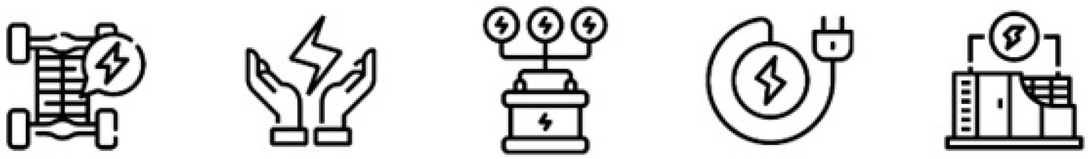

DRAFT
Energy Storage Strategy and Roadmap

An update to the Energy Storage Grand Challenge 2020 Roadmap

December 2024

U.S. Department of ENERGY

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Figures and Tables

Disclaimer

This Energy Storage Strategy and Roadmap is being disseminated by the U.S. Department of Energy. As such, this document was prepared in compliance with Section 515 of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (Public Law 106-554) and information quality guidelines issued by the U.S. Department of Energy. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government.

Acknowledgements

PLACEHOLDER: To be drafted for final version.

Executive Summary

From the first tenuous grid battery storage installations in the early 2000s, the new generation of storage technology has sufficiently matured to provide substantial grid, market, and customer benefits akin to legacy generation resources and pumped storage hydropower (PSH). Until 2020, the typical (non-hydro) grid storage resource was sized in single-digit megawatts (MW); in 2024, storage resources in the hundreds of MW are increasingly common.

Despite this unprecedented growth, Department of Energy's (DOE) role in facilitating this key technology has not slowed. DOE continues to build on its headline successes to further improve safety and supply chain resilience along the path to a fully storage-enabled clean energy future. Further, because of the transformative nature of storage functions, many use cases and markets are still underdeveloped.

Reflecting these considerations and developments, this 2024 Energy Storage Strategy and Roadmap (SRM) represents a significantly expanded strategic revision on the original Energy Storage Grand Challenge (ESGC) 2020 Roadmap. This SRM outlines actions that implement the strategic objectives facilitating safe, beneficial and timely storage deployment; empower decisionmakers by providing data-driven information analysis; and leverage the country's global leadership to advance durable engagement throughout the innovation ecosystem. The underlying motivation for DOE's strategic investment in energy storage is to ensure that the American people will have the resources needed, when needed.

This SRM articulates a revised vision and mission for DOE's crosscutting Energy Storage System Research, Development, Demonstration, and Deployment Program:

VISION:

Energy storage innovations enable resilient, flexible, affordable, and secure energy systems and supply, for everyone, everywhere.

MISSION:

To empower a self-sustaining energy storage ecosystem that develops, delivers, and deploys breakthrough solutions to meet a range of real-world applications, across multiple time horizons.

To accomplish this mission, DOE's energy storage activities will be guided by three over-arching strategic objectives (SOs):

SO 1. To facilitate safe, beneficial, and timely deployment of energy storage technologies and accelerate the development of new technologies that address current and emerging consumer needs.

SO 2. To empower decision-makers by providing unbiased and fact-based information and analysis to enhance their energy storage-related investments, policies, and goals.

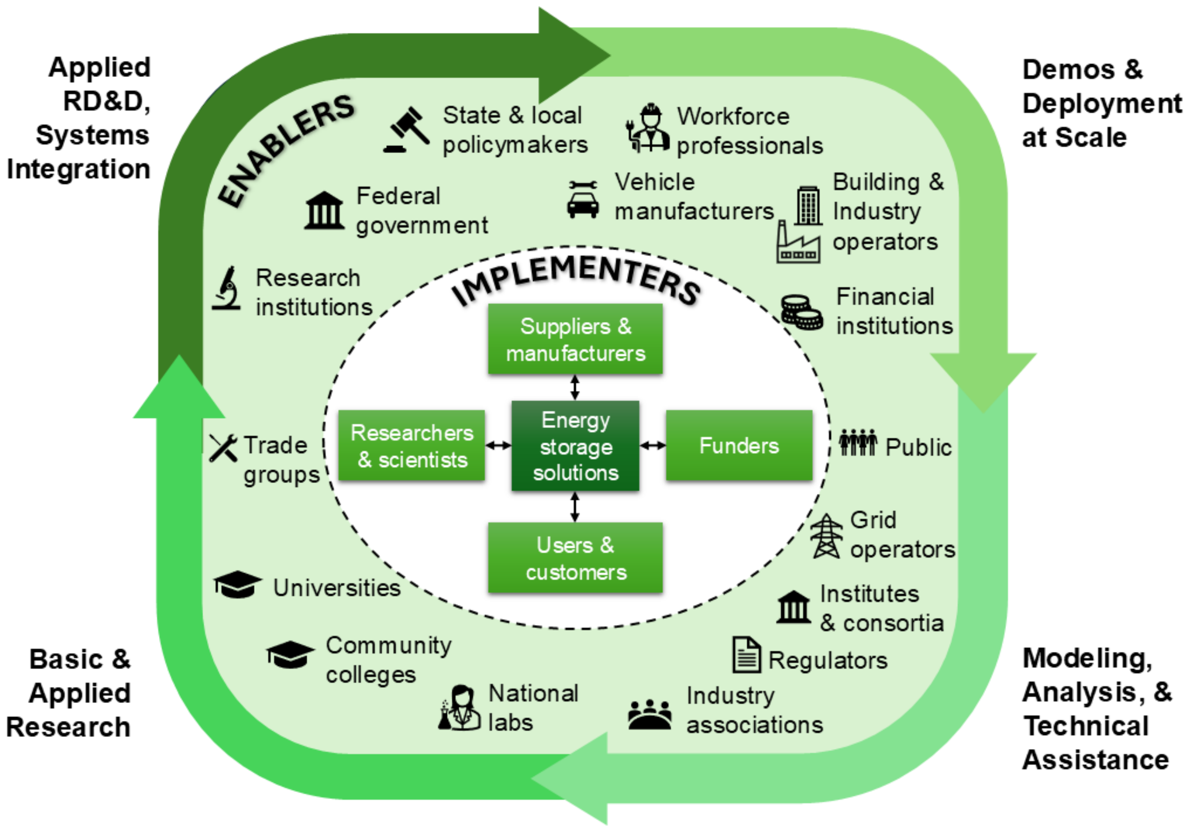
SO 3. To leverage DOE's global leadership in the energy storage community and accelerate the path from innovation to commercialization that benefits all Americans by effective and durable engagement throughout the innovation ecosystem.

These strategic objectives are supported by eight strategies:

- Make long-term investments in fundamental and responsible energy storage technology research.
- Target strategic, high-impact use cases for energy storage technologies.
- Improve energy storage implementation cost assessments.
- Inform the value proposition through development of valuation assessments and compensation mechanisms.
- Enhance safety and reliability of energy storage technologies.

- Advance equitable access to energy storage technologies to meet existing and emerging community needs.
- Strengthen and enable reliable, resilient, affordable, diverse, sustainable, and secure domestic energy storage supply chains, including critical minerals and materials and a circular economy, that helps expand American manufacturing and jobs.
- Collaborate across DOE programs, mission areas, and external to DOE.

These strategies recognize that the ecosystem around energy storage is growing and evolving, as shown in the figure below.



The implementation of these strategies will be measured by a variety of indicators. The broad metric categories include technology innovation and commercialization; stakeholder engagement and satisfaction; and collaboration and partnerships.

The SRM then identifies how DOE can best interact with the various parts of the storage ecosystem, including through basic and applied research; applied RD&D and systems integration, demonstration and deployment at scale; and modeling, analysis, and technical assistance.

The SRM updates the use case-based framework originally introduced in the ESGC 2020 Roadmap with a new focus on outcomes and the role of energy storage rather than specific applications. Use cases continue to serve as a bases for evaluating the potential of the many energy storage technologies currently being explored or developed. In this SRM, the use case framework is augmented with technology, manufacturing, and adoption readiness levels which has since been used throughout the Department (including in its ongoing series of Technology Liftoff reports).

Finally, the SRM identifies specific actions on a near-, mid-, and long-term timeline to achieve the vision of delivering energy storage innovations that enable resilient, flexible, affordable, and secure energy systems and supply, for everyone, everywhere.

Statutory Language

Publication of this Energy Storage Strategy and Roadmap (SRM) responds to the language set forth in Section 3201 of the Energy Act of 2020 (42 U.S.C. § 17232)[1]. The relevant part of Section 17232 states:

§17232. Better energy storage technology

…

(b) ENERGY STORAGE SYSTEM RESEARCH, DEVELOPMENT, AND DEPLOYMENT PROGRAM.—

…

(5) ENERGY STORAGE STRATEGIC PLAN.—

(A) IN GENERAL.—The Secretary shall develop a 10-year strategic plan for the program, and update the plan, in accordance with this paragraph.

