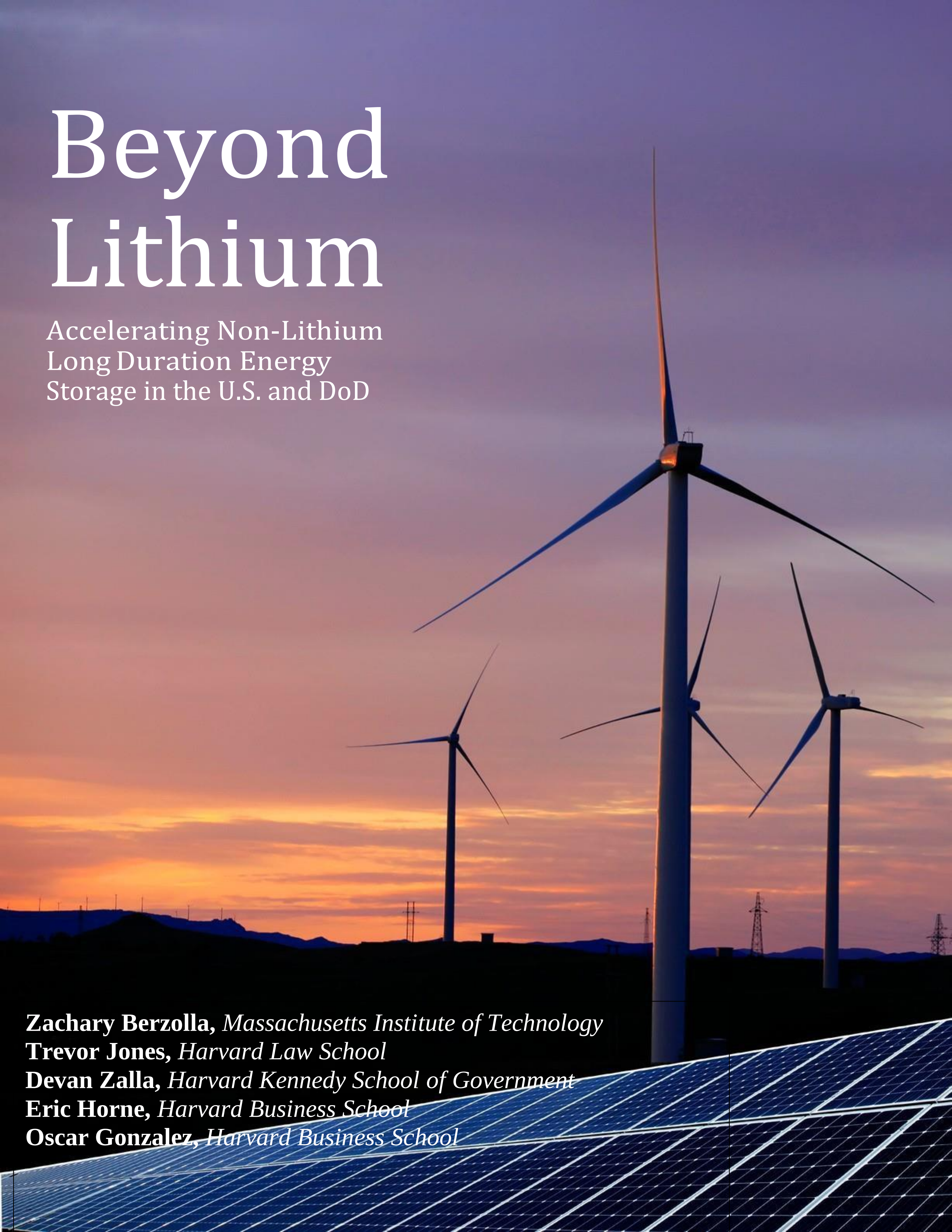

Beyond Lithium

Accelerating Non-Lithium Long Duration Energy Storage in the U.S. and DoD

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The **Cambridge Project** is a Defense Innovation Unit (DIU) program that brings together policy, business, and technical graduate students from Harvard, MIT, and Tufts Universities to apply their diverse skill sets to help solve challenges within the Department of Defense (DoD). Students help support the DIU's mission to accelerate the adoption of commercial technology for national security.

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Executive Summary

Energy is power. The energy transition and rise of renewable energy will not invalidate this basic premise. However, these changes have the potential to redraw the geopolitical map and change the global power dynamics. America's proactive efforts to ensure it remains a leader through the energy transition will be critical to its ability to project power and achieve its foreign policy goals. With the threat of disruptions to energy supply from both climate change and nefarious actors increasing, ensuring energy security is key to sustaining Department of Defense (DoD) operations at home and abroad, especially in potential future contested logistics environments. When coupled with local distributed generation, energy storage can play a crucial role in promoting a more resilient DoD. Given China's domination of Lithium-based storage technologies and manufacturing capacity, it is imperative that the U.S. accelerates the development and commercialization of domestic non-Lithium (Li) long duration energy storage (LDES) technologies and supports companies that can meet DoD and civil requirements. Because developing and procuring LDES systems is costly, large investments will be needed to cultivate this nascent market. The DoD, through the Defense Innovation Unit (DIU), is an ideal catalyst for these efforts. It is crucial at this moment that DoD leverages the DIU as a portal to the commercial world to engage a wide breadth of commercial technology. To help guide the potential actions the DIU and DoD can take, this paper aims to assess:

- The technical advantages and limitations of different novel long-duration storage technologies
- The defense applications of LDES across operational, installation, resiliency, and intermittency use cases
- Actions the DIU and DoD can use to accelerate the development of the LDES industry

To speed up the development and commercialization of non-Lithium LDES technologies for national security reasons, we present three areas of focus for DIU and the DoD. The first, strategic priorities, includes focusing on developing alternative flow battery technologies and deploying small-scale projects as demonstrations for emerging companies to prove their technology can meet DoD test requirements. A successful DoD demonstration project can be used to unlock private capital for expanded DoD and commercial applications. The second, DIU specific recommendations, focuses on better outlining how DIU projects can help companies scale-up and cultivate projects with DoD components through the Other Transaction Authority. Finally, DoD-specific recommendations focus on creating working groups for emerging tech across the DoD enterprise and better utilizing DoD procurement options – including programs of record and the rapid innovation fund – to create a strong demand signal for LDES technologies. A concentrated effort to act on this short list of actions **(**focusing on core non-Lithium LDES technologies, aligning non-Lithium LDES strategy, and aligning across multiple groups of the DoD) will be key in helping the DIU enable the U.S. to cement its role as an energy and global leader through the 21st century.

During this report's review, a press release (https://www.diu.mil/latest/defense-innovation-unit-partners-with-departments-of-the-air-force-navy-and) was posted by DIU awarding LDES demonstration projects to CellCube, DD Dannar, and Redflow Limited to demonstrate LDES technologies at several DoD installations. The authors hope this is a first step in the DoD supporting a burgeoning LDES industry.

RECOMMENDATIONS

Scaling Long Duration Energy Storage (LDES) to the level needed to meet the DoD's renewable energy, energy security, and resiliency goals will be a monumental effort - and a critical one. This effort will touch across several key DoD areas including installation energy, operational energy, and contested logistics. Energy and its supply have underpinned warfighting efforts over the last two centuries and the 21st century will be no different. Energy storage is key to unlocking the ability for renewable generation to provide grid-independent energy supply to support critical missions loads at DoD installations. It will also be critical to meeting Executive Order 14057 goals across the DoD enterprise. In this report, we provide DIU with the following recommendations across three key categories - strategic, DIU, and DoD specific recommendations.

Strategic Priorities

- **Focus the majority of LDES efforts on accelerating the development of domestic flow battery technologies.** Given the high technology readiness level (TRL) of these technologies and current availability for installation-scale deployment, DIU can play an important role in building domestic LDES alternatives to Lithium-ion (Li-ion), increasing the nation's energy resilience and innovation leadership. Other technologies such as advanced Lead can and should be supported as further evaluations in LDES technologies are carried out, but these two chemistries are the most promising today. Having a diversity of fuel and chemistry sources provides the greatest resilience benefits in a rapidly developing field.
- **Approach small-scale projects as opportunities to allow emerging companies and technologies to prove use cases, thereby unlocking access to private capital.** If a prototype hits demonstration project metrics agreed upon by the vendor and DoD stakeholders, a DIU-issued success memo can help validate the prototype and its performance in the field. By providing technical readiness to meet military grade requirements, DIU prototype evaluation helps to both buy down risk for further implementation across the DoD and pave the way for commercial investment in civilian applications. This private investment will allow emerging companies to scale more quickly and accelerate adoption of LDES technologies in both DoD and civic realms.

DIU Specific Recommendations

- **Increase visibility of the government contracting opportunities and outline clear pathways from pilot initiatives to at-scale contracts so bidding companies understand and acknowledge the immediate economic benefits of partnering with DIU and DoD.** Without a clear vision on the timeline and the full opportunity that a pilot opportunity can convert into, emerging companies have difficulty justifying the resources (time, personnel, effort) needed to win government contracts.
- **Encourage components of DoD to pursue Other Transaction (OT) contracts in partnership with DIU focused on LDES technology.** By developing prototype OT contracts for LDES technology around installation and operational energy use cases, DIU and DoD can drive emerging LDES companies ready for commercialization. OT contracts are a type of uncommon, non-Federal Acquisition Regulation (FAR)-based contract as described under 10 U.S.C.§2371 which allow for faster and more flexible contracting with the federal government. Successful prototypes then could be adopted as desired across DoD through follow on, non-competitive production OT contracts for individual installations.

DoD Specific Recommendations

- **Develop a program of record for LDES technologies that outlines requirements that an LDES solutions must meet.** By developing a program of record and standardized unit of energy storage for application across its projects, the DoD could facilitate how individual installations could procure standardized energy storage systems via the Defense Logistics Agency (DLA) (or other DoD authority) in the quantities needed for their application. Installations would then need to contract separately for installation and controls integration into their specific system. This approach would have several benefits. First, the bulk-purchasing power of the DoD would create economies of scale to reduce total cost of the energy storage system and help spur the required domestic LDES market. The large order size and time horizon would help build commercial capacity to deliver all the needed U.S. or ally-sourced components for the DoD and develop market maturity for the commercial market. Second: the standardized size would make plug-and-play abilities on first install and replacement if needed easier and reduce the workload (and thus cost) of the third-party contractors used for the installation and management of LDES systems.

- **Create working groups for specific emerging technologies across DoD agencies (e.g., DARPA, DIU, DoD) focused on promoting select technologies across the TRL scale.** By increasing coordination across DoD groups, efforts to accelerate and impulse critical technologies across the TRL scale (from early stage to commercial stage) can become more efficient and effective. ‘Pooling’ resources will help align strategy and investment decisions across the DoD, helping it fully leverage its scale.
- **Expand Rapid Innovation Fund (RIF) projects to include projects at earlier stages of RIF (when available) to create additional paths to monetization and investor backing.** By moving lower down the RIF curve to technologies at sub-6 TRL, the RIF can help companies with less mature technologies build use cases to prove technological feasibility, potentially attract additional investor capital, and accelerate their development towards TRL 8-9.

While these recommendations are not exhaustive, they do provide a short-list of actions that the DIU and DoD could take. Doing so effectively will require coordination not only within the DIU, but also alignment and collaboration with multiple groups within the DoD.

INTRODUCTION

The links between energy, a country's national security, and its ability to project power in the geopolitical sphere have been apparent for centuries. For a major part of the 19th and 20th centuries, these relationships centered around fossil fuels. Just like coal was key in cementing Britain's position during the Industrial Revolution, the role of oil and gas as a key commodity impacting 20th century power politics emerged in 1945 at The Yalta Conference. Those meetings - attended personally by Franklin Roosevelt and Joseph Stalin in Crimea - gave extraordinary leverage to countries that either controlled a substantial portion of the world's oil reserves or facilitated their trade.[1]

America has been no exception, basing its national energy resource reserves in petroleum since 1975.[2] Throughout the second half of the 20th century, America used fossil energy as "a means or instrument to achieve non-energy related foreign policy goals," such as using them to target foreign adversaries (e.g., Iran economic sanctions) or tightening alliances (e.g., increasing liquid natural gas exports to Europe).[3]

The link between energy, national security, and power projection will most likely endure, but the global energy transition will change the type of energy assets that these relationships center around. While global energy demand is expected to continue to grow through 2050, estimates indicate that electricity will represent the largest portion of future energy use, expanding from 20 percent of the consumption mix in 2020 to 40 percent in 2050.[4] Throughout this same period, fossil-fuel consumption is expected to fall 40 percent.[5] This shift will have wide-ranging technology, geopolitical, and military implications.[6]

Technology Applications

The rise of electrification across all sectors may move renewable energy technology to the center of the global energy landscape. Renewable assets are expected to account for half of the power generation mix by 2030 and 85 percent by 2050. Most renewable generation growth will be concentrated in solar and wind assets.

The variable nature of solar and wind energy sources will make battery technology a critical part of the energy transition as well. As renewable power generation and end-user demand for energy increases, demand for batteries is expected to experience exponential growth.[7] As an example, demand solely for Lithium-ion batteries is expected to increase 17-fold between 2020 and 2030.[8]

The growth of renewable and battery technologies will drive the need to access, extract and refine critical minerals, such as lithium, graphite, and other rare earth elements (REE). The increased demand for REE minerals includes substantial demand for battery electric vehicles and battery storage is expected to increase 30- fold, while low-carbon power generation (i.e., wind and solar) will triple its mineral demand by 2040.[9]

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[1] "Powering America's Defense: Energy and the Risks to National Security, Center for Naval Analysis, May 2009; The Yalta Conference, 1945, U.S. State Department World Wide Web Site, Office of the Historian, available at https://history.state.gov/milestones/1937-1945/yalta-conf

[2] Strategic Petroleum Reserve Origins, Office of Cybersecurity, Energy Security, and Emergency Response, Department of Energy World Wide Web Site, available at https://www.energy.gov/ceser/spr-origins.

[3] "The Geopolitics of Energy: Out with the Old, In With the New?," Oxford Institute for Energy Studies, February 2021.

[4] "Global Energy Perspective 2022," McKinsey & Company, April 2022.

[5] "Global Energy Perspective 2022," McKinsey & Company, April 2022.

[6] "A New World: The Geopolitics of the Energy Transformation," International Renewable Energy Agency, 2019.

[7] Johnny Wood, "Batteries are a Key Part of the Energy Transition. Here's Why," World Economic Forum, September 15, 2021.

[8] Johnny Wood, "Batteries are a Key Part of the Energy Transition. Here's Why," World Economic Forum, September 15, 2021.

[7] "The Role of Critical Minerals in Clean Energy Transitions," International Energy Agency.

Geopolitical Implications

The geopolitics of the energy transition are global, staging the scene for rearranging political, military, and economic structures. As power systems based in renewable and energy storage resources deploy, REEs necessary to manufacture renewable energy and storage technologies have the potential to become a major geopolitical force like oil and gas that may end up redrawing the geopolitical map.[10] Three types of leaders could emerge from this transition:

- **Countries with high technical potential for renewable generation due to their environmental and natural resources**. These countries, such as Australia, Brazil, and Norway, stand to gain from becoming significant exporters of renewable electricity.
- **Mineral-rich countries that contain the natural resources critical to the energy transition.** These countries, such as Bolivia and the Democratic Republic of the Congo (DRC), will have the opportunity to become an integral part of the global renewable supply chain and boosting their economic development.
- **Leaders in renewable technological innovation.** These countries, including the U.S., India, and China, will lead global efforts in R&D, investment, and manufacturing of clean-energy technologies across generation, storage, transmission, and distribution.

