that bolstered demand for EV batteries through consumer-focused incentives such as vehicle tax credits. NASA's Commercial Orbital Transportation Services (COTS) program and Operation Warp Speed are additional examples of demand-side programs that bolstered adoption of new technologies in the space and biotech industries. Similar programs could be considered by NASA for space-based energy storage as well as for space-related battery technologies. The DoE should consider similar types of programs that emphasize electric grid modernization and storage. The DoD could support grid-scale storage solutions at its extensive military installations which might serve as a testbed for such technologies. And lastly, in the area of electric aviation, the DoD and other departments could serve as lead customers in adoption potential solutions to also supporting these growing markets. In addition, consistent with current deregulation in drones outlined in the Executive Order "Unleashing American Drone Dominance", there are other mechanisms available to the government to support the emergence of the electric aviation market including a pathway to pre-certification of eVTOL aircraft in national airspace.[188] Of course, under this current U.S. administration, tariffs have also come into more widespread use and could also be utilized to shape end-markets or the intermediate markets for batteries and might be judiciously considered in areas of nascent U.S. competitiveness (rather than for existing lithium ion batteries which simply increase prices in an area where U.S. cannot catch up).[189]

INCENTIVIZE LONG-TERM CAPITAL

Third, incentives are needed to create long-termism in the capital markets both for returns to deep tech solutions that take time to scale, but also for investments in scaled production. This would serve to bridge the "missing middle" in technology investment that exists today in the U.S.: insufficient capital is allocated toward the maturation of new technologies to ensure that they can be manufactured at scale in the U.S. Favorable capital gains taxes to reward long-term investments is an example of such an incentive that would encourage early- and later-stage venture capital and private equity to invest in

companies that are scaling manufacturing. At the early-stage, the government should signal that new battery chemistries are a strategic sector, to drive private sector contributions by directing public sector investment from e.g., In-Q-Tel. At the later-stage, government debt instruments that support manufacturing initiatives for strategic scaleup ventures, as well as opportunities to pay for manufacturing facilities (not simply cost of goods) should be built into contracts for strategic priority technologies such as e.g. batteries in the space economy. The U.S. tax code should also be modified to eliminate the requirement that companies spread deductions for capital investments (for example to build a manufacturing facility) over a thirty-nine-year period. These expenses cannot be immediately deducted from taxable income resulting in a reduction in the real value of deferred deductions over time due to inflation and the time value of money. This causes an overstatement of taxable income for manufacturers which is an effective tax penalty that discourages investment.[190]

DEREGULATE

Fourth, to enable production at scale, a competitive regulatory environment should be provided for the battery manufacturing industry. This means streamlining the federal, state, and local permitting processes needed for rapid approval to break ground and ultimately construct manufacturing facilities. Today the U.S. regulatory environment is prohibitive: battery facilities take at least twice as long to build in the U.S. than in China (estimated to be at 9 months from breaking ground to ramping production). The thicket of local regulations — including up to 93,000 different building codes across U.S. counties and municipalities — has also led to inefficien-

cies in the U.S. construction industry which has seen the lowest productivity growth of any U.S. business sector.[191] Federal and local governments should work to streamline and standardize building codes to enable more rapid construction timelines. Accelerated development of standards and specifications is also a powerful measure to incentivize early adoption and procurement of new technologies.

ATTRACT FOREIGN DIRECT INVESTMENT

Fifth, it is essential for the U.S. to work closely with allies and partners to attract FDI and on-shore expertise to support the burgeoning sector in new ways. Opportunities include:

+ Attracting foreign battery makers from e.g. Japan and South Korea to build plants and to partner with new battery scale-ups so as to more rapidly build up manufacturing industrial base and reinvigorate industrial clusters.
+ Expediting human talent development by creating collaboration between foreign battery manufacturers and local education programs, thereby translating specific expertise not only at the frontier of innovation but the frontiers of production.
+ Engage foreign capital from trusted partners e.g. NATO Allies, the QUAD etc., who can be encouraged to work closely as early- and late-stage capital providers. While existing networks including the Transatlantic Defense Innovation Network (DIN) and its QUAD counterpart are useful in this regard, they are not well focused on strategic priorities to date. CFIU.S. should be engaged to ensure that no adversarial capital enters the funding mix and that U.S. jurisdiction is maintained over U.S.-funded technologies.