(B) CONTENTS.—The strategic plan developed under subparagraph (A) shall—

(i) be coordinated with and integrated across other relevant offices in the Department;

(ii) to the extent practicable, include metrics that can be used to evaluate storage technologies;

(iii) identify Department programs that—

(I) support the research and development activities described in paragraph (2) and the demonstration projects under subsection (c); and

(II)

(aa) do not support the activities or projects described in subclause (I); but

(bb) are important to the development of energy storage systems and the mission of the Department, as determined by the Secretary;

(iv) include expected timelines for—

(I) the accomplishment of relevant objectives under current programs of the Department relating to energy storage systems; and

(II) the commencement of any new initiatives within the Department relating to energy storage systems to accomplish those objectives; and

(v) incorporate relevant activities described in the Grid Modernization Initiative Multi-Year Program Plan.

(C) SUBMISSION TO CONGRESS.—Not later than 180 days after December 27, 2020, the Secretary shall submit to the Committee on Energy and Natural Resources of the Senate and the Committees on Energy and Commerce and Science, Space, and Technology of the House of Representatives the strategic plan developed under subparagraph (A).

(D) UPDATES TO PLAN.—The Secretary—

1 Sec. 3201(b)(5), Division Z - Energy Act of 2020, Consolidated Appropriations Act, 2021, Pub. L. 116-260 (Dec. 27, 2020) (42 U.S.C. § 17232(b)(5)).

(i) shall annually review the strategic plan developed under subparagraph (A); and

(ii) may periodically revise the strategic plan as appropriate.

Foreword

Energy storage in 2024 exists at an inflection point. From the first tenuous grid battery storage installations in the early 2000s, the new generation of storage technology has sufficiently matured to provide substantial grid, market, and customer benefits akin to legacy generation resources and pumped storage hydropower (PSH). Until 2020, the typical (non-hydro) grid storage resource was sized in the single-digit megawatts (MW); in 2024, storage resources in the hundreds of (MW) are increasingly common. In the 2010s, storage accounted for a fraction of a percent of total new capacity additions; in 2024, the U.S. Energy Information Agency (EIA) projects that new storage capacity additions will eclipse wind, nuclear, and all fossil capacity combined. While planners from just a few years ago may have been hesitant to include storage, over 70 utility integrated resource plans (IRPs) include some form of energy storage. With the triple drivers of dramatically decreased cost, increased market value, and standalone tax credits from the Inflation Reduction Act of 2022 (IRA), the question for most people in energy is not “if” storage, but “how much” and “when.”

Despite this unprecedented growth, Department of Energy’s (DOE) role in facilitating this key technology has not slowed. DOE continues to build on its headline successes to further improve safety and supply chain resilience along the path to a fully storage-enabled clean energy future. As developers seek more sites for new deployments, neighbors and permitting officials are raising questions about safety. As over 95 percent of deployments continue to utilize lithium-based batteries, having “different chemistries among the options” for storage “could increase the resiliency of the overall supply chain.” [1]

As the average duration of new storage resources in 2024 still struggles to reach 4 hours, market refinements and technology improvements will still be required to enable the long duration applications (intra-day, multi-day, and weekly) such as resilience and deep decarbonization. Beyond grid-centric applications, energy storage technologies are being integrated into industrial processes and building designs. Chemical and concrete industries are large consumers of energy, many plants having their own power generators and energy storage systems. Likewise, buildings can be seen as self-contained cities with their own energy infrastructure. Energy storage coupled with energy production are being designed into both industry and new building construction as part of larger efforts toward decarbonization and energy resilience.

Reflecting these considerations and developments, this 2024 Energy Storage Strategy and Roadmap (SRM) represents a significantly expanded strategic revision from the original Energy Storage Grand Challenge (ESGC) 2020 Roadmap. Despite the apparent speed at which energy storage has moved past the early adopter phase, there are benefits to guiding this technology towards outcomes that secure critical energy storage supply chains; ensure safety, reliability, and resilience; grow quality jobs and workforce; and enable affordability and versatility, among other key objectives.

This SRM outlines actions that implement the strategic objectives facilitating safe, beneficial and timely storage deployment; empower decisionmakers by providing data-driven information analysis; and leverage the country’s global leadership to advance durable engagement throughout the innovation ecosystem. When successful, this strategy should result in energy storage innovations that deliver solutions enabling resilient, flexible, affordable, and secure energy systems for everyone, everywhere.

This SRM is one of the early steps in the process of achieving the full potential of the energy storage era. This document sets the stage for future updates and refinements as required by the Better Energy Storage Technologies (BEST) section of the Energy Policy Act of 2020 [2], no less frequently than annually.

Introduction

In January 2020, Department of Energy (DOE) launched the Energy Storage Grand Challenge (ESGC) to facilitate a department-wide strategy to accelerate the development, commercialization, and use of next-generation energy storage technologies and sustain American global leadership in energy storage. This Energy Storage Strategy and Roadmap (SRM) implements the “Energy Storage System Research, Development, and Deployment Program” as required by the Better Energy Storage Technology (BEST) section of the Energy Policy Act of 2020 [2]. The ESGC executes DOE’s overarching strategy to address energy storage for the benefit of all Americans along the following tracks (see Appendix D.3.1 for additional details):

- The Investment, Commercialization, and Scale-Up Track
- The Manufacturing and Supply Chain Innovations, Workforce Track
- The Markets and Valuation Track
- The Technology Development Track

Through the core ESGC DOE offices[2], DOE has or currently supports over 30 distinct energy storage technologies, including specific methods of storage via electrochemical, electromechanical, thermal, flexible generation, and controllable loads, as well as power electronics (Figure 1). For example, the development and commercialization of Li-ion technologies being used in grid storage applications, based on lithium nickel cobalt aluminum (NCA) and lithium iron phosphate (LFP) chemistries, were supported by DOE’s Vehicle Technologies Office (VTO) for electric vehicle (EV) applications over the past 30 years.

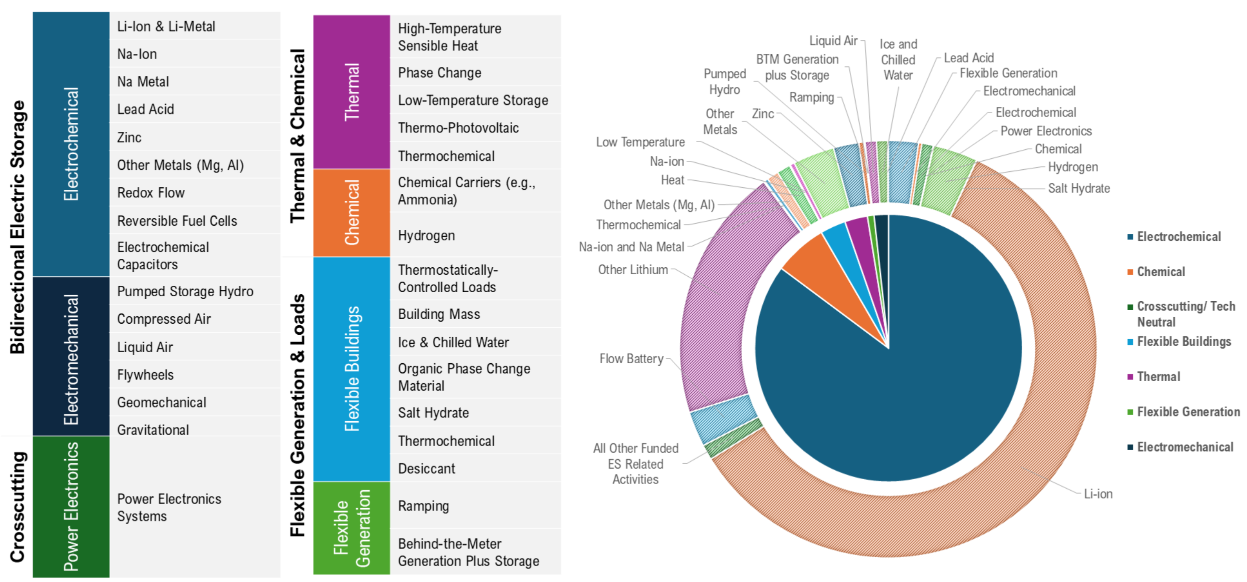


Figure 1. DOE support across 30+ energy storage technologies (FY2021-FY2023).

[2] DOE’s Office of Energy Efficiency and Renewable Energy (EERE) and Office of Electricity (OE) co-chairs the ESGC. Other ESGC core offices include the Offices Clean Energy Demonstrations (OCED), Fossil Energy and Carbon Management (FECM), Manufacturing and Energy Supply Chains (MESC), Nuclear Energy (NE), Science (SC), Technology Transitions (OTT), the Advanced Research Projects Agency-Energy (ARPA-E), the Federal Energy Management Program (FEMP), and the Loan Programs Office (LPO). See Appendix A for more information about DOE offices engaged in energy storage RDD&D.

