U.S. DEPARTMENT OF ENERGY

Grid Energy Storage

Supply Chain Deep Dive Assessment

U.S. Department of Energy Response to Executive Order 14017, “America’s Supply Chains”

February 24, 2022

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About the Supply Chain Review for the Energy Sector Industrial Base

The report "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition" lays out the challenges and opportunities faced by the United States in the energy supply chain as well as the Federal Government plans to address these challenges and opportunities. It is accompanied by several issue-specific deep dive assessments, including this one, in response to Executive Order 14017 "America's Supply Chains," which directs the Secretary of Energy to submit a report on supply chains for the energy sector industrial base. The Executive Order is helping the Federal Government to build more secure and diverse U.S. supply chains, including energy supply chains.

To combat the climate crisis and avoid the most severe impacts of climate change, the U.S. is committed to achieving a 50 to 52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030, creating a carbon pollution-free power sector by 2035, and achieving net zero emissions economy-wide by no later than 2050. The U.S. Department of Energy (DOE) recognizes that a secure, resilient supply chain will be critical in harnessing emissions outcomes and capturing the economic opportunity inherent in the energy sector transition. Potential vulnerabilities and risks to the energy sector industrial base must be addressed throughout every stage of this transition.

The DOE energy supply chain strategy report summarizes the key elements of the energy supply chain as well as the strategies the U.S. Government is starting to employ to address them. Additionally, it describes recommendations for Congressional action. DOE has identified technologies and crosscutting topics for analysis in the one-year time frame set by the Executive Order. Along with the capstone policy report, DOE is releasing 11 deep dive assessment documents, including this one, covering the following technology sectors:

- carbon capture materials,
- electric grid including transformers and high voltage direct current (HVDC),
- energy storage,
- fuel cells and electrolyzers,
- hydropower including pumped storage hydropower (PSH),
- neodymium magnets,
- nuclear energy,
- platinum group metals and other catalysts,
- semiconductors,
- solar photovoltaics (PV), and
- wind

DOE is also releasing two deep dive assessments on the following crosscutting topics:
- commercialization and competitiveness, and
- cybersecurity and digital components.

More information can be found at www.energy.gov/policy/supplychains.

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List of Acronyms and Abbreviations

C&I	commercial and industrial
C1	Class 1 (nickel)
CAES	compressed air energy storage
CAGR	compound annual growth rate
CSP	concentrated solar power
CATL	Contemporary Amperex Technology Company, Limited
CMI	Critical Materials Institute
DOE	U.S. Department of Energy
DRC	Democratic Republic of the Congo
EO	Executive Order
EOL	end-of-life
ESIB	Energy Sector Industrial Base
ESS	energy storage system
EV	electric vehicle
FB	flow battery
FESS	flywheel energy storage system
GDP	gross domestic product
Grid ESS	electric grid-connected energy storage system
GW	gigawatt
GWh	gigawatt-hour
HDV	heavy-duty vehicle
HDV-PEM	PEM fuel cell designed for HDVs
HPMSM	High-purity manganese sulfate monohydrate
IEA	International Energy Agency
IHA	International Hydropower Association

IIJA	Infrastructure Investment and Jobs Act of 2021
LCO	lithium cobalt oxide
LCOE	levelized cost of energy or levelized cost of electricity
LDES	long-duration energy storage
LFP	lithium iron phosphate
LMO	lithium manganese oxide
NCA	nickel cobalt aluminum oxide
NGCC	natural gas combined cycle
NMC or NMCO	nickel manganese cobalt oxide
NMCA	nickel magnesium cobalt aluminum
NREL	National Renewable Energy Laboratory
OE	Department of Energy, Office of Electricity
PEM	polymer electrolyte membrane
PSH	pumped storage hydropower
R&D	research and development
RAZB	rechargeable aqueous zinc batteries
RDD&CA	research, demonstration, deployment, and commercial application
ROA	Rest of Asia
ROW	Rest of World
RMB	rechargeable magnesium battery
SA	South America
T&D	transmission & distribution
TES	thermal energy storage
V2G	vehicle-to-grid
VFB	vanadium flow battery
Wh	Watt-hour

ZFB	zinc flow battery

Executive Summary

In February 2021, President Biden signed Executive Order (EO) 14017, *America's Supply Chains*, directing four executive agencies to evaluate the resilience and security of the nation's critical supply chains and craft strategies for seven industrial bases that underpin America's economic and national security. As part of the one-year response to EO 14017, the U.S. Department of Energy (DOE), through the National Laboratories, conducted evaluations of the supply chains that encompass the Energy Sector Industrial Base (ESIB), with a particular focus on technologies required to decarbonize by 2050.

The U.S. ESIB will require radical transformations to decarbonize by 2050, including renewable energy generation and transportation from carbon-neutral sources, combined with storage of that energy. Increased variable renewables on the grid and the need to provide electricity for the growing electric vehicle market requires that U.S. utilities not only produce and deliver electricity, but also store it. Electric grid energy storage is likely to be provided by two types of technologies: short-duration, which includes fast-response batteries to provide frequency management and energy storage for less than 10 hours at a time, and long-duration, which provides load shifting over many hours or days and is currently dominated by pumped storage hydropower (PSH). Other technologies may have market relevance within the next few years, including lead-acid batteries, flow batteries, hydrogen, and compressed air energy storage (CAES).

DOE's Office of Electricity (OE) thus has particular interest in evaluating the supply chain risk and resilience of critical products for the electrical grid. The domestic supply chain of the most prevalent electric grid storage technology (<10 hours duration), lithium-ion batteries, depends upon other countries, primarily China, for most of the raw and processed materials, subcomponents, and the batteries themselves. Even end-of-life (EOL) recycling and reuse processing is dominated by other countries, and most used batteries collected in the United States today are exported.

This report provides an overview of the supply chain resilience associated with several grid energy storage technologies. It provides a summary of each technology's supply chain, from the extraction of raw materials to the production of batteries and other storage systems, and an analysis of the vulnerabilities of each supply chain. It also discusses the current supply chain risk and resilience for the United States, as well as competitiveness of the U.S. supply chain and potential opportunities. This analysis serves as a basis for highlighting several vulnerabilities and their causes in the grid energy storage supply chain to inform policy and decision makers in their efforts to increase supply chain resiliency and global competitiveness.

Globally, over 30 gigawatt-hours (GWh) of grid storage are provided by battery technologies (BloombergNEF, 2020) and 160 gigawatts (GW) of long-duration energy storage (LDES) are provided by technologies such as pumped storage hydropower (PSH) (U.S. Department of Energy, 2020)[1]. As the United States and the world increase electrification as part of efforts to decarbonize energy use, the need for reliable and cost-effective energy storage methods will become even more critical. For example, the International Energy Agency (IEA) recently released a study on how to achieve net zero emissions by 2050 (IEA 2021), which projected global grid storage

[1] Units for energy storage are generally expressed in terms of the maximum amount of energy, e.g., watt-hours that can be made available over a specified amount of time (e.g., 2 hours), as the device is not generating energy but merely storing it for later use. In some instances, the size/capacity of energy storage technologies is reported in terms of maximum power output, such as watts. PSH systems, in particular, are given in terms of power ratings. While this inconsistency in units can make direct comparisons difficult, site- and design-specific data for PSH installations are necessary to convert capacities to energy units but are generally not widely available.

to grow to almost 2,500 GWh by 2030. Projected grid storage growth in the United States is expected to steeply increase as well. The Biden-Harris Administration's high-level strategy to achieve net zero by 2050 projects significant growth in grid storage, increasing from an average deployment of 1.6 to 11 GWh/year in the 2020's up to 40 to 250 GWh/yr deployed in the 2040s. Two recent studies by Princeton University (Larson, et al., 2020), and the National Renewable Energy Laboratory (NREL) (Denholm, Cole, Frazier, Podkaminer, & Blair, 2021) also looked at the U.S. grid storage market through 2050 with Princeton evaluating scenarios to reach net zero carbon and NREL looking at the maximum economic deployment of storage technologies. One of the cases in the Princeton study projects the U.S. grid storage to grow slowly to 50 GWh by 2030 and then grow to over 1300 GWh in 2050. The most aggressive NREL case projects quicker early growth, reaching 200 GWh by 2035. Neither study evaluated the specific technologies that would be used for this growth.

The technical characteristics and domestic supply chains of three commercially available battery technologies and five LDES methods are evaluated. Additional nascent technologies are also briefly described in Section 1.1.8. The sections focusing on each technology are shown in parentheses. Section 2 focuses on mapping the supply chains for technologies which are seen as having the greatest near-term market potential, while Section 3 evaluates the risks to resilient supply chains. Near- and long-term key vulnerabilities are summarized in Sections 3.6 and 3.7, while Section 3.8 focuses on the areas which should be addressed first.

Short-duration energy storage:

- Lithium-ion batteries (Sections 2.2 and 3.1)
- Lead-acid batteries (Sections 2.3 and 3.2)
- Flow batteries (Sections 2.4 and 3.3)
- Thermal energy storage (TES) (Section 1.1.6)
- Flywheel energy storage systems (Section 1.1.7)
- Emerging technologies (Sections 2.5 and 3.4)
    - Sodium-ion batteries
    - Metal-air batteries (Zinc Zn-air; Iron Fe-air)
    - Rechargeable magnesium batteries (RMB)
    - Rechargeable aqueous zinc batteries (RAZB)

LDES (Sections 2.6 and 3.5):

- PSH
- Compressed air energy storage (CAES)
- Hydrogen

Lithium-ion batteries are expected to be the dominant commercial technology (>95%) for short-term energy storage (less than 10 hours) for the next several years. Raw materials for lithium-ion batteries include cobalt, nickel[2], lithium, manganese, iron, and graphite. Greater than 50% of the mine production of the ores is controlled by three or fewer countries and the United States has little to no mining of these materials. In 2020, the United States mined <1% of the global annual mine production of the minerals listed except lithium and iron. The U.S.

[2] It should be noted that nickel ore can be refined into class 1 (C1) or class 2 (C2) nickel. Only nickel compounds (e.g., nickel sulfate) made with refined C1 nickel products (e.g., nickel briquet or powder) can be used to make lithium-ion batteries. C1 nickel is defined as a refined product with greater than 99% nickel. In general, most of the C1 nickel products come from sulfide deposits and the C2 nickels come from laterite. However, high-pressure acid leaching (HPAL) can be used to upgrade C2 nickel into C1 (BloombergNEF, 2020a).

reserves of these materials are also the highest, at 3.6% for lithium and 1.2% for iron (United States Geological Survey, 2022). In fact, most of these materials are included on the 2021 draft Critical Materials list (2021 Draft List of Critical Materials, 2021).

While the concentration of raw material production is a vulnerability in the supply chain, the concentration of refining of these metals for lithium-ion battery production is even more limited with China producing more than 60% of the cobalt and lithium and 95% of the manganese refined materials (e.g., high-purity manganese sulfate monohydrate, HPMSM) (BloombergNEF, 2021). China is second to Russia in C1 nickel refining (BloombergNEF, 2021).

China's dominance of the lithium-ion battery supply chain and its lead over the United States becomes even more pronounced with respect to subcomponent (e.g., cathodes, electrolyte) production. Table ES-1 shows the stark difference between the United States and China in subcomponent manufacturing. Current shares are based on the latest data from several sources and differ from earlier analyses such as the 100-Day Reviews (The White House, 2021) because of the rapid changes occurring in the market for lithium-ion batteries. As more auto manufacturers announce new electric vehicle deployments, industry and governments, primarily in China and Europe, are announcing new manufacturing facility investments.

Table ES-1 United States' and China's Existing and Future Shares of Global Subcomponent Capacity

	Current		Under Development	
	U.S.	China	U.S.	China
Cathode	0.70%	63%	0%	84%
Anode materials	0.60%	84%	0%	91%
Separator[3]	3%	66%	0%	76%
Electrolyte	7%	69%	2%	75%

Source: (BloombergNEF, 2021)

The United States has a better position in cell manufacturing, with 13% of the world's lithium-ion cell manufacturing capacity (~520 GWh), but China is still dominant with almost 80%. China is projected to increase its share of cell manufacturing capacity as it has almost 60% of the facilities planned or under construction while the United States has less than 10% of planned or under construction cell manufacturing facilities.

China has a dominant position in end-of-life options with over 80% of the global lithium-ion battery recycling capacity while the United States has just 7% of capacity (Li & Frith, 2021). While projections of reuse were not obtained, China also has numerous policies promoting reuse (Li, 2021).

[3] Separators for lithium-ion batteries are generally made of polyethylene, polypropylene, or layered combinations of both. BloombergNEF did not specify the type of separator in their database.

Lead-acid batteries are also used in grid storage, primarily outside the United States, but their use in this market is declining. Lead-acid batteries have a strong, well-developed domestic supply chain from raw materials to end-of-life recycling. Over 99% of lead-acid batteries are recycled in the United States and these supply the raw materials for 70% of new batteries. All raw materials, refined materials, subcomponents, and batteries have numerous domestic suppliers. The biggest supply chain concerns for lead-acid batteries are their technical performance and lack of sufficient battery management systems needed for the grid storage market. Work is currently underway to improve system performance.

Flow batteries, primarily based on vanadium, iron, or zinc, are a grid storage technology that are expected to grow significantly. They can be used in applications up to 12-hours of storage and are thus a potential LDES technology. Due to the relatively small size of the flow battery market, the supply chain is not fully developed. However, at this point, except for vanadium and possibly zinc supply, there do not appear to be the potential bottlenecks and dependence on foreign countries shown with lithium-ion batteries. Zinc and iron are abundant materials, and the United States is a net exporter of iron ore and mined zinc, but it has a net import reliance[4] of >75% of its apparent consumption of refined zinc (United States Geological Survey, 2022). Zinc was just added to the proposed critical materials list and so even though it is abundant, there could be some issues due to the recent notable increase in the concentration of global mine and smelter production and the concurrent decrease in zinc smelting in the United States (Nassar & Fortier, 2021). Flow battery components are generally common (pumps, tanks, acids) and easily obtainable. While all countries would likely have these advantages, the domestic supply chain of flow batteries is in a strong position in that there are several domestic flow battery technology developers and vendors.

Emerging technologies such as sodium-ion, metal-air, rechargeable magnesium, and rechargeable zinc are still being developed and do not have a defined supply chain. However, they are similar to flow batteries in that most are based on abundant materials and simpler components.

LDES technologies such as CAES and PSH do not have supply chain concerns as they use common equipment and materials. They are more limited by geography, being least expensive when sited near a suitable geological formation (e.g., salt caverns). TES typically does not have significant geographical limitations, and generally uses conventional materials such as molten salts or ice. Hydrogen is another potential LDES technology that is not expected to have significant supply chain constraints[5].

Based on the risk assessments of the energy storage technologies, several near-term vulnerabilities were identified. These vulnerabilities are based on lithium-ion batteries as they are projected to be dominant for grid deployments, but many are applicable to other emerging and potentially grid-viable storage technologies.

- Reliance on other countries for critical materials, components, and products
- Lack of a domestic manufacturing and recycling infrastructure
- Environmental, social, and climate impacts of steps along the supply chain, particularly with regard to raw material acquisition and refining, manufacturing, and recycling
- Lack of deployment of grid storage alternatives that can meet a wide variety of applications and conditions
- Safety (e.g., thermal runaway) concerns with lithium-ion batteries

[4] Net import reliance is defined *imports – exports + adjustments* for Government or industry stock changes (United States Geological Survey, 2022)
[5] Availability of electrolyzers or other hydrogen generating equipment is out of the scope of this analysis and is covered in the hydrogen technology supply chain report.

- High barriers to market entry including high capital requirements, skilled workforce demands, changing technology, and the subsequent need for continual research and development (R&D)
- Difficulty in obtaining capital due to the lack of "Tier 1" suppliers or standardization of offerings and long-term off-take contracts, especially for standalone energy storage.

In the longer term, competition from other sectors (e.g., transportation) may prove problematic for securing materials, components, and devices for grid energy storage. The transportation sector is expected to be the major driver of battery storage demand, especially for lithium-ion batteries. This demand could negatively impact the supply of new batteries for grid deployment. Reuse of batteries after their end of life in the transportation sector may provide an affordable and secure source of batteries for grid energy storage.

Four key focus areas are identified to address the most significant vulnerabilities:

- **Reliance on other countries for raw and refined materials, components, and products—**The United States lags Asia, and especially China, in the manufacture and supply of materials, components, and end products for grid storage.
- **Environmental and climate impacts of material refining, battery manufacturing, and recycling industries—**Raw material extraction, refining, and recycling are energy- and resource-intensive processes with significant potential environmental, environmental justice, and climate impacts. Any effort to address supply chain risks in terms of a secure supply must also address climate and environmental impacts.
- **Broad application requirements (e.g., performance, environmental) and a lack of standardization for energy storage applications—**Lithium-ion batteries are the current dominant choice due to their cost-effectiveness, power-to-weight ratio, and performance. However, given that demand for lithium-ion batteries for the transportation sector is estimated to be almost 10-times greater than that from ESS by 2030 and in general, has more restrictive performance characteristics (e.g., higher specific energy), it is likely that other alternatives (e.g., flow batteries, low-cobalt chemistries) should be developed to ensure that there are reliable, economic and robust alternatives for ESS instead of competing with a much larger industry in a vulnerable, complicated domestic supply chain. A recent paper from the National Academy of Sciences (Trahey, et al., 2020) concluded that:
  "The need for a diversity of battery platforms beyond the current technology and the inability of existing technologies to meet all of the required performance metrics for a given application are the two biggest challenges for energy storage."
  Because of this, the strategy and operation of the Joint Center for Energy Storage Research (JCESR) is focused on addressing these issues. Although differing chemistries could complicate supply and end of life issues, thus making the supply chain more vulnerable, the wide range of ESS applications and operating conditions more than make up for this potential, as having more than one technology and different chemistries among the options for grid energy storage systems (ESS) could increase the resiliency of the overall supply chain.
- **Lack of developed supply chains for nascent technologies—**many long duration-capable technologies utilize materials that are inexpensive and abundant. However, due to their minimal adoption, supply chains for these new technologies have yet to be established. Development of supply chains for grid storage options like flow batteries, CAES, or TES would reduce grid storage vulnerabilities to transportation demand and supply chain bottlenecks with lithium batteries.

The fundamental and essential activities of American life revolve around an economic and reliable electric grid. Sustainably and securely upgrading that grid to deliver clean energy for homes, businesses, industries, and transportation will require the piecing together of supply chains that interconnect raw materials, equipment manufacturing, a strong workforce, and policies. Ensuring that the future United States grid is built with a focus on a domestic and resilient supply chain that provides equitable opportunities for all communities will enhance global leadership and secure a decarbonized future.

Find the policy strategies to address the vulnerabilities and opportunities covered in this deep dive assessment, as well as assessments on other energy topics, in the Department of Energy 1-year supply chain report: "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition."

For more information, visit www.energy.gov/policy/supplychains.

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1 Introduction

In February 2021, President Biden signed Executive Order (EO) 14017, "America's Supply Chains," directing four executive agencies to evaluate the resilience and security of the nation's critical supply chains and craft strategies for six industrial bases that underpin America's economic and national security. As part of the one-year response to EO 14017, the U.S. Department of Energy (DOE), through the National Laboratories, conducted evaluations of the supply chains that encompass the Energy Sector Industrial Base (ESIB), with a particular focus on technologies required to decarbonize by 2050.

The U.S. ESIB will require radical transformations to decarbonize by 2050, including renewable energy generation from carbon-neutral sources combined with carbon-neutral transportation. While efficient clean energy and carbon-neutral transportation technologies are available to help achieve these goals, they currently rely on raw materials characterized by opaque and volatile global markets and often concentrated in geopolitically sensitive areas. Furthermore, midstream stages of supply chains, such as material processing and the manufacturing of components, are also concentrated in foreign countries which have complicated geopolitical relationships with the United States. DOE's Office of Electricity (OE) has particular interest in evaluating the supply chain risk and resilience of critical products used within the electric grid.

Energy storage is an important component of the electric grid today and an essential piece of the evolving grid of tomorrow. Globally, over 30 gigawatt-hours (GWh) of storage is provided by battery technologies (BloombergNEF, 2020) and 160 gigawatts (GW) of long-duration energy storage (LDES) is provided by technologies such as pumped storage hydropower (PSH) (DOE 2020). These technologies can enable greater use of variable renewable generation and higher levels of resilience for unexpected system outages. As the United States and the world increase electrification and decarbonize energy use, the need for reliable and cost-effective energy storage methods will become even more critical.