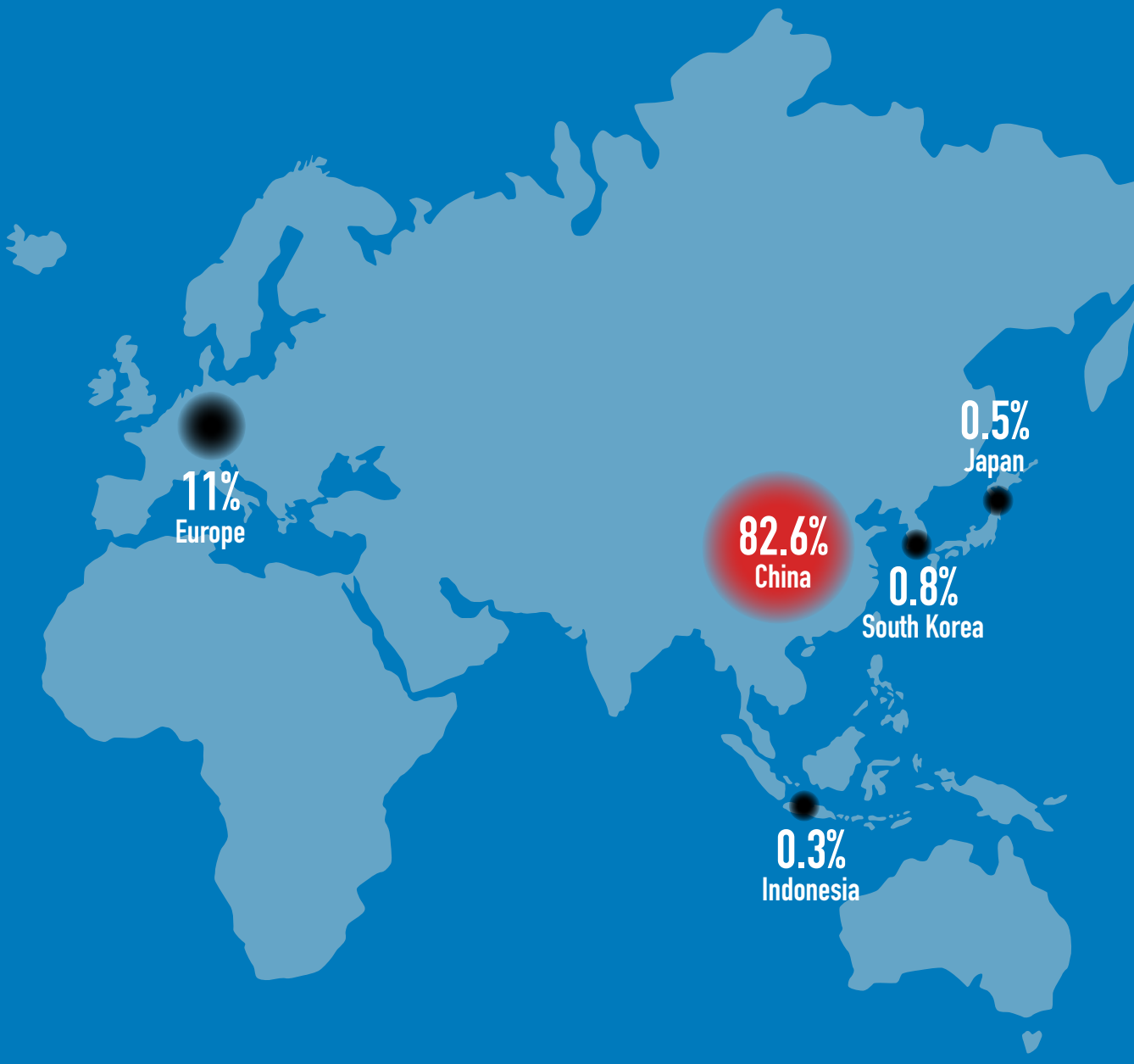
ALL POLITICS ARE LOCAL

Federal government policies and state government policies should be structured to work in consort to rebuild battery manufacturing. Recent examples of federal policies consist of the 2021 Bipartisan Infrastructure Law (BIL) and the 2022 Inflation Reductio Act (IRA). The combination of the two bills provided tax credits, grants, loans, and market-access supporting supply-push and demand-pull incentives. State governments responded by providing local incentives such as land grants, construction cost assistance, state tax benefits, and workforce training programs. This has led to the emergence of a Battery Belt in the south eastern U.S., with states jockeying to attract foreign battery manufacturers.[192] Continuity of these federal and state provisions beyond administration turn-over is key to long-term signaling to industry of a stable business environment in the U.S. that is committed to competing in battery manufacturing.