DOE's Electricity Advisory Committee (EAC) is required by Congress to periodically evaluate DOE's energy storage activities (see Appendix I). The EAC's 2022 Biennial Energy Storage Review [3], based on a months-long review of obstacles and challenges facing the energy storage industry, determined areas of pressure and pain; assessed whether DOE was addressing these obstacles and challenges in its funding, policy, initiatives, and other efforts; and provided recommendations to DOE. The EAC review included the following core recommendations for DOE to prioritize for Fiscal Years 2023 through 2025 (see Appendix I and reference [3] for more details):

1. Conduct macro-energy storage analysis.
2. Coordinate with industry to promote efficient markets for energy storage.
3. Support local efforts by states and regulators to remove barriers to facilitate markets and remove disincentives for energy storage.
4. Improve the resilience of critical services by supporting the deployment of energy storage at critical services and interdependent network infrastructure.
5. Increase the resilience of the grid and support customer, critical services, and grid-level resilience by facilitating the bidirectional storage capacity of electrified mobility.
6. Facilitate the cost-effective deployment and interoperability of fixed and mobile storage assets by promoting standards that support consistent best practices among the industry and user groups.
7. Address barriers and develop use cases for the industry and end users to facilitate timely and efficient interconnection and accelerate the integration of storage assets to maintain stability and promote resilience as the grid transitions.

Additionally, three primary gaps were identified:

- Supporting policymakers and regulators in efforts to remove barriers to adoption, showcase successful use cases and best practices to promote feasible deployments, and develop plans that appropriately value and integrate energy storage into energy, resilience, and climate policy.
- Supporting efforts to overcome the technical and practical challenges of interconnecting energy storage systems to the grid or behind-the-meter.
- Focusing on technology development challenges around mid-stage technology development (Technology Readiness Levels (TRLs) 5–7) [4] with regard to improving performance, safety, reliability, and cost outcomes for adopters.

In recognition of these recommendations from the EAC and other stakeholders across the energy storage sector, this SRM report presents a clarified mission and vision, a strategic approach, and a path forward to achieving specific objectives. *This report does not address new policy actions, nor does it specify budgets and resources for future activities.*

Section 1 of this document presents the mission and vision driving DOE's energy storage activities across various DOE programs and offices. The mission identifies the purpose of DOE's coordinated energy storage efforts while the vision describes the desired end-state for this SRM.

Section 2 describes the strategic approach and high-level direction for DOE's energy storage RDD&D that establishes the blueprint for DOE's energy storage roadmap (Section 5). The roadmap provides more tactical direction, informed by the mission, vision, and strategic approach.

Section 3 presents an overview of the types of DOE activities that support DOE's Energy Storage SRM. Activities include not only conventional research activities, but also those efforts that are foundational and crosscutting in support of the mission and vision of the SRM as well as stakeholder engagements. Representative activities are identified in the appendix.

Section 4 describes the portfolio of energy storage technologies and highlights opportunities for future DOE investment based on the current landscape of technologies and use cases.

Section 5 describes the path forward to achieve the strategic objectives and vision of this Energy Storage SRM. This section highlights DOE activities to facilitate technology innovation and deployment, to empower decision-makers, and to strengthen collaboration throughout the energy storage ecosystem.

Finally, **Section 6** summarizes anticipated outcomes and next steps as DOE works to implement this Energy Storage SRM.

Appendix A identifies DOE offices with relevant energy storage R&D programs.

Appendix B provides a list of acronyms used in this document.

Appendix C provides a list of key terms and definitions used in this document.

Appendix D provides updates to the ESGC 2020 Roadmap action items and targets; it also describes major transitions from the ESGC 2020 Roadmap to the current SRM.

Appendix E identifies representative DOE activities contributing to DOE's energy storage portfolio.

Appendix F reviews the relevant 2015 GMI MYPP energy storage activities for connections to this SRM and DOE's energy storage activities. Additionally, relevant elements of the GMI MYPP 2020 Update are also discussed.

Appendix G highlights relevant policy and regulatory drivers impacting the energy storage landscape.

Appendix H highlights representative examples of DOE's international energy storage activities and initiatives.

Appendix I summarizes the recommendations from the Electricity Advisory Committee's 2022 Biennial Energy Storage Review, which focused on the ESGC 2020 Roadmap.

This SRM responds to the Energy Storage Strategic Plan periodic update requirement of the Better Energy Storage Technology (BEST) section of the Energy Policy Act of 2020 [2].

1 Mission and Vision

DOE ensures America's security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions [5]. To ensure energy security, the grid is adapting to a rapidly changing landscape, including economic integration of renewable resources and increasing climate volatility. DOE is fostering new storage technologies and applications to tackle these challenges — from supporting research on storage at the DOE National Laboratories, to making investments that take startup concepts to grid-scale solutions [6].

VISION:
Energy storage innovations enable resilient, flexible, affordable, and secure energy systems and supply, for everyone, everywhere.

MISSION:
To empower a self-sustaining energy storage ecosystem that develops, delivers, and deploys breakthrough solutions to meet a range of real-world applications, across multiple time horizons.

The evolving energy storage ecosystem (see Figure 2) concentrates on emerging technologies and market opportunities to address a variety of consumer needs. The interdependencies within the ecosystem leverage the knowledge and capabilities across subject matter experts, including the DOE National Laboratories and partners from academia, industry, local and state governments, other Federal agencies, and international organizations. The diversity of stakeholders, the accessibility of data, tools and analysis, and the availability of resources support a successful ecosystem.

As the market for energy storage has expanded, so has the technology's ecosystem. Changes to the grid's generation mix have increased the value proposition for energy storage and shone a light on its potential application to a variety of use cases. As consumer needs continue to shift, the energy storage ecosystem is adapting. Once focused on a smaller pool of implementers – tech developers, manufacturers, off-takers, and funders – new storage applications have both expanded the implementer pool and highlighted the importance of enabling more stakeholders. With this widened aperture, the actions of direct and indirect stakeholders highlight the interconnectedness of the various market, academic, and institutional actors in the greater storage ecosystem.

While there are many facets of the ecosystem that contribute to its success, this Energy Storage Strategy and Roadmap (SRM) focuses primarily on DOE's research, development, demonstration, and deployment (RDD&D) efforts. This SRM also acknowledges additional activities that are important to the development of energy storage systems and achieving DOE's mission for the benefit all Americans.

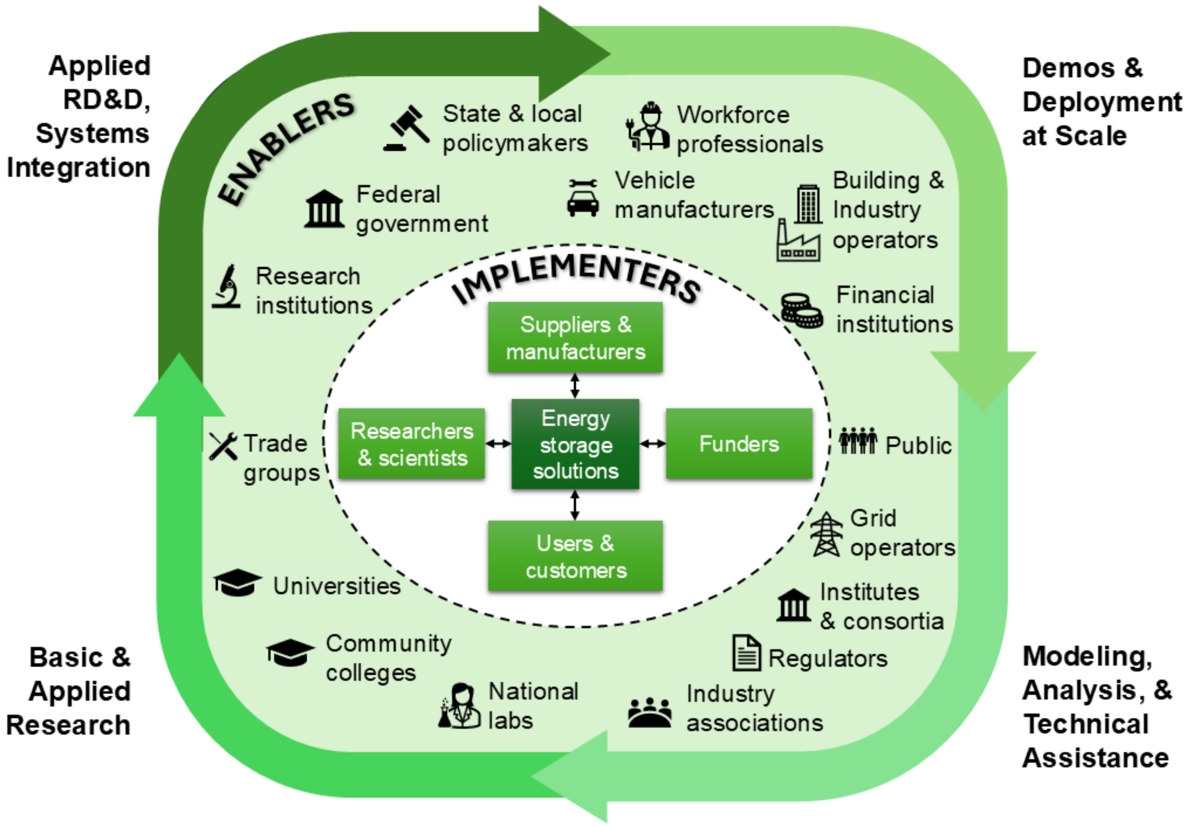


Figure 2. The energy storage ecosystem comprises numerous perspectives that participate in a variety of capacities that align with DOE's RDD&D activities.

