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Federal Policy to Accelerate Innovation in Long-Duration Energy Storage: The Case for Flow Batteries

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Affordable long-duration energy storage will be needed to decarbonize the U.S. energy system. Flow batteries are promising, but for that promise to be realized, DOE must invest heavily and more effectively in research, development, testing, and demonstration.

KEY TAKEAWAYS

- A massive build-out of renewable resources will be needed to decarbonize the U.S. energy system. Affordable long-duration energy storage (LDES) resources would dramatically reduce the cost of such a build-out.
- Today's dominant energy-storage technology, lithium-ion batteries, is not well-suited for LDES. Flow batteries—which use liquid electrolytes stored in tanks outside the power-generating cell—have fundamental advantages and have made great progress.
- Flow battery systems have been installed in many parts of the world, but the flow battery industry remains very small. To scale up, the technology needs to become cheaper and develop a track record.
- In the absence of "first markets" that can rapidly pull flow battery innovation, the U.S. Department of Energy (DOE) should push it forward with investments in research, development, testing, and demonstration.
- To drive flow battery and other LDES innovation with all due urgency, DOE should fund R&D at universities and companies, create a dedicated funding program, and support test facilities and demonstration projects at national labs and elsewhere.

INTRODUCTION

In order to decarbonize the U.S. energy system, a rapid increase in renewable electricity generation capacity in the grid is needed. Such a massive build-out could be achieved much more affordably with long-duration energy storage (LDES).[1]

The grid is an incredibly complex system, in which demand must be balanced at every moment with supply. On today's fossil fuel-powered grid, grid operators draw on storage systems that can supply energy for a few hours. As tomorrow's grid will have a much higher penetration of variable renewables, longer duration storage will be needed in order to avoid disastrous imbalances that could lead to blackouts. LDES resources can store large quantities of electricity generated when supply exceeds demand, and deliver it later, over the course of several days. This capacity will enable the grid to function normally even when solar and wind systems run below their normal output for extended periods.

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A U.S. energy system with net-zero greenhouse gas (GHG) emissions could require as much as 180 gigawatts (GW) of new storage capacity.[2] Most of today's capacity (23 GW) is pumped hydroelectric storage (PHS). However, the U.S. Energy Information Administration (EIA) projects that no more PHS will be added through 2050, due to siting restrictions.[3] As of November 2020, the United States had 1.4 GW of grid-scale battery storage capacity—and this figure is rapidly increasing.[4] Grid storage is expected to continue growing exponentially over the next decade.[5]

This report examines the potential for a little-known type of storage—flow batteries—to emerge as a cheap and scalable LDES technology. Drawing on interviews with academic, government, and industry experts, it shows that flow batteries have several advantages for LDES applications. While the technology's progress has been substantial in recent years, federal policy intervention is needed to unlock further breakthroughs in cost and performance that will allow flow batteries to scale up and help the grid reach net-zero emissions. The report makes three recommendations to the U.S. Department of Energy (DOE) and the congressional committees that oversee it:

1. Directly fund research and development (R&D) on LDES at universities and companies.
2. Give grid storage R&D a permanent home within DOE.
3. Expand DOE support for testing and demonstrations.

LITHIUM-ION IS NOT A SILVER BULLET

The vast majority of grid-scale storage being installed today uses lithium-ion (Li-ion) batteries, the same basic technology used in mobile phones and other electronics as well as in most electric vehicles.

Li-ion battery installations are generally able to discharge at maximum power for four hours or less. Notable examples of such installations, which have broken records for size, include Australia's Hornsdale Power Reserve, which has less than a two-hour duration, and California's

Moss Landing Energy Storage Facility, which can last four hours.[6] At today's relatively modest levels of intermittent renewables, storage installations such as these are sufficient to meet the grid's needs.

