Written testimony of
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Before the
House Committee on Science, Space, and Technology
For the hearing titled
Pedal to the Metal: Electric Vehicle Batteries and the Critical Minerals Supply Chain

April 21, 2022

Chairman Foster and distinguished members of the subcommittee, thank you for inviting me to testify at this important hearing. My name is Venkat Srinivasan and in my roles at Argonne National Laboratory, I serve as the Director of the Argonne Collaborative Center for Energy Storage Science, or ACCESS, and as the Deputy Director of the Joint Center for Energy Storage research, or JCESR. I'm honored to represent our nation's 17 national laboratories, many of which are hard at work addressing the topic of our conversation today.

We are at a unique moment in time where the United States can become a dominant force in energy storage technology. We have a once-in-a-lifetime opportunity to seize the moment to discover, manufacture, and commercialize future storage technologies to enable a carbon-free economy, ensure our energy security, create equitable jobs that benefit everyone, and position the U.S. as a leader in one of the most important technologies of the 21st century.

This is a historic moment for the U.S. energy storage ecosystem:

After a century of powering cars with gasoline and producing electricity using coal, we are at the cusp of a revolution in the energy sector. At the heart of this transition is energy storage, long considered the "holy grail" for decarbonization of transportation and the electric grid. Robust research and development, coupled with innovations in manufacturing, have led to an order of magnitude cost reduction for lithium-ion (Li-ion) batteries in the last decade. This dramatic change has led to light duty electric vehicles (EV) achieving cost and range parity with internal combustion engine (ICE) vehicles. In addition, in regions with high electricity costs, such as California and Hawaii, Li-ion batteries, coupled with solar panels, provide electricity at lower cost compared to fossil-fuel generation.

Significant reduction in battery costs have led to three trends which, combined, are poised to alter the landscape for batteries in the U.S. First, the market for EVs has grown tremendously in the last five years. In 2021, EVs accounted for 9% of global car market (6.6 MM), more than tripling their market share compared to 2019.[1] With recent announcements from practically

[1] https://www.iea.org/commentaries/electric-cars-fend-off-supply-challenges-to-more-than-double-global-sales. Accessed: April 9, 2022

every major auto manufacturer for expanding their EV offerings, the global electric vehicle market is expected to exceed 30 MM cars by 2030.[2] Estimates suggest that the U.S. Li-ion battery market to power these EVs will exceed one Terra-watt-hour (TWh) a year by 2030[3].

In addition, increasing penetration of renewable resources on the electric grid further drives the market for Li-ion batteries, especially for energy storage in the 4-6h duration. The actual size of the storage market for the grid is dependent on possible build out of interstate transmission (more transmission serves to buffer intermittency of renewables and thereby decreasing the dependance on distributed storage).[4] Despite this ambiguity, achieving the administration's 2035 100 percent clean electricity target will require an additional 0.5-1 TWh/year of Li-ion battery manufacturing capacity in the U.S. Between EVs and grid storage, the market for Li-ion batteries in the U.S. is expected to increase by a factor of twenty to thirty in the next decade.

The second trend is access to vast private capital aimed at commercializing storage technologies. Companies in the "green" sector raised $90B in 2021, many in the field of battery technology and EVs.[5] Through mechanisms such as mergers with Special Purpose Acquisition Companies (SPACs), battery startups have raised hundreds of millions to billions of dollars' worth of capital, enabling them to transition from small-scale R&D into large-scale manufacturing. Considering the large capital costs for battery materials and cell manufacturing facilities, access to capital is a prerequisite to ensuing a robust industrial base. The last two years has seen this much-needed infusion of capital into batteries.

Finally, the Biden administration has sent a clear signal on the need to transition the country toward a carbon-free economy. This includes the goal for half of all new passenger vehicle sales to be EVs by 2030, converting the electric sector to net-zero by 2035, and transitioning the economy to net-zero by 2050. Further, the Bipartisan Infrastructure Law (BIL) allocates nearly $7B to strengthen the U.S. battery supply chain. This level of investment has provided capital markets and battery companies with the assurance to expand on their investments, further reinforcing the positive momentum.

The convergence of these factors has resulted in a once-in-a-lifetime opportunity for the U.S. to become the dominant player in this critical technology. The U.S. has long been a powerhouse in energy storage research, however, in the 1990's lost manufacturing to Asian countries. We now have an opportunity to reverse that trend and bring battery manufacturing back to the U.S.