Lithium-ion batteries comprise the majority of grid-energy storage for durations of less than 10 hours. PSH currently provides most of the longer-duration (10 hours and above) storage. Lithium-ion batteries are the least expensive alternative at shorter durations and are expected to continue to earn significant market share. Lithium-ion batteries and other grid storage technologies enable greater penetration of renewables through load-shifting and arbitrage, improve grid reliability, reduce congestion, and increase profitability. They also provide ancillary services such as frequency regulation or reserves and help better utilize existing transmission and distribution assets, thus deferring investments. Finally, they provide peak shaving and time-of-use optimization. These services are critical in protecting and modernizing the electric grid, a cornerstone of America's Energy Sector Industrial Base.

This report provides an overview of the supply chain resilience associated with several grid energy storage technologies. It provides a map of each technology's supply chain, from the extraction of raw materials to the production of batteries or other storage systems, and discussion of each supply chain step. It also discusses the current supply chain risk and resilience in the United States, as well as competitiveness of the U.S. supply chain and potential opportunities. This report complements and is consistent with other recent government-supported reports such as the National Blueprint for Lithium Batteries (Federal Consortium for Advanced Batteries, 2021) and the 100-Day Report (The White House, 2021), but expands the discussion beyond the electrification of the transportation sector. This analysis serves as a basis for highlighting several vulnerabilities (and their causes) of technologies relevant to the grid energy storage supply chain needed to decarbonize the Energy Sector Industrial Base.

1.1 Technology Descriptions

Several technologies are commercially available or will likely be commercially available for grid storage in the near-term. The technologies evaluated provide storage durations that range from hours to days and response times of milliseconds to minutes. Four families of battery technologies and three LDES technologies are evaluated. Additional nascent technologies are also briefly described in Section 1.1.8. Section 2 focuses on mapping the supply chains for each technology, while Section 3 evaluates the risks to resilient supply chains. Near- and long-term key vulnerabilities are summarized in Sections 3.6 and 3.7, while Section 3.8 focuses on the areas which should be addressed first.

Short-duration energy storage:

- Lithium-ion batteries (Sections 2.2 and 3.1)
- Lead-acid batteries (Sections 2.3 and 3.2)
- Flow batteries (Sections 2.4 and 3.3)
- Thermal energy storage (Section 1.1.6)
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  - Metal-air batteries (Zinc Zn-air; Iron Fe-air)
  - Rechargeable magnesium batteries (RMB)
  - Rechargeable aqueous zinc batteries (RAZB)

LDES (Sections 2.6 and 3.5):

- PSH
- Compressed air energy storage (CAES)
- Hydrogen

Short technology descriptions are provided in the following sections.

1.1.1 Lithium-Ion Batteries

Lithium-ion batteries are a class of rechargeable batteries in which lithium ions move between an anode and a cathode through an electrolyte. The anode and cathode are separated by a porous, nonconducting material that allows the ions to pass through when charging or discharging. Most lithium-ion batteries have a graphite anode, although numerous companies are developing silicon-based anodes. The cathode of a lithium-ion battery can have many different chemistries, depending upon the application. Common cathode chemistries include, but are not limited, to the following:

- Lithium cobalt oxide (LCO)
- Nickel manganese cobalt oxide (NMC or NMCO)
- Nickel cobalt aluminum oxide (NCA)
- Nickel magnesium cobalt aluminum (NMCA)
- Lithium iron phosphate (LFP)
- Lithium manganese oxide (LMO).

By naming convention, NMC, NCA and NMCA omit the "L" for lithium, but they do still contain lithium. NMC batteries can have several configurations and are denoted by "NMC," followed by three numbers that correspond to the molar ratio of nickel, manganese, and cobalt in the cathode. For example, NMC111 has equal molar ratios of all three components while NMC811 has eight times as much nickel as either manganese or cobalt. LCO batteries are used exclusively for consumer electronics. In general, the most energy-dense cathodes (e.g., NCA or NMC811) are used primarily in vehicles, and less-dense chemistries such as NMC532 or LFP are used for stationary applications. The specific energy range of lithium-ion batteries is 100–265 Wh/kg (Clean Energy Institute - University of Washington, 2020). Figure 1 shows the metal content (wt%) of the various chemistries of lithium-ion batteries. It should be noted that any oxygen that is included in these battery chemistries (e.g., LMO) is not included in this chart. While oxygen affects the mass energy density values, it is not a concern from a supply chain perspective as the elements shown are.

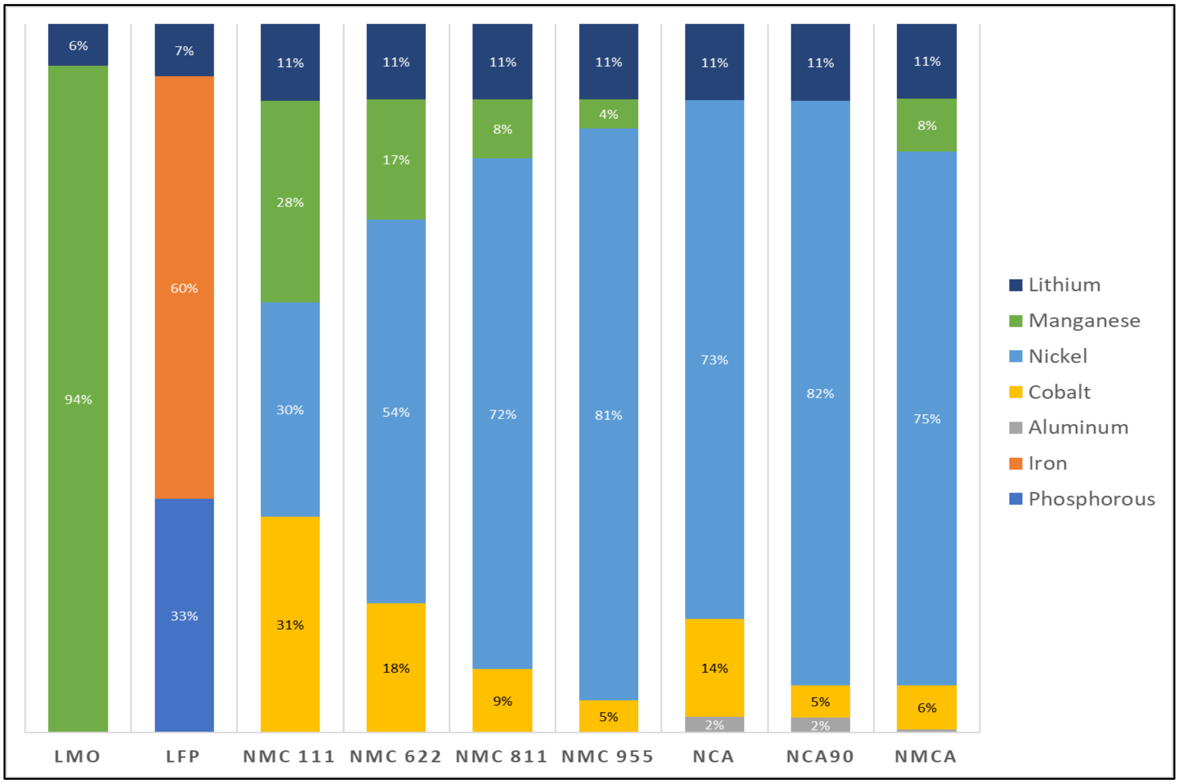

Figure 1. Metal content (wt%) of lithium-ion battery cathodes.

Source: BNEF (2020)

The most common lithium-ion batteries today rely on three metals of particular importance with regard to resilient supply chains: cobalt, nickel, and lithium. As discussed in greater detail in Section 2 of this report, the United States has very few reserves of these materials except lithium at approximately 3% of global reserve, essentially no material refining operations, scant manufacturing of intermediate components such as cathodes and anodes, and only a nascent presence in recycling. As discussed in Section 1.2, lithium-ion batteries have emerged as the dominant player in the growing energy storage market, creating immense concerns about the country's ability to develop a resilient supply chain.

1.1.2 Lead-Acid Batteries

Lead-acid batteries are the most widely used rechargeable battery type in the world. They are used for a wide range of applications including starting, lighting, and ignition in conventional vehicles as well as uninterruptible power supplies and grid storage.

Lead-acid batteries use lead dioxide as the active material on the positive electrode, metallic lead as the negative active material, and sulfuric acid as the electrolyte. Lead-acid batteries have a relatively low specific energy (35–40 Wh/kg) compared to other battery types (Chian, et al., 2019).

State legislation (Battery Council International, 2022) is aimed at keeping lead out of landfills and preventing it from seeping into groundwater, and federal regulations encourage recycling of lead acid batteries (U.S. Environmental Protection Agency, 2021). Because of these legislative factors and the profitable reuse of lead for new batteries, lead-acid batteries are recycled at extremely high rates—greater than 99% in the United States.

1.1.3 Flow Batteries

A flow battery (or redox battery, named for reduction-oxidation) is a type of battery in which power is generated by redox-active electrolytes from large storage tanks flowing through an electrochemical cell. One tank of the battery holds the cathode and the other holds the anode. The cathode and anode liquids, separated by an ion exchange membrane that allows ionic conduction, are pumped through the electrochemical cell. Figure 2 shows a simple schematic of a flow battery.

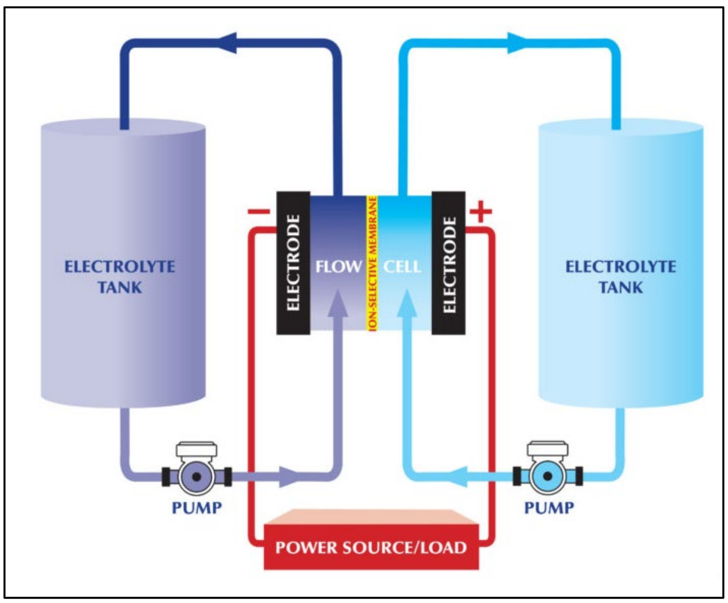

Figure 2. Flow battery schematic.

Image Source: International Flow Battery Forum (2021)

Although flow batteries have a relatively low specific energy (~20 Wh/kg), they are unique in that they decouple the energy and power ratings, allowing for easier and more economic scaling across a larger range of sizes, from kilowatts to megawatts. The energy storage duration for which flow batteries are typically designed is on the order of 10 hours, making them particularly well-suited for energy arbitrage, but they can also be used for other short- or long-duration applications. Three commercially available flow batteries—vanadium flow batteries, zinc flow batteries, and iron flow batteries—are discussed in this report.

1.1.4 Emerging Technologies

Other emerging battery technologies are being developed for grid-based applications; four of these emerging technologies are described below. While these technologies may still have future market potential, they will need to compete with the extraordinary technical progress made by lithium-ion batteries due to the right combination of energy density, cost, cycle life, and calendar.

1.1.4.1 Sodium-Ion Batteries

Sodium-ion batteries are a type of rechargeable battery that is analogous to lithium-ion batteries except that they substitute sodium for lithium, which is ubiquitous and cheaper to produce. This technology is not yet commercially deployed, although Contemporary Amperex Technology Company, Limited (CATL) announced in July 2021 that they expect to commercialize their sodium-ion battery technology by 2023 (Xu & Reid, 2021). The CATL battery has a specific energy of up to 160 Wh/kg and has a capacity retention rate of greater than 90% at -20°C (CATL, 2021).

1.1.4.2 Metal-Air Batteries

Metal-air batteries are composed of a metal (Li, Na, K, Mg, Al, Fe and Zn) anode, a porous gas diffusion cathode, and an electrolyte. Zinc- and iron-based metal-air batteries generally use an aqueous electrolyte while the others use a nonaqueous electrolyte. Metal-air batteries have several potential advantages including high theoretical energy densities and potentially low fabrication costs (Marschilok, 2021). NantEnergy and Zinc8 are two companies developing zinc-air batteries. Zinc8 will demonstrate a 100-kWh/1-MWh system at the University of Buffalo to provide peak shaving capability and increase campus resiliency (Zinc8, 2021). Form Energy is developing an iron-air battery with a targeted storage capacity of 100 hours (Form Energy, 2022).

1.1.4.3 Rechargeable Magnesium Batteries

RMBs are currently being developed due to the high elemental abundance of magnesium and its magnesium metal anode. Magnesium metal anodes are advantageous due to their high theoretical capacity (2200 mAh/g), stability in ambient atmosphere, and lower generation of toxic compounds. Cathodes currently under development include $Mg_2Mo_6S_8$ and vanadium oxides. Commercialization of RMBs depends upon finding the correct cathode and electrolyte combination for long cycle life and sufficient voltage range (Marschilok, 2021).

1.1.4.4 Rechargeable Aqueous Zinc Batteries

RAZBs have a zinc metal anode and use the divalent form of zinc as the charge carrier in an aqueous electrolyte. The electrolyte can be alkaline (pH 14) or acidic (pH 4). Cells using the alkaline electrolyte are similar to standard primary Zn/MnO_2 cells. While the acidic electrolyte can be used with many types of cathodes, 2M $ZnSO_4$ or 3M Zn triflate are generally used. An RAZB using the alkaline electrolyte is currently being deployed in a 1-MWh system for the City University of New York (Marschilok, 2021).

1.1.5 Long-Duration Energy Storage

LDES is generally any technology that stores energy for more than about 4 hours (McNamara, 2021). For this analysis, however, LDES technologies are based on a minimum storage duration of 10 hours, consistent with DOE definitions (DOE EERE, 2021). Many LDES technologies have significantly larger storage capacities, including days-long durations.

1.1.5.1 Pumped Storage Hydropower

PSH is one of the earliest energy storage methods and was first deployed in the late 1800s in Europe. It is a type of hydroelectric energy storage that features two water reservoirs at different elevations. Power is generated when the water is discharged from the higher reservoir and passes through a turbine. The system uses energy from the grid to pump the water back up to the higher reservoir and “recharge” the system.

1.1.5.2 Compressed Air Energy Storage

CAES stores energy as compressed air and is generally deployed in large underground caverns such as salt domes, salt beds, and aquifers. CAES is similar to PSH systems, but instead of pumping water to an elevated reservoir when extra power is available, air or another gas is compressed and stored in a cavern. When electricity is required, the pressurized air is heated and expanded in a turbine, driving a generator for power.

1.1.5.3 Hydrogen Storage

Hydrogen can be stored many ways, including both physically and chemically. Gaseous hydrogen storage includes pressurized vessels, salt caverns, depleted gas fields, and rock caverns. Liquid hydrogen is stored at low temperature in cryogenic vessels. Hydrogen can also be converted to molecular energy carriers such as ammonia, methanol, and other liquid organic carriers such as methylcyclohexane, allowing for storage and delivery under lower pressures and higher temperatures.

Salt caverns are a secure (i.e., negligible leakage), low-cost method for storing very large quantities of gaseous hydrogen, which makes them attractive for long-duration storage. Cryogenic liquid storage is currently cost-prohibitive for long-duration storage and will not be addressed in this analysis. While storing hydrogen as molecular carriers may be feasible, it is beyond the scope of this report. Only gaseous hydrogen storage will be addressed.

For grid storage, the hydrogen must be generated, stored, and then converted back to electrical energy. The hydrogen would be made via electrolysis and stored underground in caverns or in storage structures (e.g., pipes or tanks). Converting the hydrogen to electricity for the grid can be done with a combustion turbine or a fuel cell. Hydrogen has not been deployed for grid storage due to high capital costs and low round-trip efficiencies, but a recent study (Hunter, et al., 2021) reports that the costs of polymer electrolyte membrane (PEM) fuel cell systems may decrease significantly through research and development (R&D). High temperature fuel cell and electrolyzer technologies, such as those based on solid-oxide materials, are also under development, offering the potential for higher round-trip efficiency (U.S.DOE HFTO, 2021)[6].

1.1.6 Thermal Energy Storage

Thermal energy storage (TES) technologies are used to store heat or cold for several hours for later use in buildings, district heating systems, or steam turbine generators. Storage of thermal energy can be accomplished by heating or cooling liquids or solid materials (e.g., rocks, concrete) without causing a phase change in the material, or by taking advantage of the enthalpy made available in the phase change between the solid and liquid states (e.g., ice). Depending on the enthalpy of the energy being stored and the application, different materials are used. Molten salts, aluminum, concrete, and advanced phase-change materials are examples that can be used to store energy at higher temperatures. Materials used to store energy for use in buildings are generally at lower temperatures, including water (ice), water solutions, and low-quality steam.

Low-temperature TES is applicable to grid ESS in that grid-delivered electricity can be converted to heat (through resistive heating) or cold (through chillers, air conditioning, or refrigeration cycles) and stored in secondary materials, thus load-shifting heating and cooling demands. Conversion of the stored energy back to electricity is generally cost-prohibitive at lower temperatures because of efficiency losses and the capital cost of

[6] The supply chain for hydrogen is further discussed in the separate “Water Electrolyzers and Fuel Cells Supply Chain Review.”

low-temperature heat transfer. In high-temperature TES, the heat can be used to create steam for steam turbine generators, thus producing electricity that can be sold back to the grid. This approach is used in concentrated solar power (CSP) and could be viable in storing heat generated by industries such as metal smelting. Alternatively, companies such as Malta, Inc. are commercializing the use of heat pumps to convert electricity to heat for storage in molten salts, followed by conversion back to electricity. Known as a Carnot battery, thermal storage to electricity systems may gain increasing traction as a greater share of the economy is electrified (Dumont, et al., 2020).

1.1.7 Flywheel Energy Storage Systems

Flywheel energy storage systems are mechanical devices that store energy in a rotating mass. The mass is generally made of steel or a dense composite and is secured in a vessel under vacuum to minimize drag and improve overall efficiency. Typical flywheels connect to a motor that generates electricity when the shaft is engaged, at nearly instantaneous rates. Modern flywheels can operate at 100,000 revolutions per minute or higher, and store electrical energy at quite high efficiencies. Flywheel systems have been around for centuries, but are gaining increased attention due to the growing amount of variable renewable energy on the grid as well as the development of new materials such as composites and battery control systems (U.S. Department of Energy, 2021) (Olabi, Wilberforce, Abdelkareem, & Ramadan, 2021).

Flywheels are well-suited to smooth out power and frequency fluctuations in electrical systems, and when combined with battery systems, can improve the system output and extend the life of the battery. While the capital cost for flywheels can be high, their long lifetimes of millions of charge/discharge cycles and low maintenance requirements could make their levelized cost of storage competitive with that of battery systems (Zakeri & Syri, 2015). Newer analysis is needed to confirm this, as battery prices have decreased significantly in recent years. Flywheels are constructed of readily available components, although the use of permanent magnets may create supply chain issues due to reliance on China for rare earth elements; this issue is discussed in detail in the EO 14017 Supply Chain Review of Rare Earth Permanent Magnets.

Commercialization of flywheels for grid energy storage is at an early but promising stage. Beacon Power installed a 20 MW flywheel in Stephenson, NY in June 2011, performing between 3,000 and 5,000 cycles per year. Another 20 MW installation in Hazel Township, Pennsylvania was commissioned in 2014. (Beacon Power, 2018). Actual capacity of these installations is difficult to judge as energy storage capacity is necessarily rated in Watt-hours. The Sandia Global Storage Database (Sandia National Laboratories, 2020) lists several other projects, summing to 53 MW, but the operational status and commissioning dates are unclear.

1.1.8 Other Nascent Technologies

Given the increasing need of grid-scale energy storage, other novel technologies are gaining attention and pre-commercial research funding (U.S. Department of Energy, 2021). Examples include gravity batteries, which raise heavy objects such as concrete blocks or sandbags, pumped storage of high-density fluids, liquid air energy storage, and chemical storage (e.g., ammonia and some hydrocarbons). Biomethane, or renewable natural gas, is usually produced via anaerobic digestion or gasification of organic wastes but can also be produced from electricity via water electrolysis and biosynthesis of methane from hydrogen and CO_2. Biomethane can be integrated into existing natural gas networks and used to generate heat or electricity.

1.2 Global Market Assessment

The global grid energy storage market was estimated at 9.5–11.4 GWh/year in 2020 (BloombergNEF (2020); IHS Markit (2021)[7]). By 2030, the market is expected to exceed 90 GWh, with some projections surpassing 120 GWh. Reaching 90 or 120 GWh represents compound annual growth rates (CAGRs) of 23% and 29%, respectively. Figure 3 summarizes the projected growth, although it should be recognized that growth estimates for energy storage have been changing rapidly as the costs for batteries and grid-tied variable renewable generators have dropped. The following sections include multiple demand growth estimates. While each estimate will vary according to when it is performed and what assumptions were used, it is important to note that no estimate will be fully prescient in this extremely fast-changing market.