Once the penetration level of wind and solar exceeds 60 percent, however, variations in the weather and consumption will drive up the required storage duration from several hours to several days.[7] Some states already foresee this situation and have begun seeking out LDES in the range of 10–100 hours. Resource planners in California, for instance, are calling for 1 GW of additional LDES by 2026, and a coalition of community choice aggregators intends to procure 0.5 GW.[8]

LDES systems need to be extremely cheap compared with systems of shorter duration because they discharge infrequently, thereby limiting revenue. The energy subsystem (e.g., the storage medium and its container) for an economically viable 10-hour battery should have a capital cost of around $40 per kilowatt-hour (kWh) at most.[9] Li-ion batteries are much more expensive than that, coming in at around $350 per kWh in 2020.[10]

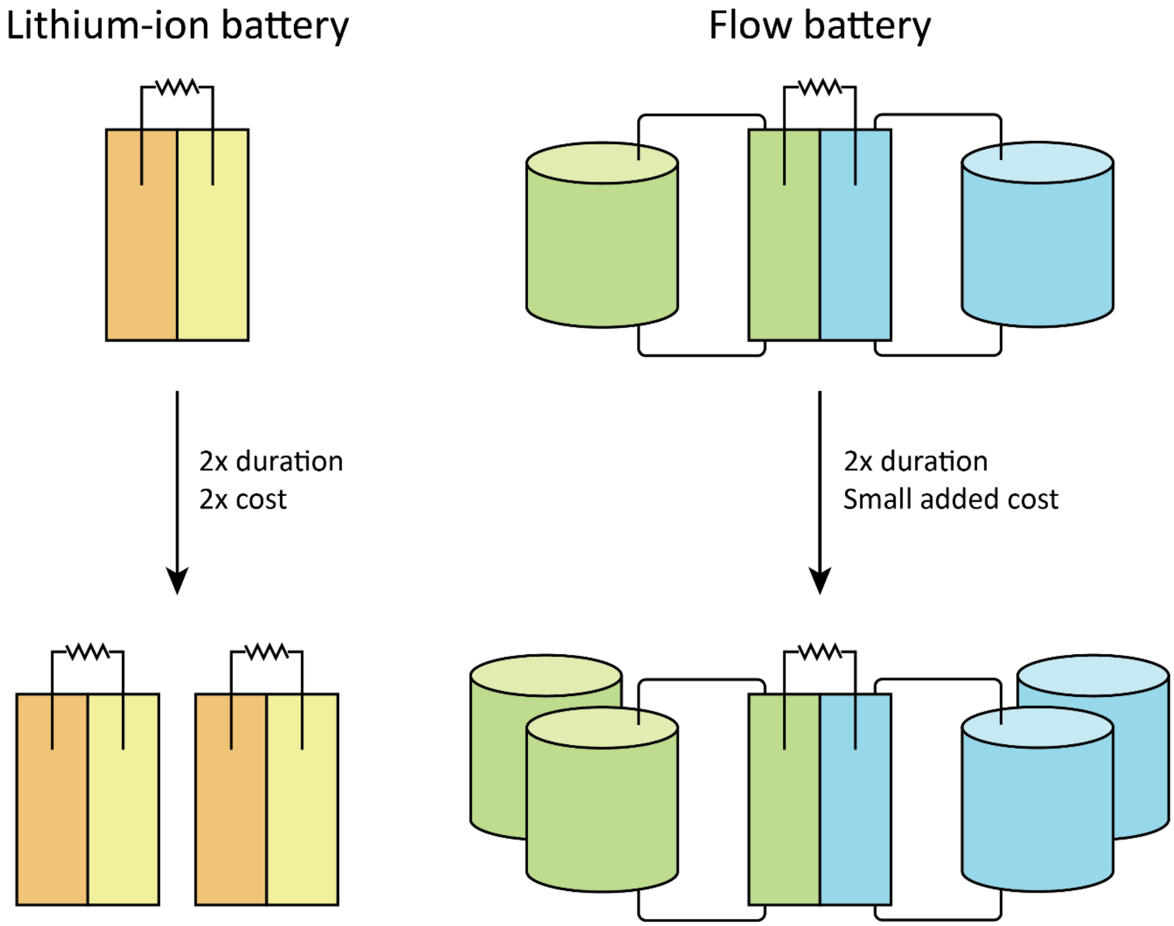
In addition to the cost barrier, supplies of key materials required for Li-ion batteries (especially cobalt) may be constrained, which would prevent them from being deployed at scale for grid applications.[11] Furthermore, Li-ion batteries pose significant safety hazards. Even at very small scale, thermal runaway can lead to explosions or fires. This risk could escalate severely for the larger systems required for cost-effective LDES installations.[12]