2 Strategic Overview

The purpose of this Energy Storage Strategy and Roadmap (SRM) is to provide strategic direction and identify key opportunities to optimize DOE's investment in and planning of energy storage activities over the next 10 years. This document not only describes the current landscape and the integral role of DOE in enabling and sustaining advancements in energy storage, but it also lays the groundwork for enhanced coordination, internally and externally, to address near-, mid-, and long-term needs.

2.1 Strategic Objectives

DOE's energy storage activities are guided by three over-arching strategic objectives (SOs):

SO 1. To facilitate safe, beneficial, and timely deployment of energy storage technologies and accelerate the development of new technologies that address current and emerging consumer needs.

SO 2. To empower decision-makers by providing unbiased and fact-based information and analysis to enhance their energy storage-related investments, policies, and goals.

SO 3. To leverage DOE's global leadership in the energy storage community and accelerate the path from innovation to commercialization that benefits all Americans by effective and durable engagement throughout the innovation ecosystem.

2.2 Strategies to Achieve DOE's Energy Storage Vision

This SRM is driven by eight strategies to guide specific DOE efforts through 2035 on advancing and scaling a portfolio of technologies that address the SOs (see Section 2.1) while also equipping the policy and regulatory community (described in Appendix G) to be ready for these new capabilities. Each of the eight strategies is described below. Figure 3 illustrates the connectivity between each of the strategies and the SOs that will help DOE achieve its energy storage vision.

MISSION
To empower a self-sustaining energy storage ecosystem that develops, delivers, and deploys breakthrough solutions to meet a range of real-world applications, across multiple time horizons.

Vision: Energy storage innovations that enable resilient, flexible, affordable, and secure energy systems and supply, for everyone, everywhere.

Strategic Objectives	To facilitate the safe, beneficial, and timely deployment of energy storage technologies and accelerate the development of new technologies that address current and emerging consumer needs.	To empower decision-makers by providing unbiased and fact-based information and analysis to enhance their energy storage-related investments, policies, and goals.	To leverage DOE's global leadership in the energy storage community and accelerate the path from innovation to commercialization by effective and durable engagement throughout the innovation ecosystem.
Make long-term investments in fundamental and responsible energy storage technology research.	✓		✓
Target strategic, high-impact use cases for energy storage technologies.	✓	✓	✓
Improve energy storage implementation cost and valuation assessments to uncover potential cost savings.	✓	✓	
Inform the value proposition through development of valuation assessments and compensation mechanisms.	✓	✓	
Enhance safety and reliability of energy storage technologies.	✓	✓	
Advance equitable access to energy storage technologies to meet existing and emerging community needs.	✓	✓	
Strengthen and enable reliable, resilient, affordable, diverse, sustainable, and secure domestic energy storage supply chains.	✓	✓	✓
Collaborate across DOE programs, mission areas, and external to DOE.	✓	✓	✓

Figure 3. Eight strategies support the three strategic objectives that will help DOE achieve its vision and mission.

2.2.1 Strategy 1: *Make long-term investments in fundamental and responsible energy storage technology research.*

Research investments in next-generation energy storage technologies – whether materials, components, or design – will help drive toward new advancements that will serve the public good and enable the U.S. to remain a competitive world leader in energy storage. Advancing capabilities and efficiencies in support of this research will help focus efforts to achieve more reliable, sustainable, and affordable solutions. Responsible research investments can inform near-, mid-, and long-term research and development (R&D) innovation, providing benefit across a longer time horizon. Accelerating the path from innovation to commercialization, in turn compressing the time to market, is an opportunity for next generation (leapfrog) storage technologies from domestic manufacturers to overtake international competitors.

2.2.2 Strategy 2: *Target strategic, high-impact use cases for energy storage technologies.*

Strategic, high-impact use cases help guide R&D investments and enhance the impact of those investments. The transformational nature of storage means that consumers, and those who act on their behalf, will continue to discover energy storage technology solutions, how they can be used, their value propositions, and ultimately the motivation to adopt the solutions. Since development for every eventuality would be inefficient, efforts should focus on those use cases that will deliver step change value improvements to the consumer.

2.2.3 Strategy 3: *Improve energy storage implementation cost assessments.*

As new storage technologies are integrated into more systems, the associated costs (e.g., development, capital expenditure (CAPEX), financing, operation and maintenance (O&M)) become more complex. The costs of and cost reductions from technology solutions can accrue at various levels, from individual components to system designs and operation schemes. Improvements to cost and valuation assessments, especially in specificity, comparability, transparency, and accessibility, can help expand the pool of decisionmakers who are equipped to evaluate storage investments.

2.2.4 Strategy 4: *Inform the value proposition through development of valuation assessments and compensation mechanisms.*

Like many new clean technology solutions, the upfront cost of storage may be considered prohibitive despite its long-term value proposition. While existing generation-centric compensation mechanisms (such as arbitrage and capacity payments) have already led to substantial storage deployments, other benefits such as improved resilience or resource diversity have been more difficult to quantify. More complete assessment of storage value propositions, and their translation into compensation and market mechanisms, can encourage wider adoption of the technology solution.

2.2.5 Strategy 5: *Enhance safety and reliability of energy storage technologies.*

Safety and reliability are mandatory components for all technology and infrastructure deployments. These attributes are magnified for storage, since new or incremental benefits can accrue as storage is deployed closer to its end use and applications. All stakeholders that engage with the technology (e.g., developers, installers, regulators, end users, communities) must be included in fostering a strong culture of safety and reliability. Efforts in this area can include establishing clear expectations (i.e., documented procedures, well-defined standards, accepted best practices), effective communication, and a continuous learning environment. By prioritizing safety and reliability, the storage ecosystem – especially those who may be new to the arena – can better manage the risks associated with their application and fostering acceptance for broader use.

2.2.6 Strategy 6: *Advance equitable access to energy storage technologies to meet existing and emerging community needs.*

Innovation and energy justice are at the forefront of DOE’s mission. Equitable access to energy storage refers to all consumers having access to the technology solutions and information about technology solutions. As storage technologies become more accessible in size and scale, disadvantaged, marginalized, underserved, or under-represented communities should have the opportunity to benefit their deployment to meet their current and existing needs, such as increasing resilience or maximizing energy flexibility. The Justice40 Initiative (see Appendix G.1.4.1) further reinforces the need to address energy equity challenges as DOE continues to invest in storage technologies and technical assistance [7].

2.2.7 Strategy 7: *Strengthen and enable reliable, resilient, affordable, diverse, sustainable, and secure domestic energy storage supply chains, helping expand American manufacturing and jobs.*

The U.S. needs resilient, diverse, and secure supply chains to ensure our economic prosperity and national security. As storage is a major component of current and future energy systems, securing the energy storage supply chain can provide dual benefits of safeguarding critical infrastructure components and strengthening domestic manufacturing and workforce. DOE roles include supporting re-shoring, skilling, and scaling of U.S. supply chains for energy storage technologies; developing tools for supply chain vulnerability and innovation analysis; and championing workforce investments across the industry. The broad options for storage technologies provide an opportunity to decouple, diversify, and expand supply chains, while also improving recycling and circularity of materials, and delivering substantial environmental, economic, and community benefits. With increased reliance on domestic energy storage supply chains comes the potential to expand American manufacturing and the jobs to support that expansion.

2.2.8 Strategy 8: *Collaborate across DOE programs, mission areas, and external to DOE.*

The expansive nature of the energy storage opportunity – potentially benefitting "everyone, everywhere" as noted in the vision statement – means that many parts of DOE will be called upon to address the many facets of energy storage technology innovation. A collaborative approach will be the backbone from which DOE will build on successful relationships – internal and external to DOE – to strengthen its institutionalized coordination bodies.[3] Effective coordination and collaboration increases efficiency and effectiveness while addressing a broader range of opportunities across DOE mission areas.[4]

External collaborations with other government agencies, private and public sector partners, and universities and research institutions will further extend DOE's reach by capitalizing on the strengths of each collaborator, including, but not limited to, scientific or technical expertise, access to resources, analytical capabilities, technology innovations, and relationships. Collaborators will mutually benefit from these interactions, working together to meet the breadth of opportunities for energy storage technology innovation.