Leaders in renewable technological innovation may stand to benefit the most, both politically and economically, from the energy transition. A country can increase its energy resilience and independence, while establishing itself as a leading exporter of clean energy technology and, consequently, in a position of technological dominance.

The strategic importance of becoming a leader in renewable technological innovation has been recognized by the White House. In its 2022 *National Security Strategy*, the Biden administration referenced a hastening of the clean energy transition as "integral to [America's] industrial strategy, economic growth, and security."[11] Additionally, the DoD has earmarked $3.1B to "bolster U.S. security" in the face of a changing climate. Almost $2.8B of this total was towards "installation resiliency and adaptation" (e.g., on-site renewable power generation, energy storage installations) and "science and technology" (e.g., advanced energy storage and battery development).[12]

Military Implications

In December 2021, President Biden signed Executive Order (EO) 14057, which seeks to have the federal government pave the way towards a U.S. electricity sector with no carbon pollution by 2035 and to reach net-zero emissions by 2050.[13] EO 14057 stipulates that each federal agency will have fully carbon pollution free electricity sources on a net annual basis before 2030.[14] As the largest energy consumer by far within the federal government, DoD will have to make the most significant reductions in its overall energy consumption to meet these lofty goals.[15] In addition to this government-wide shift, DoD has begun to focus on climate change as a national security priority, seeking to integrate concerns about climate into its policies, strategies, and decision-making.[16]

In FY 2021, DoD consumed 852 trillion British thermal units (BTU) of energy, far exceeding any other

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[10] "A New World: The Geopolitics of the Energy Transformation," International Renewable Energy Agency, 2019.

[11] 'National Security Strategy" The White House, October 2022.

[12] "Meeting the Climate Challenge," Department of Defense, Office of the Under Secretary of Defense (Comptroller), April 2022.

[13] "EO 14057," FedCenter, September 22, 2022, available at https://www.fedcenter.gov/programs/eo14057/.

[14] "EO 14057," FedCenter, September 22, 2022, available at https://www.fedcenter.gov/programs/eo14057/.

[15] "U.S. Government Energy Consumption by Agency and Source," U.S. Department of Transportation, Bureau of Transportation Statistics, available at https://www.bts.gov/content/us-government-energy-consumption-agency-and-source.

[16] "Tackling the Climate Crisis," U.S. Department of Defense, available at https://www.defense.gov/spotlights/tackling-the-climate-crisis/, accessed on March 23, 2023.

U.S. government federal agency or single private entity.[17] [18] Only 18 trillion of the BTU DoD consumed came from renewable sources, with fossil fuels or electricity derived from fossil fuel power generation comprising most of DoD's power consumption.[19] In early February 2022, DoD released a new request for information (RFI) seeking to gather information on how the U.S. market can support DoD in meeting EO 14057's electricity goals.[20] Because of challenges in transitioning to high amounts of variable renewable sources of energy generation, large investments in new transmission, load management, and storage infrastructure will be necessary to phase out reliance on fossil fuel energy production. Similarly, large investments in storage technologies and infrastructure will be necessary for increasing electrification of vehicles and equipment to reduce fossil fuel emissions.

As DoD increasingly focuses on climate change as both an environmental imperative and a national security concern, exploiting REE minerals in addition to and in lieu of oil and gas opens the door to meeting needs with alternative energy chemistries. Prime among these are LDES chemistries that offer to help DoD incorporate new renewable energy and storage resources. Non-Li LDES introduces electro-chemical components with capacity to perform like a standard combustion generation set comprised of diesel generators and furrows new ground to accelerate grid resiliency by creating a new offset to counter to emergent supply chain vulnerabilities attributable to Li-ion batteries. DoD seeks to require alternative LDES chemistries which can be produced domestically or through allied supply chains and at comparable or lower costs than Li-ion batteries. DoD's shift in focus continues its tradition of shaping how new technologies are introduced and applied, this time it envelops multiple REE minerals, chemistries, and domains. Due to the EO's recognition that energy security greatly impacts national security, DoD will almost certainly be motivated to innovate requirements that solve for both installation and operational energy as well as contested logistical environments; hence, alternative LDES chemistries will need to provide significant advantages over traditional fossil fuels for the spectrum of energy facilities and their operations together with the deployed operational platforms that project nation-state power.

Policy Implications

While the White House and DoD have recognized the importance of being an innovative technological leader in the energy transition, the U.S. lags China in key technological aspects and in securing the critical minerals to build them. China is responsible for more than 50 percent of the global solar panel module exports and controls 80 percent of the global Lithium-ion battery refining and 77 percent of the global battery cell capacity.[21] China's dominance of the storage market will make the global energy transition dependent on its exports. This energy dependence can become geopolitical power, as the world may "rely on close economic cooperation and trade with China to realize carbon neutrality…as urgency over decarbonization increases in the years to come, Beijing will likely see its diplomatic and economic leverage grow significantly."[22]

A Chinese-dominated battery market poses substantial energy resilience and geopolitical risk for the United States as well. As the U.S. military accelerates its shift towards electrification, for example, it could find itself reliant on foreign sources, i.e., China, to meet its battery needs.

Building a domestic Li-ion supply chain that is competitive in technology performance and cost, however, will take time and require the build-up of new capabilities and infrastructure. As the U.S. seeks

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[17] "U.S. Government Energy Consumption by Agency and Source," U.S. Department of Transportation, Bureau of Transportation Statistics, available at https://www.bts.gov/content/us-government-energy-consumption-agency-and-source.

[18] "FY 2021 AEMRR," U.S. Department of Defense, Acquisition and Sustainment, Office of the Undersecretary of Defense, October 2022, available at https://www.acq.osd.mil/eie/Downloads/IE/FY%202021%20AEMRR.pdf.

[19] "U.S. Government Energy Consumption by Agency and Source," U.S. Department of Transportation, Bureau of Transportation Statistics, available at https://www.bts.gov/content/us-government-energy-consumption-agency-and-source.

[20] David Vergun, "DoD Turns to Industry to Meet Carbon Pollution-Free Energy Targets," U.S. Department of Defense, February 3, 2022, available at https://www.defense.gov/News/News-Stories/Article/Article/2922149/dod-turns-to-industry-to-meet-carbon-pollution-free-energy-targets/.

[21] Parker Bolstad, "Energy Independence Doesn't Mean What it Used To," Foreign Policy, July 26, 2021.

[22] Parker Bolstad, "Energy Independence Doesn't Mean What it Used To," Foreign Policy, July 26, 2021.

to quickly close this capability gap with China and promote onshoring of the Li-ion value chain through efforts such as the *American Battery Materials Initiative*, it also risks becoming more dependent on foreign-owned cell manufacturers. While these manufacturers will be able to quickly ramp-up domestic manufacturing capacity, it may lead to the U.S. becoming primarily a manufacturing and fabrication center of foreign-owned manufacturers seeking entry to the U.S. market – a "mere assembler" for other countries. The high-value add activities of research & development, as well as sales and marketing, would remain concentrated in foreign—owned companies.

To become a global innovative technology leader in battery and long-duration energy storage (LDES) technologies, the U.S. must look beyond lithium and look to accelerate the growth and adoption of novel long-duration storage battery technology and manufacturing capacity. This will allow the U.S. to decrease its energy and material reliance on foreign countries, while increasing its investment in its technology and human capital.

As the China example shows, government support is a key enabler in building a LDES industry, either through accommodative policy (e.g., subsidies) or fulfilling a role as a consumer. Similarly, the DIU and DoD writ-large have the potential to play a role in the growth of a domestic LDES market.

To help guide the potential actions the DIU and DoD can take, this paper aims to assess:

- The technical advantages and limitations of different novel long-duration storage technologies
- The defense applications of LDES across operational, installation, resiliency and intermittency use cases
- Actions the DIU and DoD can use to accelerate the development of the LDES industry

DEFENSE MARKET

Because of the massive size and scale of the DoD, nearly every civilian use case for LDES also provides a use case "bogey" for DoD, in addition to numerous, unique military use cases. DoD use cases for various LDES technologies broadly fall under two categories of DoD energy consumption: operations and installations.

Operational Use Cases

DoD defines operational energy as "energy required for training, moving, and sustaining military forces and weapons platforms for military operations," which comprises roughly two thirds of DoD's overall energy consumption.[23] In FY 2020, DoD consumed roughly 78 million barrels of fuel (450 trillion BTUs) costing $9.2 billion to support its operational energy needs, which included powering ships, aircraft, tactical vehicles, and contingency bases.[24] [25] While DoD elements increasingly rely on Li-ion batteries for numerous operational applications in their warfighting platforms, including unmanned vehicles, communications systems, and ground tactical vehicles, fossil fuel use still reigns supreme for operations.[26] As the federal government continues to shift focus towards a net-zero future, DoD desires to pursue renewable energy sources to replace high-density fossil fuels that were the mainstay for more than a century. Renewables plus adopting new storage technologies will be critical for storing and dispensing renewable energy.

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[23] "FY 2021 AEMRR," U.S. Department of Defense, Acquisition and Sustainment, Office of the Undersecretary of Defense, October 2022, available at https://www.acq.osd.mil/eie/Downloads/IE/FY%202021%20AEMRR.pdf.

[24] "FY 2021 AEMRR," U.S. Department of Defense, Acquisition and Sustainment, Office of the Undersecretary of Defense, October 2022, available at https://www.acq.osd.mil/eie/Downloads/IE/FY%202021%20AEMRR.pdf.

[25] "Fiscal Year 2020 Operational Energy Annual Report," U.S. Department of Defense, Office of the Under Secretary of Defense for Acquisition and Sustainment, May 2021, available at https://www.acq.osd.mil/eie/Downloads/OE/FY20%20OE%20Annual%20Report.pdf

[26] "Climate Adaptation Plan 2022 Progress Report," U.S. Department of Defense, October 2022, available at https://media.defense.gov/2022/Oct/06/2003092213/-1/-1/0/2022-DoD-CAP-PROGRESS-REPORT.PDF.

Electrified Mobility Use Cases

With a massive, highly dispersed DoD presence across the globe, providing logistical support is already costly during peacetime, and exceedingly expensive in a combat environment. During the conflicts in Iraq and Afghanistan over the past two decades, DoD transported an incredible amount of fuel to sustain forward operating bases (FOBs), military operations, and military service members abroad, leading to exorbitantly high costs and high fuel consumption to simply transport fuel to where it would be consumed, in some cases costs potentially as high as $400 per gallon.[27] Today, transporting 1 gallon of fuel to DoD servicemembers and installations in the Arctic or Pacific, which are further from available fossil fuel resources and logistical support lines, can require as many as 10 gallons of fuel.[28] In addition to high financial and environmental costs, heavy reliance on fossil fuel power generation has also had a significant human cost, with numerous casualties resulting from improvised explosive devices emplaced on supply routes and attacks on logistical convoys.

In FY 2007, U.S. forces suffered 1 casualty for every 24 fuel-related resupply convoys in Afghanistan, and 1 casualty for every 39 fuel-related resupply convoys in Iraq.[29] As the DoD shifts from focusing on counterinsurgency and stability tasks towards large-scale combat operations, the risk to logistical support lines will be much greater.

In the recent Russia-Ukraine conflict, Ukrainian forces have exploited occupying Russian forces' reliance on fuel resupply by heavily targeting Russian fuel tankers, leading to an estimated 239 Russian fuel tankers lost as of December 2022.[30] Vulnerabilities in the fuel supply can degrade not only motorized transportation, but also generators, heaters, electronics, and myriad equipment reliant on fuel. Similar vulnerabilities could also affect ships, aircrafts, and stationary generators for FOBs.

Increased electrification of vehicles and equipment necessary for DoD operations could allow DoD to rely instead on renewable energy sources much closer to where U.S. forces operate, dramatically reducing energy costs and logistical vulnerabilities. As of 2021, DoD has already begun to explore the possibility of employing mobile vehicle-centric microgrids, which could allow for incorporating renewable energy sources and LDES technology for grid storage as part of ground military movement.[31] Additionally, advancements in increasingly energy dense battery chemistry technology have allowed some private firms like Joby Aviation to build electric vertical take-off and landing (EVTOL) prototypes that could eventually form the basis for future electrified military aviation technology.[32] All these developments could help to reduce DoD reliance on fuel lines to support expeditionary operations, reducing risks and vulnerabilities for deployed forces.

Separate from simply providing benefits of increased electrification and reduced fuel reliance, some LDES technology firms have suggested possible dual-use properties for LDES beyond solely mobile power storage. Powered Armor Technologies, a carbon electrochemical capacitor technology firm, has proposed using its batteries as armor for FOBs, vehicles, or individuals, providing extremely durable LDES technology.[33] Electrifying large, heavy military vehicles, aircraft, and equipment will require light, energy dense, and cost-effective storage sources. While the DoD's initial research has focused on Li-ion storage, alternative chemistries will very likely be necessary to scale due to already identified issues with

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[27] David J. Gorsich and Andr Boehman, "Driving Fuel Choices," U.S. Army, December 14, 2020, available at https://www.army.mil/article/241758/driving_fuel_choices.

[28] Interview with Charles Decker and David Pogue, U.S. Army Corps of Engineers, Engineer Research and Development Center - Construction Engineering Research Laboratory, Champaign, IL, March 7, 2023.

[29] David S. Eady, Steven B. Siegel, R. Steven Bell, and Scott H. Dicke, "Sustain the Mission Project: Casualty Factors for Fuel and Water Resupply Convoys," September 17, 2009, available at https://apps.dtic.mil/sti/pdfs/ADB356341.pdf.

[30] Vikram Mittal, "Ukrainian Military Is Targeting Russian Fuel Supply Lines As Winter Approaches," Forbes, December 11, 2022.

[31] Dan Lafontaine, "Army Researches Vehicle Grid for Resilient Battlefield Power," U.S. Army, May 17, 2021, available at https://www.army.mil/article/246348/army_researches_vehicle_grid_for_resilient_battlefield_power.

[32] Thom Patterson, "Cracking the Code for eVTOL Batteries," Flying Mag, September 8, 2022, Available at https://www.flyingmag.com/cracking-the-code-for-evtol-batteries/.

[33] P. VanBeek, "Powered Armor Technologies Interview," January 20, 2023.

the Li-ion market and supply chains.[34]

Leveraging non Li-ion LDES technologies could offer dual use benefits that would help to increase the applicability of LDES to heavier and heavier military vehicles, making LDES overall more and more deployable throughout the DoD. Ultimately, taking transportation and communications as exemplars, LDES could play a role in enabling DoD operations and installations by (i) electrifying vehicles and equipment, (ii) incorporating renewable energy sources into electric power systems and distribution grids, and (iii) deploying energy storage strategically to increase overall DoD resiliency and lethality.