FLOW BATTERIES COULD EXCEL

The Li-ion battery industry has grown rapidly, primarily to serve the electric vehicle market. Its domination of energy storage applications presents a risk of technological lock-in. Other technologies that are more suitable for LDES have languished, even though Li-ion technology's limits are apparent to most observers.[13] The risk of lock-in is growing as Li-ion battery costs plummet.[14]

Flow batteries are one of the most promising options among the alternative storage technologies being explored for LDES. The distinguishing feature of this technology is that its active materials are stored separately from each other, outside of the cell in which power is generated. The archetypal flow battery has two tanks of liquid electrolytes, which are pumped into and out of the cell, exchanging ions through a membrane as the battery charges and discharges. This architecture can be implemented using a broad range of chemicals as active materials.

Figure 1: Schematic of Li-ion and flow batteries, illustrating the cost advantage of the flow architecture for LDES applications



Experts interviewed for this study described several advantages of flow batteries over Li-ion batteries for LDES.

- **Scalable duration.** The architecture of flow batteries decouples energy and power. If one compares a battery to a reservoir, its total energy can be thought of as the volume of water, while power is the rate at which water flows out of it. The active materials stored outside of a flow battery's cell determine the battery's energy capacity. The cell itself determines the battery's power rating. The tanks that hold the active materials can be scaled up separately from the cells. The duration of a flow battery with a given rated power, therefore, can be extended simply by increasing the amount of active material available—in essence, using a bigger tank. (See figure 1.)
- **Modular product capabilities.** Another benefit of decoupling energy and power is the ability to tailor products to custom applications. A Li-ion battery with a fixed duration is unlikely to be well matched to a customer's needs, either over- or under-delivering on energy to provide the needed power. The energy capacity and power rating of a flow battery can be sized separately to fit specific use cases.[15]

- **Reduced safety hazards.** Because the active materials in a flow battery are stored separately from each other and then combined in a controlled way while the battery is operating, these materials are completely isolated when the battery is inactive. This design makes flow batteries safer than Li-ion batteries, which are fully enclosed and can generate excessive heat and spontaneously ignite when the cell is damaged.[16] In addition, the electrolytes used in flow batteries are typically aqueous and therefore less flammable than the electrolytes used in Li-ion devices.[17]
- **Long lifetimes.** The lifetime of a flow battery has the potential to be much longer than that of a Li-ion battery, both in years of stable shelf life and the number of times it can cycle.[18] Its active materials can be replaced easily as the device ages.

As one interviewee put it:

> The benefits to power and energy being decoupled is huge for stationary storage in my opinion, because you don't get to sell a million of the same thing. Every customer wants something a little different. "I want eight hours of energy," "I want six," "I want five and a half." "I want one megawatt," "I want half a megawatt," "I want 10 megawatts." So for stationary products … modules are key.

FLOW BATTERY TECHNOLOGY IS STUCK

Flow batteries were first developed decades ago, but they have progressed only slowly toward commercialization since then.[19] While flow battery systems have been installed all over the world, especially in Europe and Asia, the flow battery industry remains very small. The largest flow battery project so far is a 60 megawatt-hour (MWh) installation in Hokkaido, Japan.[20] For comparison, that project is just one-twentieth the size of the Moss Landing Li-ion project in California.

Flow batteries struggle to compete with Li-ion batteries in grid storage applications. Over the past 15 years, Li-ion battery costs have dropped precipitously, driven by innovation and economies of scale in consumer markets such as portable electronics and, more recently, electric vehicles.[21] Rapid growth is expected to continue in both of these end uses, especially electric vehicles, which some analysts expect could demand as much as 4,000 gigawatt-hours (GWh) of Li-ion battery storage annually by 2025.[22] As of 2019, all flow battery projects installed worldwide combined totaled less than 1 GWh of power.[23]

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The problem for flow batteries is that grid operators currently only demand storage durations of six hours or less.[24] Flow batteries, despite their advantages for LDES, are not able to provide storage at sufficiently low cost and low risk for these relatively short duration applications. As the grid evolves to include higher penetration of renewables and thus requires more LDES, flow batteries' costs and risks are likely to come down. This slow innovation process is typical of energy technologies throughout history, but it is incompatible with the urgent response demanded by the current climate crisis.[25]

Interviewees pointed to three key shortcomings in the current status of flow battery development. First, the flow battery industry is still seeking a home-run active material that is based on abundant materials and can be cheaply scaled up. (See box 1.) Vanadium flow batteries are already approaching cost competitiveness with Li-ion at long durations, but vanadium is not abundant and will not be cheap enough in the long run.[26]

Second, the roundtrip efficiency of flow batteries is often lower than that of Li-ion batteries, which increases their operating cost for shorter durations with more frequent cycles. Efficiency losses are, however, expected to be less of a barrier as renewable electricity becomes cheaper over time.