2.3 Guiding Principles for an Agile Strategy

Guiding principles help decision-makers achieve a desired vision. They help us nurture the culture that will facilitate our vision and strategic intent. While practices can change, business models are disrupted, and technology evolves, principles are intended to be evergreen and durable. Guiding principles codify overarching guidance and values that underly the activities and decisions that meet SOs and achieve DOE's energy storage vision. DOE will use these guiding principles (see Figure 4) as the SRM is developed and continuously refined.

[3] The Energy Storage Grand Challenge (ESGC) represents one institutionalized body within DOE tasked with coordinating DOE's energy storage activities. DOE's Energy Earthshot™ Initiative [94] comprises eight different Shots™, including the Long-Duration Storage Shot™ (see Appendix G.4.1). Additionally, DOE has several other cross-cutting initiatives (e.g., working groups, Science and Energy Tech Teams (SETTs)) that draw on expertise and capabilities stewarded by multiple DOE offices to address forefront energy challenges.

[4] An example is the significant battery R&D effort within VTO on EV batteries where, as noted earlier, the near-term and long-term R&D has proved useful for stationary applications. We expect that successful next generation batteries for EVs can translate to stationary applications.

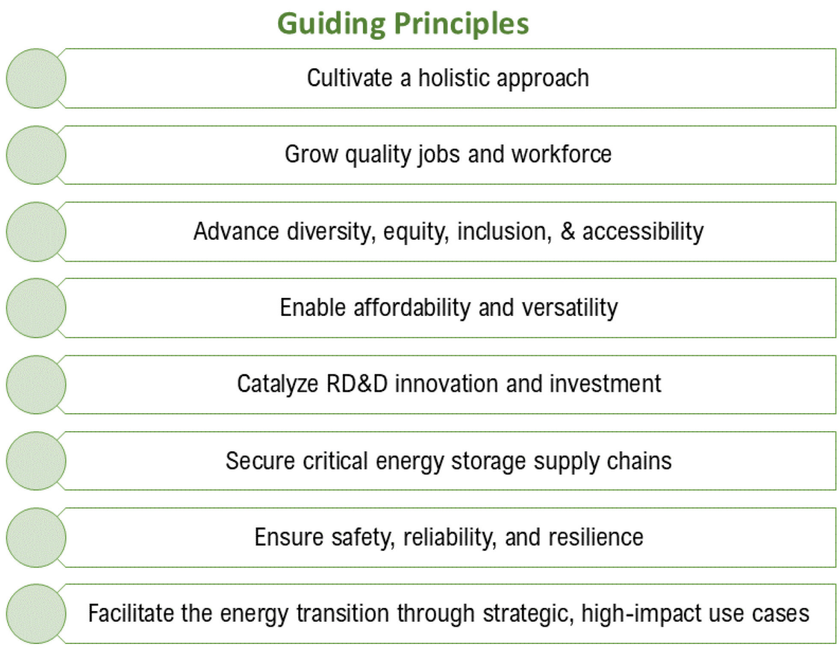


Figure 4. Guiding principles for the development and deployment of energy storage technologies.

2.3.1 Cultivate a holistic approach.

DOE will employ a concerted, intentional, holistic approach when developing energy storage activities (including, but not limited to, the Long Duration Storage Shot™, programs, projects, targets, and efforts pertaining to energy storage technologies, markets, and infrastructure) across the energy storage pipeline. DOE will holistically consider services that energy storage can provide across the stakeholder ecosystem, from local, municipal, and state governments and other entities in the electrical power system. DOE offices will seek to understand and advance storage development in alignment with local, state, regional, and Federal permitting, policy, and regulations. DOE will foster rigorous and transparent analyses on social, environmental, economic, and energy impacts to help guide sustainable development of the nascent global energy storage industry.

2.3.2 Grow quality jobs and workforce.

DOE will focus on preserving and growing quality jobs by making meaningful impacts to the direct and indirect energy storage workforce. These jobs are defined as good-paying, family-sustaining jobs with pathways for advancement, worker voice in workplace health and safety plan design and implementation, and the free and fair chance to join a union.

DOE's actions will also provide opportunities for workers and communities transitioning away from carbon-intensive sectors, leveraging existing and developing new skills across industries by utilizing and expanding education for workforce development, registered apprenticeship programs, working with partners to support training programs, and developing other sectoral strategies for workforce development. DOE will work to capitalize and expand upon the potential for job creation within the storage sector.

2.3.3 Advance diversity, equity, inclusion, and accessibility (DEIA).

DOE will pursue a comprehensive, systemic approach to advance equity[5], including delivering energy and environmental justice by fulfilling the Justice 40 Initiative (see Appendix G.1.4.1). DOE and awardees of DOE funding and grants should strive to identify, evaluate, and communicate harmful impacts due to burdens, disparities, and negative externalities associated with DOE activities, with careful attention toward impacts on historically overburdened and underserved communities. DOE will seek to increase transparency, community engagement, economic opportunities, and access to energy storage technologies that can help improve the health and well-being of communities, especially rural, underserved, and/or disadvantaged communities affected by the clean energy transition.

DOE will promote DEIA during selection of awardees for competitive opportunities to effectively advance the U.S. research, innovation, and commercialization enterprise. DOE's actions will support stewardship and promotion of diverse and inclusive workplaces that value and celebrate a diversity of people, ideas, cultures, and educational backgrounds that are foundational to delivering on DOE's energy storage strategy.

2.3.4 Enable affordability and versatility.

DOE will target affordability and versatility by advancing new materials and manufacturing platforms that can be leveraged for the development of innovative technologies to improve efficiencies, quality, and resilience. DOE will also seek to provide transparency around technology costs and performance for stakeholders. By clearly outlining use cases, cost reductions, and performance enhancements, DOE can guide stakeholders in comprehensive valuation of the benefits of storage technologies and highlight the complementarity of short-, med-, and long-duration storage.

2.3.5 Catalyze RDD&D innovation and investment.

DOE will foster partnerships with industry, academia, national laboratories, and other stakeholders to invest in innovation. DOE's actions will stimulate energy storage market growth, a competitive domestic energy storage industry, and sustained private investment, building upon American ingenuity, talent, and initiative. DOE envisions a globally competitive U.S. manufacturing sector that accelerates the adoption of innovative materials and manufacturing technologies. Fundamental scientific research, applied energy storage research, and deployment opportunities will accelerate bi-directional electrical energy storage technologies as a key component of the future-ready grid. DOE will engage with stakeholders to accelerate market recognition of the value of energy storage technologies for emerging and known use cases and services.

2.3.6 Secure critical energy storage supply chains.

When developing energy storage activities, including supporting critical material, component, device, and system level production, DOE will consider potential local, regional, and domestic supply chain implications. DOE activities will support U.S. re-shoring, skilling, and scaling of U.S. manufacturing, to ensure robust, secure, and resilient supply chains. DOE's actions will utilize multiple tools, from grants to financing to facilitating partnerships. DOE will also support the development of analytical tools to characterize and identify gaps, vulnerabilities, and other needs across U.S. supply chains for energy storage.[6] In addition,

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[5] The term "equity" is consistent with Executive Order 14091 [76].

[6] Recent DOE analyses have characterized the makeup of storage technologies, as well as vulnerabilities in the supply chain for transportation and stationary storage technologies. Examples include America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition [77], the Grid Energy Storage Supply Chain Deep Dive Assessment [1], and dedicated sections of the Long Duration Storage Shot Technology Strategy Assessments [22].

DOE will begin to evaluate the viability of new domestically-sourced and -processed materials for energy storage applications.

2.3.7 Ensure safety, reliability, and resilience.

DOE will seek to identify and support safe, low-cost, and earth-abundant materials for energy storage development and scale up. Furthermore, DOE will support activities that anticipate and address energy storage safety concerns, supporting early adoption by improving storage reliability and safety. DOE will inform and support workforce development to implement safety practices and reduce risk.

2.3.8 Facilitate the energy transition through strategic, high-impact uses.

DOE will facilitate administrative goals to support the energy transition through targeted deployments of energy storage in sectors where its use has the most impact, including commercial, industrial, residential, mobility, and grid services. These strategic deployments will be informed through analyses and stakeholder input to address key priorities.

2.4 Current Storage Ecosystem Landscape and Path

Section 2.2 identifies eight strategies that embody not only how DOE has historically engaged with the energy storage ecosystem, but also how DOE anticipates being able to achieve the SOs in support of this SRM's mission and vision. As a starting point, DOE considers how these strategies align with the current energy storage landscape and ecosystem, and how they provide direction for the path forward.