Installation Use Cases

As of FY 2021, the DoD owned and maintained 284,359 buildings comprising 2.31 billion square feet of space at over 500 installations across the globe.[35] DoD is responsible for running the equivalent of several hundred small to moderate sized towns in both the U.S. and overseas, each with substantial power generation requirements and an increasing number of installations operating on independent microgrids rather than relying on public utilities.[36] While DoD operations comprise most of DoD's energy consumption, DoD installations' requirements comprise roughly a third of DoD's overall consumption.[37] In FY 2021, DoD spent $3.43 billion on mostly fossil fuel derived energy sources to operate their installations and a fleet of approximately 160,000 non-tactical vehicles residing on the installations.[38] [39] The transition to renewable energy sources for these DoD installations as part of EO 14057 will likely drive DoD to adopt LDES technology for many of the same use cases as the civilian sector, especially grid storage to overcome resiliency and variability challenges from many renewable energy sources. The scale of LDES capacity required for carbon-free energy production at DoD installations along with the price and supply- chain vulnerabilities of existing Li-ion batteries will incentivize DoD to increasingly rely on alternative LDES chemistries and pursuing multiple potential technologies in the early stages can help mitigate risks to succeeding.

Resiliency and Intermittency Use Cases

DoD views its facilities' ability to withstand utilities and power disruptions as critically important to carrying out its missions and seeks to ensure its installations are not overly reliant on solely commercial power generation.[40] In FY 2021, DoD installations experienced 6,288 unplanned utility outages costing $128 million, generally caused by weather or mechanical failure.[41] DoD has historically relied on building-level, fossil fuel powered backup generators for emergency power, but has increasingly shifted towards microgrids to increase installation energy resilience due to concerns that these building-level generators will not support DoD critical missions in the event of a large-scale outage.[42] Critical, power-intensive facilities like hospitals, clinics, and data centers located on DoD installations would be at high risk during this sort of outage. In February 2022, the U.S. Army announced plans to install a microgrid on all its installations before 2035 and has already scoped and planned 24 microgrid projects at its installations through 2024.[43] In May 2022, the U.S. Navy and Marine Corps also committed to

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[34] Andrew Eversden, "Army Ground Vehicle Lab Researches Different Batteries in Quest for Electrified Fleet," BreakingDefense.com, August 4, 2022.

[35] "FY 2021 AEMRR," U.S. Department of Defense, Acquisition and Sustainment, Office of the Undersecretary of Defense, October 2022, p. 5, available at https://www.acq.osd.mil/eie/Downloads/IE/FY%202021%20AEMRR.pdf.

[36] Lee Robinson interview, January 19, 2023.

[37] Timothy Renahan, "Realizing Energy Independence on U.S. Military Bases," National Defense University Press, October 14, 2021, available at https://ndupress.ndu.edu/Media/News/News-Article-View/Article/2808076/realizing-energy-independence-on-us-military-bases/.

[38] "FY 2021 AEMRR," U.S. Department of Defense, Acquisition and Sustainment, Office of the Undersecretary of Defense, October 2022, p. 5, available at https://www.acq.osd.mil/eie/Downloads/IE/FY%202021%20AEMRR.pdf.

[39] "Installation Energy," U.S. Department of Defense, Office of the Assistant Secretary of Defense for Sustainment, available at https://www.acq.osd.mil/eie/IE/FEP_index.html.

[40] "FY 2021 AEMRR," U.S. Department of Defense, Acquisition and Sustainment, Office of the Undersecretary of Defense, October 2022, p. 16, available at https://www.acq.osd.mil/eie/Downloads/IE/FY%202021%20AEMRR.pdf.

[41] "FY 2021 AEMRR," U.S. Department of Defense, Acquisition and Sustainment, Office of the Undersecretary of Defense, October 2022, pp. 17-18, available at https://www.acq.osd.mil/eie/Downloads/IE/FY%202021%20AEMRR.pdf.

[42] "FY 2021 AEMRR," U.S. Department of Defense, Acquisition and Sustainment, Office of the Undersecretary of Defense, October 2022, p. 63- 64, available at https://www.acq.osd.mil/eie/Downloads/IE/FY%202021%20AEMRR.pdf.

[43] Jen Judson, "With New Climate Strategy, Army Aims to Prepare Soldiers for Harsher Environments," DefenseNews, February 8, 2022.

increasingly deploying microgrids as part of their climate action strategy.[44] As DoD shifts towards microgrids and increasingly incorporates renewable energy sources as part of initiatives related to EO 14057, DoD will need to increase energy storage capacity to manage variable power output, store energy generated onsite, and reduce reliance on diesel fuel resupply requiring new efficient and cost-effective LDES infrastructure.[45]

DoD Case Studies

At Fort Carson, Colorado, the Army has begun to install new LDES infrastructure to support the resiliency and intermittency use case, including redox flow battery technology. In November 2022, Fort Carson began constructing a 10 megawatt hour (MWh) redox flow battery to increase the installation's resiliency, adding to an existing 2 megawatt (MW) Li-ion battery system supporting solar panels at the installation.[46] [47] This larger project follows earlier battery projects at DoD facilities including Marine Corps Recruit Depot Parris Island, which in 2015 began implementing a comprehensive resiliency project including the construction of a 4 MW Li-ion storage system.[48] Compared to existing Li-ion storage systems, Fort Carson's new redox flow system can be operated more flexibly at expanded operational parameters that would have risked damaging Li-ion systems, and has very limited degradation over time to ensure long-term use.[49]

Examining Twentynine Palms' unique microgrid and storage needs helped to illustrate how a one-size-fits-all storage solution will not meet the needs of each installation's microgrid project. Twentynine Palms has an extremely hot, dry, and dusty climate. They have already set up a microgrid powered by gas turbines and solar on the installation to promote resiliency and are seeking storage to help smooth out the combination of these two technologies.[50] One of the key requirements for Twentynine Palms is that whatever storage solutions are used must be able to endure extreme temperatures and to store energy for several days if bad weather prevents solar power generation.[51] In contrast, a cold climate installation or a substantially larger installation may require a very different storage solution and potentially different storage chemistry for their microgrid project. Additionally, the Twentynine Palms case study highlighted an operational challenge of where to install LDES systems. Due to fire codes and uniform facility codes focused on minimizing flammability risks of Li-ion systems, Twentynine palms is installing their LDES system at their central utility plant.[53] This is both a challenge and an opportunity: the LDES system can serve as a backup power source for the central utility plant but increases the complexity of the control system to integrate the LDES onto the installation's power grid.[53] Each installation electrical grid and control system will be very different, and these differences will influence how battery systems are installed and the control system they use.[52] With microgrids installed at only a handful of over 500 DoD installations worldwide, demand for a variety of higher MW LDES technology solutions will only increase in the coming years as DoD strives to meet its future microgrid deadlines across vastly different types of installations.

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[44] "Department of the Navy Releases Climate Action 2030," U.S. Navy, Navy.mil, May 24, 2022.

[45] Robert Fares, "Renewable Energy Intermittency Explained: Challenges, Solutions, and Opportunities," Scientific American, March 11, 2015.

[46] Rob Verger, "How the Massive 'Flow Battery' Coming to an Army Facility in Colorado Will Work," Popular Science, June 16, 2022.

[47] Valerie Mills, "Battery Project Makes Fort Carson More Self-sufficient," Fox21 Local News, available at https://www.fox21news.com/news/battery-project-makes-fort-carson-more-self-sufficient/.

[48] "Comprehensive Resiliency Project Assures Continuity of Mission-critical Operations at MCRD Parris Island," Amaresco, available at https://www.ameresco.com/portfolio-item/parris-island/.

[49] Andy Colthorpe, "Lockheed Martin Putting Long-duration Flow Battery at U.S. Army's Fort Carson," Energy Storage News, June 15, 2022, available at https://www.energy-storage.news/lockheed-martin-putting-long-duration-flow-battery-at-us-armys-fort-carson/.

[50] Interview with Gary Morrissett from Twentynine Palms on February 28, 2023.

[51] Interview with Gary Morrissett from Twentynine Palms on February 28, 2023.

[52] Interview with Gary Morrissett from Twentynine Palms on February 28, 2023.

ALTERNATIVE CHEMISTRIES TO LITHIUM ION

LDES can play a key role in meeting the DoD's resilience and energy security needs as it seeks to project power in future contested environments. Enabling this capability without relying on critical minerals for the LDES from non-allied countries, however, necessitates a move away from the current generation of Lithium-based energy storage solutions. This section evaluates the leading non-Lithium chemistries that can be used for LDES.

There are two key variables when evaluating different energy storage systems: capacity, measured in kilowatt or megawatt hours (kWh or MWh), and power, measured in kilowatts or megawatts (kW or MW). Capacity is sometimes measured by duration, e.g., a six-hour battery, which means the battery can sustain its peak power for six hours. For example, a 4 MW battery with 24 MWh of capacity at maximum load would have the ability to last six hours, or six-plus hours at lower load levels. This report focuses on long-duration storage which we define as at least eight hours of storage capacity.[53, 54] There are generally tradeoffs between energy capacity and power with different chemistries. Figure 1 shows this trade-off for several common chemistries today. The higher power chemistries can provide instantaneous responses to changing energy demands but may not be able maintain this for an eight-plus hour duration or it may not be cost effective. On the other hand, a high specific energy means more energy can be stored for longer. The figure compares these on a per kilogram (kg) basis, giving a sense for the scale (and cost) of the different chemistries. It is important to note that many of the technologies evaluated show potential for eight-plus hour duration storage but have not yet been demonstrated at this duration. Key chemistries evaluated in this report include: lead acid, sodium, rechargeable alkaline zinc, metal-air, nickel iron, vanadium, zinc-bromine, and iron flow batteries, and electrochemical capacitors.

This section will provide an overview of the LDES market and key technical figures for each chemistry. The available technologies are evaluated on four main criteria: storage duration, cost, technology readiness level (TRL), and current challenges to deploying this technology. A prerequisite for our evaluation is ensuring a U.S. value chain for the battery chemistry. This means being able to source the key components (i.e., minerals) from the U.S. or allied nations as well as the ability to assemble the product domestically. The storage duration and cost are based on publicly-available material. For cost, we evaluate how economies of scale might enable long-term cost declines and what the critical bottlenecks are for cost. Furthermore, most companies do not cite the "balance of plant" cost which would detail all the costs to get a system connected and instead report the cost of the core battery materials itself. The TRLs assigned in this report are based on our own assessments from publicly-available documents, articles, and interviews for each technology and are assigned based on the DoD's TRL definitions Table A-1 in Appendix A. One overarching current challenge in the LDES space is deploying new technology at a DoD-relevant scale. Many technologies exist today at residential (~10 kW) and commercial (~100kW) scales, but few have been deployed at a DoD-relevant scale, which we define as a minimum of 1MW for a demonstration project. For LDES to have an impact across the DoD, there will need to be hundreds of deployments from 1 MW to 10s of MW. This will need to happen in a form factor (i.e. battery density) that is scalable and be coupled with battery management technology to make repeated cycling feasible.

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[53] The U.S. Department of Energy defines LDES as 10 hours not 8 hours. DIU meanwhile adds a requirement of a minimum of 50kW discharge power over 8 hours for any LDES technology. This means the LDES must have at least 400 kWh of available capacity. This discharge requirements eliminates the possibility of using a standard battery but not discharging a lot of power over a long duration. For this, please see "DIU Leverages Commercial Technology to Drive Climate and Energy Resilience," Defense Innovation Unit, April 21, 2023, available at https://www.diu.mil/latest/diu-leverages-commercial-technology-to-drive-climate-and-energy-resilience.

[54] Paul Denholm, Wesley Cole, et al., "The Challenge of Defining Long-Duration Energy Storage," National Renewable Energy Laboratory, 2021.

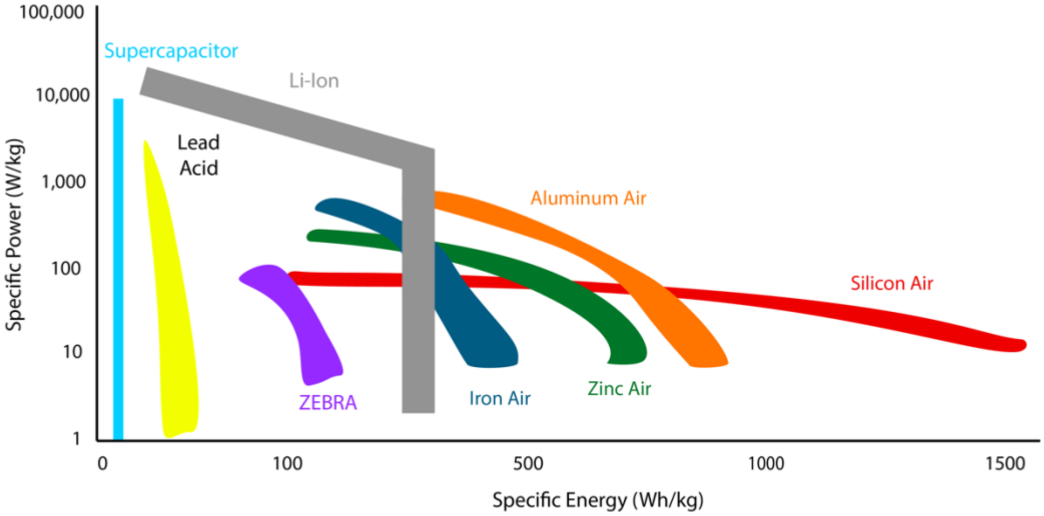

Figure 1. *A "Ragone plot" that compares energy capacity (x-axis) with power (y-axis) for different chemistries based on a normalized weight. Figure data from H. Budde-Meiwes et al. 2013*[55] *and G.P. Wheeler et al. 2022.*[57]

Lead-Acid

First developed in 1859, Lead-acid batteries are amongst the oldest types of rechargeable batteries. With mature technology found everywhere from car batteries to large data centers, lead-acid batteries offer a mature (TRL-10), relatively low cost solution ($260/kWh)[56] extensively deployed around the world (as of 2017, lead-acid chemistries had the largest rechargeable battery market share by way of sales and capacity (MWh)).[57] However, lead-acid batteries face numerous integration challenges with renewable energy and many larger, grid-scale deployments are being replaced with other technologies, especially Li-ion.[58] Relatively low cycle lives, often three years or less if used daily,[59] rates of charging and discharging, and energy density for Lead-acid batteries make them less economical for grid-scale energy storage applications and the market preference for newer technology is likely to continue.[60] Most lead-acid batteries are designed for short-duration storage, on the order of one to four hours. Research into advanced lead batteries, however, hopes to change this. Researchers have designed an advanced Lead-Carbon battery that in laboratory testing has achieved a cycle life of 1,000 to 5,000 cycles to 80% depth of discharge.[61] This performance, if scaled from the lab to full-scale implementation, would beat out almost all Li-ion systems. Advanced Lead batteries are still at TRLs less than 5, however, and more development work is needed to get them to full scale production.[62]

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[55] H. Budde-Meiwes et al., "A Review of Current Automotive Battery Technology and Future Prospects," Proc. Inst. Mech. Eng. Part J. Automob. Eng., vol. 227, no. 5, pp. 761-776, May 2013, doi: 10.1177/0954407013485567.

[56] K Mongird, V Viswanathan, et al., "Energy Storage Technology and Cost Characterization Report," U.S. Department of Energy, Hydrowires, July 2019.

[57] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), pp. 7, 10, 13, doi: 10.1017/9781009030359.

[58] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), p. 13, doi: 10.1017/9781009030359.

[59] K Mongird, V Viswanathan, et al., "Energy Storage Technology and Cost Characterization Report," U.S. Department of Energy, Hydrowires, July 2019.

[60] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), p. 14, doi: 10.1017/9781009030359.