Box 1: Looking Ahead to New Materials

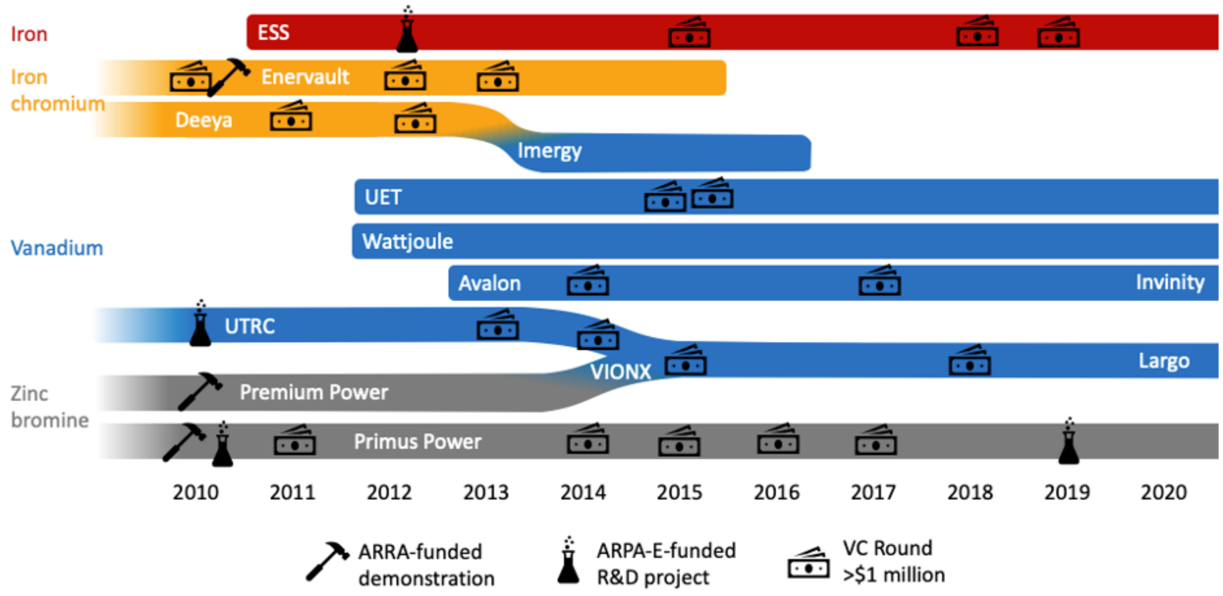
The most common and mature flow battery chemistry today uses vanadium as the active material.[27] Vanadium is not an abundant element; it is typically produced as a byproduct of iron ore. Vanadium prices have fluctuated dramatically over the past 30 years.[28] Cost estimates for just the vanadium active material itself range from $100 to over $150 per kWh, which is far too high to meet the cost target for LDES.[29]

Other flow battery materials offer an opportunity to reduce capital costs by using inexpensive and earth-abundant elements. One notable alternative to vanadium is a hybrid flow battery, such as in zinc-bromine or all-iron systems, which involves plating a solid metal onto the electrode when charging.[30] Aqueous sulfur is also being explored as a flow battery electrolyte.[31]

Aqueous organic electrolytes are another promising alternative.[32] These materials are currently pre-commercial but have the potential to be produced at very low cost. The cost of producing organic active materials depends on the complexity of the molecule and the efficiency of manufacturing techniques—factors that can benefit from the mature chemical processing industry. Organic electrolytes today are derived from petrochemicals. With further advances in chemistry, they could be generated instead from a renewable carbon feedstock, such as captured CO_2.