2.4.1 Storage Ecosystem Inventory

The energy storage ecosystem has been expanding in response to the breadth of interest in and applications for energy storage technologies to meet a variety of customer needs. Table 1 provides a snapshot of the different entities engaged across the ecosystem and their relative order of magnitude for participants in the ecosystem.

Table 1. Energy storage ecosystem entities, by relative order of magnitude.

1s	U.S. Federal Government (e.g., U.S. DOE, Federal Energy Regulatory Commission (FERC), Federal Consortium for Advanced Batteries (FCAB))
100s	Universities and Community Colleges
10s	National Laboratories
10s	Research Institutions: Industry/Utility (e.g. the Electric Power Research Institute (EPRI)) or State Government (e.g., California Energy Commission (CEC), New York State Energy Research and Development Authority (NYSERDA), Washington State Department of Commerce)
100s	Suppliers and Manufacturers, including Technology Vendors, Developers, Integrators
10s	Trade Groups, Industry Associations, and Consortia, including commercial Nationally-Recognized Testing Labs (NRTLs)
100s	Grid Operators, including Regional Transmission Organizations (RTOs), Independent System Operators (ISOs),Transmission Operators (TOs), Distribution System Operators (DSOs)
10s	State and Local Policymakers (e.g., public utility commissions (PUCs))
10s	Integrators (e.g., vehicle manufacturers or system vendors)

10000s	Users and Customers
1000s	Utilities
100s	Financial Institutions (e.g., investors, lenders, insurers)
10s	International Partners (e.g., government bodies, research institutions and private associations)
10s	U.S. Standards development organizations (e.g., National Fire Protection Association (NFPA))

With such a wide range of participants, and their individual activities, understanding how DOE's strategy can complement other on-going activities across the ecosystem will help DOE better align its opportunities to address gaps, inspire innovation, and enhance ecosystem-wide collaboration and communication.

2.4.2 How the Ecosystem Measures against Strategies

This section identifies relevant indicators to assess how well the U.S. energy storage ecosystem is achieving the SOs identified earlier in this draft SRM. Metrics have been identified to support each of the strategic objectives for this SRM. As part of the draft, these metrics appear in a proposed form and will be populated in the final SRM.

Strategic Objective 1 focuses on technology innovation and deployment. Four metrics will inform how the ecosystem currently measures against this SRM (strategies) and how the pathways, as they are implemented, continue to make progress against these metrics.

- **Innovation Rate**: Assesses the success of R&D projects to support achievements towards reaching the market and achieving commercial viability, including through the RDD&D cycle.
- **Commercialization Success Rate**: Assesses the ability of R&D projects that become commercially viable to be recognized by and meet consumer/market needs.
- **Time to Market**: The time from the initiation of an R&D project to the commercial launch of the product.
- **Return on R&D Investment**: Of the projects receiving DOE support, how have they informed or influenced the ecosystem (e.g., valuation, manufacturing, safety/reliability).

Strategic Objective 2 focuses on empowering decision-makers. Four metrics will inform how the ecosystem currently measures against this SRM (strategies) and how the pathways, as they are implemented, continue to make progress against these metrics.

- **Quality and Customer Satisfaction:** Assesses the quality of the R&D outputs (e.g., work products, tools, analysis) and ability to meet customer needs.
- **Stakeholder Engagement Influence**: Assesses the effectiveness of DOE's stakeholder engagement efforts with respect to decision-making processes, policies, or initiatives, e.g., the extent to which DOE's engagement activities result in tangible changes or improvements that reflect stakeholder input.
- **Stakeholder Engagement Return on Investment (ROI)**: Assess the financial and non-financial benefits derived from DOE's stakeholder engagement efforts and the overall value of the stakeholder engagement.
- **Stakeholder Engagement Relevance**: Assesses the alignment of DOE's stakeholder engagement efforts with DOE's overall strategy and objectives, and stakeholder needs.

Strategic Objective 3 focuses on strengthening collaboration. Four metrics will inform how the ecosystem currently measures against this SRM (strategies) and how the pathways, as they are implemented, continue to make progress against these metrics.

- **Stakeholder Collaboration and Partnership Success**: Assesses DOE's ability to successfully engage with stakeholders in collaborative initiatives and partnerships and assesses the effectiveness of DOE's efforts to leverage stakeholder input, expertise, and resources to achieve shared goals.
- **Collaboration Effectiveness**: Assesses the effectiveness of collaboration efforts within R&D teams and with external partners (e.g., to enhance innovation quality and speed, leverage diverse expertise and perspectives).
- **Co-marketing performance**: Assesses the benefits of co-marketing collaboration with respect to sharing knowledge, resources, and other capabilities; co-marketing is when two or more organizations collaborate to market to a shared audience.
- **Product Engagement**: Assesses the degree to which DOE R&D products are embraced by the ecosystem, including with references or endorsements.

The tables that follow summarize the major ecosystem participants and their roles, as well as propose relevant metrics and measures for each SO, based on their alignment with each strategy (refer to Figure 2, page 21, and Figure 3, page 23). These metrics would be collected periodically over the life of the SRM.

2.4.2.1 Strategy 1: Make long-term investments in fundamental and responsible energy storage technology research.

Strategy 1	**Make long-term investments in fundamental and responsible energy storage technology research.**

Major Ecosystem Participant	**Role**
DOE, State Research Agencies	sets agendas for and funds long-term investments in technology research
Research Institutions	coordinates and performs long term research
Technology Vendors	commercializes, incorporates technology research

Strategic Objective	**Metric**	**Measure(s)**
Technology Innovation and Deployment	Return on RDD&D Investment	▪ Number and type of RDD&D awards ▪ Number and proportion of innovations commercialized, capital invested, technology deployment and sales
	Commercialization Success Rate	▪ Commercialization activity (e.g., patent licensing)
	Time to Market	▪ Duration between commencement of work in one domain to when a subsequent downstream entity validates that work and incorporates it into the next innovation (e.g., materials to cell to system to demo to manufacturing to deployment)
Empowering Decision-Makers	n/a	
Strengthening Collaboration	Stakeholder Collaboration and Partnership Success	▪ [placeholder]
	Collaboration Effectiveness	▪ Participation in facilitation-type activities (e.g., count of participants in the Long-Duration Energy Storage National Consortium)
	Co-marketing performance	▪ [placeholder]
	Product Engagement	▪ Industry leverage of national lab capabilities (e.g., number of Cooperative Research and Development Agreements (CRADAs), Strategic Partnership Projects (SPPs), systems

		tested at the Grid Storage Launchpad (GSL), Advanced Research on Integrated Energy Systems (ARIES))

2.4.2.2 Strategy 2: Target strategic, high-impact use cases for energy storage technologies.

Strategy 2	**Target strategic, high-impact use cases for energy storage technologies.**
Major Ecosystem Participant	**Role**
DOE	funds research into use cases
Research Institutions (Academia, National Labs)	performs research on use cases
Technology Vendors	designs products and services to obtain a return on use cases
Regulators: FERC, State Commissions	sets rules that determine the viability of use cases
Grid Operators: RTO	sets rules that determine the viability of use cases

Strategic Objective	**Metric**	**Measure**
Technology Innovation and Deployment	Innovation Rate	▪ Number of new use cases published
	Time to Market	▪ Speed of rulemakings – measuring how quickly the functions enabled by new technology propagate into market and regulatory structures
Empowering Decision-Makers	Quality and customer satisfaction	▪ [captured in metrics below]
	Stakeholder Engagement Influence	▪ Citation of research in procedural rulemakings
	Stakeholder Engagement ROI	▪ Market/system opportunity (e.g., by megawatt (MW)/gigawatt (GW) capacity) that becomes “storage-enabled” per dollar of technical assistance investment
	Stakeholder Engagement Relevance	▪ Quantifying technical assistance, e.g., “From 2020-2024, the Office of Electricity (OE) Energy Storage Program-provided webinars, modeling, or other assistance to X state commissions”
Strengthening Collaboration	Stakeholder Collaboration and Partnership Success	▪ Degree of peer-to-peer information sharing among decision-makers
	Collaboration Effectiveness	▪ Participation levels of different stakeholder groups, ▪ Frequency of meetings/collab opportunities ▪ # of actionable outcomes developed through collaborations
	Product Engagement	▪ Breadth of the portfolio of emerging technologies
	Co-marketing performance	▪ Number of webinars and media projects for DOE activities

2.4.2.3 Strategy 3: Improve energy storage implementation cost and valuation assessments to uncover potential cost savings.