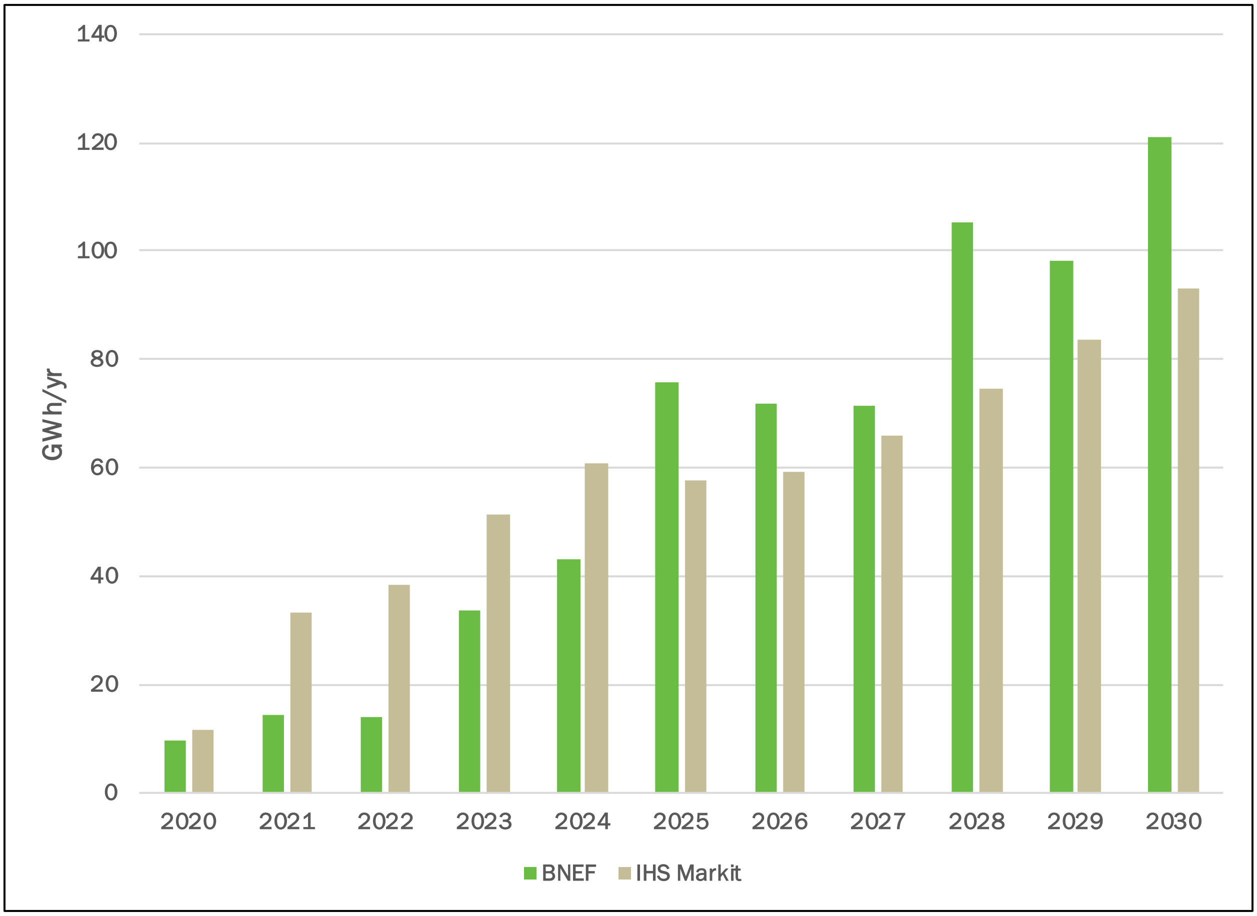

Figure 3. Projected global grid energy storage growth.

Sources: Bloomberg New Energy Finance (2020); IHS Markit (2021)[7]

[7] Source: © 2021 IHS Markit.

Lithium-ion batteries are expected to be the dominant commercial technology for short-term energy storage (less than 10 hours) for the next several years. Flow and other batteries increase market share at the expense of lead-acid batteries. By 2030, the share of lead-acid grid storage is projected to be less than 0.1% (IHS Markit, 2021)[7].

The grid energy storage sector of the United States is expected to mirror the global market in that tremendous growth is expected. In 2020, grid energy storage deployments were estimated at 2.9–4.7 GWh, and as shown in Figure 4, deployments are projected to increase to 18–27 GWh per year, or even higher, by 2030. Estimates by Wood-Mackenzie (2021) project that the market will reach 42 GWh by 2026. Each analyst projects a CAGR of at least 19%, with Wood-Mackenzie projecting a CAGR of greater than 50% as it based on enactment of the Build Back Better legislation. The large range of projections is also likely due to the uncertainty in 2021's supply chain due to COVID-19 issues as well as the high level of interest in the market, which can lead to rapidly changing information.

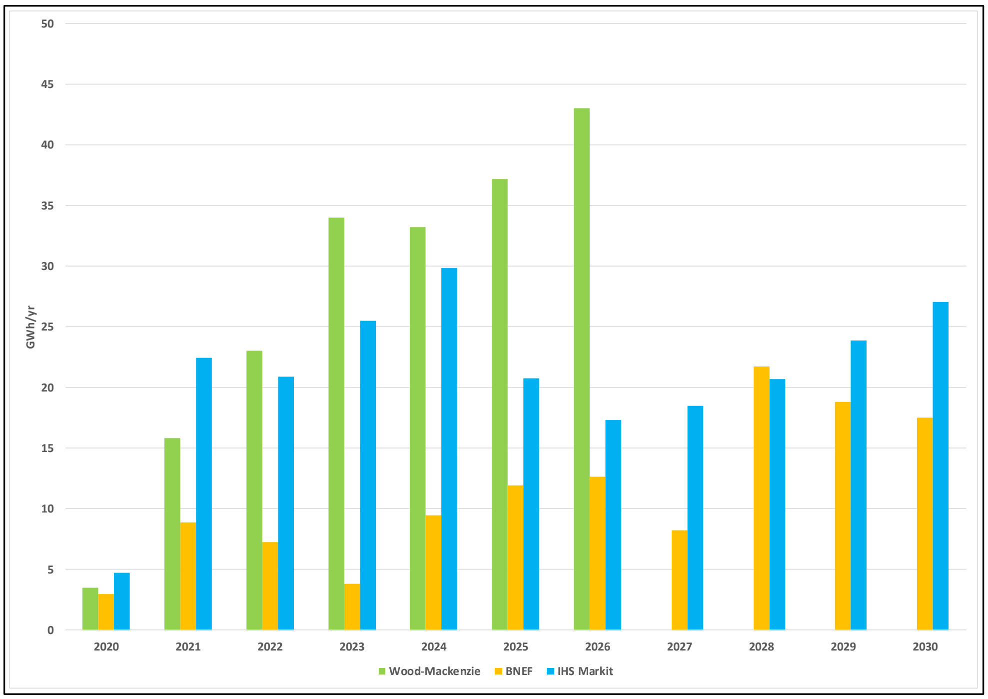

Figure 4. Projected U.S. annual grid storage.

Sources: Blomberg New Energy Finance (2020); IHS Markit (2021)[7]; Wood-Mackenzie (2021)

The projected technology distribution varies slightly during the study period but is expected to be composed of more than 99% lithium-ion batteries until 2029, when flow batteries capture a little more than 1% of the market. From 2021 on, based on these projections, lead-acid batteries are not projected to be used for grid storage in the United States.

PSH is also used for grid storage, currently dwarfing all other forms of energy storage. Historical *cumulative* global PSH deployment is shown in Figure 5, reaching 160 GW in 2019 with most of the installed capacity in Europe and Asia (Sandia National Laboratories, 2020). Although the amount of operating PSH is significant, it should be noted that not all of it was designed to meet today's grid challenges, including frequency response and distribution capacity deferral.

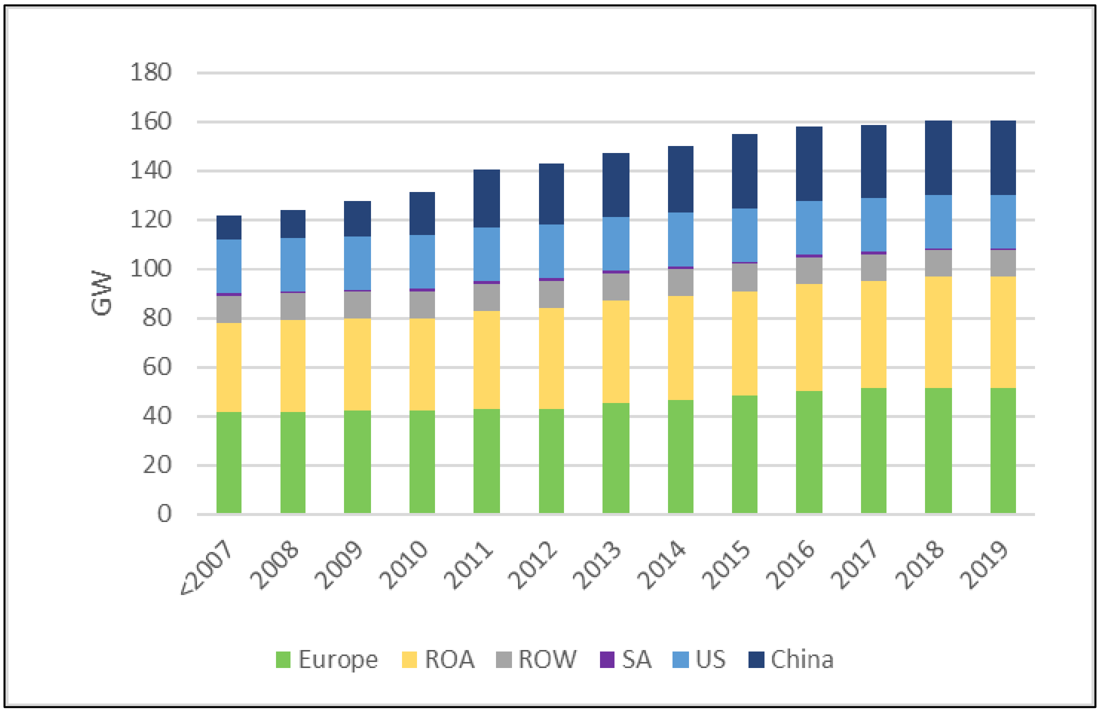

Figure 5. Global cumulative PSH deployment.[8]

ROA: Rest of Asia; ROW: Rest of World; SA: South America
Source: Sandia National Laboratories (2020)

The International Hydropower Association (IHA) reports mid-2020 global operational PSH capacity of 164 GW across 357 installations, with another 124 installations in the pipeline (under construction, planned, or announced) (International Hydropower Association, 2021). They project capacity to increase by 50% to 240 GW by 2030, with 65 of the new projects in China, 19 in the United States, and 10 each in Australia and Indonesia. Using the head and reservoir volume, IHA estimates the energy storage rating of these installations to be greater than 17 terawatt-hours, with another 0.5 terawatt-hours in the pipeline. This value may be underestimated, as

[8] Capacity is given only in GW in the database.

many facilities do not report reservoir size or head (International Hydropower Association, 2021). Figure 6 is a snapshot of the IHA database (October 2021) showing the locations and sizes of the PSH installations.

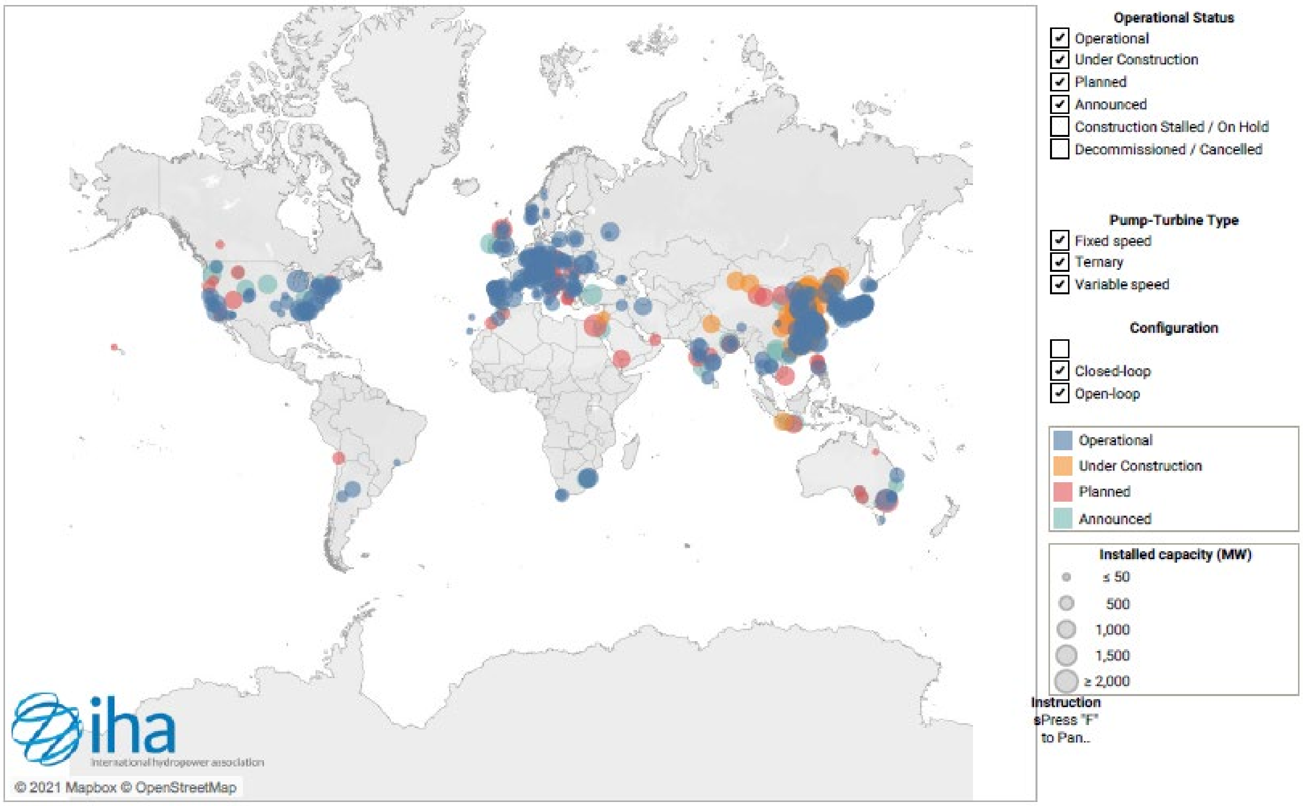

Figure 6. Global PSH installations.

Source: IHA (2021)

Projected PSH installed capacity deployments as of mid-2020 are shown in Figure 7. These projected deployments include projects that are either under construction or planned for development and have sought or received regulatory approval; announced projects are not included. As shown in Figure 7, annual PSH deployment can vary significantly, with no projected deployments during some years. This variability is in part related to relatively long project development lead times PSH due to preparation for regulatory approval or funding commitment.

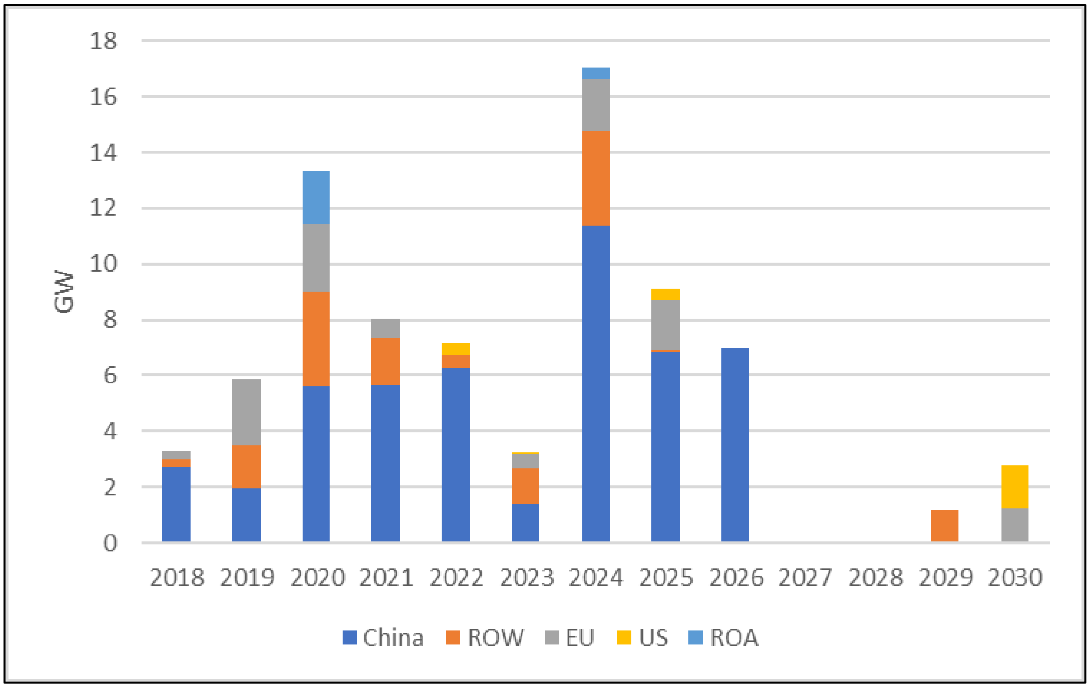

Figure 7. Projected global PSH installations.

Source: IHA (2018); ROW:Rest of World; ROA:Rest of Asia

1.3 Market Projections Under Deep Decarbonization

While the grid storage market is expected to expand rapidly under a business-as-usual scenario, the market growth expands even faster under deep decarbonization scenarios. The International Energy Agency (IEA) recently released a study on how to achieve net zero emissions by 2050 (International Energy Agency (IEA), 2021). This study projected global grid storage to grow to almost 2,500 GWh by 2030, which is more than 20 times the amount projected under the scenarios presented above. Figure 8 shows the grid storage growth projected by IEA based on battery storage with an average storage duration of 4 hours (International Energy Agency (IEA), 2021).

IEA mentions only PSH and hydrogen with respect to LDES. It states that PSH currently provides storage for grid flexibility over hours, days, or weeks, and will so in the future, but it does not provide an estimate of PSH deployment. By 2050, hydrogen use is projected to be 530 million metric tons with 50% in heavy industry and transport, 30% for other hydrogen-based fuels (e.g., ammonia), and 17% (about 90 million metric tons) used for gas-fired power plants to balance renewables and to provide for long duration seasonal storage.

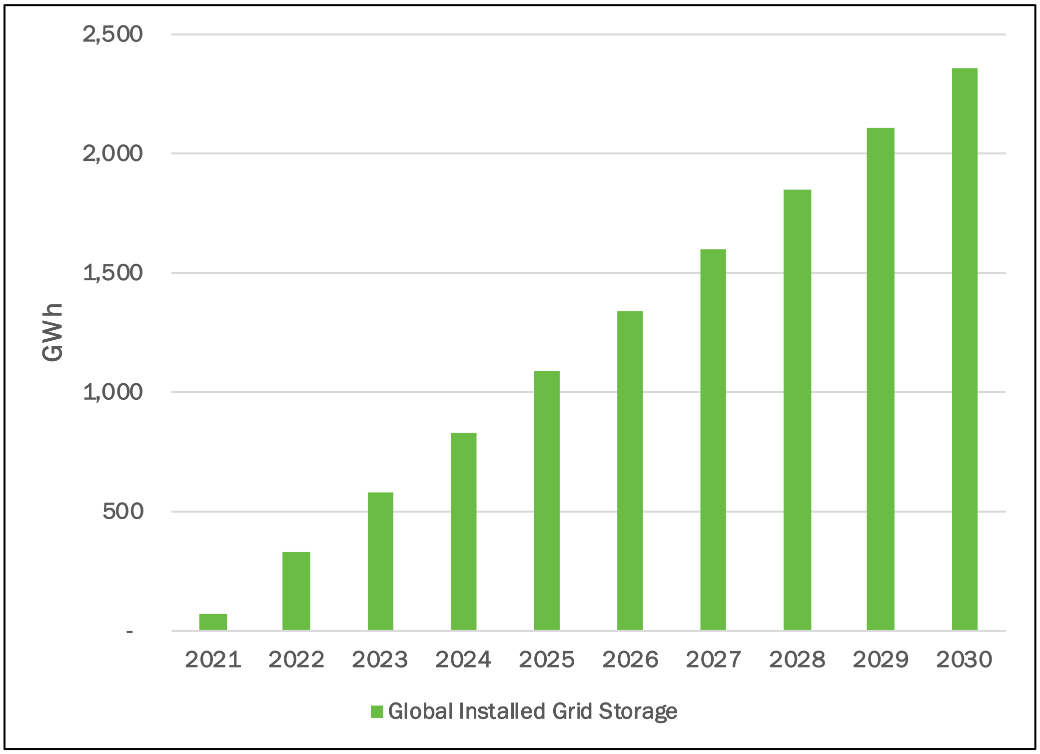

Figure 8. Global grid storage capacity to 2030 for Net Zero in 2050.