The flow battery architecture is flexible enough for an improved active material to potentially serve as a drop-in replacement for vanadium. Innovation in device components and field demonstrations of vanadium-based systems can proceed in parallel with material selection and optimization.

Figure 2: Selected U.S. flow battery companies from 2010 to 2020[33]



UET: UniEnergy Technologies.
UTRC: United Technologies Research Center.

The third and most serious barrier for flow batteries is the lack of "first markets" in which manufacturers can gain production experience. The Li-ion battery industry has gained a significant cost advantage as suppliers have worked their way down the learning curve in markets for electronics and vehicles. But there is no comparable opportunity for flow batteries, which are not suited for either of these end uses.

This lack of production experience also drives the perception that flow batteries are riskier than Li-ion batteries. Although flow batteries are a decades-old technology, they lack sufficient long-term performance data to demonstrate reliability of systems in the field. Utilities that consider buying them have a low risk tolerance and are rarely early adopters of innovative technologies. They expect grid storage systems to be backed by warranties and prefer well-known suppliers who will be around to handle the systems' maintenance and ultimate disposal.

The world cannot afford to wait for the slow dance between undercapitalized flow battery producers and hesitant utility technology adopters to play out. By the time the market for LDES grows and producers respond by lowering costs and developing a track record, decades will have passed.

PUBLIC R&D AND DEMONSTRATIONS HAVE MADE SOME HEADWAY

Despite its challenges, the flow battery industry has made significant advances in the past 10 years, thanks in part to government intervention. Interviewees emphasized federal R&D grants and demonstration projects as two key enablers of progress.

In 2010, DOE's Advanced Research Projects Agency-Energy (ARPA-E) launched its first round of R&D funding. The first cohort of ARPA-E-funded start-ups contained a high percentage of energy storage companies.[34] ARPA-E has enabled progress on grid storage in general, as noted by the

National Academies' assessment of the agency.[35] While ARPA-E does not have a dedicated funding stream for LDES, a review of its projects between 2010 and 2019 reveals a total of $40.3 million in R&D funding for flow batteries.[36]

One early ARPA-E program called GRIDS (Grid-Scale Rampable Intermittent Dispatchable Storage) targeted low-cost grid storage technologies, including a variety of projects on flow batteries.[37] Flow battery companies ESS, Primus Power, and UTRC were funded through this program. GRIDS's investments resulted in significant improvements in the power density and cycle lifetimes of flow batteries, often by adapting knowledge from the researchers' experience in fuel cells.[38] ARPA-E later funded several university projects on alternative active materials for flow batteries through the OPEN 2012 program. It also funded Primus Power and UTRC through the DAYS (Duration Addition to electricitY Storage) program, which targeted storage applications of 10–100 hours.[39]

The DOE Office of Electricity's Energy Storage (OE-ES) program also supported flow battery companies in 2010 by funding demonstration projects with Enervault, Premium Power, and Primus Power through the American Recovery and Reinvestment Act (ARRA). In the case of Primus Power, the ARRA-funded demonstration and the ARPA-E R&D grant worked in concert to help the company push the needle on zinc bromine flow batteries. The demonstration helped them establish a track record for their first-generation product, while the ARPA-E grant supported them in developing a new type of electrode.

These DOE grants for flow battery R&D and demonstration, each on the order of $1 million to $10 million, played a catalyzing role for flow battery companies. All told, they spurred complementary private investments of over $100 million for some companies. (See figure 2.)

ENERGY STORAGE: A BLIND SPOT IN THE DEPARTMENT OF ENERGY

Despite this early success, the private investment landscape for flow batteries is still shaky. Several venture capital (VC)-backed U.S. companies have shuttered in recent years. Enervault closed in 2015 after raising $26 million in VC. Imergy Power Systems (formerly Deeya) closed in 2016 after raising $82 million.[40] Unless the surviving companies find traction, the flow battery industry may see its pool of investors dry up. As one interviewee put it:

> These companies are often around for over a decade. They may raise 50 to 100 million dollars and then decide to close or change direction. I think the VC community now feels, "Wow, this is not for the faint of heart."

In light of these challenges and the success of DOE's public investments over a decade ago, one could reasonably ask: Why hasn't the department done more to push the flow battery industry forward in the years since ARRA? Flow battery experts consistently noted in the interviews that DOE does not have a program to fund extramural R&D in flow batteries. As a result, when innovators at U.S. companies or universities have novel ideas in this field, there are very few opportunities to pursue them.