Strategy 3	**Improve energy storage implementation cost and valuation assessments to uncover potential cost savings.**
Major Ecosystem Participant	**Role**
DOE	funds research on cost and valuation assessments
Research Institutions (Academia, National Labs)	performs research on cost and valuation assessments
Utilities, Grid Operators, State Regulators	incorporate cost and valuation assessments into long term plans

Strategic Objective	**Metric**	**Measure**
	Innovation Rate	▪ Cost declines in storage, such as changes in the levelized cost of storage (LCOS) or other financial indicators

Technology Innovation and Deployment	Commercialization Success Rate	▪ Market share ▪ Revenue generation ▪ Customer adoption rate or number
	Time to Market	▪ Assessments should exhibit minimal lag as new technology attributes (cost, performance) are revealed
	Return on R&D Investment	▪ [placeholder]
Empowering Decision-Makers	Quality and customer satisfaction	▪ [placeholder]
	Stakeholder Engagement Influence	▪ Number and type of participants who provide input into assessments
	Stakeholder Engagement ROI	▪ Citations of assessments in procedural rulemakings
	Stakeholder Engagement Relevance	▪ [placeholder]
Strengthening Collaboration	n/a	

2.4.2.4 Strategy 4: Inform the value proposition through development of valuation assessments and compensation mechanisms.

Strategy 4	**Inform the value proposition through development of valuation assessments and compensation mechanisms.**	
Major Ecosystem Participant	**Role**	
DOE	funds research on compensation mechanisms	
Research Institutions (Academia, National Labs)	performs research on compensation mechanisms	
Regulators	incorporates assessments into reforms or adopts new market mechanisms	
Developer	utilizes new compensation mechanisms to deploy storage for new use cases	
Strategic Objective	**Metric**	**Measure**
Technology Innovation and Deployment	Innovation Rate	▪ [placeholder]
	Commercialization Success Rate	▪ Number of markets adopting reforms ▪ Change in use cases (indicated by duration or other factors) for new deployments
	Time to Market	▪ Duration between mechanism research, implementation, and deployments
	Return on R&D Investment	▪ Rate of market expansion versus input effort
Empowering Decision-Makers	Quality and customer satisfaction	▪ [placeholder]
	Stakeholder Engagement Influence	▪ [placeholder]
	Stakeholder Engagement ROI	▪ Citations of assessments in procedural rulemakings
	Stakeholder Engagement Relevance	▪ [placeholder]
Strengthening Collaboration	n/a	

2.4.2.5 *Strategy 5: Enhance safety and reliability of energy storage technologies.*

Strategy 5	Enhance safety and reliability of energy storage technologies.
Major Ecosystem Participant	**Role**
DOE	funds research, development, validation, and demonstration to enhance safety and reliability
Research Institutions (Academia, National Labs)	provide foundational research for safety and reliability methods
Commercial NRTLs	incorporate new safety and reliability knowledge into standards and testing and certification procedures
North American Electric Reliability Corporation (NERC)	sets standards for the reliable operation of the bulk power system
Developer	implements safety and reliability standards into storage deployments
Host Community	assesses and weighs energy storage system benefits versus risks
Owner and Project Host	communicates risks and benefits to community members
Lender, Insurer	quantifies energy storage system risks to price insurance or capital
Local Authorities Having Jurisdiction	approves storage deployments on the basis of compliance with safety rules, regulations
Standards Development Organizations	establishes standards for design and integration of devices/systems
Local First Responders	trained on risks and appropriate responses to any misoperations of the storage deployment

Strategic Objective	Metric	Measure
Technology Innovation and Deployment	Innovation Rate	▪ Successful safety tests
	Commercialization Success Rate	▪ Codes and standards avoid creating barriers to new technologies ▪ Decisionmaker awareness of safety results for DOE energy storage projects
	Time to Market	▪ Codes and standards should exhibit minimal lag as new technologies reach commercialization
	Return on R&D Investment	▪ Compare investment into safety and reliability enhancement activities to savings in fewer misoperations and benefits from faster or greater deployment
Empowering Decision-Makers	Quality and customer satisfaction	▪ Reversals of energy storage moratoriums (citation of DOE research in decision)
	Stakeholder Engagement Influence	▪ Decisionmaker use of DOE testing and validation or deployment results
	Stakeholder Engagement ROI	▪ Jurisdictions incorporating storage-aware codes and standards (number, share, etc.) ▪ Codes and standards incorporate existing and new storage technologies ▪ Time lag between first commercial deployments and appearance in codes and standards ▪ Citations of DOE-supported results in codes and standards development ▪
	Stakeholder Engagement Relevance	▪ Education on safety impacts of emerging technologies to avoid rulemaking/policy barriers
Strengthening Collaboration	n/a	

2.4.2.6 *Strategy 6: Advance equitable access to energy storage technologies to meet existing and emerging community needs.*

Strategy 6	Advance equitable access to energy storage technologies to meet existing and emerging community needs.
Major Ecosystem Participant	**Role**
DOE	funds capacity building, demonstration projects for use cases that emphasize equitable access
Workforce	supports development, manufacturing, deployment, operation, management, and regulation of energy storage systems
Trade groups, Industry Associations and Consortia	industry groups and labor unions for reaching consensus in host communities
Integrators, utilities, and co-ops	funds and sites pilot and demonstration projects
State and local policymakers	sets DEIA targets
Host Community	dedicates resources to research, planning, design, execution of a new beneficial storage deployment
Suppliers and manufacturers	design and deploy solutions that are beneficial to community use cases

Strategic Objective	**Metric**	**Measure**
Technology Innovation and Deployment	Innovation Rate	▪ [placeholder]
	Commercialization Success Rate	▪ Project development in new communities ▪ Deployments of energy storage technologies ○ in Energy Community geographies ○ with Community buy-in or ownership
	Time to Market	▪ [placeholder]
	Return on R&D Investment	▪ The Small Business Innovation Research and Small Business Technology Transfer Programs (SBIR/STTR), Justice40-qualifying RD&D activities under the Energy Storage Grand Challenge (ESGC)
Empowering Decision-Makers	Quality and customer satisfaction	▪ Local support of DOE-funded energy storage projects (e.g., number of approved projects vs contested projects) ▪ Repeat deployments of energy storage projects
	Stakeholder Engagement Influence	▪ Total of capacity building activities under ESGC
	Stakeholder Engagement ROI	▪ [placeholder]
	Stakeholder Engagement Relevance	▪ Decisionmaker use of valuation assessments of storage benefits
Strengthening Collaboration	n/a	

2.4.2.7 *Strategy 7: Strengthen and enable reliable, resilient, affordable, diverse, sustainable, and secure domestic energy storage supply chains, helping expand American manufacturing and jobs.*

Strategy 7	Strengthen and enable reliable, resilient, affordable, diverse, sustainable, and secure domestic energy storage supply chains.
Major Ecosystem Participant	**Role**
DOE	incorporates supply chain considerations into RDD&D portfolio and objectives
Suppliers and manufacturers	have primary responsibility for implementing new supply chain capacity and methods
Workforce	develop new skillsets/reskill workforce for energy storage needs
Users and customers	benefit from a secure, resilient, and diverse supply chain

Strategic Objective	Metric	Measure
Technology Innovation and Deployment	Innovation Rate	▪ Costs at scale
	Commercialization Success Rate	▪ Production rate for components and systems
	Time to Market	▪ [placeholder]
	Return on R&D Investment	▪ Domestic supply chain capacity sufficient to meet market demand ▪ Percentage of raw materials sourced locally or geographically dispersed (i.e. not concentrated in certain regions) ▪ Supply chain is resilient to disruptions (i.e. recyclability rate)
Empowering Decision-Makers	Quality and customer satisfaction	▪ Success rate of tax credit utilization
	Stakeholder Engagement Influence	▪ Clarity and standardization in definitions for policymakers as related to supply chains/deployment
	Stakeholder Engagement ROI	▪ [placeholder]
	Stakeholder Engagement Relevance	▪ Stakeholders have sufficient information to make long term supply chain investments
Strengthening Collaboration	Stakeholder Collaboration and Partnership Success	▪ Communities have buy-in as part of supply chain capacity expansions
	Collaboration Effectiveness	▪ Clarity in roles along value chain (producers, users, end-of-life)
	Co-marketing performance	▪ [placeholder]
	Product Engagement	▪ [placeholder]

2.4.2.8 Strategy 8: Collaborate across DOE programs, mission areas, and external to DOE.

Strategy 8	Collaborate across DOE programs, mission areas, and external to DOE.
Major Ecosystem Participant	**Role**
DOE	share expertise with other agencies/organization, domestically and internationally; learn from others about challenges and successes
Other Federal Agencies	share energy storage needs and knowledge with DOE/other agencies; utilize DOE expertise, tools, other resources (via FCAB or similar mechanisms)
State & Local Agencies/Organizations	share energy storage needs and knowledge with DOE/other agencies; utilize DOE expertise, tools, other resources
International Governments/Organizations	share energy storage needs and knowledge with DOE/other agencies; utilize DOE expertise, tools, other resources