[61] "Technical Roadmap: Research and Innovation Pathways for Next-generation Advanced Lead Batteries," Consortium for Battery Innovation, September 2021, available at https://batteryinnovation.org/innovation/research-excellence/technical-roadmap/.

[62] "Technical Roadmap: Research and Innovation Pathways for Next-generation Advanced Lead Batteries," Consortium for Battery Innovation, September 2021, available at https://batteryinnovation.org/innovation/research-excellence/technical-roadmap/.

Lead-Acid Market Overview

Due to technology maturity, the market for lead-acid batteries is fragmented, but there are many American producers including C&D Technologies (U.S.), EaglePicher Technologies (U.S.), EnerSys (U.S.), Exide Technologies (U.S./EU), and Rolls Battery Engineering (U.S.).

Sodium (Na)

Sodium-Sulfur batteries are a molten-salt battery that is commonly used in commercial grid-scale storage today (TRL-10).[63] These batteries use commonly available elements (sodium and sulfur) and have an energy density four times that of lead-acid batteries.[64] They have a lifetime of 2,500 cycles to 90% depth of discharge, but they must be maintained at 300°C which poses operational challenges and risks.[65] This high operating temperature further complicates manufacturing, requiring specialized processes.[66] Cost estimates vary widely, ranging from $40-$661/kWh.[67,68]

Consequently, recent development has been focused on improvements in Sodium-Metal Halide Batteries, often called ZEBRA batteries. ZEBRA batteries often use Sodium, Chlorine, and Nickel, of which only Nickel is expensive to obtain, so proposals for the use of Zinc or Iron have been evaluated.[69] They also have the benefit of operating at lower temperatures (less than 100°C) and use less corrosive elements so are intrinsically safer.[70] Ultimately, while Sodium-Sulfur batteries are commercially available today, their downsides have pushed researchers toward ZEBRA batteries, which are still at low TRLs today.

Another Sodium-based chemistry is Sodium-ion. These batteries are higher-mass and lower energy density, which is ideal for stationary grid storage.[71] Compared with Li-ion, they are more stable and less flammable.[72] Similar to other Sodium-based batteries, the raw materials are widely available domestically.

Sodium Battery Market Overview

Sodium battery deployments largely consist of Na-S (Sodium-Sulphate) and ZEBRA ($Na-NiCl_2$) chemistries. Na-S batteries can have lower total costs than some chemistries, however, safety concerns over high operating temperatures, reliance on highly flammable chemicals, and the prerequisite of a

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[63] D. Kumar, S. K. Rajouria, S. B. Kuhar, and D. K. Kanchan, “Progress and Prospects of Sodium-Sulfur Batteries: A Review,” Solid State Ion., vol. 312, pp. 8-16, December 2017, doi: 10.1016/j.ssi.2017.10.004.

[64] D. Kumar, S. K. Rajouria, S. B. Kuhar, and D. K. Kanchan, “Progress and Prospects of Sodium-Sulfur Batteries: A Review,” Solid State Ion., vol. 312, pp. 8-16, December 2017, doi: 10.1016/j.ssi.2017.10.004.

[65] D. Kumar, S. K. Rajouria, S. B. Kuhar, and D. K. Kanchan, “Progress and Prospects of Sodium-Sulfur Batteries: A Review,” Solid State Ion., vol. 312, pp. 8-16, December 2017, doi: 10.1016/j.ssi.2017.10.004.

[66] D. Kumar, S. K. Rajouria, S. B. Kuhar, and D. K. Kanchan, “Progress and Prospects of Sodium-Sulfur Batteries: A Review,” Solid State Ion., vol. 312, pp. 8-16, December 2017, doi: 10.1016/j.ssi.2017.10.004.

[67] K Mongird, V Viswanathan, et al., “Energy Storage Technology and Cost Characterization Report,” U.S. Department of Energy, Hydrowires, July 2019.

[68] “CATL Reveals Sodium-Ion Battery With 160 Wh/kg Energy Density,” CleanTechnica, July 30, 2021, available at https://cleantechnica.com/2021/07/30/catl-reveals-sodium-ion-battery-with-160-wh-kg-energy-density/, accessed on February 24, 2023.

[69] X. Zhan, M. M. Li, J. M. Weller, V. L. Sprenkle, and G. Li, “Recent Progress in Cathode Materials for Sodium-Metal Halide Batteries,” Materials, vol. 14, no. 12, Art. no. 12, January 2021, doi: 10.3390/ma14123260.

[70] X. Zhan, M. M. Li, J. M. Weller, V. L. Sprenkle, and G. Li, “Recent Progress in Cathode Materials for Sodium-Metal Halide Batteries,” Materials, vol. 14, no. 12, Art. no. 12, January 2021, doi: 10.3390/ma14123260.

[71] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781009030359.

[72] G. Hough and C. Grant, “Natron Battery Technology and U.S. Safety Codes and Standards,” Energy Safety Response Group, June 17, 2022, available at https://natron.energy/wp-content/uploads/ESRG-Natron-Battery-Safety-Report.pdf.

water-free environment makes Na–S batteries unattractive to many customers and use cases.[73] Until these issues are resolved, or risks better understood in rugged operating environments, it is unlikely that Na batteries will be DoD's chosen alternative to Li-ion chemistries. ZEBRA batteries face similar challenges to Na–S and are more expensive per kWh.[74] As with many nascent technologies, the market for Na batteries is consolidated and manufacturing is largely located outside of the U.S., although many manufacturers are allied nations. Current producers include Natron Energy (U.S.), Faradion (UK-India owned), NGK Insulators (Japan), Tiamat (France), HiNa Battery Technology Co. (China), Contemporary Amperex Technology Co. (China). Natron Energy is one of the only U.S.-based companies. They are currently focused on small-commercial scale deployments, particularly for data centers.[75] They have not demonstrated any storage at the MW-scale that the DoD needs.

Rechargeable Aqueous Zinc Battery

Rechargeable aqueous zinc batteries (RAZB) are highly energy dense, safe, and use low-cost elements.[76] These batteries are essentially rechargeable versions of alkaline batteries (i.e., the AA's you buy at the grocery store). Zinc is the main element and very inexpensive, but more research is needed to deploy it to commercial scale as the TRL is at or below an 8.[77] RAZBs can have lifetimes approaching 10 years.[78]

Rechargeable Aqueous Zinc Battery Market Overview

Urban Electric Power currently markets a RAZB based on over a decade of research, with a handful of test installations at commercial[79] and residential scales.[80] They purport to have 4.5 hours of storage duration at a cost of $400/kWh for their initial residential unit, which has 8.8kWh of capacity and a peak output of 2 kW.[81] They have not yet reached wide scale deployment at the MW-scale needed for DoD installations.

Metal-Air

Metal Air batteries have been around in various forms for decades, primarily in the form of Zinc-air batteries for hearing aids.[82] Metal air batteries rely on a reaction between oxygen in the air and a metal electrode, often made of abundant elements such as Zinc, Aluminum, Silicon, or Iron.[83] Metal air batteries have higher capacities per kg than Li-ion, although their power can be an order of magnitude lower, making them ideal for long-duration, high capacity energy storage.[84] The Ragone plot for several different chemistries can be found in Figure 1.

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[73] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), p. 32, doi: 10.1017/9781009030359.

[74] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), p. 34, doi: 10.1017/9781009030359.

[75] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781009030359.

[76] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781009030359.

[77] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781009030359.

[78] K Mongird, V Viswanathan, et al., "Energy Storage Technology and Cost Characterization Report," U.S. Department of Energy, Hydrowires, July 2019.

[79] "Urban Electric Power Installs 1,000-kWh Alkaline Battery Backup System for San Diego Supercomputer Center," Urban Electric Power, Apr. 18, 2022, available at https://urbanelectricpower.com/2022/04/18/urban-electric-power-installs-1000-kwh-alkaline-battery-backup-system-for-san-diego-supercomputer-center/, accessed on February 23, 2023.

[80] A. Lenthall, "Urban Electric Power's Rechargeable Alkalines Offer Non-toxic Energy Equity to Navajo Nation and Families Off-the-grid," EIN Presswire, June 22, 2022, available at https://www.einpresswire.com/article/577266483/urban-electric-power-s-rechargeable-alkalines-offer- non-toxic-energy-equity-to-navajo-nation-and-families-off-the-grid, accessed on February 23, 2023.

[81] Ohm Core - OHM by Urban Electric Power," OHP World Wide Web Site, available at https://ohmproducts.com/products/ohm-core, accessed on February 24, 2023.

[82] A. G. Olabi et al., "Metal-Air Batteries - A Review," Energies, vol. 14, no. 21, p. 7373, November 2021, doi: 10.3390/en14217373.

[83] A. G. Olabi et al., "Metal-Air Batteries - A Review," Energies, vol. 14, no. 21, p. 7373, November 2021, doi: 10.3390/en14217373.

[84] A. G. Olabi et al., "Metal-Air Batteries - A Review," Energies, vol. 14, no. 21, p. 7373, November 2021, doi: 10.3390/en14217373.

Metal-Air Market Overview

Zinc-Air batteries have been deployed in microgrid use around the world by Fluidic Energy (formerly NantEnergy), although round-trip efficiency is low (less than 65% compared to 80-90% for other chemistries) and long-term durability remains open questions.[85] [86] Zinc-Air batteries are thus at a TRL-10. Iron-air batteries are still in prototyping stages (TRL-6) but offer the possibility of very low-cost, long-duration energy storage for stationary grid-scale applications.[87] Form Energy is a leader in Iron-Air batteries, with a promise to make a 100-hour battery, but they have yet to deploy any batteries in 2023, with their first commercial installations expected in 2024.[88] Additionally, to achieve their desired cost thresholds by reducing balance of plant costs, Form is looking to deploy 10+ MW of their LDES at a single installation.[89] At this scale, Form Expects the cost to be $20/kWh at full rate production. Even at this low per kWh cost, the capital cost will be high — on the order of $20 million a unit — considering the 100-hour duration and 10 MW minimum size.

Nickel-Iron

Nickel-Iron batteries are currently in use for small-scale stationary storage solutions around the world. They have several disadvantages including low energy storage capacity per kg and a self-discharge of greater than 1% a day, meaning they lose stored energy over time more quickly than other chemistries.[90] Even though the component elements are in theory less expensive and more abundant, they tend to be more expensive than Lead-Acid and Li-ion batteries.[91] They have durations ranging from 4 to 10 hours, at a cost of $1,000/kWh.[92] One key benefits is that when properly maintained, they have long expected lifetimes of potentially 30 years.[93]

Nickel-Iron Market Overview

Iron Edison sells Nickel-Iron batteries today at commercial scales, but they require maintenance and upkeep that generally makes them less than ideal for wide scale deployment.[94] They are also often very costly compared to their competitors.

Flow Batteries

One of the emerging approaches to electrical energy storage is using flow batteries. First proposed in 1879, their development has had fits and starts in the intervening century.[95] With renewed research interest in the last few decades, flow batteries show growing promise to meet energy storage needs

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[85] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781009030359.

[86] "ARPA-E Project | High-Power Zinc-Air Energy Storage," U.S. Department of Energy, available at http://arpa- e.energy.gov/technologies/projects/high-power-zinc-air-energy-storage, accessed on February 24, 2023.

[87] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781009030359.

[88] A. Colthorpe, "Year in Review 2022: Long-duration Storage with Iron-air Battery Company Form Energy," Energy Storage News, January 11, 2023, available at https://www.energy-storage.news/year-in-review-2022-long-duration-storage-with-iron-air-battery-company-form-energy/, accessed on February 24, 2023.

[89] Interview with Leonardo Yuque from Defense Innovation Unit, March 14, 2023.

[90] F. Hussain, M. Z. Rahman, A. N. Sivasengaran, and M. Hasanuzzaman, "Chapter 6 - Energy Storage Technologies," in MD. Hasanuzzaman and N. A. Rahim, eds., Energy for Sustainable Development (Cambridge, MA: Academic Press, 2020), pp. 125-165, doi: 10.1016/B978-0-12- 814645-3.00006-7.

[91] F. Hussain, M. Z. Rahman, A. N. Sivasengaran, and M. Hasanuzzaman, "Chapter 6 - Energy Storage Technologies," in MD. Hasanuzzaman and N. A. Rahim, eds., Energy for Sustainable Development (Cambridge, MA: Academic Press, 2020), pp. 125-165, doi: 10.1016/B978-0-12- 814645-3.00006-7.

[92] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781009030359.

[93] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781009030359.

[94] F. Hussain, M. Z. Rahman, A. N. Sivasengaran, and M. Hasanuzzaman, "Chapter 6 - Energy Storage Technologies," in MD. Hasanuzzaman and N. A. Rahim, eds., Energy for Sustainable Development (Cambridge, MA: Academic Press, 2020), pp. 125-165, doi: 10.1016/B978-0-12- 814645-3.00006-7.

[95] Y. V. Tolmachev. "Review—Flow Batteries From 1879 To 2022 And Beyond," Journal of Electrochemical Society (2022).

without the same critical minerals as traditional electrochemical batteries.[96] There are several promising chemistries within the broader flow battery category: vanadium redox, zinc bromine, polysulfide bromine, and iron chromium.[97] Flow batteries are based on two tanks of solution, one negatively charged and the other positively charged, which when they interact by passing ions across a membrane, creates a flow of electric charge to an electrode.[98] The power output is determined by the size of the electrode and the number of electrodes while the energy capacity is based on the volume of the solutions and their specific composition.[99] Flow batteries are readily scalable to any storage duration needed, limited only by space and cost. Unlike many other chemistries, flow batteries can be discharged for tens of hours or more, and hold their charge relatively indefinitely, meaning they are good for long- term energy storage.[100] While long-term storage is possible, they are best used for frequent cycling and have a long lifetime that aligns with the lifetime of renewable energy systems, often estimated at 25+ years.[101] One of the other benefits to flow batteries is they use mostly non-flammable solutions and abundant elements, making their scalability potential attractive for both cost and safety considerations.[102] Costs are generally expected to be about $400-$500+/kWh.[103] Most flow battery chemistries have been demonstrated on commercial scales, but there are still some manufacturing challenges to low-cost, full- scale up that need to be addressed.[104]

Flow Battery Market Overview

Flow batteries present the largest growth over recent years of all non-Li-ion systems and may offer the most compelling alternative to Li-ion systems for both commercial and defense customers. Vanadium redox flow batteries (VRBs) are a current commercial leader, making up nearly 70% of all operational redox flow battery systems today. VRBs are particularly appealing for grid-scale energy storage due to their scalability and flexibility, excellent durability, high round-trip efficiency, and little environmental impact.[105] In general, the flow battery market is consolidated with relatively few U.S.-based participants: VRB Energy (Canada), Sumitomo Electric (Japan), Schmid Group (Germany), Primus Power Solutions (U.S.), Lockheed Martin–GridStar Flow (U.S.), Largo Inc. (Canada), ESS Inc. (U.S.), Redflow (Australia), CellCube (Austria), Invinity Energy Systems (UK), and StorEn (U.S.).

Invinity is one company currently deploying VRBs, with 65 MWh deployed or contracted around the world in 2023.[106] Invinity claims their batteries will last 25 years.[107] Lockheed Martin's GridStar is currently installing a 10 MWh redox flow battery at Fort Carson, CO which they claim to be the first long-duration system for the DoD.[108] The exact chemistry of the GridStar Flow battery is proprietary.