However, the U.S. has a significant challenge in meeting the expected demand:

While the expected TWh/year market for Li-ion batteries presents an historic opportunity, the U.S. manufacturing capacity is currently around 59 GWh/year, requiring rapid capacity building, in the order of twenty-five "gigafactories" within the next decade. In the last year, automakers

[2] National Blueprint for Lithium Batteries, June 2021.
[3] 1 TWh can power ~10M EVs, each with ~350 mile driving range
[4] Brown & Botterud, Joule 5, 1–20, January 20, 2021
[5] https://www.wsj.com/articles/green-startups-flush-with-cash-face-pressure-to-make-climate-advances-11647682202?st=pvemxctfo8de1ew&reflink=desktopwebshare_permalink Accessed: April 9, 2022

have partnered with large battery manufacturers to break ground on several gigafactories, which is a much-needed development but still far too small to meet the expected demand.

Every Li-ion battery consists of three active components: the anode, typically graphite; the cathode, typically based on a nickel, cobalt, and manganese-based oxide (NMC); and an electrolyte, typically a salt of lithium in an inorganic solvent. In addition, the battery also has inactive components: a polymer separator, and copper and aluminum current collectors. These components are carefully assembled into cells that are packaged to meet the energy, power, life, safety, and cost metrics for use in different applications. The critical role of the battery in the device necessitates a level of sophistication and automation in manufacturing that is not easily achieved. Building the manufacturing capacity requires deep expertise, complex supply chains, and access to vast capital (A typical gigafactory can cost $2-3B).

Even more urgent is the need to build facilities to synthesize the battery materials that are the core of these devices. These materials need to be processed to achieve specific properties. For example, battery cathodes require synthesis with exquisite control over their structure, morphology, size, and shape to ensure that they provide superior performance and life. This requires sophisticated material synthesis expertise. While the U.S. has small-scale cathode, electrolyte, and anode material manufacturing, these facilities will need to scale significantly to meet the expected demand.

Further upstream, metal salt precursors are needed to synthesis active materials. For example, the NMC cathode requires sulfate salts of the transition metals along with a hydroxide salt of lithium. The U.S. does not have facilities that refine and synthesize these precursors. Investments must be made to build these facilities at the scale needed to feed the gigafactories.

Finally, the domestic supply of minerals that go into the battery, especially nickel and cobalt, are not sufficient. As an example, the reserves of nickel in the U.S. only provide enough materials for 167 GWh: an order of magnitude less than the yearly requirement. Cobalt, another critical mineral, has more availability in the U.S. than nickel (U.S. reserves could satisfy up to 700 GWh capacity), but significantly lower than long-term needs.[6] While the U.S. has recently explored unconventional sources, such as the geothermal mines in the Salton Sea in California for lithium, developing these sources requires significant investments and time, including for permitting and environmental clearances.

The lack of upstream supply means that the US will remain dependent on foreign sources of minerals, refined materials, and battery materials for the foreseeable future, unless we act soon. Cobalt and graphite are especially important considering the concentration of these resources in specific geographic regions (50% cobalt reserves are in the Democratic Republic of Congo while 70% of natural graphite is in China).[7] Nickel, while more geographically prevalent, including in the Philippines, Canada, and Indonesia, has seen recent challenges due to the war in Ukraine and the subsequent price hikes in the London Metals Exchange.

Recycling could well hold the key to building a secure materials supply. However, today, the U.S. does not have any appreciable recycling capacity. Further, collection processes for Li-ion

[6] National Blueprint for Lithium Batteries, June 2021.

[7] Joule 1.2 (2017): 229-243

batteries already in the market, including various consumer devices, remains inadequate. While recycling is cost effective for cobalt and nickel, the volume of spent batteries is too small to meet the growing demand. Recycling can and should be part of the solution but will remain a small fraction of what the demand will be for battery critical materials in the near term.

Mining is also reputationally-challenged due to a lack of environmental social and governance (ESG) considerations in much of the world. ESG consideration will need to be front and center as the U.S. develops domestic resources for battery critical materials. Further, the environmental impact requires the active support of affected communities and a pathway to ensure that the benefits of the transition to clean energy reach underserved communities that have been most affected by these actions.

Last, but not least, the workforce needed to enable this transition is a significant challenge that requires careful consideration. The battery community, spanning academia, National Labs, and industry, is facing an unprecedented shortfall in a skilled workforce. This shortfall is across skill levels and could derail the opportunity to grow this industry.

In summary, the U.S. has a significant supply chain challenge for meeting the expected demand for lithium batteries. Bridging the gap requires a comprehensive strategy.