Source: IEA (2021)

Grid energy storage is projected to grow significantly in the United States as well. The Biden-Harris Administration recently published *The Long-Term Strategy of the United States* (LTS), a high-level strategy for the United States to reach its ultimate goal of net-zero emissions no later than 2050 (U.S. Department of State and the U.S. Executive Office of the President, 2021). The LTS developed several scenarios to reach the net zero goal and used two models, the Global Change Assessment Model (GCAM) and the Office of Policy – National Energy Modeling System (OP-NEMS), to evaluate the various scenarios. Grid energy storage is an important component of the LTS. The LTS projects energy storage to average between 1.6 to 10.8 GWh per year from 2021-2030, increasing significantly to 12 to 160 GWh per year from 2031-2040 and then rising again to 44 to 256 GWh/yr from 2041-2050 (U.S. Department of State and the U.S. Executive Office of the President, 2021). A complementary report, *The U.S. National Climate Strategy (NCS)*, will be released soon that details immediate policies and actions that will put America on track to meet its 2030 climate targets.

Other organizations have also looked at the future of grid energy storage in the United States. Figure 9 summarizes two studies that project rapid growth of the grid storage sector: *Net Zero America*, published by Princeton University (Larson, et al., 2020), and *Four Phases of Storage Deployment*, published by NREL (Denholm, Cole, Frazier, Podkaminer, & Blair, 2021). Both studies looked at the U.S. market through 2050; the Princeton study identified scenarios to reach net zero carbon and the NREL study looked at the maximum economic deployment of storage technologies. Figure 9 shows the high-renewable scenario for the Princeton study ("Net Zero"), and the average of all cases for the NREL study, illustrating wide potential variation in projected U.S. grid storage capacity. In 2035, the high NREL case projects 200 GWh for U.S. grid storage capacity while the average case projects just over 100 GWh. The Net Zero case grows more slowly to less than 50 GWh in 2030. Neither of these studies projected the specific battery storage technology but both show a significant uptick in capacity in 2030. The rapid growth continues through 2050, with the Net Zero study projecting over 1300 GWh of domestic installed grid storage capacity by 2050.

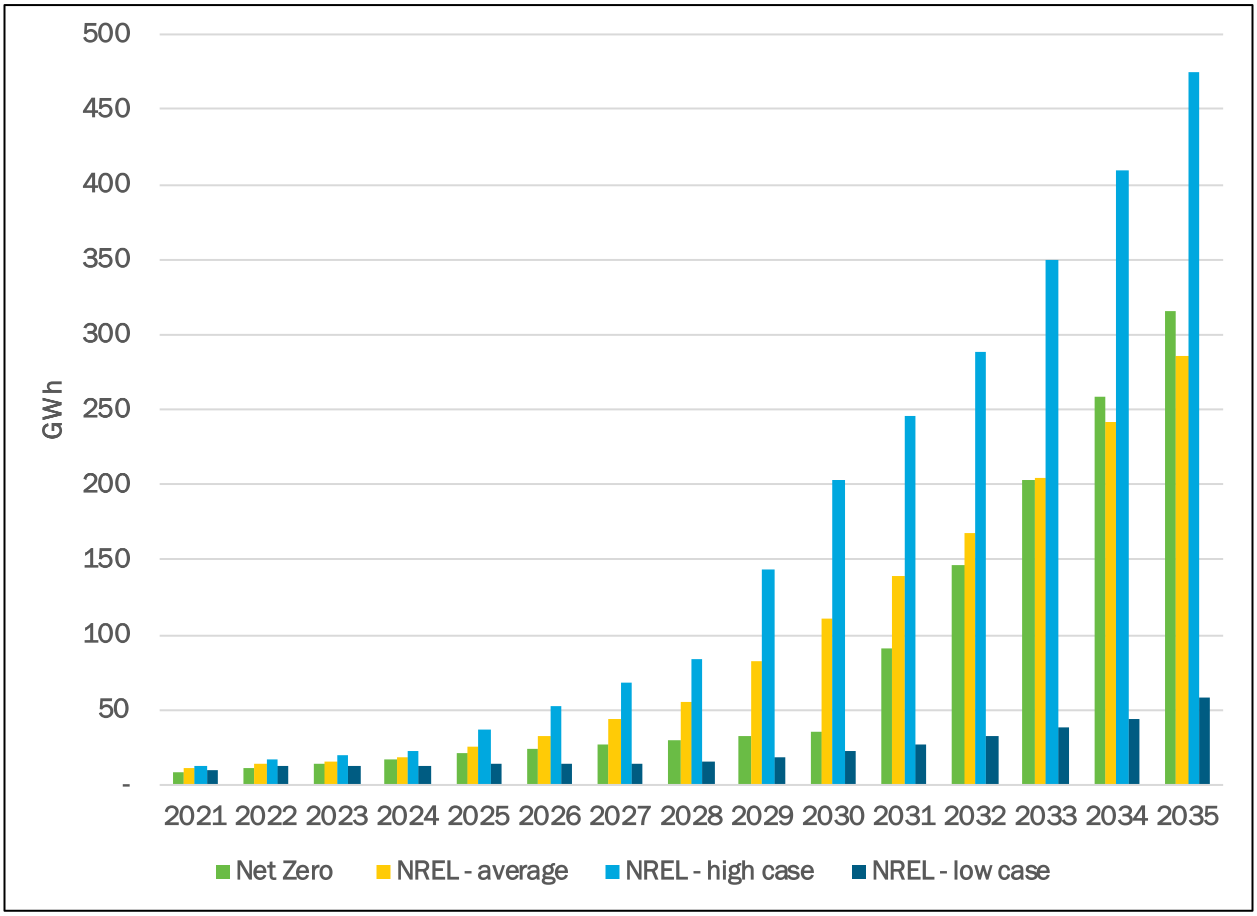

Figure 9. Scenario projections of cumulative U.S. grid storage capacity.

Sources: (Larson et al. (2020); Denholm et al (2021))

The NREL study also included PSH for long-duration (12-hour) storage. The amount of long-duration storage is not expected to increase significantly over the study period and was estimated at 275 GWh (Denholm et al. 2021).

The Net Zero study did not include any LDES technologies; all grid electricity storage was assumed to have average durations of 5–7 hours (Larson, et al., 2020). While it stated that “ultra-cheap long duration energy storage” technology options are required post-2030, the study does not appear to have included this option. Hydrogen use was primarily for direct combustion for electricity production, use in heavy-duty vehicle fuel cells, and for direct iron reduction in steel plants (Larson, et al., 2020).

2 Supply Chain Mapping

The supply chain of each technology is broken down into its main production steps or products, and each step is summarized, including discussion of the size of the global market, identification of countries with the largest supply chain presence, and major companies operating in that segment. The status of the United States in each segment is highlighted.

2.1 Technology Overview

As noted earlier, five of the technologies evaluated are batteries. In general, battery supply chains encompass raw material procurement, refining, component manufacturing (electrodes, electrolytes, and separators), end-use products, and recycling. Figure 10 shows a typical battery system supply chain segmented into upstream components (raw and refined materials), midstream components (subcomponents such as electrodes and separators), downstream components (battery cells, packs, and end-use), and recycling, which recovers materials from the end use and sends them to upstream and midstream component steps.

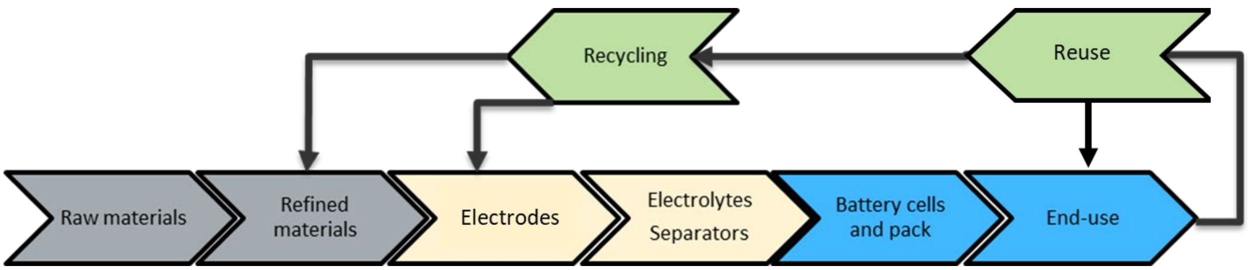

Figure 10. Typical battery supply chain, including recycling and reuse steps.

2.2 Lithium-Ion Batteries

The lithium-ion battery supply chain includes raw materials, refined materials, subcomponents, product, and end-use. Figure 11 presents a high-level view of the supply chain for most lithium-ion battery chemistries. The diagram is a simplification of the supply chain and only shows the main active cathode and anode materials and the major components of separators and electrolytes. Materials such as copper foil (anode), binders, and additives are not shown.

Each major sectors of the supply chain, including the materials and processes, are described following Figure 11.

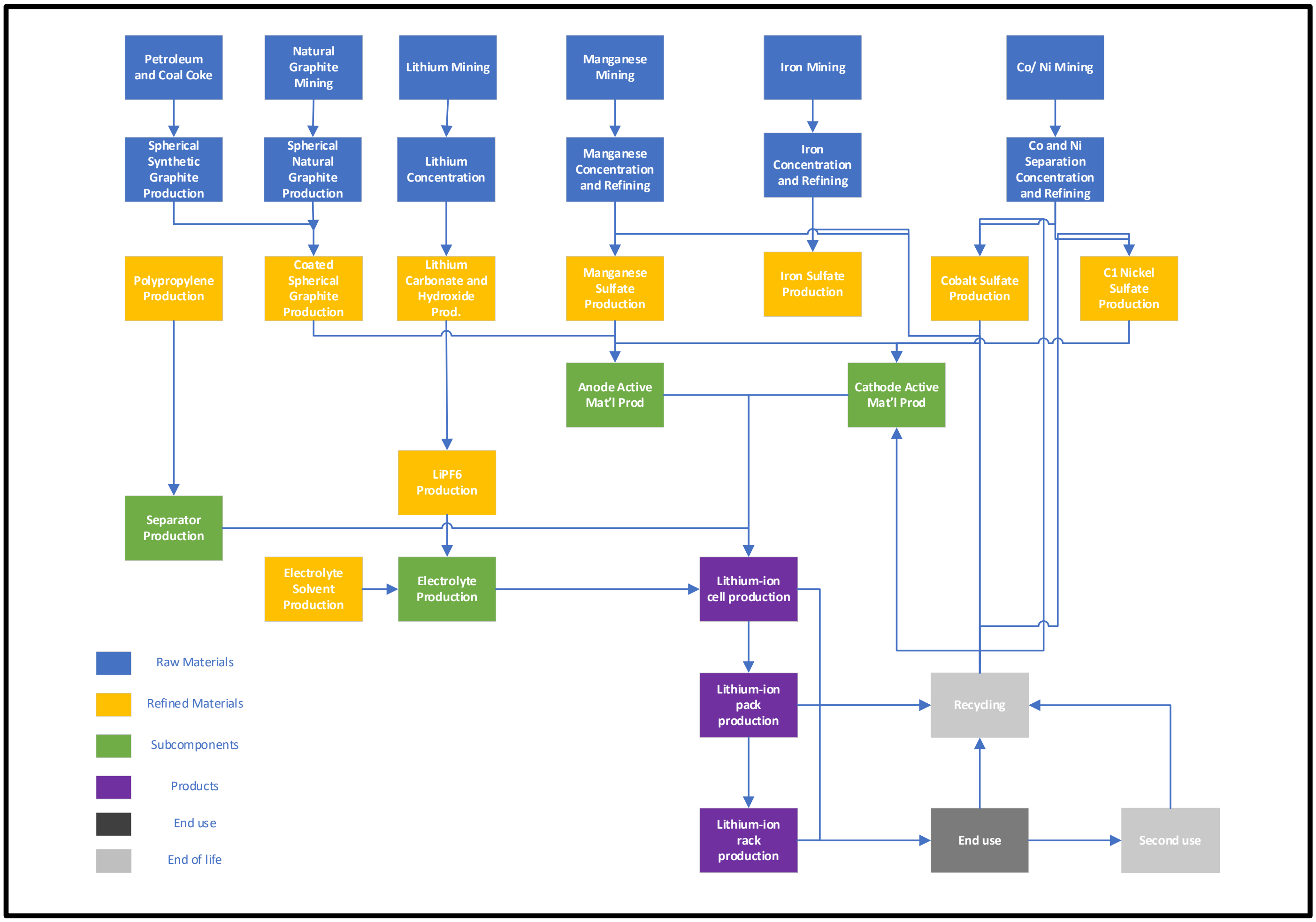

Figure 11. Lithium-ion Battery Supply Chain Diagram

2.2.1 Raw Materials

Raw materials for lithium-ion batteries include cobalt, iron, nickel, manganese, lithium, and graphite. As shown in Figure 12, the mine production for almost every material is highly concentrated in one or two countries. For example, in 2021, China produced an estimated 82% of the world's natural graphite and the Democratic Republic of the Congo (DRC) produced 70% of the world's mined cobalt. Lithium mining is slightly more diverse, but Australia still produces over 50% of all lithium mined. While the sources of manganese and nickel are more widespread, it is estimated that 50% of these ores and concentrates originate from just two countries each in 2021.

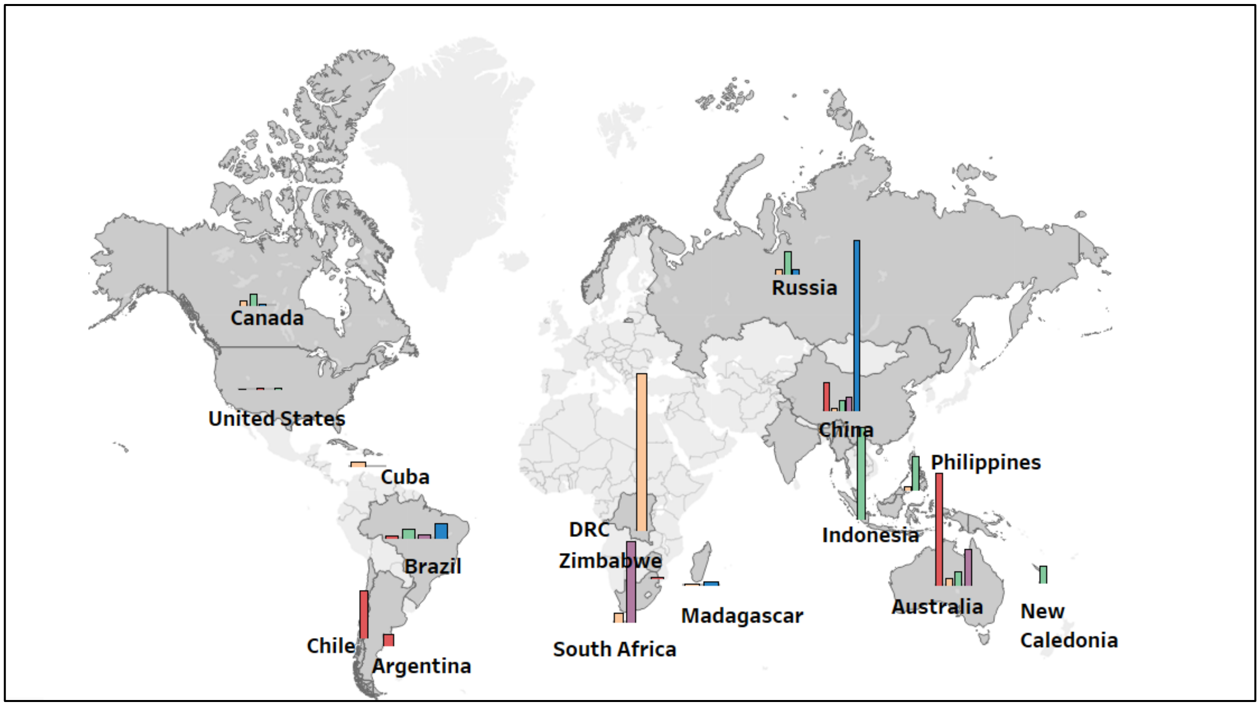

Figure 12. Estimated 2021 mining production of raw lithium-ion materials.

Source: (United States Geological Survey, 2022)

The United States has limited production (i.e., <2% of global) for all lithium-ion battery raw materials as well as limited reserves for all except lithium, where the United States has over 3% of global reserves (see Table 1). In 2020, all domestic lithium production was from the Albemarle Silver Peak brine operation in Nevada (Dentzer, 2021), but more domestic lithium production projects are in various stages of development (United States Geological Survey, 2022). The United States has no production of and essentially no reserves of both natural graphite and manganese. Domestic nickel and cobalt are co-produced in Michigan and Missouri. The Eagle Mine in Michigan produces a cobalt-containing nickel concentrate, and a nickel-copper-cobalt concentrate is produced in Missouri from mine tailings. Most of the domestic cobalt production is secondary recovery from recycled scrap (United States Geological Survey, 2022). In 2021, the United States mines produced 1.8% of the estimated global production of iron (as iron ore), primarily in Michigan and Minnesota (United States Geological Survey, 2022).

Table 1. 2021 Estimated U.S. Mine Production and Reserves of Lithium-ion Raw Materials

	2021 Estimated Mine Production (MT of contained mineral)		2021 Estimated Reserves (MT of contained mineral)	
Mineral	U.S.	% of Global	U.S.	% of Global
Cobalt[1]	700	0.4%	69,000	0.4%
Graphite (natural)	0	0	≈ 0	≈ 0
Iron	29 million	1.8%	1,000 million	1.2%
Lithium[2]	940	0.9%	750,000	3.4%
Manganese	0	0%	0	0%
Nickel	18,000	0.7%	340,000	0.4%

[1] In 2021, the United States also produced an estimated 1,600 MT of cobalt from recycled scrap.

[2] Lithium production value is from the BloombergNEF Batteries Metal Database, Mining and Refining - BloombergNEF (2021)

Sources: U.S. Geological Survey (2022) and BloombergNEF (2021)

Both natural (shown above) and synthetic graphite can be used in the anodes of lithium-ion batteries. Natural graphite has several forms including flake, amorphous, lump and chip, but only flake graphite is suitable for lithium-ion battery anodes. Graphite One is developing a vertically-integrated graphite facility, including mining on the Seward peninsula in Alaska (Graphite One, 2021) and Westwater Resources is developing the Coosa Graphite project in Alabama (Westwater Resources, 2021). Finally, Syrah Resources is developing a 10,000 tpy spherical graphite materials plant in Vidalia, LA using raw material from Mozambique (Syrah Resources, 2021).

Synthetic graphite is produced from refining hydrocarbon materials such as petroleum coke, pitch coke, and needle coke. Needle coke is a premium type of petroleum and coal tar-based coke and is the main raw material for synthetic graphite. Synthetic graphite generally costs more than natural graphite, but has higher quality (e.g., longer cycle life, higher fast charging ability and better safety) (BloombergNEF, 2021). DOE is currently supporting synthetic graphite production from coal and coal refuse (U.S. DOE, 2021).

In addition to the conventional mineral sources outlined above, numerous nonconventional sources are being evaluated and/or developed across the world for lithium-ion battery materials. Some of these sources include mine tailings, coal-based sources, and lithium-rich brines such as the Salton Sea in California.

2.2.2 Refined Materials

Lithium: After lithium-rich ore or brine is extracted, it is initially refined to produce lithium carbonate, lithium hydroxide, and lithium chloride. Lithium carbonate and lithium hydroxide are by far the main compounds produced for use in Li-ion cells, in cathodes and electrolyte salts. Lithium chloride is further refined into lithium metal for use in primary lithium batteries and other applications. Refined lithium products for lithium-ion batteries include lithium carbonate and lithium hydroxide. China has over 60% of the current global lithium refining capacity, followed by Chile with 26%. The United States has 3% of the global lithium refining capacity with two facilities (BloombergNEF, 2021).

Cobalt: Refining cobalt-bearing ores is accomplished through hydrometallurgical technologies, sometimes in combination with pyrometallurgical technologies. End products from cobalt refining include cobalt oxide, cobalt metal, cobalt powder, and cobalt sulfate or other cobalt compounds. China has 72% of the global cobalt refining capacity (BloombergNEF, 2021).