VRBs compete directly with Li-ion battery manufacturers for market share, and demand is elastic. Price

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[96] M. Park, J. Ryu, W. Wang, and J. Cho, "Material Design and Engineering of Next-generation Flow-battery Technologies," Nat. Rev. Mater., vol. 2, no. 1, Art. no. 1, November 2016, doi: 10.1038/natrevmats.2016.80.

[97] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781009030359.

[98] M. Park, J. Ryu, W. Wang, and J. Cho, "Material Design and Engineering of Next-generation Flow-battery Technologies," Nat. Rev. Mater., vol. 2, no. 1, Art. no. 1, November 2016, doi: 10.1038/natrevmats.2016.80.

[99] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781009030359.

[100] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781009030359.

[101] M. Park, J. Ryu, W. Wang, and J. Cho, "Material Design and Engineering of Next-generation Flow-battery Technologies," Nat. Rev. Mater., vol. 2, no. 1, Art. no. 1, November 2016, doi: 10.1038/natrevmats.2016.80.

[102] T. Casey, "U.S. Army Tests A New Flow Battery from Lockheed Martin," CleanTechnica, January 03, 2023, available at https://cleantechnica.com/2023/01/03/us-army-tests-a-new-flow-battery-from-lockheed-martin/, accessed on February 24, 2023.

[103] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781009030359.

[104] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), doi: 10.1017/9781009030359.

[105] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), pp. 7, 16, doi: 10.1017/9781009030359.

[106] "Utility-Grade Energy Storage / Invinity Energy Systems," Invinity, available at https://invinity.com/, accessed on February 24, 2023.

[107] "Utility-Grade Energy Storage / Invinity Energy Systems," Invinity, available at https://invinity.com/, accessed on February 24, 2023.

[108] "How the Large 'Flow Battery' Coming to Colorado Will Work," Popular Science, June 16, 2022, available at https://www.popsci.com/technology/flow-battery-for-army-fort-carson/, accessed on February 24, 2023.

sensitivity has been a challenge for VRBs which have had higher average total installation costs (for more see cost estimates in G. P. Wheeler et al. 2022) than Li-ion chemistries.[109] In the Department of Energy's (DOE) 2022 *Energy Storage Grand Challenge Cost and Performance Assessment*, a ten-hour VRB system deployed at a 1 MW scale has an estimated total installation cost (in 2021) of $436/kWh, compared to $402/kWh for a Lithium-iron-phosphate system with the same capacity and power output. Li-ion's lower perceived costs, particularly in upfront capital expenditures, hurts demand for VRB manufacturers who, in the absence of robust demand, are struggling to raise capital, increase capacity, and achieve cheaper prices through economies of scale.[110] DOE predicts that average prices for VRBs will decline by 2030, but Li-ion batteries will continue to drop in price at a faster rate (see Figure 2 for Invinity Energy System's estimates for their Vanadium Flow Battery and Mongirid et al. (2020) for DOE's current cost estimates and 2030 predictions for VRB and Li-ion lithium ferro phosphate (LFP) batteries).[111, 112]

In *Beyond Li-ion Batteries for Grid-Scale Energy Storage*, three scientists at Brookhaven National Laboratory summarize the pricing dynamics of VRBs as of June 2022:

> "*The VRB is the most mature flow battery technology and accounts for 75 MWh of deployed systems. The current technologies are still expensive in capital cost and life-cycle cost. VRBs are the most expensive flow battery chemistry, forecasted to cost $516/kWh in 2024 based on a model developed by Lux Research. [Redox flow] developers claim that sourcing vanadium from fly ash could reduce costs from over $500/kWh today to $300/kWh at scale. However, it has been estimated that even in the unrealistic scenario of a free vanadium electrolyte, VRB system costs will be $324/kWh in 2024. The Energy Storage Technology and Cost Characterization Report from DOE projected an even higher cost at $425/kWh in 2025. Recent research has suggested that improving the power density of VRB will drive down costs. Improvements in cell stack power density, for example, can cut costs by 33%.*"[113]

Despite facing serious competition with Li-ion batteries on price, VRBs offer several unique value propositions to commercial and defense customers. To better understand the opportunities and challenges facing VRB manufacturers, we conducted case studies, including executive interviews, of leading VRB manufacturers, which can be found in the following section.

There remain several open questions in the VRB space. First, the biggest cost component of most VRB systems is the vanadium itself. Companies need to identify approaches to bring this cost down if VRB is going to be cost-competitive with other chemistries. Furthermore, while several of the case studies mentioned potential vanadium supply in the U.S., this is a big risk as currently 75% of the market is from China. Transitioning to North American might be technically feasible, but this comes back to a question of cost: will North American VRB systems be cost-competitive enough to gain a foothold in the market? Some of these challenges could be addressed through the DIU's ability to support LDES technology that provides national security benefits that the market might not otherwise value. If the DoD is serious about supporting non-Lithium LDES technology for national security reasons, then substantial investment into alternative chemistries will be needed.

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[109] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), pp. 7, 16, doi: 10.1017/9781009030359.

[110] Kendall Mongird, Vilayanur Viswanathan et. al., "2020 Grid Energy Storage Technology Cost and Performance Assessment," U.S. Department of Energy, December 17, 2020, pp. 24, 42.

[111] Kendall Mongird, Vilayanur Viswanathan, et. al., "2020 Grid Energy Storage Technology Cost and Performance Assessment," U.S. Department of Energy, December 17, 2020, pp. 24, 42.

[112] Note that Invinity uses a different cost model that generates substantially lower $/MWh for both VRBs and Li-ion chemistries than DOE's industry analysis. This report does not render a judgment on the validity of Invinity's price comparison model, but it is included for demonstrating how VRBs may compete with Li-ion on pricing. For this, please see What Does Battery Storage Cost, Invinity World Wide Web Site, available at https://invinity.com/what-does-battery-storage-cost/#LCOS2A, accessed on March 22, 2023.

[113] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), p. 22, doi: 10.1017/9781009030359.

Electrochemical Capacitors

Electrochemical capacitors (often called ultracapacitors or supercapacitors) directly store electrical charge, meaning no energy conversion takes place and they can charge and discharge quickly.[114] Consequently, capacitors have long cycle lifetimes and do not wear out like most electrochemical batteries (50+ year lifetimes are possible).[115] They are currently used primarily for short-duration storage on the scale of seconds to minutes but show promise for future growth for the shorter end (8-10 hours) of long-duration storage applications. Electrochemical capacitors constructed using graphene (a form of carbon) can be integrated into vehicles and structures in the form of carbon-fiber, reducing total weight vs. steel and providing built-in energy storage capacity.[116] For example, the average sedan's roof, doors, and hood could be turned into capacitors that can propel the vehicle over 80 miles while reducing the vehicle's gross weight 15%.[117] Further development is needed to increase energy density and reduce cost.[118] However, one of the key benefits of electrochemical capacitors is they are fundamentally a non-flammable design because they rely only on charged carbon (or similar elements) for energy storage instead of potentially reactive mixes of different elements.[119, 120] This has potential implications when siting energy storage systems and applying them in different areas.

Electrochemical Capacitors Market Overview

The electrochemical capacitor field is growing with companies researching many ways to improve the design.[121] Many of the products in the electrochemical capacitor space are TRLs below 6. While basic research is ongoing, some technologies are ready to scale up out of the lab but need additional funding. Powered Armor Technologies (PAT) is one company in this position. PAT has prototypes for an ultracapacitor and is in the process of testing their first commercial-scale prototype, as discussed in the Case Study section. Other companies in this space include Maxwell Technologies (Korea).

Chemistry Conclusion

There are numerous private and public companies in the LDES space today at varying TRLs. The number of deployments of these systems offer some insight into the market's demand for the technology with over 500 Li-ion projects completed, announced, or in development in 2020 and fewer than 100 projects for any other chemistry.[122] The data shows that the standout alternatives to Li-ion in terms of currently deployed commercial LDES systems are Advanced Lead, Sodium, and redox flow. It is also important to point out that determining the best chemistry is only a portion of the challenge for achieving LDES goals. Battery management systems (BMS) are a key part of the technology stack for each chemistry.[123] Even if a company is producing an LDES system with the best chemistry, the system will not perform if the BMS

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[114] U.S. Department of Energy, "Energy Storage Grand Challenge Roadmap," December 2020, available at https://www.energy.gov/energy- storage-grand-challenge/articles/energy-storage-grand-challenge-roadmap, accessed on February 24, 2023.

[115] U.S. Department of Energy, "Energy Storage Grand Challenge Roadmap," December 2020, available at https://www.energy.gov/energy- storage-grand-challenge/articles/energy-storage-grand-challenge-roadmap, accessed on February 24, 2023.

[116] C. Bloch, J. Newcomb, S. Shiledar, and M. Tyson, "Breakthrough Batteries: Powering the Era of Clean Electrification." Rocky Mountain Institute, 2019, available at https://rmi.org/insight/breakthrough-batteries/, accessed on February 24, 2023.

[117] C. Bloch, J. Newcomb, S. Shiledar, and M. Tyson, "Breakthrough Batteries: Powering the Era of Clean Electrification." Rocky Mountain Institute, 2019, available at https://rmi.org/insight/breakthrough-batteries/, accessed on February 24, 2023.

[118] C. Bloch, J. Newcomb, S. Shiledar, and M. Tyson, "Breakthrough Batteries: Powering the Era of Clean Electrification." Rocky Mountain Institute, 2019, available at https://rmi.org/insight/breakthrough-batteries/, accessed on February 24, 2023.

[119] C. Bloch, J. Newcomb, S. Shiledar, and M. Tyson, "Breakthrough Batteries: Powering the Era of Clean Electrification." Rocky Mountain Institute, 2019, available at https://rmi.org/insight/breakthrough-batteries/, accessed on February 24, 2023.

[120] P. Simon and Y. Gogotsi, "Perspectives for Electrochemical Capacitors and Related Devices," Nat. Mater. Rev., vol. 19, no. 11, pp. 1151- 1163, November 2020, doi: 10.1038/s41563-020-0747-z.

[121] P. Simon and Y. Gogotsi, "Perspectives for Electrochemical Capacitors and Related Devices," Nat. Mater. Rev., vol. 19, no. 11, pp. 1151- 1163, November 2020, doi: 10.1038/s41563-020-0747-z.

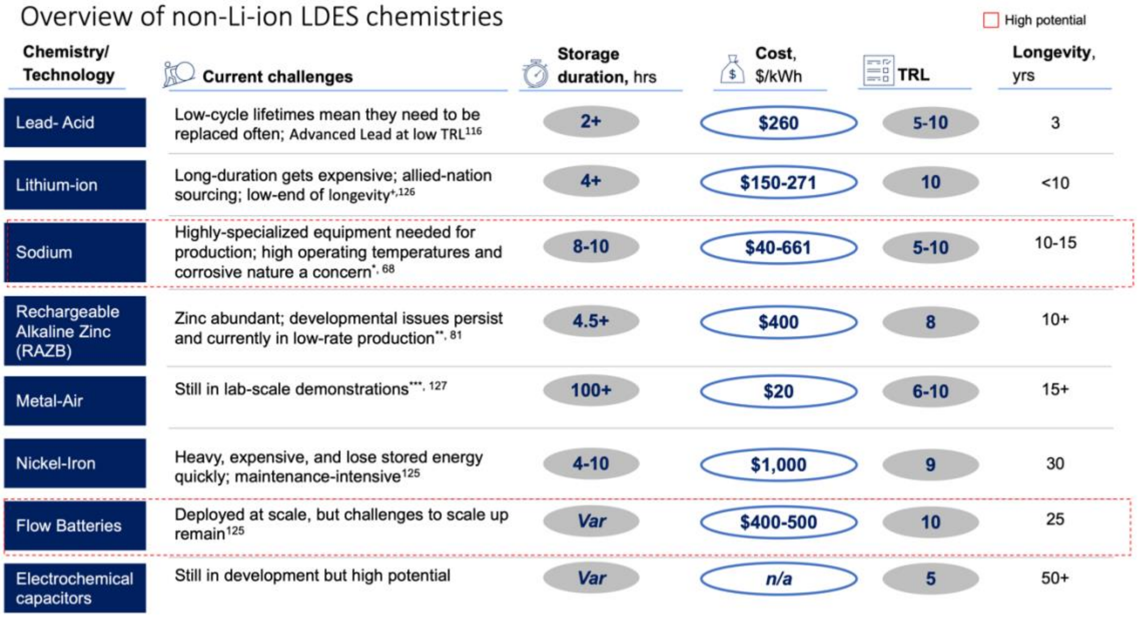
[122] G. P. Wheeler, L. Wang, and A. C. Marschilok, Beyond Li-ion Batteries for Grid-Scale Energy Storage, 1st ed. (Cambridge, UK: Cambridge University Press, 2022), p. 4, doi: 10.1017/9781009030359.

[123] Personal Communications with Charles Decker, U.S. Army Corps of Engineers, Engineer Research and Development Center - Construction Engineering Research Laboratory, Champaign, IL, April 6, 2023.

is not well-designed.[124] The BMS prolongs the lifetime of the system, ensures it can respond to changing energy needs from the consumer, and prevents malfunctions. A well-functioning BMS is as critical to LDES success as the best chemistry.

Lead-acid batteries were some of the first deployed for energy storage due to their general ubiquity in daily life (e.g., cars) but advanced Lead batteries that allow for 80% depth of discharge and lifespans of greater than 10 years are not yet commercially deployed. Sodium sulfur batteries have seen widespread grid-scale deployment, but the high operating temperatures of current generation chemistries means they may need to be de-risked for DoD use. Several commercial companies are delivering vanadium flow units to customers today. See the Case Studies" section for more discussion on the challenges of scaling up these companies within the DoD context. A DoD pilot of a flow battery, being installed this year at Fort Carson, is several years away from providing actionable insights for deployment to the rest of the DoD. Table 1 documents the key chemistries reviewed in our analyses. Ultimately, the DoD needs to identify and leverage a non-Lithium chemistry to meet its energy security and resilience needs. Removing the geopolitical challenges associated with using Li-ion for LDES is only part of the solution, however. As shown in this review, the best non-Lithium LDES chemistry at the MW-scale the DoD needs has yet to be decided. It is crucial at this moment that DoD leverages the DIU as a portal to the commercial world to engage a wide breadth of commercial technology. DIU has selected three LDES companies to demonstrate technologies at DoD installations. Going forward, DIU should continue to support additional LDES companies to ensure a variety of technologies are represented, as this is the best way to hedge against developmental challenges down the road.

Table 1. *Overview of main chemistries reviewed in these analyses. Note that desired storage duration is 8+ hours.*



Overview of non-Li-ion LDES chemistries

☐ High potential

Chemistry/ Technology	Current challenges	Storage duration, hrs	Cost, $/kWh	TRL	Longevity, yrs
Lead- Acid	Low-cycle lifetimes mean they need to be replaced often; Advanced Lead at low TRL[116]	2+	$260	5-10	3
Lithium-ion	Long-duration gets expensive; allied-nation sourcing; low-end of longevity[†,126]	4+	$150-271	10	<10
Sodium	Highly-specialized equipment needed for production; high operating temperatures and corrosive nature a concern[*, 68]	8-10	$40-661	5-10	10-15
Rechargeable Alkaline Zinc (RAZB)	Zinc abundant; developmental issues persist and currently in low-rate production[**, 81]	4.5+	$400	8	10+
Metal-Air	Still in lab-scale demonstrations[***, 127]	100+	$20	6-10	15+
Nickel-Iron	Heavy, expensive, and lose stored energy quickly; maintenance-intensive[125]	4-10	$1,000	9	30
Flow Batteries	Deployed at scale, but challenges to scale up remain[125]	*Var*	$400-500	10	25
Electrochemical capacitors	Still in development but high potential	*Var*	*n/a*	5	50+

† This price is predicted to rise due to constrained supply of key input minerals[125]

* Based on CATL's full-scale production of their sodium-ion battery; sodium-sulfur costs are not widely available although 10-year-old costs were very high

** Based on the product sheet for Urban Electric Power's residential storage system

*** Based on Form Energy's proposed product at full-scale production.[126] Note that these costs are based on 100-hour batteries at this cost per kWh, so the initial capital cost is high, and they can only be purchased in larger blocks.