Deep decarbonization requires next generation batteries, beyond today's Li-ion:

While advanced Li-ion batteries have had an outsized impact on EVs and short-duration (<4h) stationary storage, some challenges remain, including further reduction in cost, faster charging, and increased lifetimes. Achieving these targets requires new chemistry solutions, and new materials. Recent trends, including the use of silicon as the anode and solid-state batteries that use lithium metal as the anode, suggest that a leapfrog in technology is imminent. In the R&D pipeline, chemistries that can meet the EV cost target of $60-80/kWh, such as lithium-sulfur batteries, which have higher energy density and reduced costs, are being examined. While these changes don't eliminate the critical materials dependence completely, they lighten the burden by diversifying the supply. Beyond light duty passenger cars, electrifying long haul trucks requires almost twice the energy density of today's Li-ion battery. The challenges become more acute for electric aviation with targets that can be more than three to five times what is possible today.[8] Decarbonizing these sectors will require new storage chemistries.

While Li-ion batteries have become the preferred solution for solar-connected storage, the chemistry becomes less attractive for longer storage times. With increasing renewable penetration, past 60% of total electricity generation, long duration storage, ranging from multi-day to seasonal, becomes more important. The cost targets for these applications are significantly more aggressive compared to short-duration storage. For example, the recently announced Department of Energy earth shot on long duration storage calls for a 90% reduction in cost for storage times greater than 10h.[9] Further, grid installations require lifetimes of multiple

[8] https://www.anl.gov/article/white-paper-assessment-of-the-rd-needs-for-electric-aviation Accessed: April 9 2021

[9] https://www.energy.gov/eere/long-duration-storage-shot Accessed: April 9 2021

decades, rather than the 8-year lifetime for EVs. Achieving this target will require new storage technologies.

While the technology targets for deep decarbonization are challenging, it also presents an opportunity to discover the battery of the future that is made from earth abundant materials using low energy routes. Such a battery will not be found by tweaking today's systems; rather a fundamental science-based approach is needed that can revolutionize our ability to harness the capabilities of materials and chemistries to store electrons. Discovering such a battery will allow the U.S. to leapfrog existing batterie technologies to enable a carbon-free economy, maintain US scientific leadership, establish manufacturing prowess, and create the jobs of the future.

Addressing the supply chain gap requires a multipronged strategy:

The significant challenges presented above require a comprehensive approach that embraces two aspects (i) a near-term strategy to build the domestic supply chain for lithium batteries and (ii) ensuring that long-term sustainable technologically advanced solutions are discovered that can enable economy-wide decarbonization.

To achieve the near-term objectives, we suggest the following five approaches:

1. **Incentivize domestic mining and refining of battery critical materials**: The country should take advantage of the resources in our lands and ensure that they are extracted with consideration for environmental impact, water, and energy use. Incentivizing the discovery and development of novel, cost effective, low-energy routes is critical for this endeavor.
2. **Encourage the development of low-cost recycling processes**: Battery recycling, worldwide, is still in its infancy. Developing cost effective recycling, not just for critical elements, but for all the components in the battery, will allow the U.S. to develop intellectual property and be leaders in this emerging industry.
3. **Spur research into the development of substitutes**: Recent efforts have led to cobalt content decreasing from 30% to less than 10%. Further decreasing, and ultimately eliminating cobalt, is critical. In addition, consideration should be given to minimizing and removing nickel. Discovering new chemistries with earth abundant materials, like sodium, manganese and iron, should continue to be a focus of research.
4. **Prioritize chemistry-agnostic R&D to ensure that the right battery is used for the right application**: Transportation beyond light duty vehicles, and long duration storage beyond 10h, require storage beyond Li-ion batteries. Alternates such as flow batteries, aqueous batteries, thermal storge, and chemical storage, provide alternative pathways that can help diversify and decrease dependence on Li-ion materials. Innovation in these areas, for example at the Joint Center for Energy Storage Research (JCESR), provide an opportunity for generating intellectual property while encouraging material diversity.[10] An example is the early focus in JCESR on long duration storage that led to the creation of Form Energy, a Massachusetts startup focused on low-cost multi-day storage.

[10] Proceedings of the National Academy of Sciences 117.23 (2020): 12550-12557

5. **Establish international collaborations**: The geographical location of Li-ion raw materials is such that the U.S. needs partners to build its supply chain. Countries such as Canada, and Australia, and regions such as Southern Africa have access to these materials. Further, R&D collaborations with the EU and Great Britain could accelerate the development of sustainable chemistries and recycling technologies.

Success in these five areas require seamless interaction between fundamental science, applied research and development, and industrial production. Accelerating the deployment of new materials requires such close interactions, pulling together the strengths of the various stakeholders.

The near-term objectives listed above should be complemented with a long-term view of developing solutions that will be the basis for a sustainable, carbon-free economy. Deep decarbonization requires storage with significantly higher energy density, lower cost, incredible safety, complete circularity, multidecadal lifetimes, utilizing earth abundant materials. Such chemistries are not achievable with incremental improvements to today's Li-ion batteries. Rather, a basic science approach that brings new insights into energy storage, integrates the latest tools such as artificial intelligence and machine learning, and enables accelerated discovery of novel materials, architectures, and systems will ensure long-term U.S. leadership in this technology.