Nickel: Refined nickel is produced in two classes, C1 and C2, and only C1 nickel, with a purity of >99%, can be used to produced lithium-ion batteries. McKinsey estimates that 46% of the nickel produced in 2019 was C1 (Azevado, Gottaux, & Hoffman, 2020). In general, C1 nickel is obtained from sulfide deposits (60%–70%) or through processes such as high-pressure acid leaching of laterite ore (Azevado, Gottaux, & Hoffman, 2020); (Nickel28, undated). C1 refined nickel products include C1 nickel refining capacity is more evenly distributed than cobalt with significant capacity in Russia (21%), China (16%), and Japan (15%) (BloombergNEF, 2021). The United States has no C1 production facilities; BloombergNEF reports that all the nickel from Michigan is sent to Canada for processing into C1 nickel.

Manganese: High-purity manganese sulfate, also known as high-purity manganese sulfate monohydrate (HPMSM) is the refined product used to make lithium-ion cathode precursors. It can be made directly from carbonate ore or from high-purity electrolytic manganese metal (EMM). HPMSM production for lithium-ion battery production is done almost entirely (95%) in China (BloombergNEF, 2021); (BloombergNEF, 2020). There are only two operating HPMSM facilities outside of China, Prince Minerals in Belgium and Nippon in Japan. Ten additional HPMSM facilities are currently under development with seven in China and one each in the Czech Republic, Australia, and Indonesia (BloombergNEF, 2020).

Graphite: The refined graphite product is coated spherical graphite. This is produced from either synthetic or natural graphite, using slightly different processes. Natural graphite is concentrated, micronized and made into spheres. After purification to 99.95% graphite, it is coated with amorphous carbon. Synthetic graphite is crushed and pulverized, calcined, granulated, and graphitized before being coated with amorphous carbon. Synthetic coated spherical graphite is more expensive than natural coated spherical graphite, but it has better thermal and lifetime properties. Thus, it is expected to be the choice for the more demanding vehicular applications, while stationary sources are expected to use synthetic sources (BloombergNEF, 2021).

A summary of the locations of battery-grade material production refineries for lithium-ion batteries are refined is shown in Table 2 (BloombergNEF, 2021). These represent the annual production capacity of operating facilities (e.g., mothballed or abandoned facilities are not included) to make the refined products, but this capacity is for <u>all</u> industrial uses of the products, not just the lithium-ion battery industry. The exception to this is nickel because the nickel used to make nickel sulfate must be C1 nickel (i.e., >99% Ni). The nickel sulfate capacity shown is based on the capacity of facilities that are known to process refined nickel C1 intermediates (e.g., briquettes, pellets, electrolytic nickel and powders).

Currently, the United States does not refine any C1 nickel, cobalt, or manganese, and only refines 3% of the world's lithium. Except in the case of C1 nickel refining, for which Russia leads, China has near absolute dominance of today's refining capacity for metals necessary for lithium-ion batteries.

Table 2. 2020 Lithium-ion Battery Refined Material Capacity by Country, Percent of Total by Material

C1 Nickel Sulfate	
Russia	21%
China	16%
Japan	15%
Canada	13%
Australia	10%
Norway	8%
Finland	6%
Madagascar	5%
UK	3%
South Africa	2%
France	1%

Cobalt Sulfate	
China	72%
Finland	9%
Canada	4%
Norway	4%
Australia	3%
Japan	3%
Madagascar	2%
Morocco	1%
Belgium	1%

Lithium Hydroxide and Carbonate	
China	61%
Chile	26%
Argentina	10%
US	3%

Manganese (HPMSM)	
China	95%
Belgium	<5%
Japan	<5%

Source: NREL Analysis, BloombergNEF Metals Database, Mining and Refining (2021) and Global Manganese Outlook 2020-2030 (2020)

2.2.3 Subcomponents

There are five major components of a lithium-ion battery: anode, cathode, electrolyte salts, electrolyte solutions, and separators. China has an overwhelming presence in terms of both current and planned capacity for all subcomponents. The United States has less than 10% of global capacity for any subcomponent and has very little, if any, capacity planned or under construction. Table 3 summarizes the subcomponent market positions of the U.S. and China. Data for current and future manufacturing capacities differ from earlier analyses such as the 100-Day Reviews (The White House, 2021) because of the fast-paced evolution of the markets for lithium-ion batteries, principally in the transportation sector. New facilities are announced almost weekly, and data from government sources such as those in China, often lag announcements from industry by several months. Additionally, future estimates change often due to new policies related to decarbonization and country-level competitiveness. These figures thus indicate overall industry dominance of China over the United States across the battery component supply chain rather than absolute market size. A small market size does not necessarily define the United States supply chain as fragile since resilience can be increased through international agreements and diverse trade sources. However, the level to which China dominates these markets signifies a high level of global reliance on Chinese policies and manufacturing.

Table 3. United States' and China's Existing and Under Development Shares of Global Lithium-Ion Battery Subcomponent Capacity

	2021		Under Development	
	U.S.	China	U.S.	China
Cathode	0.70%	63%	0%	84%
Anode materials	0.60%	84%	0%	91%
Separator	3%	66%	0%	76%
Electrolyte	7%	69%	2%	75%

Source: BloombergNEF (2021)

Leading companies in cathode manufacturing include Sumitomo of Japan and Tianjin B&M Science and Technology Joint-Stock Co Ltd, Shenzhen Dynanonic Co Ltd, Ningbo Shanshan Co Ltd and Ningbo Ronbay New Energy Technology Co Ltd in China. In the United States, two foreign-owned companies, BASF and Toda Kogyo, produce cathode materials. Leading anode manufacturers include BTR (China), and Hitachi and Nippon Carbon (Japan). The United States has a single anode manufacturer, Pyrotek Incorporated. The largest separator company is Zhuhai Enjie New Material Technology Company in China. Three companies, Celgard, DuPont, and Entek, have separator manufacturing facilities in the United States. The United States has a more competitive liquid electrolyte manufacturing sector with four companies making liquid electrolytes, Enchem America LLC, Honeywell International, Mitsubishi Chemical America, and Soulbrain MI; and one, Huntsman Petrochemical, LLC, making electrolyte solvents (NAATBatt, 2021); (BloombergNEF, 2021).

2.2.4 Product

China has almost 80% of the current global lithium-ion battery cell manufacturing capacity (~520 GWh), as shown in Figure 13. This includes current and planned lithium-ion manufacturing facilities, as well as almost 60% of the 2800 GWh planned and under construction (BloombergNEF, 2021). The United States is the next-largest manufacturer at 13% of current global capacity, with the Tesla-Panasonic plants in Nevada comprising the majority. Europe has 800 GWh of facilities announced or under construction, while the United States has almost 200 GWh. Battery chemistry is generally regional, with the United States currently manufacturing primarily NCA batteries while NMC facilities dominate in Europe and Asia. Asia also manufactures small amounts of lithium iron phosphate and lithium manganese oxide chemistries and the planned facilities in the U.S. are trending towards the NMC and NMCA chemistries.

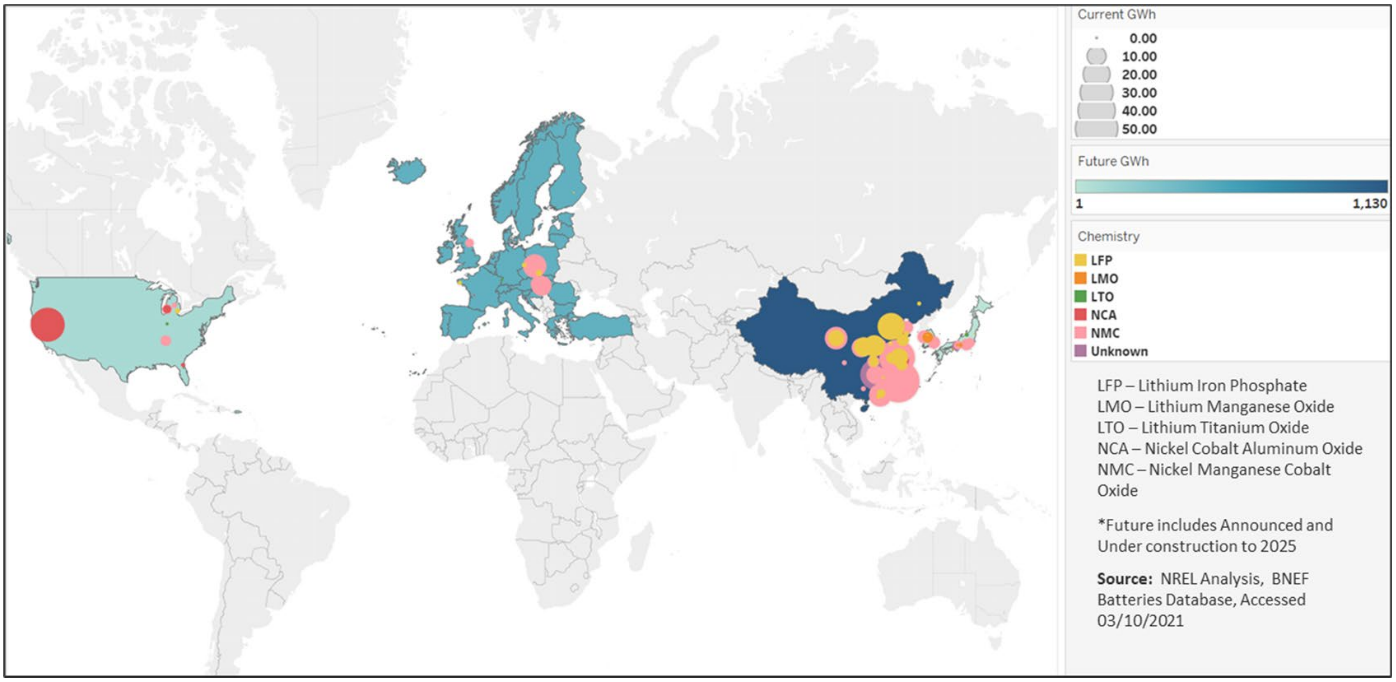

Figure 13. Current and planned lithium-ion battery manufacturing facilities.

2.2.5 End-of-Life

Several options are available for lithium-ion batteries after they have reached the end of life in the application for which they were designed. Generally due to degradation of performance and capacity, these batteries can be repaired, remanufactured, refurbished, repurposed, or recycled (see Figure 14); these are the Five Rs for a circular economy. Repairing, remanufacturing, and refurbishing are not truly end-of-life options as they are processes for reusing the battery in the same application or for the same purpose. Many companies in the United States and around the world are seeking to increase the value of batteries through circular economy research, in which waste and energy are reduced while additional value is obtained from raw material resources. The NAATBatt Lithium-ion Supply Chain Database (NAATBatt, 2021) has identified five domestic companies focused on repair, remanufacturing and refurbishing: Sybesma's Electronics, Spiers New Technologies, Global Battery Solutions, Heritage Battery Recycling, and Battery M.D. Inc. (NAATBatt, 2021). True end-of-life processes are repurposing (i.e., reusing) and recycling. In repurposing, the battery is modified for a new purpose or application; it is given a "second life." In recycling, the battery is broken apart into components and rebuilt into the same or an entirely new item. This section will focus on repurposing (i.e., second life) and recycling only.

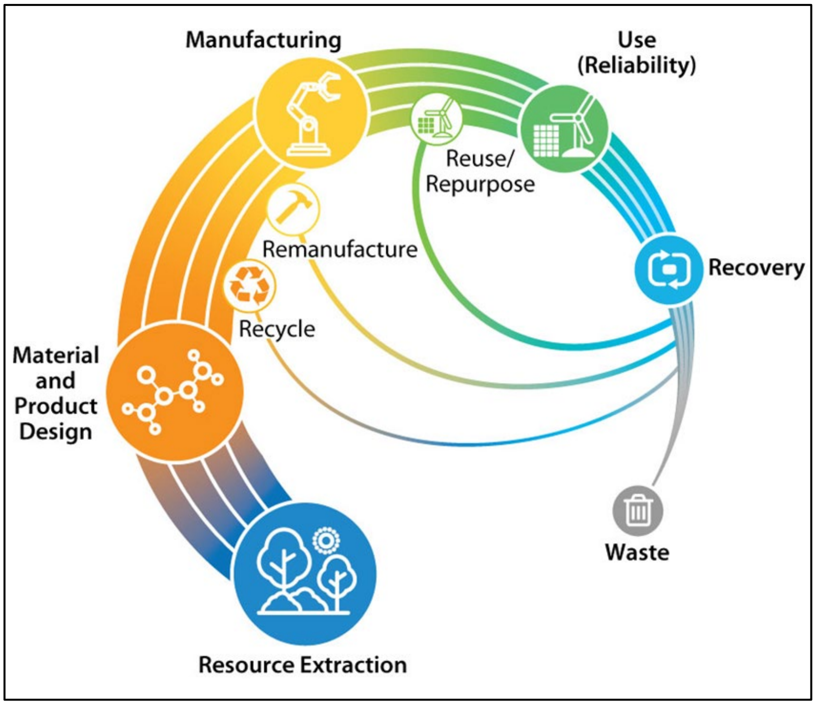

Figure 14. The circular economy model.

Source: NREL (2021)

2.2.5.1 Second-Life Batteries

Repurposing lithium-ion batteries is one of the areas that may be especially beneficial to the stationary storage sector. Several studies (Kelleher Environmental (2019); (Li, 2021); (Faessler, 2021)) have noted that when electric vehicle (EV) batteries reach the end of their life, they may still be usable for stationary storage applications. In general, EV batteries need to be replaced when they reach 70%–80% of their original capacity, but they can still be used for less demanding applications such as grid storage. The availability of EV batteries for reuse is impacted by their chemistry. Batteries such as NMC or NCA would be valuable to recycle due to their cobalt content. LFP, on the other hand, has no cobalt and is of little value to recyclers. BNEF (Li, 2021) estimated that LFP batteries would be worth $2/kWh to recyclers while NCA or NMC111 would be 10–16 times more profitable based on March 2021 metal spot prices. Wards Intelligence came to a similar conclusion in their study finding that recycling instead of repurposing is favored as the price of lithium-ion batteries falls and cobalt retains its high value (Schweinsberg & Sunde, 2020).

Estimates for the quantity of batteries that will be reused/repurposed in second-life applications vary widely. BNEF (Li, 2021) estimates that globally almost 40 GWh of EV batteries will be available for reuse by 2030, and over 275 GWh will be available by 2035.[9] McKinsey estimates that second-life battery capacity for stationary storage could be greater than 200 GWh by 2030, exceeding the total demand for stationary applications (Engel, Hertzke, & Siccardo, 2019). More than 50% of the second-life batteries will be in China—they currently have

[9] Availability assumes 70% of LFP and 40% of NMC and NCA batteries enter the second life market.

the most EVs; additionally, LFP is the preferred chemistry for e-buses and commercial EVs while also constituting a large percentage of passenger EVs.

The end-of-life EV batteries can be repurposed for stationary sources at the pack or module level; repurposing EV batteries for stationary sources is not currently feasible at the cell level due to high labor costs. Repurposing at the pack or module level may also be expensive due to issues such as different size elements (e.g., module energy content), dissimilar states of health among components, and/or significant design differences. Some EV companies such as GM, Rivian, and Proterra are working to improve the economics of second-life batteries by designing their batteries with reuse in mind (Pyper, 2020). Difficulties associated with collecting, sorting, storing, and transporting used batteries for recycling or second use are being addressed by the DOE's Lithium-Ion Battery Recycling Prize [10].

Several companies in the United States as well as numerous companies around the world are focused on repurposing EV batteries for the grid or other stationary applications (e.g., uninterruptible power supply). Faessler (2021) analyzed the European market for EV batteries repurposed for grid storage and found more than 20 sites where EV batteries were repurposed for stationary applications across Europe. In general, the projects were based on batteries with NMC chemistry from BMW, Renault, and Volkswagen and were used for behind-the-meter applications to increase self-consumption of renewables. The study also looked at trends in the rest of the world and found that North America, Asia, and Australia had second-use applications similar to Europe while South America and Africa focus on off-grid and backup power (Faessler, 2021). Very little information is available on the second-use market in China, other than that it is developing very quickly due to supportive government policies and the availability of end-of-life batteries (Faessler, 2021). GEM, China's largest battery recycler, is developing processes for battery pack regeneration and second-use modules. Many EV batteries are replacing lead-acid backup power systems.

BNEF (Li, 2021) conducted a technoeconomic analysis of the secondary-battery market and concluded that second-life batteries are best suited to applications such as transmission and network investment deferral that are less than 10 MWh and do not include frequent cycling. Figure 15 maps out the most suitable operating characteristics for second-use batteries.

[10] https://americanmadechallenges.org/batteryrecycling/

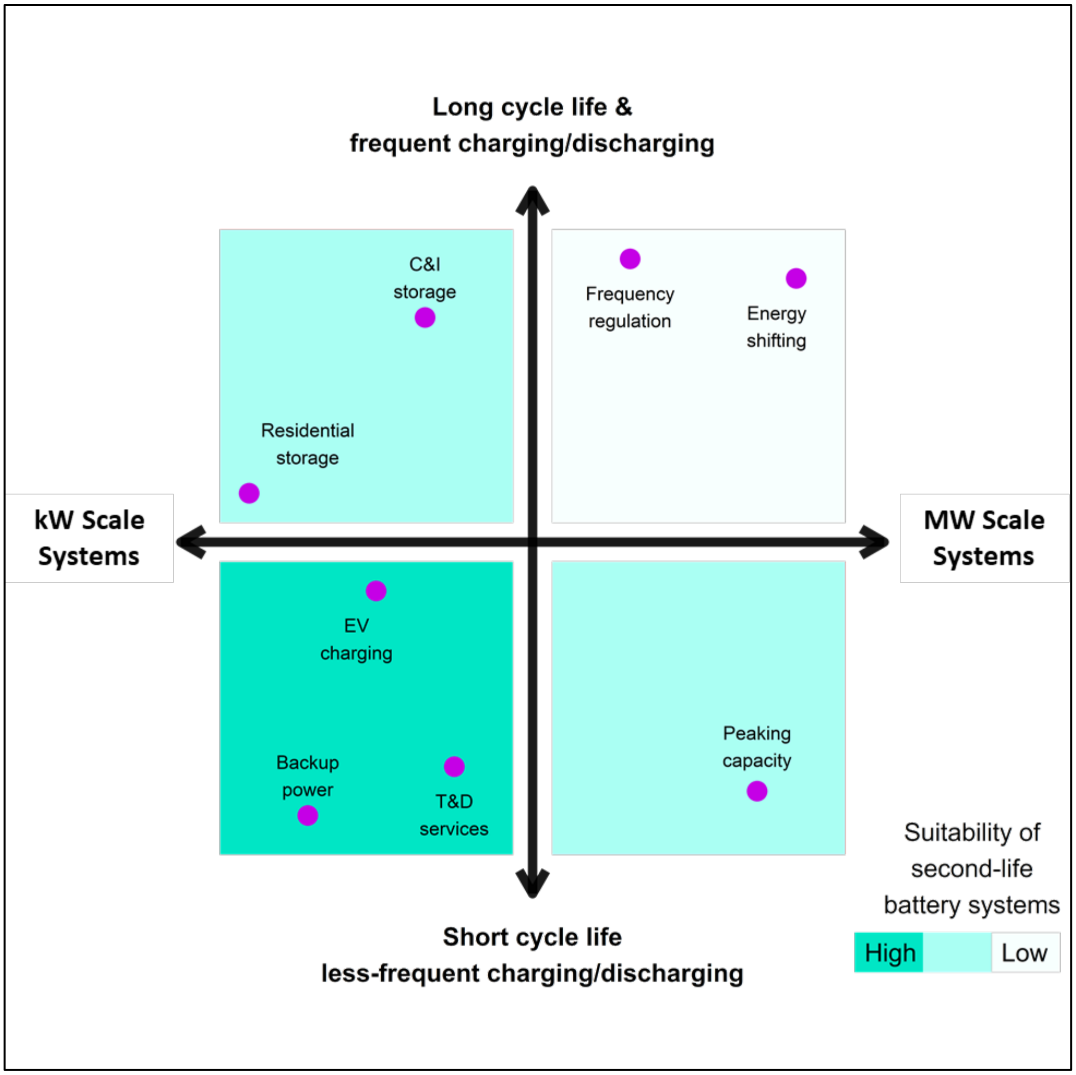

Figure 15. Second-use battery opportunity space.

Source: Reproduced from Li (2021)
T&D = transmission and distribution
C&I = commercial and industrial

Automakers, battery recyclers, utilities, and developers are forming partnerships to test and develop second-life batteries for grid and other stationary uses. For example, Huayou (recycler) has partnerships with Toyota and VW. VW also works with Bosch (developer). Eaton and Connected Energy are two European developers working to develop second-life batteries. EDF Renewables, B2U, RePurpose, Smartville Energy, and ReJoule are domestic companies working in this area.