Grid storage efforts at DOE involve a complicated patchwork of activities across different organizations, and flow batteries are no exception. (See Table 1.) The main institutional lead on these efforts is OE-ES, whose budget has been growing rapidly in recent years—from $20.5 million in FY 2016 to $56 million in FY 2020.[41] But OE-ES funding is entirely distributed through the national labs, primarily Pacific Northwest national laboratory (PNNL) and Sandia national laboratories.

Table 1: DOE activity on redox flow batteries[42]

Stage	DOE Office	Activity
Materials	Office of Science	Fundamental R&D
Materials	ARPA-E	Applied R&D
Materials	Advanced Manufacturing Office	Manufacturing R&D
Components & Devices	ARPA-E	Applied R&D
System Design	Office of Electricity	Applied R&D, Commercialization
System Integration	Office of Electricity	Commercialization
System Integration	Loan Programs Office	Commercialization
System Integration	Fossil Energy	Applied R&D
Investment/Finance	Office of Electricity	Applied R&D
Investment/Finance	Loan Programs Office	Commercialization
Operations	Office of Electricity	Applied R&D
Markets/Value	Vehicle Technologies Office	Applied R&D
Markets/Value	Office of Electricity	Applied R&D, Commercialization
Markets/Value	ARPA-E	Applied R&D
Markets/Value	Solar Energy Technologies Office	Applied R&D, Commercialization
End of Life	None	None

The contrast between this approach and DOE's standard practice is striking. Most DOE offices have a formal process for engaging and funding researchers across industry and academia in which they select the best ideas through a competitive process. One example is the Solar Energy Technologies Office (SETO) in the Office of Energy Efficiency and Renewable Energy (EERE). SETO posts funding opportunities and solicits proposals on particular topics, such as perovskite photovoltaic devices.[43] Their awards are spread across the entire United States and go to all types of organizations, including national labs, private companies (small and large), universities, nonprofits, and state and local governments.[44]

OE-ES, in contrast, does not offer open solicitations. Researchers at the national labs who receive OE-ES funding may subcontract to collaborators at companies or universities, but this process is ad hoc and opaque. There is no mechanism for a researcher outside of the network to propose a new project, and those who are fortunate enough to have a subcontract with one of the national labs face significant uncertainty. Unlike dedicated funding received through a DOE grant or cooperative agreement, subcontracts are subject to delay or termination due to disruptions such as government shutdowns or budget changes.

Multiple interviewees noted this gap in coverage even as they expressed appreciation for the national labs, which offer substantial talent and research capabilities. Flow battery research at PNNL spun out UniEnergy Technologies in 2012. Research from the Joint Center for Energy Storage (JCESR), a DOE Energy Innovation Hub hosted by Argonne national laboratory (ANL), contributed to the founding of Form Energy in 2017. The fact remains that these companies and others like them are not able to access public funding to support innovation in flow batteries.

OPPORTUNITIES TO SPEED INNOVATION IN LONG-DURATION ENERGY STORAGE

New active materials for flow batteries represent a major opportunity for innovation in LDES technologies. Similar opportunities exist across many LDES alternatives, including mechanical, thermal, and compressed air storage. For even longer duration storage (100+ hours), innovation in electrolysis and hydrogen fuel cells present promising pathways to balance seasonal variations in supplies of renewables.

A surge of funding for grid storage innovation at DOE, with an emphasis on longer duration timescales, could be extremely impactful to these technology trajectories. Recent proposed legislation would increase spending to $280 million per year for OE-ES (over five times the current level).[45] To get the most out of such an investment and address problems with the current program, three major changes should be made:

1. Directly fund R&D in LDES at universities and companies.
2. Give grid storage R&D a permanent home.
3. Expand testing and demonstrations.

Directly Fund R&D in LDES at Universities and Companies

Competitive R&D funding opportunities for LDES technologies must be made available to universities and private companies—not as substitutes for national lab efforts, but as invaluable complements. In the U.S. flow battery industry, the most important players are relatively young companies, with pressure from VC investors to focus on short-term marketable products. These start-ups in particular need an avenue to compete for public R&D funds and contribute to long-term innovation needs for LDES.