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[124] Personal Communications with Charles Decker, U.S. Army Corps of Engineers, Engineer Research and Development Center - Construction Engineering Research Laboratory, Champaign, IL, April 6, 2023.

[125] "Lithium Prices Continue to Rise - LPI Explains Why," Innovation News Network, January 16, 2023.

[126] "Form Energy's $20/kWh, 100-hour iron-air battery could be a 'substantial breakthrough,'" Utility Dive, July 26, 2021, available at https://www.utilitydive.com/news/form-energys-20kwh-100-hour-iron-air-battery-could-be-a-substantial-br/603877, accessed on February 24, 2023.

CASE STUDIES

As the DoD seeks to promote resilience and energy security with LDES, it is important to understand the current commercial market for LDES and the challenges and opportunities LDES companies face as they pursue dual use technology development. In this section, we share four case studies across three VRB companies and a fourth emerging LDES technology (electrochemical capacitor) company to provide limited market insight to DIU and DoD stakeholders.

Invinity Energy Systems

Invinity Energy Systems is a VFB (note: Invinity uses the acronym VFB instead of VRB) manufacturer based in the U.S., UK and Canada, that was created through the 2020 merger of two leading redox flow battery providers: redT energy and Avalon Battery.[127] Invinity provides a turnkey, modular, off-the-shelf energy storage system and has done 70 projects across 14 countries, with 65MWh deployed or contracted with customers.[128] Invinity has the largest deployed flow battery fleet of any VFB manufacturer, demonstrating how a mature VFB solution can compete in the energy storage market. With VFBs lasting 25+ years, Invinity markets its solution as qualitatively superior to Li-ion batteries and other chemistries in terms of safety, capacity retention, performance degradation, and lifetime Levelized Cost of Storage (LCOS).[129] Invinity argues that over the long term (40 years), a 10 MW/40MWh VFB with a high throughput equivalent to 700 full depth of discharge cycles per year will outcompete a comparable Li-ion battery on LCOS.[130] While Invinity's VFB has higher capital expenditures at the beginning, Li-ion batteries end up more expensive in the long term due to the cost of augmenting/replacing the batteries which have shorter useful lives and greater annual capacity degradation (see Invinity's price comparison in Figure 2).[131]

With a competitive LCOS and qualitative value proposition, Invinity demonstrates the potential for VFBs to serve as an alternative to the Li-ion batteries that currently dominate the energy storage market and pose long-term environmental and security issues. Of critical importance is Invinity's ability to produce VFBs with a value chain centered in the U.S./allied nations. While some components are likely sourced from China given the need to compete on price, the core raw material (vanadium) can be sourced sustainably in the U.S. and Invinity announced a U.S.-based joint venture with U.S. Vanadium LLC in 2022.[132] Despite these tailwinds, Invinity has yet to achieve rapid growth in manufacturing and deployments of its technology at a scale that would threaten the dominance of Li-ion batteries. To better understand the environment facing more mature VFB manufacturers, we interviewed Matt Harper, Co-founder and Chief Commercial Officer at Invinity. Harper described several key challenges facing Invinity as it seeks to scale its technology: trust in VFBs, regulatory challenges, high capital expenditures, and the difficulty of doing business with government (including DoD).

Trust in VFBs: Harper explained that while demand for energy storage systems has been accelerating in recent years, particularly after the passage of the Inflation Reduction Act, VFB demand has lagged Li-ion because Li-ion is a known entity: "no one ever got fired for buying an IBM." Poor customer trust is likely due the relative nascency of VFB technology and lack of long-duration deployments demonstrating extended reliability and safety, key value propositions. Invinity has made significant steps to improve this

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[127] About Us, Invinity World Wide Web Site, available at https://invinity.com/about-us/, accessed on March 22, 2023.
[128] Home, Invinity World Wide Web site, available at https://invinity.com/, accessed on March 22, 2023.
[129] Vanadium Flow Batteries, Invinity World Wide Web site, available at https://invinity.com/vanadium-flow-batteries/, accessed at March 22, 2023.
[130] What Does Battery Storage Cost, Invinity World Wide Web Site, available at https://invinity.com/what-does-battery-storage-cost/#LCOS2A, accessed on March 22, 2023.
[131] Note that Invinity uses a different cost model that generates substantially lower $/MWh for both VFBs and Li-ion chemistries than DOE's industry analysis. This report does not render a judgment on the validity of Invinity's price comparison model, but it is included for demonstrating how VFBs may compete with Li-ion on pricing. For this, please see What Does Battery Storage Cost, Invinity World Wide Web Site, available at https://invinity.com/what-does-battery-storage-cost/#LCOS2A, accessed on March 22, 2023.
[132] "U.S. Vanadium and Invinity Sign MoU to Form U.S. Joint Venture," News, Invinity World Wide Web Site, August 16, 2022, available at https://invinity.com/us-vanadium-and-invinity-sign-mou-to-form-us-joint-venture/.

position, notably through the recent completion of a “Bankability Study” by global engineering consultancy DNV. Customer trust is expected to increase as Invinity deploys more systems but may create an obstacle to exponential growth in the near-medium term.

Regulatory challenges: Harper described the regulatory environment facing Invinity at the local, state, and federal levels to be extraordinarily complex. Interconnection with the grid, certifications, and lagging customer deployment of cleared technology all slow the pace of growth. Harper described one instance of a VFB system that was delivered to a customer two years ago but is still not interconnected because of issues complying with California state regulations. Interconnection approval timelines in many jurisdictions where VFBs could be deployed are stretching out many years, hindering adoption.

Difficulty doing business with government: Invinity has been held back on projects with state and federal customers because of the significant resources and human capital required to navigate the complex regulatory environment and contract/grant amounts that are often too small/uncertain to justify the expenditure. That said, Invinity recently announced that it was chosen to receive a portion of a $31 million grant providing a 10 MWh VFB to the Viejas Tribe of Kumeyaay Indians and expects to ship the first units in the first half of 2023. This grant demonstrates how government customers can acquire off-the-shelf VFB technology when the dollar amount and regulatory environment are favorable.

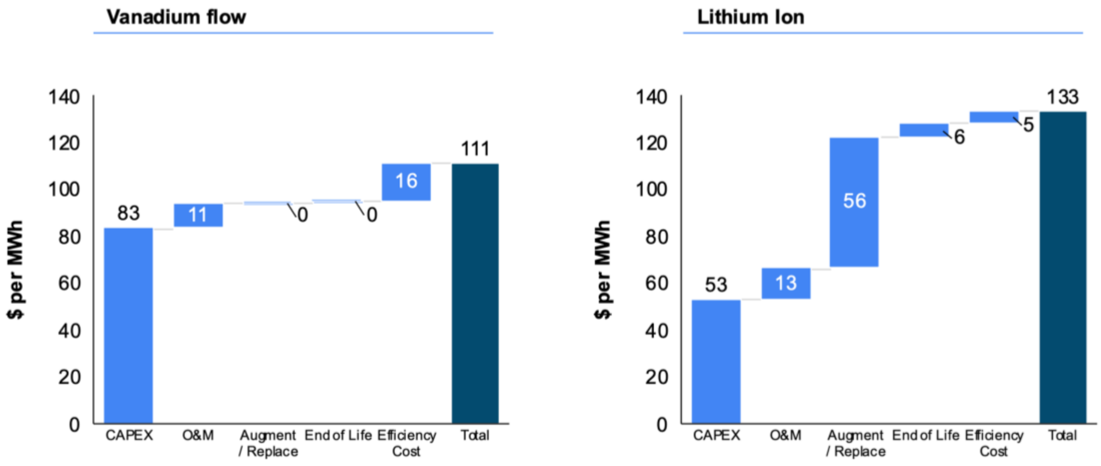

Figure 2. *Levelized cost of storage (LCOS) breakdown for vanadium flow versus Li-ion based on Invinity’s internal research for a 40-year contract. Shared with permission of Matt Harper.*

Persistent opportunities: Invinity has partnered with Marine Corps Air Station Miramar on enhancing base energy resilience and Harper expressed optimism about Miramar opening larger scale opportunities with DoD customers. A challenge Harper highlighted is the lackluster return on investment for a traditional contract for a single contract for a single pilot demonstration with a small award and an uncertain/nonexistent pathway to a larger contract if successful. However, this challenge is solved for those vendors who are selected to participate in DIU’s commercial solutions opening for LDES using the other transaction authority, whereby a clear path to follow on projects is possible for vendors who successfully complete project milestones.[133] Successful scaled contracts with the DoD can confer an additional advantage: a signal of credibility that may help to alleviate the customer trust-deficit in the commercial sphere.

StorEn

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[133] “DIU Leverages Commercial Technology to Drive Climate and Energy Resilience,” Defense Innovation Unit, April 21, 2023, available at https://www.diu.mil/latest/diu-leverages-commercial-technology-to-drive-climate-and-energy-resilience.

StorEn is a U.S.-based VRB manufacturer that first demonstrated a prototype VRB at the Energy Center at Stony Brook University in October 2018. StorEn seeks to build on the durability and sturdiness of VRBs and improve the electrical efficiency of the stack, the energy density of the electrolyte, and the module. With advertised battery lifetimes of 25+ years, or more than 15,000 charge-discharge cycles without any decay in capacity, StorEn's VRB offers a strong customer value proposition.[134] Still in early stages of commercialization, StorEn has installed one VRB in Australia, is under contract to deliver a unit to a Canadian customer, and has most recently signed an agreement with Connexus Energy (a utility) to demonstrate its VRB in a microgrid system to charge electric vehicles.[135] StorEn has raised over $10 million from 7,000+ investors. To better understand the environment facing early stage VRB manufacturers, we interviewed John Davis, Co-founder and CEO of StorEn. Davis described several key challenges and opportunities facing StorEn and other early stage VRB producers as they seek to scale production: raising capital, building trust in VRBs, regulatory challenges, difficulty of doing business with government, and supply chains.

Raising capital: For VRB startups like StorEn, raising capital is the most important factor in scaling operations. According to Davis, "StorEn's biggest challenge is raising capital, and demonstrating reliability over the long term is another key challenge because there is no history of long-term use. On paper, VRBs have the capacity to work over 20 years with tens of thousands of charge/discharge cycles, but there isn't history that demonstrates this is the case." This boils down to a "chicken and the egg" situation, where scaling production requires robust capital expenditures, but major investors (and customers) want to see a history of scaled production and product reliability before investing. A major buyer/investor like DoD may be able to alleviate this problem, but some risk tolerance will be required.

Trust in VRBs: Davis explained that at "the heart of VRBs is a cell stack that processes pressurized liquid (sulfuric acid solution which is costly). The components in the stack must be complementary (no metal) with the acid for a long period of time. Lots of pumps, pipes, tanks, temperature sensitivity, all requiring a battery management system. They're not flammable or explosive but very rugged." VRB technology can be intimidating to potential customers, but Davis believes that time and a history of performance will demonstrate its reliability.

Regulatory challenges: When asked about regulatory challenges, Davis explained that StorEn "hears a lot about UL compliance issues. The UL organization [UL LLC is a global independent safety certification company] has developed a test suite for different energy storage systems. Currently, generic test requirements are primarily about fire reduction which isn't an issue for our technology. We have a toxic liquid that needs to be contained so chemical storage compliance is our main concern. We use UL approved inverter tech and can work with UL to define what the test suites need to be. There's the electromagnetic component and shock precautions, but the challenge is making UL understand how the flow battery works and translate this into a set code. We're working on demonstration projects where a utility or university will take responsibility for the safety liability of the batteries, but this can't be done at scale without regulatory compliance." Until there is a reasonable regulatory regime in place, commercial demand will likely continue to be constrained by regulatory confusion over VRB safety.

Difficulty doing business with government: When asked about the prospects of doing business with the U.S. government, Davis expressed enthusiasm but highlighted the challenges in competing for government grants/contracts, especially for early-stage VRB producers:

> *"It is hard to show a mission critical organization like DoD that we are capable. If we went in the direction of pursuing business with DoD where we need extensive testing for reliability, we must pay for a ton of test equipment, employee time, and it is currently just too costly. We need investment/resources at a Lockheed/Boeing level. Those guys can develop a flow battery if they*

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[134] Our Technology, StorEn World Wide Web site, available at https://www.storen.tech/our-technology, accessed on March 22, 2023.

[135] StorEn Technology, Form 1-K, No. 024-11240, 2021, available at https://www.sec.gov/Archives/edgar/data/1720258/000110465922064761/tm2216776d1_1k.htm; StoreEn, Start Engine World Wide Website, available at https://www.startengine.com/offering/storen, accessed on March 22, 2023.

> *were tasked to. As CEO, I look at residential batteries with lower margins than industrial use cases but to work with DoD would require some entity within the Department to supply financial resources: it can't be on the company to develop the technology and perform extensive reliability testing with no clear end use case or path to revenue in mind. StorEn can make this technology work for DoD but there has to be demand at the end of the tunnel. The Department of Energy has all of these programs for long duration energy storage but they're at MWh levels that no one can do except big companies. We can't do multi-MWh projects right now. That's Skunkworks level of funding required, but there's a lot of smaller companies that could do this work and scale the technology if given the opportunity."*

The challenges Davis described likely apply to all redox flow battery producers, apart from Lockheed Martin's GridStar Flow battery. These challenges present DIU with a major obstacle to impactfully growing domestic competitors to Li-ion batteries. When asked about state government work, Davis noted that the California Electric Commission "offers such small grants with such long timelines and requirements processes that it is not possible to dedicate the resources to going after the grants. The ROI isn't there."

Supply chains: As described previously, one of the biggest disadvantages to Li-ion is the security and sustainability of the value chain. With regards to VRB supply chains, Davis explained that most producers probably "use Chinese labor, but StorEn believes manufacturing can be automated and done in the U.S.A. The chemistry is simple: vanadium is the core metal and U.S. Vanadium in Arkansas is the partner StorEn uses. Interestingly, the sulfuric acid is almost a residual of the mining process for vanadium, creating potential synergies there. That's 50% of the system, we can build the rest in America. Currently, we order some injection molded parts from China for the price, but this can be done in the U.S., albeit for a higher cost." With proper contracts at scale requiring VRB components to be made in America and a possible price premium, the DoD can incentivize U.S.-based VRB value chains.