2.2.5.2 Battery Recycling

The NAATBatt Database of the North American Lithium-Ion Supply Chain lists 36 companies engaged in battery recycling research, development, and market deployment (NAATBatt, 2021). Two major technologies are commercially deployed for recycling lithium-ion batteries: pyrometallurgy and hydrometallurgy. DOE, through its ReCell Center (DOE ReCell, 2021) and collaborations with several companies, are working on a third technology, direct recycling, where cathodes are recovered and regenerated without breaking them down into their elemental components as is done in the other two methods.

Recycling from all methods could be a significant source of cobalt and nickel for new lithium-ion batteries. For example, in 2030 up to 15% of cobalt and nickel could be recovered from recycled EV and stationary source batteries for new large-format lithium-ion batteries; this increases to 15%–30% by 2035 due to the switch to lower cobalt and nickel chemistries (Li & Frith, 2021). If domestic consumer batteries are recycled for use in the EV and stationary source markets, the amount of mined cobalt replaced by recycled cobalt could be over 50% (The White House, 2021).

The Critical Materials Institute (CMI) is also researching an electrochemical method for recovery/recycling of critical materials from EOL batteries. The bio-based method involves sulfur-dioxide leaching and electrowinning, followed by membrane solvent extraction.[11]

Battery recycling capacity is stated in terms of the total mass of batteries a facility is designed to process. The quantity of recovered metals of interest, e.g., cobalt and nickel, will depend on the process design of the recycling facility and the price at which the facility can sell recovered materials. The energy storage capacity of the batteries recycled in any given year will vary over time based on the mix of battery chemistries exiting the useful life stage. Bloomberg New Energy Finance reports that the current global lithium-ion battery recycling capacity for large-format EV and stationary storage batteries is 286,000 metric tons of batteries per year, with 81% of that capacity in China (Li & Frith, 2021).[12] The United States has 20,000 metric tons of capacity (7%) and South Korea has 8%. Another 942,000 metric tons per year of capacity has been announced or is under construction with over 90% of that being in China. The United States has 5,000 metric tons per year of recycling capacity under construction. China's dominance in recycling is due not only to its larger share of EVs, but also, and perhaps most significantly, to policies by the Chinese government regarding recycling, which are discussed in greater detail in the Section 2.2.7.

Lithium-ion recycling companies that are headquartered or are developing facilities in the United States include Retriev Technologies (Canadian), Li-Cycle, Redwood Materials, LiNiCo, American Battery Technology, and Ascend Elements (formerly Battery Resourcers). Pyrometallurgical facilities that process many types of waste in addition to lithium-ion batteries include Clean Earth and INMETCO. Products from mixed waste pyrometallurgical facilities may not be suitable for reuse in lithium-ion batteries but could be reused in other applications.

Similar to the second use market, other companies along the supply chain such as automakers and battery makers are partnering with recyclers. Panasonic and Envision AESC are partnering with Redwood Materials, while GM and Ultium Cells are partnering with Li-Cycle (Li & Frith, 2021).

Additional analysis of the current state of collection and recycling is recommended to establish the baseline of the industry today. Currently, the vast majority of used lithium-ion batteries collected in the United States are exported for recycling elsewhere, although the precise quantity is unknown. Better assessment, coordination, and industry participation in the collection of used batteries for domestic recycling, incorporation of recycled

[11] https://www.ameslab.gov/cmi/reuse-and-recycling

[12] This capacity does not include recycling centers focused on consumer batteries and it is unclear whether it includes pyrometallurgical facilities that recycle mixed metals and battery waste.

materials into new batteries by domestic battery manufacturers and use in domestic applications would increase the resilience of the supply chain for lithium-ion batteries.

2.2.6 Concurrent Use – Vehicle to Grid (V2G)

Instead of just utilizing LIBs at the end of life, there is also the opportunity to concurrently use LIBs in electric vehicles for grid use. This opportunity, vehicle-to-grid (V2G), uses the batteries in parked EVs to supply power back to the electric grid. While this opportunity is still in its early stages of development, it has the potential to help stabilize or balance the grid by using EVs to absorb excess electricity during low demand and discharge them during peak demand. Several EV companies (BMW, Volkswagen) and electric utilities (Southern California Edison, Pacific Gas & Electric) are looking to evaluate this option (Edelstein, 2021) (Hanley, 2021). Volkswagen recently announced that in 2022, it will offer a universal EV charging system that includes bidirectional charging to help enable V2G (Hanley, 2021).

2.2.7 U.S. Resilience

The United States is at a significant disadvantage with respect to the availability of raw materials for lithium-ion battery production. It has few to no reserves of manganese and natural graphite and has low levels of nickel sulfide deposits and cobalt (United States Geological Survey, 2022). However, there is potential in secondary and unconventional sources such as coal ash, mine tailings, acid mine drainage, and produced waters. It also has 750,000 metric tons of economic lithium reserves, without including nonconventional sources such as the Salton Sea, in which several companies are currently codeveloping geothermal resources and lithium recovery from brine. In addition, two of the largest lithium production companies, Albemarle and Livent, both have lithium processing facilities in the United States.

The United States has significant identified lithium resources[13]. The worldwide identified lithium resources currently total 89 million metric tons, and the United States lithium resources currently total 9.1 million metric tons (Mt), about 10% of world resources (United States Geological Survey, 2022). The 9.1 Mt of resources in the United States are obtained from a variety of sources including continental brines, geothermal brines, hectorite clay, oilfield brines, and pegmatites.

Significant bottlenecks for the domestic supply chain are the lack of chemical compound and metal refining and cathode production facilities. The United States has two lithium hydroxide and/or carbonate facilities that could produce product for lithium-ion batteries. As noted in Table 2, China has the most refining capacity for every lithium-ion battery refined material except C1 nickel sulfate, even though it does not lead in the mining of these metals (e.g., cobalt) (BloombergNEF, 2021). The country has steadily procured agreements with countries having ore reserves, worked with them to develop mining and processing operations, and built up its own refining capacities in China for all the metals.

Battery cell and pack production are two areas in which the United States has or is building resilience. United States EV manufacturers have announced almost 200 GWh of production by 2025 as shown in Table 4. It is likely that even more cell facilities will be built as American automakers increase their EV production. The United States has significant module, pack, and rack manufacturing capabilities. Data on domestic manufacturing announcements were obtained from several sources, including the NAATBatt Lithium-Ion

[13] Identified resource as defined by the USGS (United States Geological Survey, 2022): "Resources for which location, grade, quality, and quantity are known or estimated from specific geologic evidence. Identified resources include economic, marginally economic and subeconomic components. To reflect varying degrees of geologic certainty, these economic divisions can be subdivided into measured, indicated, and inferred."

Battery Supply Chain Database (NAATBatt, 2021), and Bloomberg New Energy Finance (BloombergNEF, 2021), and the Electric Vehicle Battery Supply Chain Analysis (Ultima Media Automotive, 2021).

Table 4. Proposed Domestic Lithium-Ion Cell Manufacturing Facilities

Company	Location	Proposed Commissioning Date	Annual Capacity (GWh)	Chemistry
LG Energy Solution, GM	Lordstown, OH	2022	30	NMCA
LG Energy Solution, GM	Spring Hill, TN	2023	35	NMCA
Imperium3 NY Inc	Endicott, NY	2019[a]	3	NMC
SK Innovation Co Ltd	Commerce, GA	2021–2023	21.5	NMC
BlueOval SK, Ford	Stanton, TN	2025	60	NMCA
KORE Power Inc	Maricopa, AZ	2023	12	NMC
QuantumScape Corp	San Jose, CA	2023	0.01	NMC
Tesla	Reno, NV	2022-2025	26	NCA
Tesla	Fremont, CA	2021	10	NCA
Total (GWh)			**197.51**	

[a] Facility was scheduled for 2019 but has not been built and is still planned.

Source: Bloomberg New Energy Finance (2021)

2.2.8 U.S. Competitiveness

The United States is currently not competitive with China or other countries in the upstream segments of the supply chain. While partially attributable to the lack of natural resources, China's ability to secure long-term agreements with mineral companies in countries such as the DRC (cobalt) and Australia (lithium), demonstrates how this deficiency can be overcome. China's dominance of the LIB supply chain is due to numerous factors including continued investment and strong local and global demand for its lithium-ion batteries (About BNEF, 2021).

The United States also lags in subcomponent manufacturing, partially due to a lack of demand. As the proposed new cell manufacturing facilities—as well as those predicted due to announced increases in domestic EV manufacturing—are built, it is expected that the demand for domestic subcomponents will also increase. This will likely be seen in electrolytes and separators, and possibly anodes, where the United States already has a presence and can be more easily scaled up. Developing cathode facilities may take longer and would still rely on China for the cathode metal compounds unless unconventional sources are developed.

Another area where the United States lags is recycling and second life. The Chinese government has more than 10 policies for encouraging recycling and second use. The recycling policies were first implemented in 2015 soon after it offered subsidies to develop the EV industry. In 2018, these policies were released as the National Guidance for NEV Battery Recycling (Chinese Office of the State Council, 2020) (ICCT, 2021) and included recycling industry standards and life-cycle management, with specifications that automakers and battery manufacturers are legally responsible for recycling EV batteries. Other policies establish a national battery coding and tracking system and establish a network of distributed and regional collection centers for used batteries which must be built by EV makers. In late 2020, China developed a draft policy governing second-life batteries, primarily in management principles rather than market development (Li and Frith 2021).

Europe is also developing policies and standards for both recycling and second use. These regulations would require companies that sell batteries (e.g., importers, distributors, manufacturers, second-life companies) to be responsible for end-of-life processing or disposal. The regulations cover safety, traceability, collection networks, recycling targets, sustainability, and second life (Li and Frith 2021).

Although the United States is not currently competitive in recycling and reuse/repurposing, it is a potential area of growth. Several recycling facilities are being built or expanded by Li-Cycle, Ascend Elements, and others. For example, Ascend Elementss already has an agreement with Honda to recycle all of their batteries in their expanded demo facility and subsequently in their new commercial facility (with a capacity of 30,000 tonnes/year) in Covington, Georgia that is expected online in August, 2022 (Ascend Elements, 2021) (Ascend Elements, 2022). Furthermore, the United States has a strong presence in research, development, and demonstration to develop and improve new and existing recycling technologies, both in the public (e.g., DOE's ReCell program) and private sectors. Domestic companies developing or deploying battery recycling technologies include American Hyperform, Lithion Recycling, Ascend Elements, OnTo Technologies, and Lixivia. Finally, as mentioned earlier, the repurposing of old EV batteries into grid energy storage system applications is a business model for several companies. While there are promising signs, becoming fully competitive in this area will likely require governmental policies.

An important aspect of the competitiveness of a country's manufactured goods is the global standardization of component design, protocols for interconnections with those components, and specifications associated with operation of those components. With international standards in place, components made in the United States can more easily be sold to consumers in other countries. For example, the adoption of the Combined Charging System protocols [14] allows U.S. manufacturers to sell their EVs and charging equipment across borders without having to develop special manufacturing lines or adapters to serve multiple markets. As the technologies and markets for grid energy storage are beginning their projected growth, participation of U.S. researchers and industry in international standards development is essential for increasing competitiveness and supply chain resilience.

2.3 Lead-Acid Batteries

The lead-acid battery supply chain includes raw materials, refined materials, subcomponents, product, and end of life.

[14] https://www.charin.global/

2.3.1 Raw Materials

The main raw materials for a lead-acid battery are lead and sulfur (as sulfuric acid). Both are abundant and produced domestically. The United States has nine mines that produce lead—five as the main product and four as by-products of zinc and silver mining. In 2021, these mines produced and estimated 300,000 metric tons of lead (United States Geological Survey, 2022). In addition, an estimated 990,000 metric tons of secondary lead was produced, primarily from old lead-acid batteries, which met 62% of domestic lead apparent consumption in 2021. The United States imported less than 40% of its apparent consumption of lead from Canada, Korea, and Mexico, among others (United States Geological Survey, 2022). The United States has 5 million metric tons of lead reserves, approximately 5.6% of the global reserves.

In 2021, an estimated $740 million worth of elemental sulfur and byproduct sulfuric acid were produced at 95 facilities in 27 states (United States Geological Survey, 2022). The United States has a net import reliance of 18% of its apparent sulfur consumption and produced over 10% (8.1 million metric tons) of global sulfur in 2021. An estimated 80 million metric tons of sulfur was produced in 2021 in more than 20 countries (United States Geological Survey, 2022). Since most sulfur is produced as a by-product of fossil fuel processing, the country where it is produced may not be the country of origin. The USGS (2022) states that the global reserves and resources of sulfur are significant.

2.3.2 Refined Materials

Sulfuric acid, plastics, purified lead, and lead oxide are the refined materials in a lead-acid battery. All these components have numerous suppliers in the United States.

2.3.3 Subcomponents

Subcomponents of the lead-acid battery include the anode, which is made of porous lead or graphite, and the cathode, made of lead oxide. It uses sulfuric acid as the electrolyte and has a chemically permeable membrane separator. All the subcomponents are readily available from numerous domestic suppliers. Companies that manufacture subcomponents include W.L. Gore & Associates, Cabot Corporation, Superior Graphite, Black Diamond Structures, Hammond Group, and Wirtz Manufacturing.

2.3.4 Product

Lead-acid batteries are currently the most common rechargeable battery in the world. Lead-acid batteries are deployed in both the transportation and stationary markets, primarily providing starting, lighting, and ignition for all types of on- and off-road internal combustion engine vehicles. Additionally, they provide a significant amount of energy storage for the industrial and commercial sectors, including telecom battery back-up and uninterruptible power supply, as well as energy storage for data centers and forklifts. Lead-acid battery storage for grid-related applications is relatively minor today, especially in the United States. Figure 16 provides a summary of the end uses for lead-acid batteries.

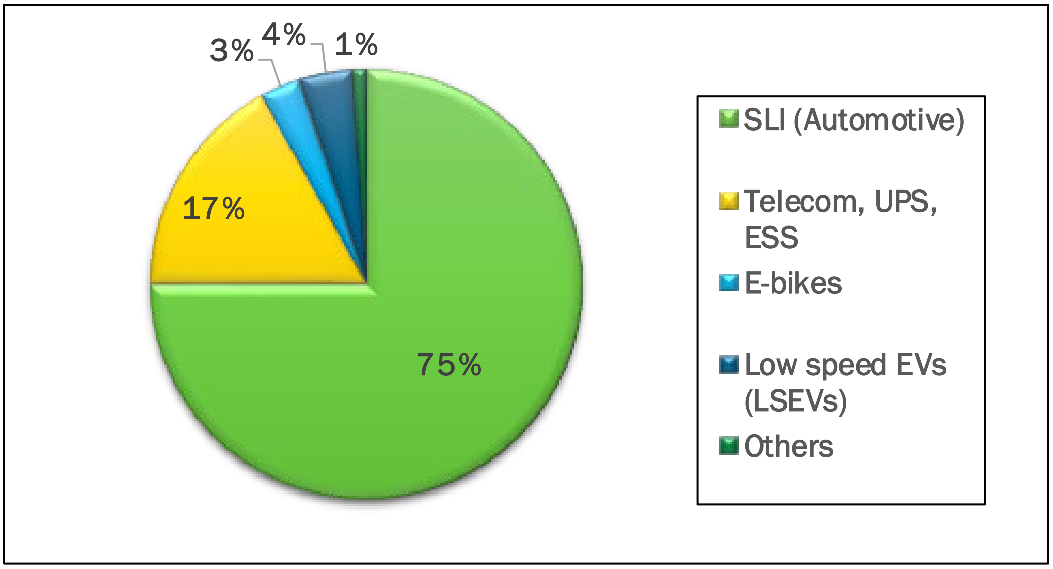

Figure 16. End-use applications for lead-acid batteries.

Source: Pillot (2019)

Johnson Controls and Enersys are the two leading companies in this market; Johnson Controls operates in the automotive sector and had $23.3 billion in sales in 2018 while Enersys had $14.2 billion in sales in the industrial sector (Pillot, 2019). Other companies in the industrial sector include Yuasa, Stryten Energy, East Penn, C&D, and Fiamm.

Globally, in 2020, almost 1000 MWh of lead-acid batteries were installed in grid applications; about .05 MWh was installed in the United States. China had the most lead-acid batteries in grid service at 700 MWh (Pillot, 2019).

2.3.5 End of Life

Because of legislation aimed at keeping lead out of landfills, lead-acid batteries adhere to a circular economy model better than most products. The recycling and reuse rate of lead-acid batteries exceeds 99%, and every new battery is comprised of an average of 80% recycled material (EDR Group, 2019). Approximately 70% of the lead in the battery is recycled. In 2020, there were 15 facilities in the U.S. involved with lead battery recycling (e.g., collection, plastics) (Battery Council International, 2020); at least one secondary lead smelter was shut down in 2021, leaving just 10 secondary lead smelters in the United States (Barboza, 2020). Companies involved in lead-acid recycling include Quemetco, Gopher Resource, U.S. Battery Manufacturing Company, and Clarios.

Sulfuric acid can also be reclaimed, regenerated, and reused. Approximately 2.5–5 million tons of spent sulfuric acid is reclaimed from petroleum refining and chemical processes each year (United States Geological Survey, 2022).

2.3.6 United States Resilience

The United States lead-acid industry is a circular, domestic industry.

The most significant disadvantages of this industry are not related to the typical supply chain—the raw materials and suppliers are domestic, competitive, and abundant. Rather, the disadvantages are due to the technology itself, related to both its popularity and its performance. Because the technology is typically deployed without dispatch controls, known as battery management systems, it is often seen as difficult to integrate into grid applications. To date, the lead-acid battery industry has not developed system-level solutions to meet the demands of the future grid. However, because of its simpler and more domestically focused supply chain, the technology may offer solutions for stationary energy storage at grid, behind-the-meter, and distributed scales (U.S. DOE, 2020). The Consortium for Battery Innovation (2021) has been established to bring together numerous North American lead-acid battery manufacturers and United States government institutes to increase cycle life, roundtrip efficiency, and cost performance for stationary applications. Research, demonstration, deployment, and commercial application (RDD&CA) activities are potential avenues that could improve the performance of lead acid batteries.

2.3.7 United States Competitiveness

The lead-acid industry has an annual output or economic impact of $26.3 billion in the United States. Lead-acid batteries are produced domestically and 99% are recycled. They are manufactured in 18 states across every region of the country. In 2020, 11 states had recycling (e.g., lead, plastics) facilities, nine had technology development, and 10 housed companies that provide supplies (e.g., graphite) or equipment to the lead-acid industry (Battery Council International, 2020). The lead-acid battery industry has created nearly 25,000 direct jobs (manufacturing, recycling, transport, distribution, and mining) in 38 states. Figure 17 shows the United States domestic lead-acid manufacturing industry.

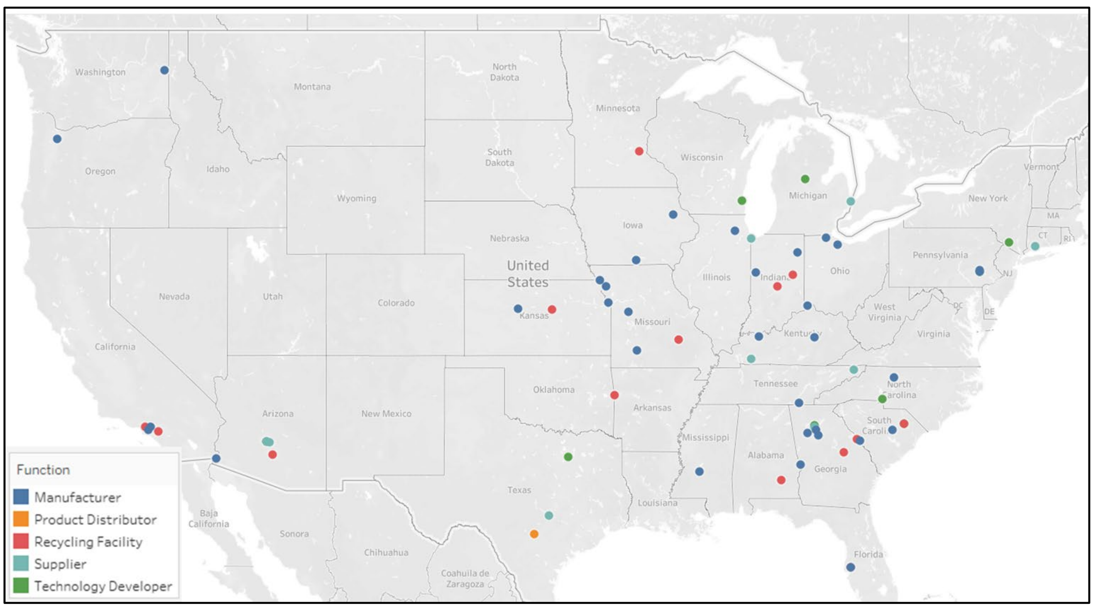

Figure 17. Domestic lead-acid battery manufacturing.