New funds for R&D on LDES should be distributed through open solicitations that seek out the best ideas across all organization types, including national labs that are not currently part of the OE-ES program, such as Argonne and Lawrence Berkeley. Meanwhile, ARPA-E should continue to competitively fund high-risk ideas for breakthrough R&D in grid storage. ARPA-E already engages the full range of actors in the innovation ecosystem—companies, universities, nonprofits, and national labs—with a team approach that combines strengths of different types of organizations.

Each ARPA-E project lasts two to three years, which is just enough time to get a new idea off the ground. Years of additional applied R&D may be needed before such an idea can be commercialized. ARPA-E needs a downstream partner within DOE to which it can hand off promising projects as they move from research into the development phase. The recent SCALEUP (Seeding Critical Advances for Leading Energy technologies with Untapped Potential) program at ARPA-E addresses this gap to some extent, with funding of up to $20 million for promising pre-commercial technologies based on prior ARPA-E projects.[46] This mode of funding should be expanded elsewhere in DOE, with a focus on grid storage.

Give Grid Storage R&D a Permanent Home

DOE needs a strong organizational structure to tackle all the known challenges of grid storage: cost-competitive systems, safety and reliability, regulatory support, and industry acceptance.[47] Technology improvements need to be coordinated, with a roadmap of cost targets for LDES applications, among others, and a multiyear investment plan to achieve these targets. In 2020, DOE's cross-departmental Energy Storage Grand Challenge (ESGC) released an initial roadmap.[48] This exercise produced a cost target of $0.05/kWh for levelized cost of electricity from LDES—but did not identify an entity that will be accountable for achieving it.

There should be a single DOE office responsible for goal setting and implementation of grid storage R&D and demonstration. Central coordination would better reflect the importance of storage in reaching the department's environmental and economic goals. Collaborations across DOE will remain critical to advancing storage technologies, which are inherently connected to end-use applications such as transportation and renewables. Designating a coordinating office would avoid the pitfalls associated with cross-cutting initiatives that have no clear home. In addition to modernizing the R&D portfolio by funding a diverse range of performers, this office should serve as a single entry point for industry partners, so lessons from research can more easily inform development across different storage applications, and vice-versa.

DOE could build this modernized and expanded grid storage effort on the foundation of the existing OE-ES, or it could create a new Office of Energy Storage. The latter option would align with the view that DOE should move away from the current fuel-based organizational structure (with separate offices for renewables, nuclear, fossil, etc.) and instead structure itself around applications (energy storage, electricity supply, fuel supply, etc.).[49]

Expand Testing and Demonstrations

In order for LDES technologies to take off, companies need opportunities to test and refine products before scaling up production. DOE can help by supporting testing and demonstrations. The Grid Storage Launchpad (GSL) being developed at PNNL is a step in the right direction.[50] GSL will help identify technical issues before technologies go to market through performance testing and validation of assembled systems less than 100 kW. New programs should be established to enable field demonstrations of validated systems. As companies develop products for beachhead residential and commercial markets, demonstrations at customer sites would be especially beneficial.

Federal agencies should also support innovation by directly procuring LDES systems.[51] The new Federal Consortium for Advanced Batteries—involving DOE, Department of Defense, Department of Commerce, and Department of State—is focused on developing the domestic industrial base for electric vehicle batteries.[52] This consortium model could be replicated for grid storage applications—and these same agencies could partner to enable LDES installations at military bases and other government sites.

In parallel with direct investments in innovation to reduce the cost of LDES technologies, a number of other energy policy levers could be pulled right away to speed deployment.[53] Recent changes in Federal Energy Regulatory Commission rules, such as Orders 841 and 2222, are removing barriers for storage to compete in electricity markets.[54] Further regulatory changes may be needed to support market participation of long-duration resources in particular. For flow batteries and other less mature LDES alternatives, policies such as these could have a huge impact in terms of innovation; the industry is poised to learn quickly as it grows.

CONCLUSION

The race between Li-ion batteries and other technologies to dominate electricity storage is a high-stakes competition for the future of the grid. Without the policy interventions recommended in this report, a crucial window for developing low-cost LDES technologies that would enable a cheap path to decarbonization could close. Immediate federal action is necessary to avoid missing this opportunity.

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