CellCube

Enerox GmbH, known publicly as CellCube, is an Austria-based VRB manufacturer with a leading global footprint of 130 installed systems.[136] CellCube's VRBs have an extensive operational track record involving systems operating for over 10 years to date with an advertised guarantee of 25 years and a minimum of 20,000 charge-discharge cycles.[137] CellCube is owned by Bushveld Minerals, a South African mineral development company with a portfolio of vanadium and other minerals, demonstrating the potential for vertical integration as a financing option in the VRB space. In May 2022, CellCube established a U.S. subsidiary in Denver, Colorado and CellCube has focused on four business segments to date: renewable energy storage for industrial customers, commercial and private deployment, green energy storage for remote microgrids and island solutions, as well as long-term back-up systems for green and critical infrastructure facilities.[138] CellCube markets its VRB, using the lifetime kWh as the price-comparative alternative to Li-ion, emphasizing the long-term replacement costs and capacity degradation of Li-ion, which are largely unknown. CellCube is a mature VRB manufacturer with an EU-centric approach but is moving into the global market and has been particularly deliberate in its expansion into the U.S. market. To better understand the decision to compete in the U.S. as a VRB manufacturer, we interviewed Peter Oldacre, Vice President - Global Growth at CellCube. Oldacre described several key challenges and opportunities facing early stage VRB producers as they seek to scale production: raising capital, building trust in VRBs, regulatory challenges, difficulty of doing business with government, and supply chains.

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[136] Who We Are, Cell Cube World Wide Website, available at https://www.cellcube.com/who-we-are/, accessed on March 22, 2023.

[137] The Cellcube System, Cell Cube World Wide Website, available at https://www.cellcube.com/the-cellcube-system/, accessed on March 22, 2023.

[138] "Austrian Vanadium Redox Flow Batteries' Expert CellCube Settles in North America," Cell Cube World Wide Website, available at https://www.cellcube.com/austrian-vanadium-redox-flow-batteries-expert-cellcube-settles-in-north-america/, accessed on March 22, 2023.

Cultural challenges doing business in the U.S.: According to Oldacre, the largest challenge for CellCube as it seeks expansion in the U.S. LDES market is the cultural shift required. Specifically, CellCube as an OEM has a model of providing the VRB system to a client who is already late in the decision-making process of which kind of battery system to use, and seeks the provision of a widget, whereas American customers are eager to have a project development partner that can provide an integrated LDES solution and support the project development as an added value to the supply of a widget. Until a larger staff complement is recruited in the U.S.A, CellCube must focus on the market segment that is already mature in their technology decision-making to provide an end-to-end LDES capability of the type that DoD would require. Oldacre noted that for CellCube's first contract "in Illinois, the technology buyer was responsible for the project development role and CellCube supplied a [VRB] system and then was not involved in the project development cycle." Oldacre noted that the project developer role is something CellCube is eager to take on in the U.S. and will require strong local hires to navigate their understanding of the regulatory environment and to support the DoD through the full project cycle.

Supply Chains: Oldacre described how CellCube's "cell stack supply chain is entirely Euro-centric and the electrolyte processing supply chain for all VRB manufacturers is currently highly dependent on China and India; both of which demand companies pay them up front before they start producing." Suppliers that demand payment in advance of producing key components can tie up working capital and free cash flows for capital expenditures, a key impediment to scaling manufacturing. CellCube has managed to diversify their supply chain with a 2022 partnership with U.S. Vanadium but will not rely on a single source of vanadium electrolyte until the electrolyte market shows more maturity and stability in supply chain logistics.[139]

The Inflation Reduction Act*:* Oldacre explained that CellCube has not yet explored partnerships with the U.S. government and that a cultural shift towards identifying key partnerships, which do not immediately rely on the sale of a widget and that focus on developing partner-specific value propositions will be required at the company to be competitive in bidding for government contracts. However, he also highlighted how the Inflation Reduction act (IRA) has been a game changer in CellCube's strategic outlook. Oldacre explained how "until the U.S. announced its IRA, we viewed Australia as the most important market to go to, but now expansion into the U.S. and Australia is taking place simultaneously. The IRA is strategically phenomenal, because now any country with any sense of the energy transition as an economic force multiplier at all will follow and try to pass something similar; the rest of the world will follow in U.S. footsteps." We suspect this is a commonly held sentiment: the IRA will drive greater expansion of international LDES producers into the U.S. market.

Powered Armor Technologies

Powered Armor Technologies (PAT) has developed a carbon-based ultracapacitor that is "five times the strength of concrete at 1/3 the weight."[140] Their technology offers "both ballistic protection and shielding from ionizing radiation" in addition to its energy storage capabilities.[141] They predict a lifetime of 100 years and their current prototype is easily scalable to power outputs from 1 kW or lower to 1 MW or higher.[142] A possible implementation of their technology would result in energy storage of ~15 kWh in a box the same size as a Tesla Powerwall (30"x45"x6").[143] PAT envisions dual-use applications for their ultracapacitor, with their initial DoD market to create energy-storing "HESCO" barriers or for integration into hangers or similar maintenance-type structures.[144] The latter use case offers synergies where electric

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[139] "U.S. Vanadium Expands Sales Agreement with CellCube for Up to 3 Million Liters/Year of Ultra-High-Purity Vanadium Redox Flow Battery Electrolyte," February 24, 2022, available at https://usvanadium.com/u-s-vanadium-expands-sales-agreement-with-cellcube-for-up-to-3- million-liters-year-of-ultra-high-purity-vanadium-redox-flow-battery-electrolyte/.

[140] Interview with P. VanBeek of Powered Armor Technologies, January 20, 2023.

[141] Interview with P. VanBeek of Powered Armor Technologies, January 20, 2023.

[142] Interview with P. VanBeek of Powered Armor Technologies, January 20, 2023.

[143] Interview with P. VanBeek of Powered Armor Technologies, January 20, 2023.

[144] Interview with P. VanBeek of Powered Armor Technologies, January 20, 2023.

vehicle charging might be needed in the future since the ultracapacitor can help reduce the electrical capacity buildout for charging infrastructure, often one of the costliest components of a new charging station.[145] PAT is expecting to deploy their first grid-scale prototype in 2024 in collaboration with a utility company. PAT is in between a TRL-5 and 6, which is an earlier stage than the other LDES technologies examined in this report and around the lowest level DIU will consider.

Supply Chains: Due to its carbon-based chemistry, the raw materials for the ultracapacitor are readily sourceable in the U.S. or allied nations. Because PAT's design does not rely on electrochemical solutions, supplying the raw materials is comparatively simple versus most other LDES technologies.

Raising Capital: To attain higher TRLs and ultimately deployment, PAT needs additional funding on the order of a few million dollars to get from prototype production to full-scale testing and a few more million to tens of millions to get to production.[146] A substantial amount of this funding is required to conduct DoD-specific tests which are not needed for commercial applications and thus not readily fundable through traditional investor-backed funding.[147, 148] This is clearly a big issue for the DoD, and "AFWERX" has been developed to help the Department of the Air Force address some of these challenges. AFWERX, specifically AFVentures, "invests in emerging technologies to scale Department of the Air Force capabilities."[149] While AFWERX has been highly successful, awarding over half a billion dollars in funding in FY2022, its core mission set is focused on the Air Force, leaving large swaths of DoD innovation uncovered.[150]

Summary

To summarize, both mature VRB producers as well as early-stage producers face numerous challenges to scaling production, particularly in customer trust affecting demand and investment, a complex regulatory environment, and major challenges doing business with government customers. DIU will consider these challenges when exploring Li-ion alternatives:

- It is easier to work in the commercial space than in the DoD space
- The growth of the VRB industry has lagged Li-ion because of lacking customer awareness on price competitiveness and validation of long-term performance/safety
- There is a chicken and the egg situation with regards to raising capital and scaling production that a risk-tolerant investor can alleviate
- VRBs can be produced in the U.S./allied countries but this may not currently be economically advantageous, "made in America" contact stipulations can act as a powerful incentive
- The IRA has fundamentally shifted perceptions of the American LDES market, providing DoD with partnership opportunities that may not have been present before.

This section has largely focused on vanadium Redox Flow battery companies, but there are other redox flow battery producers, including non-VRB chemistries that could be considered.

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[145] U.S. Department of Energy, "Energy Storage Grand Challenge Roadmap," December 2020, available at https://www.energy.gov/energy- storage-grand-challenge/articles/energy-storage-grand-challenge-roadmap, accessed on February 24, 2023.

[146] Interview with P. VanBeek of Powered Armor Technologies, January 20, 2023.

[147] Interview with P. VanBeek of Powered Armor Technologies, January 20, 2023.

[148] U.S. Department of Energy, "Energy Storage Grand Challenge Roadmap," December 2020, available at https://www.energy.gov/energy- storage-grand-challenge/articles/energy-storage-grand-challenge-roadmap, accessed on February 24, 2023.

[149] "AFWERX Announces Reimagining Energy Challenge for Department of Defense," U.S. Air Force, Press Release, October 15, 2020, https://www.af.mil/News/Article-Display/Article/2383535/afwerx-announces-reimagining-energy-challenge-for-department-of-defense/, accessed on March 21, 2023.

[150] "AFWERX Announces Reimagining Energy Challenge for Department of Defense," U.S. Air Force, Press Release, October 15, 2020, https://www.af.mil/News/Article-Display/Article/2383535/afwerx-announces-reimagining-energy-challenge-for-department-of-defense/, accessed on March 21, 2023.

HOW THE DIU CAN PROMOTE BATTERY TECHNOLOGY BEYOND LITHIUM ION

The DIU is uniquely positioned to help companies in the long-duration energy storage space overcome the challenges laid out in the previous sections. As this section will show, the DIU can use both its own authorities and the authorities of its other federal government partners including the DoD to help long duration storage companies establish themselves in the market and overcome various barriers to entry they face.

General Levers at DIU

DIU's primary statutory authority is its ability to craft and award "other transaction" (OT) prototype contracts. OT authority allows DIU to offer flexible contracts adapted to business practices in the commercial industry, attracting the participation of non-traditional defense contractors. Under 10 U.S.C. §2371b, DIU can publicly solicit and then award "prototype" OT contracts to "acquire prototype capabilities and allow for those prototypes to transition into Production OT contracts."[151] Under 10 U.S.C. §2371b(f), after a successful prototype OT contract, other agencies of DoD components can issue a non-competitive follow-on production OT contract.[152]

To support the LDES industry, DIU has worked with the Office of Operational Energy and the Office of Installation Energy at the Pentagon, the Strategic Environmental Research and Development Program and the Environmental Security Technology Certification Program within DoD, and the DOE's Office of Clean Energy Demonstrations. DIU crafted a prototype OT contract targeting non-Lithium-ion LDES technologies with problem sets that focus on the various DoD use cases outlined in Part II of this report (e.g., installation storage). DIU has completed a competitive down select and moved into production with early prototypes in the process of being fielded and/or trialed.[153] The goal of the selected companies that received OT contracts is to move from an approved prototype to deployment followed by a success memo, and, potentially, production contracts. For this to happen, an individual prototype OT has to be successful on meeting pre-arranged metrics delivering not just a proof of concept, but performance, DIU will collaborate with relevant DoD components to align on success memoranda as well as metrics ahead of production to ensure that any prototype contracts issued only proceed to production OT contracts if successful vendors meet the relevant requirements to merit actually purchasing the various LDES systems. This, in turn, could foster reindustrialization through domestication of onshore LDES manufacturing and associated capabilities.

General Levers at DoD Writ Large

The DIU can coordinate with DoD and other government stakeholders like DOE under the DoD/DOE Joint Program to support the LDES sector alongside other components of the DoD, who bring unique statutory or departmental powers to the table.

Defense Production Act (DPA), Title III

DPA Title III authority is the DoD's most powerful lever to shape the domestic defense industrial base. This authority and its surrounding regulatory framework enables the DoD's Office of Industrial Policy, with Presidential authorization, to invest in and provide incentives for the development, modernization,

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[151] "Other Transactions (OT) Guide," Defense Acquisition University, https://aaf.dau.edu/aaf/ot-guide/.

[152] "Other Transactions (OT) Guide," Defense Acquisition University, https://aaf.dau.edu/aaf/ot-guide/.

[153] "DIU Leverages Commercial Technology to Drive Climate and Energy Resilience," Defense Innovation Unit, April 21, 2023, available at https://www.diu.mil/latest/diu-leverages-commercial-technology-to-drive-climate-and-energy-resilience.

and expansion of defense industrial capabilities.[154] These authorities can be deployed in creative ways to aid the domestic production of key technologies like LDES.

Title III authority under the DPA is divided into three broad buckets: Section 301, 302, and 303. Section 301 authorizes the President to make loan guarantees, wherein the federal government promises to pay back all or part of a loan made by a non-federal lender to a non-federal borrower.[155] Section 302 authorizes the President to issue direct loans to private industry. Finally, Section 303 authorizes a broad range of actions to create, maintain, protect, expand, or restore domestic industrial base capacities. These actions include (1) purchase or purchasing commitments, (2) subsidy payments on domestically produced material, and (3) installation, purchase, and transfer of equipment or facility modifications for government and private industrial facilities.[156] A variety of agencies can take actions pursuant to these three Title III authorities, but the DoD acts as the manager of the federal government's DPA fund.[157] The use of these authorities comes with some limitations, which can be (and frequently are) waived by the President.[158]

These DPA authorities are flexible and can be designed to meet the economically unique needs of producers of the product or technology in question. For instance, in early 2022, the Biden Administration used DPA Title III authorities to support the critical mineral industry. Under Presidential Determination No. 2022-11, DoD was directed to financially support (1) feasibility studies for "mature mining, beneficiation, and value-added processing projects" for critical minerals, (2) byproduct and co- product production at existing American facilities, and (3) other improvements to increase productivity, workforce safety, and sustainability in critical minerals mining, beneficiation, and processing.[159] In response to this authority, DoD has used DPA money to fund projects including (1) subsidies to finance factory construction, (2) inventory demonstration grants, and (3) supply chain studies funding.[160]

The White House has authorized the DoD to deploy DPA Title III authority to support the energy storage space. Further, on February 28, 2023, President Biden announced a waiver on statutory limitations to DPA Title III funding for a group of key technologies including "power and energy storage."[161] This waiver streamlines the granting of subsidies under Section 303 and removes the spending limitation for aggregate action to address a single shortfall. As a result, the DoD can quickly and comprehensively deploy DPA Title III spending to support components of the energy storage industries like LDES.

Small Business Innovation Research (SBIR) Grants & the Rapid Innovation Fund (RIF)

The DoD also has authority to fund research projects at small businesses with under 500 employees under the SBIR program. Under this program, businesses with a technology at the "technical assessment and feasibility stage" (roughly TRL 1-4) can be selected for a Phase I grant, receiving $275,000 over a six month to one year period.[162] If Phase I grant research is successful, they are eligible for up to $1.8 million

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[154] Jillian Stern, The Covid-19 Pandemic and the Defense Production Act: Government Misuse and Failures, 51 Pub. Cont. L.J. 323, 237 (2022).

[155] Michael Cecire et al, "The Defense Production Act of 1950: History, Authorities, and Considerations for Congress," Congressional Research Service, 2020, p. 10.

[156] 50 U.S.C. §4533(a)-(e).

[157] Agencies authorized to use Title III authority include Agriculture, Energy, Health and Human Services, Transportation, Commerce, State, Justice, Interior, Homeland Security, ODNI, CIA, NASA, and the GSA. For this, See E.O. 13603, Section 801(h). Under COVID-related laws, HHS has its own fund to finance its DPA Title III actions not subject to DoD supervision.