Source: Battery Council International (2020)

2.4 Flow Batteries

Flow batteries have the same supply chain segments as the other battery technologies: raw materials, refined materials, subcomponents, product, and end of life. Given the material abundance and existing supply chains for the metals needed in flow batteries, additional RDD&CA could diversify the supply chain for grid energy storage options.

Figure 18 shows a high-level view of this developing supply chain. One of the interesting items of this supply chain is that the underlying metal is used both on the cathode and the anode.

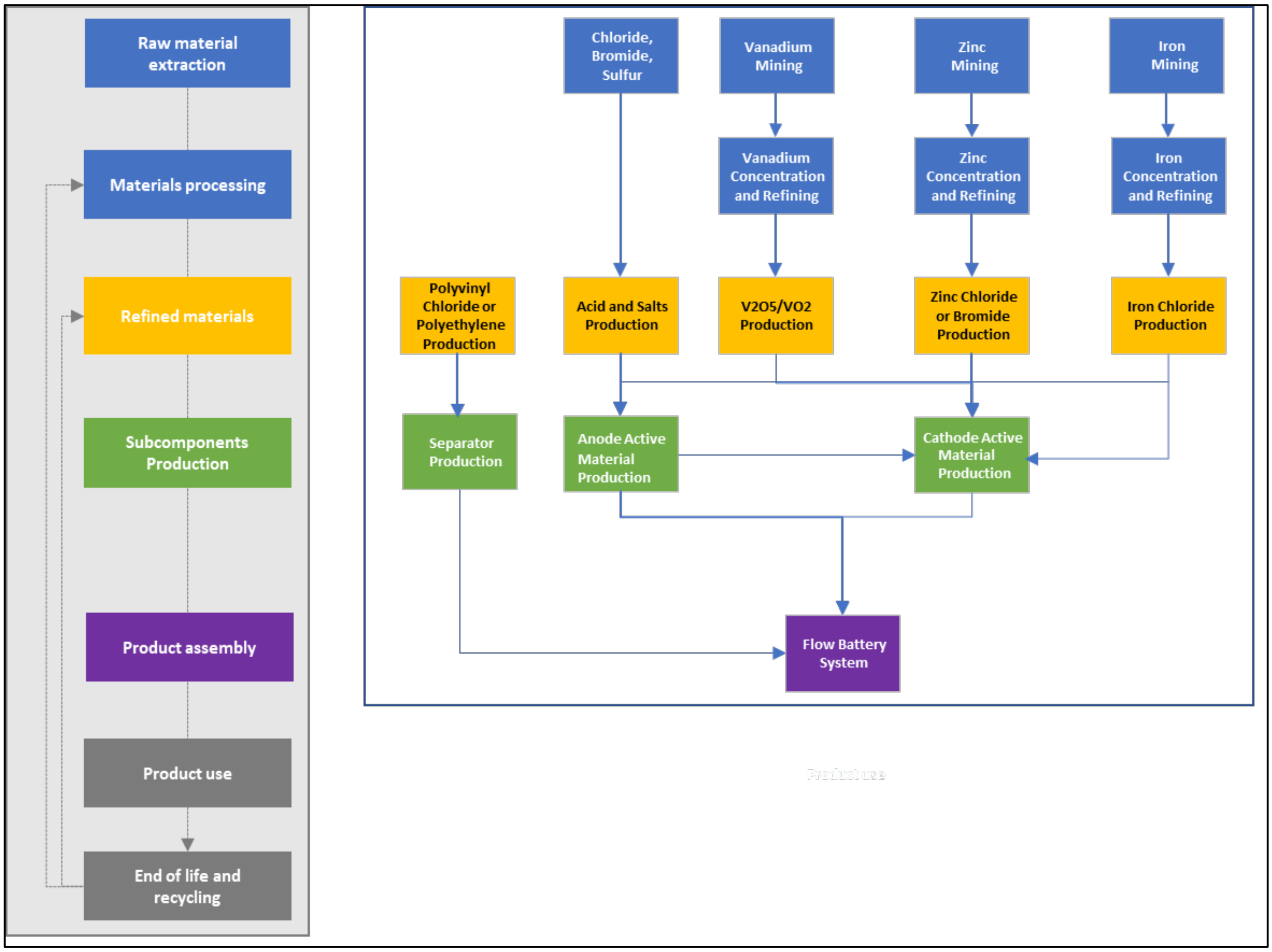

Figure 18. Flow battery supply chain.

2.4.1 Raw Materials

Three types of flow batteries—vanadium flow batteries, zinc flow batteries, and iron flow batteries—are technologically mature and commercial in small markets. As indicated by their names, iron, zinc, and vanadium are the principal metals used in flow batteries. Iron and zinc are abundant, while vanadium is more limited. The United States is currently an exporter of iron ore and has about 1.2% of the global reserve of iron (United States Geological Survey, 2022). Although 1.2% is a small percentage with respect to the total reserves, because iron is so abundant, it will likely not present an issue for domestic flow battery production. It should be noted, however, that the availability of high-grade iron is limited and is based on refined capacity. Most iron production produces products at less than 65% iron content; more refineries capable of producing high-grade iron are needed. Most domestic iron (98%) is used for steelmaking (United States Geological Survey, 2022).

Zinc is an abundant mineral and is mined in five states at seven mining operations, producing an estimated $2.4 billion of zinc in concentrates in 2021 (United States Geological Survey, 2022). The United States has three smelters—one primary and two secondary—to produce commercial-grade zinc. The United States is a net exporter of zinc ores, but relies on imports of refined zinc from Canada, Mexico, Peru, and others. An estimated 40% of the refined zinc produced in the United States in 2021 was from recycled secondary materials (United States Geological Survey, 2022).

The United States has about 0.2% of the global reserves of vanadium. Domestic vanadium is produced principally as a secondary product from wastes (United States Geological Survey, 2022). The United States is highly dependent upon imports for refined vanadium, importing an estimated 100% of its apparent domestic consumption in 2021 (United States Geological Survey, 2022).

Vanadium in the forms of ferrovanadium and vanadium pentoxide are sourced from several countries, including Brazil, South Africa, China, Austria, Canada, Russia, and Japan. The wide diversity of global sources indicates a resilient and flexible supply chain. However, given that vanadium is currently used as an alloying agent for iron and steel, as well as in catalysts for the chemical industries, any future growth of the use of vanadium for energy storage applications may alter the supply chain and necessitate an evaluation of the reliability of refined vanadium.

2.4.2 Refined Materials

Refined materials for flow batteries include purified metal compounds (e.g., vanadium pentoxide or ferrous chloride), acids such as sulfuric or hydrochloric, and chloride salts (He, et al., 2020). Vanadium is on the U.S. Geological Survey's current (2018) and draft (2021) critical materials list (2021 Draft List of Critical Materials, 2021). However, the United States does currently refine vanadium for the steel and iron industries, reducing the supply concern. Should vanadium flow batteries become commercially competitive with other storage technologies, a closer examination of the total vanadium reserve in the United States and ally countries is warranted, particularly at the refining scale.

2.4.3 Subcomponents

Subcomponents for flow batteries are readily available, commoditized products including fans, pumps, polyethylene tanks and pipes, carbon felt, steel heat exchangers, and glass fiber. These batteries are not currently being manufactured in large quantities at this time as they are not cost-competitive with lithium-ion batteries. Should flow batteries become more cost-competitive, however, greater investigation into the manufacturing and secure acquisition of these components may be warranted.

2.4.4 Product

Flow batteries are a newer technology and are used almost exclusively in stationary markets. As of October 2021, the cumulative global deployment of flow batteries was over 200 MWh, with Japan and China each deploying about one-third (BloombergNEF, 2021). An additional 900 MWh is under development. The United States has deployed about 46 MWh of flow batteries (BloombergNEF, 2021). In general, vanadium flow batteries are the most expensive to produce given the cost of vanadium.

2.4.5 End of Life

It is expected that the iron, vanadium, and zinc metals could be recovered from the batteries via either pyrometallurgical or hydrometallurgical systems. To-date, no flow battery recycling facilities have been developed.

2.4.6 U.S. Resilience

The developing U.S. flow battery industry has several advantages, including access to the raw materials and simpler production processes, but these advantages would be true for most countries. However, the United States is in a good position in that there are several domestic flow battery technology developers and vendors including ESS Inc. (iron flow batteries), Honeywell (unknown chemistry), and at least eight vanadium flow battery companies: Largo Clean Energy, VCHARGE, StorEn, Ashlawn Energy, Avalon Battery Corp., UniEnergy Technologies, LLC, Stryten Energy LLC, and ViZn Energy systems (National Minerals Information Center, 2018); (NAATBatt, 2021); (Stryten Energy, 2022). Sales of commercial products are available now, as described below.

2.4.7 U.S. Competitiveness

ESS Inc., an Oregon company, was recently contracted to deploy 2 GWh of iron flow batteries within the next five years to enhance grid resilience in utility-scale projects in Texas and California (Rathi, 2021); (Woodmac News, 2021). These installations would increase the United States deployed capacity almost 50-fold. The batteries are expected to have a 20-year life or 20,000 hours of operation. They should be able to provide 12 hours of storage, which would enable some photovoltaic facilities to provide electricity for 24 hours (Rathi, 2021). In addition to the domestic projects, ESS Inc. will supply 17 battery systems (total capacity of 8.5 MWh) to Green Power ESS España for long-duration storage and resilience.

Largo Clean Energy currently markets their VCHARGE vanadium flow battery systems at 6-, 8-, and 10-MWh scales with 100% depth of discharge and sub-second response times. Depending on power level, 4-10 hours of constant output are possible (Largo Clean Energy, 2021).

Honeywell recently announced that it had developed a flow battery that will be tested at the Duke Energy Emerging Technology and Innovation Center in 2022 (Honeywell, 2021). If successful, Honeywell has supporting systems that will enable it to become a vertically integrated energy storage solution provider from battery manufacturing through integration, management, and performance contracts.

Lockheed Martin is another large company that has developed a flow battery system, GridStar® (Lockheed Martin, 2022). This system is designed for greater than 6 hours of storage, a design life of 20 years and is made from safer mildly alkaline, aqueous electrolytes.

2.5 Emerging Technologies

Due to the early stage of development and deployment of the emerging technologies, high-level discussions of their supply chains are provided instead of in-depth discussions of each supply chain segment.

2.5.1 Sodium-Ion Batteries

CATL recently announced that it was developing a sodium-ion battery that would be used along with LFP batteries in vehicles. Commercial production is expected in 2023 (Xu & Reid, 2021). While the battery was developed for the vehicle market, Wood-Mackenzie expects that the battery will be used for storage technologies and other projects (Xu & Reid, 2021). Due to their lower cost, sodium-ion batteries could displace up to 20 GWh of LFP batteries in both vehicle and stationary storage applications (Xu & Reid, 2021). By developing a battery that does not rely on any of the very expensive battery metals used in other lithium-ion batteries—namely C1 nickel, cobalt, or lithium—this technology could provide a storage technology without significant supply chain constraints.

Raw materials for the sodium-ion batteries include sodium, iron, carbon, and nitrogen. All these components are abundant and well-distributed across the world. The subcomponents of the sodium-ion battery are very similar to those of lithium-ion battery: anode, separator, and electrolyte. The anode is hard carbon, and the separator is a porous polymer, like those used in lithium-ion batteries. The electrolyte is also very similar to that used for lithium-ion batteries, except that the lithium is replaced with sodium—$NaPF_6$ instead of $LiPF_6$. The cathode is Prussian white, which has a formula of $Na_xM[Fe(CN)_6]$.

Cells, modules, packs, and racks are the end products for sodium-ion as for all other battery technologies. There are currently no commercial producers of these technologies for sodium-ion batteries. However, due to the similar construction and technologies, it is likely that some of the same equipment (e.g., modules) could be used for either technology.

This technology is not commercial yet, so United States competitiveness cannot be assessed. However, the United States does have at least one company, Natron Energy, developing this technology (Xu & Reid, 2021). Natron Energy just finished Series D funding and started sales in 2020. Other countries that have companies developing sodium-ion technologies include United Kingdom (Faradion, AMTE, Deregallera), France (TIAMET), Sweden (ALTRIS), India (INDI Energy) and China (HINA Battery, CATL) (Xu & Reid, 2021).

2.5.2 Metal-Air Batteries

The security of the raw material supply for metal-air batteries will depend upon the metal used. Many of the potential metals such as iron, zinc, and magnesium are abundant. The porous cathode is generally constructed of porous polytetrafluoroethylene with electrocatalysts such as platinum or manganese oxide. Depending on the amount of platinum or manganese required, these could present bottlenecks for the development of this technology. It is not expected that the other subcomponents of the battery (e.g, separator; housing) will have supply chain issues. NantEnergy and Zinc8 are developers of zinc-air batteries with current or planned deployments and Form Energy is developing an iron-air battery.

2.5.3 Rechargeable Magnesium Batteries

Rechargeable magnesium batteries are attractive because magnesium is the fifth most abundant element in the earth's crust (Marschilok, 2021). While prevalent in the earth's crust, 2020 estimated global production of magnesium (12 million metric tons) is considerably less than other battery materials such as zinc (12 million metric tons) (United States Geological Survey, 2022). Several magnesium cathodes are under development, but it is too early to assess their supply chains.

2.5.4 Rechargeable Aqueous Zinc Batteries

RAZBs are similar to rechargeable magnesium batteries, except as noted above, the current global production of zinc far exceeds that of magnesium (United States Geological Survey, 2022). An RAZB is currently being deployed at an 800-kWh scale at the City University of New York, pending final UL certification and approval of the New York City Fire Department (City University of New York, 2021). Due to the immaturity of this technology, no significant supply chain issues have been identified.

2.6 Long-Duration Energy Storage

PSH, CAES, and hydrogen are LDES technologies evaluated in this report. Flow batteries can also be used as LDES, although the lower volumetric energy density limits their use in many stationary applications where space is restricted. Except for hydrogen from PEM electrolysis, which relies on materials such as platinum and iridium (refer to companion EO14017 supply chain report on hydrogen), these technologies have conventional components (e.g., compressors, pumps, vessels) that can be sourced from many vendors across the world, so it is unlikely that they would have supply-chain bottlenecks or security-of-supply issues. Instead, PSH, hydrogen, and CAES are more likely to be constrained by siting issues as they are most economical when they can be co-located with natural geologic formations such as underground caverns (e.g., CAES).

The U.S. Department of Energy has developed some aggressive targets for LDES: the Long Duration Storage Shot. The Long Duration Storage Shot is part of the U.S. DOE's Energy Earthshots Initiative, which aims to accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade as a part the Biden-Harris Administration's goal of net-zero carbon emissions by 2050. The Long Duration Storage Shot has a target of reducing storage costs by 90% compared to a 2020 lithium-ion baseline in storage systems that deliver more than 10 hours of duration, all by 2030 (U.S. Department of Energy, 2021). The Long Duration Storage Shot is not based on any specific technology—all will be considered as long as they can meet the goal. Efforts towards this goal will likely result in significant improvements in many LDES technologies.

A recent study estimated the levelized cost of electricity (LCOE) for several conventional and newer LDES systems and/or flexible power generation (e.g., natural gas combined-cycle) for >85% renewable penetration in a western U.S. location (Hunter et al 2021). Each technology was evaluated for storage durations of 12 hours to 7 days with both current and predicted performance and costs, the latter of which includes learning. Eleven low-carbon scenarios were evaluated: five storage technologies, four hydrogen storage with flexible generation, and two conventional flexible generation. Each technology is listed below, with a summary of the results shown in Table 5 [15].

- PSH - pumped storage hydropower
- VFB - vanadium flow batteries
- A-CAES - adiabatic CAES in salt caverns with thermal energy storage
- lithium-ion batteries - lithium-ion batteries
- TES - concentrated solar with thermal energy storage
- H2-PEM - H2 storage in salt caverns with a stationary PEM fuel cell
- H2-HDVPEM - H2 storage in salt cavern with a heavy-duty vehicle (HDV) PEM
- H2-CC - H2 storage in a salt cavern with a combined cycle system
- H2pipes-HDVPEM - H2 in underground pipes with an HDV PEM fuel cell
- NGCC-CCS - natural gas combined cycle with carbon capture and storage
- E-CC - ethanol with combined cycle

[15] PEM fuel cells designed today for heavy duty vehicle (HDV) use provide a lower capital cost power generation option than those designed for stationary power, which are designed for continuous operation. Seasonal storage systems would not be run continuously, with expected discharge only 10-15% of the time. Another distinction is greater cost reductions for HDV PEM due to higher volume production levels. Apart from differences in system and stack designs, however, the core PEM fuel cell technology is the same.

Table 5. Comparison of Low-Carbon LDES and Flexible Power Generation Technologies

	Scenario	Lowest LCOE	Technologies with Similar LCOE
12-hour duration	Current technology	PSH	A-CAES, lithium-ion batteries
	Future technology	Lithium-ion batteries	PSH, VFB, A-CAES
120-hour duration	Current technology	NGCC-CCS	H2-HDVPEM
	Future technology	H2-HDVPEM	NGCC-CCS, H2-PEM, H2-CC

The study also looked at seasonal storage (i.e., >120 hours) and concluded that hydrogen storage would continue to be cost effective as the duration increased, because the capital costs of storage in caverns are relatively insensitive to duration. Although the A-CAES technology is also stored in caverns, it is penalized from the high TES costs as well as the difference in energy density of storing air as physical energy versus hydrogen as chemical energy.

3 Supply Chain Risk Assessment

DOE developed a high-level methodology to identify potential supply chain risks by sector and subsector. The methodology is based on the template from DOE's Advanced Manufacturing Office as well as input from the High-Voltage Direct Current team at Idaho National Laboratory.

Each sector of all five energy storage technologies was evaluated according to criteria related to market size, projected domestic and foreign growth, United States manufacturing capabilities and suppliers, as well as exogenous factors such as environmental/climate or human rights concerns that could impact the supply chain. DOE then selected a measure for assessment and assigned a scoring scale to each resulting in a Green, Yellow, or Red score. A Green score shows strength and/or low risk or vulnerability and has specific, measurable values. Red scores indicate a potential risk and are given when the sector does not meet the Green score. In general, Yellow scores are given if there is not enough information to determine a score. Exceptions are described in the scoring criteria, measures, and scales outlined below:

- **Significant domestic supply:** Domestic supply is evaluated as significant (Green) if the domestic market supply can meet at least 50% of the estimated domestic demand.
- **Projected significant domestic demand:** The projected domestic demand is significant (Green) if the CAGR is projected to be greater than 2% for at least five years. If the specific projected demand for a sector or subsector cannot be determined, then the demand for the end-product is used as a proxy.

- **Significant global market:** If the market of the sector or subsector is greater than $5 billion, then the market is significant, earning a Green score.
- **Projected significant global market:** If the CAGR for that sector is projected to be greater than 2% for at least five years, it is considered significant or Green. If the specific projected demand for a sector or subsector cannot be determined, then the demand for the end product is used as a proxy.
- **Competitiveness of the U.S. market:** Domestic competitiveness is indicated by the number of companies in the specific sector or subsector. The presence of more than three domestic companies in the sector indicates a competitive market, receiving a Green score.
- **Competitiveness of U.S. suppliers in the global market:** U.S. suppliers are competitive if they capture at least 30% of the market.
- **Security of supply chain:** This criterion has two measures: identification as a critical mineral (2021 Draft List of Critical Materials, 2021) or the amount imported. If the material is identified or proposed as a critical mineral or is composed of a significant amount (>10%) of a critical mineral, then the supply is insecure. For other materials, if the amount imported is greater than 50%, it is significant and receives a Red score.
- **Environmental, climate, and human rights concerns:** This criterion addresses important external factors that can affect the development of the supply chain. For example, if the current supply chain relies on slave labor or typically disadvantages certain sectors of society, it makes the supply chain less resilient and makes it more important to develop an alternative source. This criterion is more subjective than the others in that DOE did not develop a numerical scale. However, we wanted to ensure that these concerns were addressed. In general, if a sector has been identified in the literature as having significant energy demands or hazardous waste issues, etc., then it would be given a Red score. Similarly, if literature has identified human rights issues (e.g., use of slave labor) in a sector, this will be given a Red score. If there are no identified issues, a Green score will be given. If the sector is not known well or there are questions, then it was assigned a Yellow score. As efforts to strengthen the domestic supply chain for lithium-ion batteries gain traction, particular attention must be given to environmental justice issues to avoid creating inequalities for communities that may disproportionately be relied upon to deliver refined materials and manufactured systems.

3.1 Lithium-Ion Batteries

Table 6 summarizes the supply chain risk assessment and is based on the discussion of each supply chain segment from Section 2.2. As shown in the table and discussed in previous sections, there is significant risk and uncertainty in the lithium-ion battery supply chain.