Parallel with the technology strategy, a complementary workforce strategy is needed to ensure that the necessary skills are part of the education system. The workforce strategy will need to anticipate of the evolution of the technology and requires a holistic approach that links the technology leaders with educators in community colleges, trade schools, 4-year universities etc.

The federal government has taken bold steps to address the challenge:

Over the last 4 years, the Department of Energy (DOE) has identified the critical challenge related to the battery supply chain and has taken strategic steps to bridge the gap. The complex nature of batteries requires strong and sustained support across multiple technology readiness levels. Fundamental science allows new learnings and leads to discovery of new materials, architectures, and devices. This in turn enables application-driven R&D to translate the learning toward real-world use, aided by industries pulling innovation from the lab to large scale production. Innovation is also not linear, often requiring new scientific knowledge at all stages of technology development.

DOE-Office of Energy Efficiency and Renewable Energy recognized that the challenge required an all-of-government approach and helped launch the Federal Consortium for Advanced Batteries (FCAB).[11] FCAB brings together fourteen federal agencies, including Energy, Defense, State, and Commerce, and is charged with developing a comprehensive strategy to address the supply chain

[11] https://www.energy.gov/eere/vehicles/federal-consortium-advanced-batteries-fcab. Accessed: April 9, 2021

gap. FCAB's strategy for the country is captured in the National Blueprint for Lithium Batteries and the 100-day supply chain report, both released last year.

Further, DOE and FCAB have partnered with Argonne National Laboratory to establish the Li-Bridge Alliance, a unique, national public-private partnership aimed at bridging the battery supply chain gap. Li-Bridge brings together the DOE National Lab system and FCAB, representing the public side of the partnership three U.S.-based convenor organizations: NAATBatt International, New York Battery and Energy Storage Technology Consortium (NY-BEST), and New Energy Nexus, representing the private side of the partnership. Li-Bridge is working with U.S. battery companies to discuss the gaps in supply chain, sources of raw materials, challenges with U.S. manufacturing, recycling issues, role of government, approaches for developing a domestic workforce, and role of new technologies.

DOE's Office of Electricity, working closely with Office of Science and EERE, has established the Energy Storage Grand Challenge (ESGC), a comprehensive effort to accelerate the development, commercialization, and utilization of next-generation energy storage technologies.[12] ESGC has released a comprehensive roadmap articulating multiple use cases for storage and a holistic approach spanning bi-directional storage, chemical and thermal storage, and flexible generation and loads. Under the leadership of the ESGC, DOE recently announced the long duration storage shot, as mentioned previously. The holistic focus of ESGC is critical in ensuring that a diverse set of solutions are implemented to meet the market demand.

DOE-Office of Science has long had research efforts aimed at discovering the next generation battery chemistries under JCESR and the Energy Frontier Research Centers (EFRCs). In these programs, fundamental materials and chemistry research is complemented with the use of the synchrotron light sources, such as the Advanced Photon Source at Argonne, to understand the changes in battery materials *in situ* during their operation. Further, the extensive use of supercomputing facilities, combined with advances in artificial intelligence and machine learning, has accelerated the discovery of new battery materials with revolutionary performance. Recently, the office has put out calls for proposals aimed at clean energy solutions, including storage, consistent with the Storage Shot. These efforts provide the pipeline of innovation that can enable sustainable solutions for deep decarbonization of the economy.

Finally, the recently announced funding for batteries as part of the Bipartisan Infrastructure Law provides a much-needed shot in the arm for building the supply chain in the U.S. and ensure that a secure, sustainable battery industry can be developed in the next decade.

Summary and conclusion:

The United States has a long and rich history of innovation in energy storage with world-class expertise in fundamental and applied sciences. Further the U.S. continues to be a hotbed for nucleating innovative startups with a well-established pipeline to move technologies from the lab to the market. However, the U.S. has struggled to translate these activities into a robust

[12] https://www.energy.gov/energy-storage-grand-challenge/energy-storage-grand-challenge Accessed: April 9, 2021

manufacturing base. We now have an opportunity to reverse this trend, buoyed by the tremendous market demand expected in the next decade. But the lack of a manufacturing base and the necessary battery supply chain can be a serious impediment to translate this opportunity into jobs and economic growth. A holistic multipronged strategy is necessary to achieve the vision of a secure domestic battery industry that is the linchpin for decarbonizing the economy. We should seize this moment and support this holistic strategy to ensure that US becomes a leader in this critical technology.

Thank you for the opportunity to address you this morning on this important topic. I would be pleased to answer any questions that you might have.