[158] Under ordinary conditions, to use Section 301 authority, the loan guarantee in question must be not otherwise available on the private market "under reasonable terms or conditions sufficient to finance the activity." Similarly, to use Section 302 authority, it must be found that without a direct loan "United States industry cannot reasonably be expected to provide the needed capacity, technological processes, or materials in a timely manner." Similarly, before the DoD can use Section 303 authority, the President must personally (i.e., via executive order or proclamation) find that there is a "domestic industrial base shortfall" of the relevant item. These two requirements can be waived "during a period of national emergency declared by Congress or the President."

[159] Heidi Peters, et. al., "2022 Invocation of the Defense Production Act for Large-Capacity Batteries: In Brief," Congressional Research Service, May 27, 2022, p. 2.

[160] U.S. Department of Commerce, Bureau of Industry and Security, Office of Technology Evaluation, "The Effect of Imports of Neodymium- Iron-Boron (NdFeB) Permanent Magnets on the National Security," September 2022, p. 36.

[161] U.S. Department of Defense, "President Biden Signs Presidential Waiver of Statutory Requirements for Supply Chain Resilience," Press Release, February 28, 2023.

[162] U.S. Department of Commerce, Bureau of Industry and Security, Office of Technology Evaluation, "The Effect of Imports of Neodymium- Iron-Boron (NdFeB) Permanent Magnets on the National Security," September 2022, p. 37.

over a two-year period.[163] SBIR grants allow the awardee to retain ownership of their inventions' intellectual property, but grant the government a "non-exclusive, nontransferable, irrevocable" license to use the invention.[164]

The DoD has successfully deployed SBIR grants to bolster domestic production of other key technologies. Over the course of 2020 and 2021, for instance, DoD awarded three SBIR grants to organizations developing neodymium rare earth magnets.[165] In another instance, the Defense Logistics Agency (DLA) deployed SBIR funding to "accelerate the development of new rare earth processing technologies."[166] The recipient of this DLA SBIR grant is using the money to scale production of rare earth oxides to 20 tons. The DoD can also coordinate its SBIR grant programs with other agencies that are authorized to make grants under this authority, including the DOE.[167]

DoD's Rapid Innovation Fund (RIF) also provides an avenue to support companies in the LDES space. RIF aims to help other-DoD funded projects that develop new, critical technologies but are not yet integrated into defense acquisition projects (i.e., the "valley of death").[168] RIF funded projects are primarily drawn from previous SBIR, defense laboratory, and academic initiatives.[169] RIF grants typically run between three and six million dollars and last no more than two years.[170] They aim to take technologies at TRL 6 and bring them to TRL 8-9, allowing them to transition either to DoD programs of record, fieldable prototype systems, or acquisitions by other non-DoD government organizations.[171] RIF authority is currently on pause, but DoD recently announced it is attempting to revitalize funding for the program.[172]

SBIR and RIF are important tools in the DoD's arsenal as it attempts to support the LDES market. DIU contracts only go to technologies that are sufficiently mature to at least provide prototypes for government use (generally between TRL 6-7). As the DIU expands its efforts to develop the LDES market, if it encounters promising companies that are not yet ready for prototype contracts, they could still recommend the companies to their counterparts at DoD's SBIR unit, who could consider them for Phase I SBIR grants. If these companies succeed, they could continue to receive SBIR money (and potentially RIF money), preparing them for later prototype contracts from DIU down the road.

General Levers at Other Agencies

Other departments outside the Department of Defense can assist in DIUs efforts to aid companies in the LDES space.

Department of Energy

Because of the energy implications of LDES, the Department of Energy (DOE) would be a natural

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[163] U.S. Department of Commerce, Bureau of Industry and Security, Office of Technology Evaluation, "The Effect of Imports of Neodymium- Iron-Boron (NdFeB) Permanent Magnets on the National Security," September 2022, p. 37.

[164] U.S. Department of Commerce, Bureau of Industry and Security, Office of Technology Evaluation, "The Effect of Imports of Neodymium- Iron-Boron (NdFeB) Permanent Magnets on the National Security," September 2022, p. 37.

[165] U.S. Department of Commerce, Bureau of Industry and Security, Office of Technology Evaluation, "The Effect of Imports of Neodymium- Iron-Boron (NdFeB) Permanent Magnets on the National Security," September 2022, p. 37.

[166] U.S. Department of Commerce, Bureau of Industry and Security, Office of Technology Evaluation, "The Effect of Imports of Neodymium- Iron-Boron (NdFeB) Permanent Magnets on the National Security," September 2022, p. 37.

[167] U.S. Department of Commerce, Bureau of Industry and Security, Office of Technology Evaluation, "The Effect of Imports of Neodymium- Iron-Boron (NdFeB) Permanent Magnets on the National Security," September 2022, p. 37.

[168] David Busigo, "2021 POST Conference: Rapid Innovation Fund (RIF) Overview," Department of Defense, March 4, 2021, available at https://defenseinnovationmarketplace.dtic.mil/wp-content/uploads/2021/03/2021-POST-Conference-RIF-Overview-Mar2021-Dist-A.pdf.

[169] David Busigo, "2021 POST Conference: Rapid Innovation Fund (RIF) Overview," Department of Defense, March 4, 2021, available at https://defenseinnovationmarketplace.dtic.mil/wp-content/uploads/2021/03/2021-POST-Conference-RIF-Overview-Mar2021-Dist-A.pdf.

[170] David Busigo, "2021 POST Conference: Rapid Innovation Fund (RIF) Overview," Department of Defense, March 4, 2021, available at https://defenseinnovationmarketplace.dtic.mil/wp-content/uploads/2021/03/2021-POST-Conference-RIF-Overview-Mar2021-Dist-A.pdf.

[171] David Busigo, "2021 POST Conference: Rapid Innovation Fund (RIF) Overview," Department of Defense, March 4, 2021, available at https://defenseinnovationmarketplace.dtic.mil/wp-content/uploads/2021/03/2021-POST-Conference-RIF-Overview-Mar2021-Dist-A.pdf.

[172] Todd Lopez, "DoD Aims to Boost Small Business Involvement in Nation's Defense," U.S. Department of Defense, News, February 23, 2023.

partner in DIU's efforts to support the development of an American LDES sector. Indeed, both DIU and DoD enjoy Congressional support under the Bipartisan Infrastructure Law. Outside its policy expertise, DOE brings several tools to the table. DOE can conduct sector-specific supply chain reports for specific energy products.[173] It also can use similar DPA Title III and SBIR authorities to fund projects in the LDES space in coordination with DoD.[174] The DOE's Office of Clean Energy Deployment could also be a key partner for LDES demonstration projects. These demonstration projects can provide test data that banks can use to underwrite future commercial systems. DOE's National Energy Technology Laboratory (NETL) also can begin research, development, and demonstration efforts to study technologies ready for commercialization. NETL's "critical minerals sustainability" program, for instance, provides grants to companies involved in U.S. rare earth production, including (1) basic and applied technology development at TRL 1-3, (2) engineering design, construction, and pilot-scale operations at TRL 3-5, and the development and operation of prototype facilities at TRL 7-8.[175] This ability, coupled with the technical expertise of NETL officials and scientists, could greatly aid companies in the LDES space should NETL choose to begin a program focused on LDES or the overall battery sector. NETL could thus be an interesting partner for DIU. Finally, DOE's Loan Program Office (LPO) gives loans and loan guarantees to companies whose technology has not yet reached full market acceptance.[176] By statute, LPO grants are limited to physical projects involved in certain areas of energy technology, but certain LDES projects — once out of the research stage at a TRL-10 — could fall under a variety of LPO's loan guarantee authorizations for clean energy financing, including its "energy infrastructure reinvestment," "distributed energy," and "innovative clean energy" programs.[177] This ability to guarantee loans for certain LDES companies provides an additional avenue of support once the technology has been demonstrated successfully. While DIU cannot co-invest with DOE programs, DoD can co-invest in technologies with DOE under the DPA.

Department of Commerce

The Department of Commerce (DoC) also brings a variety of tools to the table that DIU should be aware of in its efforts to support LDES. First, DoC can conduct Section 232 investigations into the "effects on the national security of the United States of imports of any article."[178] These investigations can be initiated by the head of any department or the President himself, and they are carried out by the Office of Technology Evaluation within DoC's Bureau of Industry and Security.[179] Section 232 investigations, in turn, produce a report that uses private non-public business information as well as other government intelligence to outline (1) U.S. dependence on foreign producers along the entire value chain of a given product, (2) challenges domestic industry faces to produce these products, and (3) potential solutions to address domestic industry shortcomings which can include policy tools ranging like tariffs, subsidies, and tax credits.[180] Accordingly, should DIU want a better picture of the LDES or related supply chains, it could - through the interagency process - request a report on it from DoC. Separately, once an American LDES industry is established, DoC will play an important role in protecting this industry from unfair competition from subsidized imports through its administration of countervailing duty laws. It also will play a key role in regulating the exports of these high-tech, sensitive products to foreign countries of concern.

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[173] U.S. Department of Commerce, Bureau of Industry and Security, Office of Technology Evaluation, "The Effect of Imports of Neodymium- Iron-Boron (NdFeB) Permanent Magnets on the National Security," September 2022, p. 30.

[174] U.S. Department of Commerce, Bureau of Industry and Security, Office of Technology Evaluation, "The Effect of Imports of Neodymium- Iron-Boron (NdFeB) Permanent Magnets on the National Security," September 2022, p. 37.

[175] National Energy Technology Laboratory, Department of Energy, "Rare Earth Elements and Critical Minerals," Report, February 2022, p. 3.

[176] Mission, Loan Programs Office, Department of Energy, available at https://www.energy.gov/lpo/mission.

[177] These projects fall under the Title 18 Innovative Clean Energy Loan Guarantee Program under section 1703 of the Energy Policy Act of 2005, as amended by the Inflation Reduction Act of 2022. For this, see Products & Services, Loan Programs Office, Department of Energy, available at https://www.energy.gov/lpo/products-services; Inflation Reduction Act of 2022, Loan Programs Office, Department of Energy, available at https://www.energy.gov/lpo/inflation-reduction-act-2022.

[178] U.S. Department of Commerce, Bureau of Industry and Security, Office of Technology Evaluation, "The Effect of Imports of Neodymium- Iron-Boron (NdFeB) Permanent Magnets on the National Security," September 2022, p. 15.

[179] See 19 U.S.C. §1862(b)(1)(A)

[180] U.S. Department of Commerce, Bureau of Industry and Security, Office of Technology Evaluation, "The Effect of Imports of Neodymium- Iron-Boron (NdFeB) Permanent Magnets on the National Security," September 2022, p. 15.

CONCLU.S.ION

Energy is power. The upcoming energy transition and rise of renewable energy will not invalidate this basic premise. But it has the potential to redraw the geopolitical map and change global power dynamics. America's proactive efforts to ensure it remains a leader through the energy transition will be critical in its ability to project power and achieve non-energy related foreign policy goals.

Maintaining a place of leadership will require America to lead global renewable energy innovation, particularly in LDES technology. Just as the U.S. grew to a global superpower in the wake of WWII on the backs of oil, the U.S. must secure its future as the world transitions to renewable energy in the coming decades. Given China's domination of Lithium-based storage technologies and manufacturing capacity, it is imperative that the U.S. looks at accelerating the development and commercialization of domestic non-Lithium LDES technologies and companies that can meet DoD and civil requirements. The DoD, through DIU, is an ideal catalyst for these efforts.

To speed up the development and commercialization of non-Lithium LDES technologies, the DIU should look to the recommendations outlined in Section I. A concentrated effort to act on a short list of actions focusing on core non-Lithium LDES technologies, aligning non-Lithium LDES strategy, and aligning across multiple groups of the DoD will be key. Taking these actions, the DIU can accelerate the impact and scale of non-Lithium LDES projects to ensconce the U.S. in a leadership role in the LDES space. By supporting the development of LDES, the U.S. will secure an allied supply chain for REEs and other minerals as well as the talent required to develop and deploy them. LDES technology can ultimately help the U.S. better project power, secure its role as a global leader, and maintain geopolitical order in the 21st century.

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APPENDIX

An Overview of the DIU for Commercial Partners

The DIU exists to help facilitate collaboration between the Defense Department and companies that do not ordinarily contract with the Defense Department. DIU's primary statutory authority to facilitate this cooperation is its ability to craft and award "other transaction" (OT) contracts. OT authority allows DIU to offer flexible contracts adapted to business practices in the commercial industry, which are more suitable to non-traditional defense contractors than the traditional defense contracting regime. Under 10 U.S.C. §2371b, DIU can issue "prototype" OT contracts to "acquire prototype capabilities and allow for those prototypes to transition into Production OTs."[181] Under 10 U.S.C. §2371b(f), after a successful prototype OT, DIU can authorize a non-competitive follow-on production OT contract.[182]

This authority is not without limits. Prototype OT contracts must be "directly relevant to enhancing mission effectiveness of military personnel, supporting platform, systems, components, or materials to be acquired by DoD, or improvements thereto."[183] Further, to grant a prototype OT contracts, the project must meet one of the following conditions (1) all participants must be small or non-traditional contractors, (2) at least one non- traditional defense contractor or non-profit research institute must participate in a "significant extent" of the project, (3) at least a third of the total costs must be paid by a party to the project other than the government, or (4) a senior procurement executive must determine in writing that exceptional circumstances justify the use of an OT contract.[184] Finally, like other forms of government contracts, DIU must publicize a problem set, area of need, or capability gap for a given OT contract, and then they must evaluate the proposals they receive to select an awardee.[185]

In practice, an OT contract begins when a component of the DoD contacts the DIU to request commercial sector assistance to solve a specific problem. The DIU works with the relevant DoD component to draft a problem statement. Then, the DIU publishes that problem statement to the public in its database of Commercial Solution Openings (CSOs). Interested parties can submit proposals that explain how they will use their technology and capabilities to produce a prototype that can solve the problem. DIU and its partners then review submitted proposals and follow up with companies for more information. Then, they perform a "competitive down select" where they select one or a few proposals that offer the best potential solutions to the problem. Typically, this occurs within two months of problem statement publication in the CSO. Companies that make it past the "competitive down select" receive a prototype OT contract.

Once the DoD component determines that the company's prototype successfully solves the problem, the company becomes eligible for sole-source production OT contracts for that solution. Importantly, this means that *any* component of the DoD can use OT authority to provide a contract for the given product without any competitive bidding procedures and requirements. This allows successful companies to market their products to DoD components as both successful and easier to obtain than the usual open contract bidding process would allow for. The DIU also maintains a catalog of all production OT eligible solutions, which DoD components can draw on.

This process offers several benefits for commercial, non-traditional defense contractors. First, unlike traditional contracts, OT contract terms, such as intellectual property sharing provisions, can be crafted to suit the needs of individual companies and industries. Second, while DIU OT contracts involve a competitive bidding process at the prototype stage, this process is less onerous and time consuming than

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[181] "Other Transactions (OT) Guide," Defense Acquisition University, https://aaf.dau.edu/aaf/ot-guide/.
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the traditional defense contracting bidding process. Finally, once a company successfully demonstrates its solution's viability, they can receive production OT contracts from any part of the DoD without any competitive bidding requirement.

Table A-1. *DoD Technology Readiness Level (TRL).*[186]

TRL	**Description**	**Criteria**
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development are initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5	Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.

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[186] "Defense Acquisition Guidebook," Defense Acquisition University, August 5, 2010.

7	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.