Table 6. Risk Assessment Matrix for the Lithium-Ion Battery Supply Chain

Supply chain segments to meet the demand of the final product	Product/ Components	Is there a significant domestic market?	Is the projected domestic demand significant?	Is there a significant global market?	Is the projected global demand significant?	Is there a competitive domestic market?	Are U.S. suppliers competitive in the global market?	Is the supply chain secure because the material is NOT on the proposed or current Critical Materials List? OR because the U.S. does NOT import > 50%	Have the environmental, climate or human rights issues, if any, been adequately addressed?
Raw materials	Lithum	No	No	No	Yes	No	No	No	No
	Cobalt	No	No	No	Yes	No	No	No	No
	Nickel	No	No	Yes	Yes	No	No	No	No
	Manganese	No	No	No	Yes	No	No	No	No
	Iron	No	No	Yes	No	Yes	Yes	Yes	Yes
	Natural Graphite	No	No	No	Yes	No	No	No	No
	Synthetic Graphite	No	No	Yes	Yes	No	No	No	No
	Silicon	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Refined materials	Refined LiOH/ Li_2CO_3	No	No	Yes	Yes	No	No	No	Yes
	Refined $CoSO_4$	No	No	Yes	Yes	No	No	No	Maybe
	Refined $NiSO_4$/ C1 Ni	No	No	Yes	Yes	No	No	No	Maybe
	Refined Manganese Sulfate	No	No	Yes	Yes	No	No	No	Maybe
	Coated Spherical Synthetic Graphite	No	Yes	No	Yes	No	No	No	Maybe
	Coated Spherical Natural Graphite	No	Yes	No	Yes	No	No	No	Maybe
	CAM/ p-CAM	No	No	Yes	Yes	No	No	No	Maybe
Subcomponents	LIB Cathodes	No	Yes	Yes	Yes	No	No	No	Yes
	Graphite Anodes	No	Yes	Yes	Yes	No	No	No	Yes
	Silicon-based anodes	No	Maybe	Maybe	Maybe	Yes	Maybe	No	Yes
	Separators	No	Yes	No	Yes	Yes	No	No	Yes
	Electrolytes	No	Yes	No	Yes	Yes	No	No	Maybe
End Products	Cells	No	Yes	Yes	Yes	Yes	No	No	Yes
	Modules/ Packs/ Racks	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
	Energy Storage System Packages	Maybe	Yes	Yes	Yes	Yes	Maybe	No	Yes
End of Life	Cells/ Packs	No	No	Yes	Yes	Yes	Yes	No	Yes
	Metals	No	No	Yes	Yes	Yes	No	No	No

Table 6 shows many of the significant risks for the lithium-ion battery supply chain. The supply of five of the raw materials (cobalt, graphite, lithium, manganese, nickel) are not secure as they are on the USGS draft 2021 U.S. Critical Mineral list (2021 Draft List of Critical Materials, 2021). The lack of a domestic market, domestic suppliers, and significant reliance on imported goods are the underlying cause. Interestingly, while almost all the components show that global demand will be significant (i.e., >2% CAGR), the domestic demand is not expected to be significant. The major reason for this is the lack of midstream component (e.g., cathode, anode) facilities existing or planned in the United States. Without the demand for the raw and processed materials, the domestic market will not be significant or competitive.

Finally, the environmental, social, and climate impacts of lithium-ion battery raw material extraction and heavy industry (refining and recycling) are known to be and/or are likely to be significant (Early, 2020);; (McKie, 2021)). A recent study (Restauro, 2021) showed that nickel had the highest carbon intensity of all base and ferrous metals. Although recycling can mitigate some of these concerns, improper design and operation of facilities can result in environmental, equity, and health issues. In fact, a planned battery recycling facility in New York by SungEel MCC was cancelled due to community concerns with toxic emissions (Golden, 2021). Both the cobalt and nickel extraction industries have human rights concerns related to the use of child labor for mining cobalt in the DRC and other metals in Indonesia (Sovacool, 2021); (Niarchos, 2021); (Strezov, Zhou, & Evans, 2021). On the other hand, reuse of lithium-ion batteries can have a positive impact on climate and the environment. Haram et al. (2021) showed that battery reuse can have significant reductions in the life-cycle greenhouse warming potential and photochemical oxidation formation potential among other factors and would have a positive impact on raw material, water, and electricity use.

3.2 Lead-Acid Batteries

The risk assessment matrix for lead-acid batteries is shown in Table 7.

Table 7. Risk Assessment Matrix for the Lead-Acid Battery Supply Chain

Supply chain segments to meet the demand of the final product	Product/ Components	Is there a significant domestic market?	Is the projected domestic demand significant?	Is there a significant global market?	Is the projected global demand significant?	Is there a competitive domestic market?	Are US suppliers competitive in the global market?	Is the supply chain secure because the material is NOT on the proposed or current Critical Materials List? OR because the U.S. does NOT import > 50%	If the environmental, climate or human rights issues, if any, been adequately addressed?
Raw Materials	Lead	No	Yes	Yes	Yes	Yes	Yes	Yes	No
	Sulfur	Yes	No	Yes	No	Yes	Yes	Yes	Yes
Processed Materials	Refined Lead	Maybe	Yes	Yes	Yes	Yes	Yes	Yes	No
	Sulfuric Acid	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Polyolefin	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Subcomponents	Separator	Maybe	Yes	Maybe	Yes	Yes	Yes	Yes	Yes
	Electrolyte	Maybe	Yes	Maybe	Yes	Yes	Yes	Yes	Yes
End Products	Lead Acid Batteries	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
	Lead Acid ESS	No	No	Maybe	No	No	Maybe	Yes	Yes
End of Life	Lead	No	Yes	Yes	Yes	Yes	Yes	Yes	No

The lead-acid battery risk assessment matrix shows the strengths and weaknesses of the lead-acid battery supply chain. It clearly shows the strength of the domestic market in terms of its domestic and global competitiveness as well as its high rates of recycling. Most of the lead used in the United States is from domestic sources.

The weakness of the supply chain is also apparent in that the demand for lead-acid grid ESS is declining in the United States and abroad. Furthermore, it is not clear if U.S. suppliers are competitive in this market as they do not offer full grid ESS packages. “No” scores were given for the domestic markets for lead and recycled lead because the value of the lead market is lower than the $5 billion threshold, which is not concerning by itself. Also, the projected global and domestic demand for sulfur is not expected to grow at more than 2% per year, so each of those received a “No” score. Finally, the matrix contains several “Maybe” scores where information was not available.

In addition to the declining demand, the environmental and potential human health impacts of lead mining and lead smelting (primary and secondary) are well-documented (Fuhrman, 2021); (Singh, 2014); (Zhang, et al., 2012). Unsafe lead smelting practices were found recently at a lead smelter in Florida (Johnson, Woolington, & Murray, *Poisoned*, 2021) and it faces over $500,000 for violations (Johnson, Woolington, & Murray, *Tampa lead factory faces $518,000 in more fines for environmental violations*, 2022). Further, Exide’s recent bankruptcy left a large, polluted site from a shuttered a battery recycling plant in California (Barboza, 2020). Exide had also been sued for violating the Clean Air Act at its Muncie smelter in 2015 (U.S. EPA, 2015) and its environmental trust from the bankruptcy is cleaning up another hazardous waste site from a lead battery manufacturing site in Frankfort, Indiana (U.S. EPA, 2022). Citizens groups and Earth Justice are opposing

Quemetco's expansion plans and renewal of its hazardous waste permit (Fuhrman, 2021). In the last decade, more than one-third of secondary lead smelters in the United States have gone out of business, including one in South Carolina in 2021 (Johnson, Woolington, & Murray, Poisoned, 2021). For these reasons, lead mining and smelting (primary and secondary) and lead-acid battery production received a Red score.

3.3 Flow Batteries

The risk assessment matrix for flow batteries is shown in Table 8.

Table 8. Risk Assessment Matrix for the Flow Battery Supply Chain

Supply chain segments to meet the demand of the final product	Product/ Components	Is there a significant domestic market?	Is the projected domestic demand significant?	Is there a significant global market?	Is the projected global demand significant?	Is there a competitive domestic market?	Are US suppliers competitive in the global market?	Is the supply chain secure because the material is NOT on the proposed or current Critical Materials List? OR because the U.S. does NOT import > 50%	If the environmental, climate or human rights issues, if any, been adequately addressed?
Raw materials	Iron	Yes	No	Yes	No	Yes	Yes	Yes	Yes
	Vanadium	No	No	Yes	No	Yes	No	No	Maybe
	Zinc	Yes	No	Yes	No	Yes	Yes	No	No
	Manganese	No	No	No	Yes	No	No	No	No
	Sulfur	Yes	No	Yes	No	Yes	Yes	Yes	Yes
Refined material	Refined Iron	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	V_2O_5/ VO_2	No	No	Yes	No	Yes	No	No	Maybe
	Refined Zinc	Yes	No	Yes	No	Yes	Yes	No	No
	Hydrochloric Acid	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Graphite	No	No	Yes	Yes	No	No	No	Maybe
	Sulfuric Acid	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Polyethylene	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Subcomponents	Separator - Polyethylene	No	Yes	No	Yes	Yes	No	No	Yes
	Pumps	Yes	Maybe	Yes	Maybe	Yes	Yes	Yes	Yes
	Heat Exchangers	Yes	Maybe	Yes	Maybe	Yes	Yes	Yes	Yes
	Electrolyte	No	Yes	No	Yes	No	Maybe	No	Maybe
End Products	Fe Flow Batteries/ Systems	No	Yes	No	Yes	No	Yes	Maybe	Yes
	Vanadium Flow Batteries/ Systems	No	Yes	No	Yes	No	No	Maybe	Maybe
	Zinc Flow Batteries/ Systems	No	Yes	No	Yes	No	No	Maybe	Yes

The risk assessment matrix highlights the early status of the flow battery market. Neither the domestic nor the global flow battery markets come close to the $5 billion threshold for significance. However, the risk assessment also shows that both the global and domestic demands for these batteries for grid storage are projected to grow significantly.

Vanadium, zinc, and manganese are all on the recently proposed critical materials list (2021 Draft List of Critical Materials, 2021) and so they and their refined compounds are considered to have an insecure supply. The United States is a net exporter of iron ore (United States Geological Survey, 2022) and so iron is considered a secure supply. Refined materials such as sulfuric acid, hydrochloric acid, and polyethylene for separators also have a secure domestic supply. Components such as pumps and heat exchangers are made domestically and should be able to meet demand. The availability of the electrolyte is uncertain due to the early status and small size of the market, and the exact formulation for each battery type is unknown.

3.4 Emerging Technologies

No risk assessment matrix was developed for the emerging technologies as they are still precommercial.

3.5 Long-Duration Energy Storage

No significant risks have been identified with PSH or CAES for LDES as they both are based on common equipment that can be sourced from numerous companies around the world. In general, their biggest risk is their dependence upon specific geologic formations.

The least expensive hydrogen storage technology, salt cavern storage, also depends upon geologic formations, but underground storage pipes may also be cost-effective in the future (Hunter, et al., 2021). Other material supply chain risks exist (i.e., difficult to obtain materials) for hydrogen storage technology with respect to cost-effective electrolyzers and PEM fuel cells (noting that the same risk does not apply to alternative technologies such as alkaline electrolysis and solid oxide fuel cells). As noted earlier, researchers expect that the costs of both will decrease with R&D and industrial learning. Furthermore, use of HDVPEMs may be the low-cost option as they are less expensive than stationary PEMs and their design (i.e., fewer discharges per year) matches well with the demands of seasonal storage (Hunter, et al., 2021). The most technologically advanced PEM electrolyzers, however, rely on platinum and iridium, which are expensive and have global supply constraints. Alkaline electrolysis does not rely on difficult-to-obtain raw materials. Refer to the companion report on supply chain issues for hydrogen systems for additional information.

3.6 Key Vulnerabilities (Near Term)

Analysis of key vulnerabilities for grid energy storage in the *near-term* will focus on the supply chain for lithium-ion batteries because of their dominance in of market price and share estimates. Based on a qualitative assessment of the “No” boxes in the risk matrix shown in Table 6, three key vulnerabilities in the U.S. supply chain for grid energy storage, specifically for lithium-ion batteries, have been identified:

- Reliance on other countries for critical materials, components, and products
- Lack of a domestic manufacturing and recycling infrastructure
- Environmental and climate impacts of the supply chain.

Several other vulnerabilities have been identified that are not apparent from the risk matrix. Deployment of grid storage requires technologies that can meet a wide variety of applications and conditions. Currently, lithium-ion batteries are the technology of choice and there are limited substitutes due to less favorable economics and lower levels of development and/or severely limited application due to physical or operating constraints. However, lithium-ion batteries have some safety concerns due to thermal runaway. Lithium-ion grid ESS installations in Korea have experienced 29 fires since 2017, with 11 of these occurring in 2019 (Bloomberg New Energy Finance, 2020). Development of other technologies is critical to meet the varied demands of grid storage. This is especially true for LDES technologies as current PSH and CAES technologies have geographical limitations. Technologies such as the flow battery may help in this regard.

Entry into the energy storage market is difficult due to the high capital requirements, skilled workforce demands, changing technology, and the subsequent need for continual R&D (Longhinin, 2021). An additional barrier is the difficulty in obtaining capital due to the lack of "Tier 1" suppliers or standardization of offerings and long-term off-take contracts, especially for standalone energy storage [(Plautz, 2021); (Walters, 2021)]. The lack of standardization is problematic not only in that each installation is unique due to the industry's variability (e.g., market and climate conditions), but also because performance guarantees and contractual terms are highly variable from upstream suppliers (Walters, 2021).

Several of the technologies examined, including flow batteries and sodium-ion batteries, are still developing market relevance and thus have fewer choices among suppliers. Losing even a single supplier could impact the overall supply chain. The lead-acid industry is well-established and domestic. However, it has relatively low penetration into the grid storage market and likely needs to improve its offering (e.g., battery management systems) to increase market share.

3.7 Key Vulnerabilities (Longer Term)

In the longer term, competition from other sectors (e.g., transportation) may prove problematic. The transportation sector is expected to be the major driver of battery storage demand, especially for lithium-ion batteries. This demand could negatively impact the supply of batteries for grid deployment. However, on the other hand, the demand from EVs could encourage more development of domestic manufacturing supply chains, which in turn would reduce vulnerabilities.

3.8 Key Focus Areas

Of the vulnerabilities included in the risk assessment matrices above, three key focus areas were identified and are described below.

Reliance on other countries for critical raw and refined materials, components, and products—The United States lags Asia, and especially China, in the manufacture and supply of materials, components, and end products for grid storage. While the United States lacks significant reserves of the requisite raw materials, it has also failed to develop the resources it does possess (e.g., lithium) or to secure raw materials through agreements with countries that do have reserves; however, in recent years, the United States has made progress in this area, especially with Canada and Australia (U.S. Department of Commerce, 2021) (Reuters, 2021). It has also failed to develop refining or manufacturing capabilities along the supply chain, or to ensure the development and deployment of alternative technologies.

Environmental and climate impacts of battery manufacturing and recycling industries—Raw material extraction, refining, and recycling are energy- and resource-intensive processes with significant potential environmental, environmental justice, and climate impacts. Any effort to address supply chain risks in terms of a secure supply must also address these impacts.

Broad application requirements (e.g., performance, environmental) and a lack of standardization for energy storage applications—Lithium-ion batteries are the current dominant choice due to their cost-effectiveness. However, given the competition from the transportation sector as well as the concerns with cobalt and C1 nickel availability and processing, more R&D should be dedicated to other technical alternatives (e.g., flow batteries) as well as continued research into low-cobalt alternatives. LFP is an excellent option for grid ESS, and its share of the grid ESS market is expected to increase significantly. Growth in LFP within the automotive sector is continuing as well, so other low-cobalt options may also be appropriate such as NMC811 or 955 to increase diversity. Having more than one technology and different chemistries among the options for grid ESS would increase the resiliency of the overall supply chain.

Lack of developed supply chains for nascent technologies—other technologies such as flow batteries, which decouple power from energy storage, would be excellent additions and would allow greater flexibility in application and storage time, potentially offering economic long or longer-term storage which lithium-ion batteries do not offer. Most of these technologies utilize materials that are inexpensive and abundant. However, due to their minimal adoption, supply chains for these new technologies have yet to be established. Development of supply chains for grid storage options like flow batteries, CAES, or TES would both reduce grid storage vulnerabilities to transportation demand and supply chain bottlenecks with lithium batteries.

4 U.S. Opportunities and Challenges

Key opportunities and challenges for developing the domestic grid energy storage industry are outlined below.

4.1 Key Opportunities

To address the key vulnerabilities in the grid storage supply chain, the United States should:

- Develop domestic, sustainable manufacturing and recycling capabilities along the energy storage supply chain
- Maximize the use of domestic resources by focusing on second life and recycling technologies
- Enable the diversification and deployment of grid storage technologies through targeted RDD&CA activities.

Addressing these opportunities will have significant impacts with respect to increasing well-paying skilled domestic jobs, improving gross domestic product (GDP), and ensuring minimal environmental and climate impacts. NREL, in an unpublished report, evaluated the impact of investing in domestic manufacturing facilities along the lithium-ion battery supply chain and showed that there was a return of more than 50% in GDP for each dollar invested and that the increase in employment was roughly 10 full-time jobs per year, per million dollars of investment. This same study estimated that it would require $7 billion to construct a domestic supply chain[16] to meet the projected 50 GWh of grid storage required in 2030, as part of the 2050 net zero plan. This investment would result in a GDP increase of $3.5 billion and 70,000 jobs annually.

[16] Supply chain includes separator, anode, cathode, cell and pack manufacturing, and recycling facilities.

Because the United States lacks the raw materials for many of the key grid storage technologies, it is imperative that it evaluate all sources of raw materials including unconventional sources (e.g., brine from the Salton Sea, secondary recovery, mine tailings, coal-based sources, seabed nodules) as well as the current domestic stockpile of used and in-use batteries through reuse, redeployment, and recycling. Currently, most batteries that are collected for recycling are sent to Canada for smelting and then to Europe or China for refinement. If these resources were kept in the United States and repurposed or recycled, it would significantly diminish its dependence on foreign sources. Studies have shown that 30% to more than 50% of the domestic cobalt demand for storage and transportation applications could be met with recycling (The White House, 2021). Furthermore, every year that a battery is repurposed decreases the demand for raw materials from other countries. Finally, developing and deploying new alternative technologies such as flow batteries that are based on domestic resources and simpler components will also reduce this dependence.

4.2 Key Challenges

Key challenges to realizing these opportunities include potential siting challenges of new facilities, the significant capital requirements of supply chain investment, and the current dearth of supply chain infrastructure. Addressing real and perceived environmental concerns with the public is critical for developing a domestic grid ESS manufacturing supply chain. Several projects, SungEEL MCC being the most recent, have had facilities cancelled due to public concern over environmental and other concerns.

Developing a domestic, sustainable energy storage supply chain will take significant investment, and private industry may not be able or willing to assume this risk without governmental incentives. The United States is many years behind its competitors with respect to investment in the energy storage supply chain and it will take significant and sustained effort to reverse this.

5 Conclusions

The electric grid is a cornerstone of the U.S. economy and the industrial energy base. To meet decarbonization goals, increased electrification and deployment of renewable energy are required, and grid energy storage is critical for both. Lithium-ion batteries are currently the most cost-effective and widely used technology for durations of 6 hours or less, while PSH is the most common for longer durations. It is unlikely that these technologies alone can meet the future demand for storage, and continued RDD&CA of alternatives is required.

The United States is currently at a significant disadvantage with respect to the supply chain for lithium-ion batteries. It lags China in capacity for all segments of the supply chain, and behind the rest of Asia and Europe in some. It is especially weak in upstream segments (i.e., raw material acquisition and refining) as well as the midstream components production (i.e., cathodes and anodes). China has policies to encourage the development of this supply chain for internal resilience, and Europe is quickly developing policies and a domestic industrial manufacturing base. To become globally competitive in the manufacturing and secure acquisition of grid energy storage technologies, the United States could increase focused efforts in the following areas:

- Development of a second-use industry that repurposes end-of-life batteries for grid storage
- Development of sustainable upstream, midstream, and recycling facilities and industries
- Development of diverse cost-effective, sustainable technologies for grid storage.

The fundamental and essential activities of American life revolve around an economic and reliable electric grid. Sustainably and securely upgrading that grid to deliver clean energy for homes, businesses, industries, and transportation will require piecing together supply chains that interconnect raw materials, equipment manufacturing, a strong workforce, and policies. Ensuring that the future U.S. grid is built with a focus on a domestic and resilient supply chain will enhance global leadership and secure a decarbonized future.

Recommended policy actions to address the vulnerabilities and opportunities covered in this report may be found in the Department of Energy 1-year supply chain review policy strategies report, "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition." For more information, visit www.energy.gov/policy/supplychains.

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