Beyond the first recommendation, and to a lesser extent the second with its focus on demand-side market shaping, the remaining four require a different playbook from the one used to solely support the innovation ecosystems that have enabled U.S. private sector ingenuity. The industrial base requires concerted emphasis on building shared expertise that consists of equipment manufacturers, advanced materials suppliers, industrial construction firms, advanced manufacturing labor force, and supporting infrastructure in the form of utilities and transportation. The erosion of the U.S. industrial clusters has been well documented and has led to an uncompetitive manufacturing environment for batteries and many other products.[193]

The most expeditious way to link innovation to industrialization is for the U.S. to signal the importance of industrialization to innovators and investors while simultaneously attracting established battery manufacturers and investors from South Korea, Japan, and even China to its shores. By doing so, the U.S. will benefit from importing manufacturing best practices and supply chains. These large companies will bring their supply chains with them. The U.S. will also benefit from upskilling its labor force to the discipline and expertise needed for high volume manufacturing and advanced chemistry research, as well as creating domestic ecosystems and regulatory environments that excel at rapid construction and manufacturing. Developing robust industrial clusters are essential to all down-stream battery enabled sectors. They will also provide an add-on benefit of reducing U.S. import reliance on China for existing Li-ion batteries.

ESTIMATED SHARE OF GLOBAL LITHIUM-ION MANUFACTURING CAPACITY IN 2024



SOURCE: Volta Foundation 2024 Battery Report


4.8%
United States

ADDENDUM

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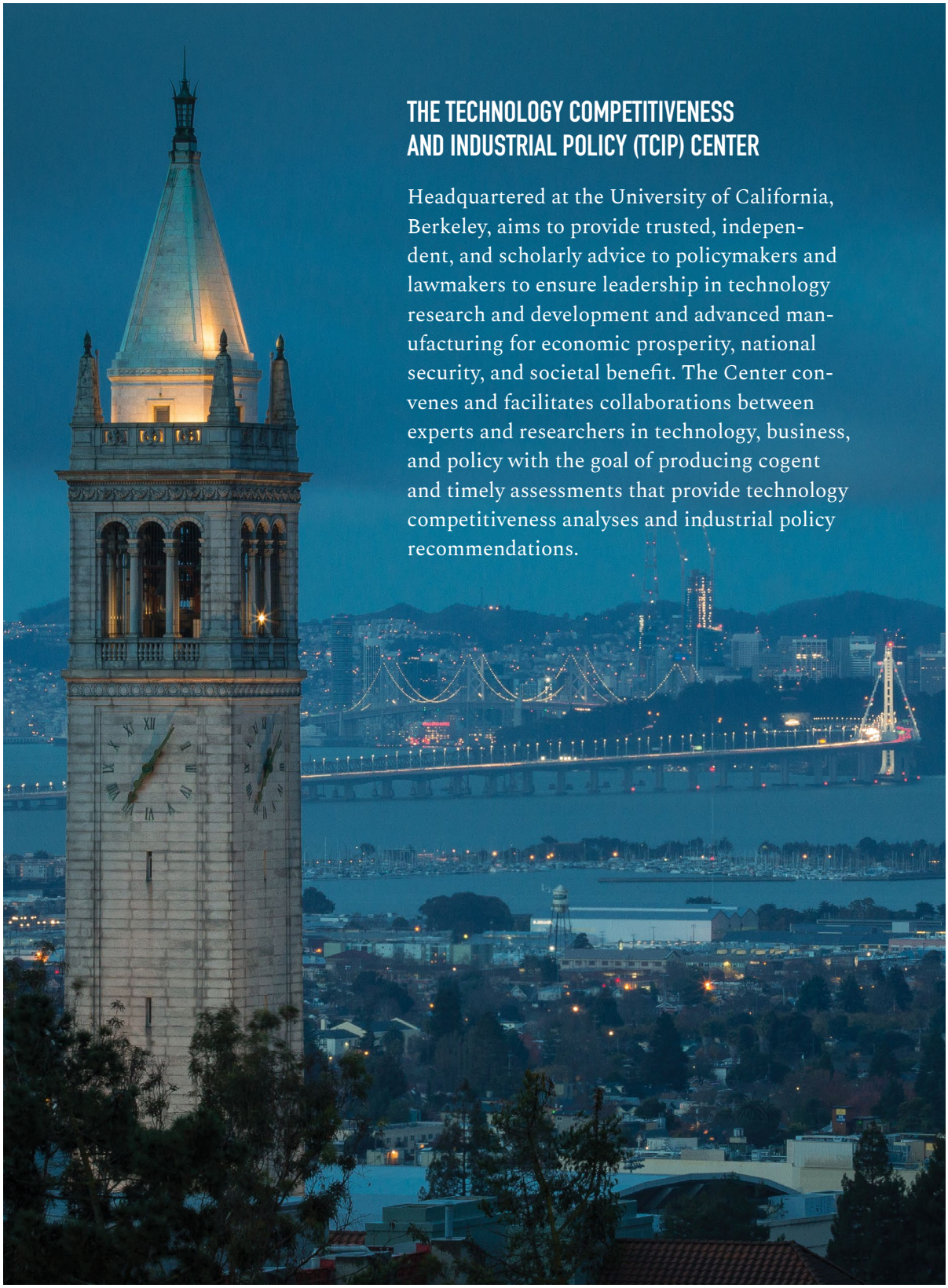

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