Strategic Objective	Metric	Measure
Technology Innovation and Deployment	Innovation Rate	▪ Accelerated timeline to solution by exchange of technical knowledge/experience
	Commercialization Success Rate	▪ [placeholder]
	Time to Market	▪ [placeholder]
	Return on R&D Investment	▪ Use of DOE facilities
Empowering Decision-Makers	Quality and customer satisfaction	▪ Hosting of and participation in capacity building events ▪
	Stakeholder Engagement Influence	▪ DOE sets example/model for other agencies/organizations
	Stakeholder Engagement ROI	▪ [placeholder]

	Stakeholder Engagement Relevance	▪ [placeholder]
Strengthening Collaboration	Stakeholder Collaboration and Partnership Success	▪ Agreements, MOUs with domestic and international partners (i.e., FCAB agreement) ▪ Lab-industry partnerships ▪ Private working sessions/closed door sessions ▪ Co-appearances with domestic and international partners ▪ RFI announcements ▪ Progression of funding recipients across offices as they move across RDD&D (i.e. funding of Form Energy by multiple offices over time – JCESAR to OCED now)
	Collaboration Effectiveness	▪ DOE: cross-citations of documents in office funding opportunity announcements FOAs (e.g., if an OE FOA references an EERE document) ▪ DOE: Cross-office references in public facing documents (i.e. strategy documents and Notice of Funding Opportunities (NOFOs)) ▪ Cross-office participation in FOA reviews
	Co-marketing performance	▪ Increased engagement because of partnered/co-organized efforts
	Product Engagement	▪ [placeholder]

3 Activities Supporting DOE's Energy Storage Strategy and Roadmap (SRM)

To support the key strategies (see Section 2.2), DOE leverages the entire continuum of activities across basic science through applied research, development, demonstration, and large-scale deployments. The research, development, demonstration, and deployment (RDD&D) continuum provides a useful framework for mapping the stages of a technology's progression to commercialization – starting with research into an innovative idea and ending with commercial scale deployment. As shown in Figure 5, the continuum of activities will be supported by foundational and crosscutting efforts to promote diversity, equity, inclusion, and accessibility (DEIA); engage communities, ranging from environmental justice groups to Tribes, tribal organizations and labor unions; develop the workforce; advance policy; support the technology and energy transition; and enable market adoption at scale.

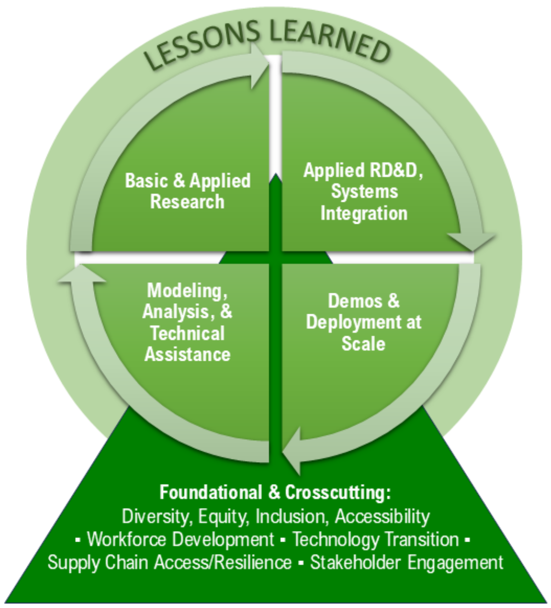

Figure 5. A diverse portfolio of activities supporting DOE's Energy Storage SRM across the RDD&D continuum.

The Federal Government sponsors research and development (R&D) activities under a variety of types of awards, most commonly grants, cooperative agreements, and contracts, to achieve objectives agreed upon between the Federal awarding agency and the non-Federal entity. The types of R&D conducted under these awards vary widely. Subject to annual congressional appropriations and private sector investment, Federal agencies and other stakeholders will undertake additional actions across the RDD&D continuum. Federal research investments pay rich dividends to the Nation. The pursuit of innovation not only enables the private sector to generate new knowledge and adopt novel technologies, but these activities often lead to commercial success, increased jobs, and improved quality of life for all Americans.

3.1 The RDD&D Continuum

The sections that follow describe the elements of the continuum and provide context for the types of activities that each element represents. Throughout each element of the continuum, valuable lessons are learned and provide opportunity for improvement not only within each element, but as progress is made around the continuum. Appendix E provides representative examples of recent and ongoing DOE activities that align with the elements of the continuum.

3.1.1 Basic & Applied Research

Research is a systematic study directed toward fuller scientific knowledge or understanding of the subject studied [8] [9]. Research is classified as either basic or applied:

Basic research: experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts. Basic research may include activities with broad or general applications in mind.

Applied research: original investigation undertaken in order to acquire new knowledge. Applied research is, however, directed primarily towards a specific practical aim or objective.

Research can also be defined as intramural or extramural research:

Intramural research: research conducted by scientists employed by the Federal Government, as well as DOE-funded research at the DOE National Laboratories.

Extramural research: research conducted by investigators and institutions outside of the Federal Government.

Research is planned search or critical investigation aimed at discovery of new knowledge with the hope that such knowledge will be useful in developing a new product or service (hereinafter “product”) or a new process or technique (hereinafter “process”) or in bringing about a significant improvement to an existing product or process.

In the context of Federal grants and awards, R&D means all research activities, both basic and applied, and all development activities that are performed by non-Federal entities. The term research also includes activities involving the training of individuals in research techniques where such activities utilize the same facilities as other R&D activities and where such activities are not included in the instruction function [10] [11].

DOE’s energy storage portfolio embraces both basic and applied research. The DOE National Laboratories provide a wealth of expertise and execute directed research in support of DOE’s energy storage portfolio. Additionally, DOE offers a variety of funding opportunities to external entities to conduct R&D activities that align with various program missions, in furtherance of DOE’s energy storage goals. Appendix E.1 offers representative examples of DOE’s basic and applied research activities. These examples include DOE National Laboratory-led partnerships, external partner-led activities, and university collaborations. Through these engagements, DOE can maximize the breadth and impact of its investments by leveraging a larger portfolio of experts and innovators. Collectively, these efforts advance the foundational understanding of various energy technology materials, designs, and performance to yield technology solutions with potential to support real-world energy storage applications.

3.1.2 Applied RD&D and Systems Integration

Applied research, development, and demonstration (RD&D) include efforts that focus on creative and systematic work, drawing on knowledge gained from research and practical experience, which is directed at producing new products or processes or improving existing products or processes [8] [9]. Development also includes the use of research findings applied to the production of useful materials, devices, systems, or methods, including design and development of prototypes and processes [10] [11].

Demonstration activities that are part of R&D that are intended to prove or to test whether a technology or method does in fact work. Demonstrations of prototypes or processes from the R&D phase provide a platform to test and evaluate the ability of the prototype or process to perform as designed before it is demonstrated in a real-world setting. These demonstrations help determine whether or not the prototype or process should move forward in the continuum and whether it should be promoted as an innovative solution to the application for which it was designed.

Systems integration provides tailored technical and programmatic support to ensure a disciplined approach to the research, design, development, and validation[7] of complex systems. Systems integration provides independent, strategic, systems-level expertise and processes to enable system-level planning, data-driven decision-making, effective portfolio management, and program integration. Tailored to the particular requirements of a robust, comprehensive (RD&D) program, this approach can take advantage of experience, and lessons learned from industry, academia, international sources, and other Federal agencies.

DOE's energy storage portfolio embraces opportunities to test and evaluate performance of energy storage technologies supporting different applications to help improve the understanding of the technologies, their performance and capabilities under different scenarios, and the cost implications of those technology applications. Not only does this kind of work help establish a baseline for innovative solutions, but it also helps identify remaining opportunities for further advancement. Through this level of test and evaluation, DOE helps guide technologies as they make progress along the continuum. Appendix E.2 offers representative examples of DOE's applied RD&D and system integration activities. These examples include a validation initiative seeking to aggregate performance data across technology developers and a focused DOE national laboratory facility that will enable broader testing and evaluation of energy storage systems, among other capabilities.

3.1.3 Demonstrations and Deployment at Scale

Demonstration involves testing and validating the new technology, process, or product in a real-world setting. This may involve conducting field tests or pilot projects to assess the effectiveness and feasibility of the innovation. The data and feedback collected during the demonstration stage can then be used to refine the innovation further and prepare it for commercialization. [8] [9]

Deployment requires project proponents to ensure that their product or service meets all requirements before it can be released into the market. This includes ensuring compliance with applicable regulations and conducting tests to ensure that the product works properly in real-world situations.

DOE's energy storage demonstration and deployment activities often engage external partners selected through competitive funding opportunities to leverage the resources and expertise of those partners to execution real-world demonstrations and larger scale deployments. Through these opportunities, DOE's investments provide additional performance validations and real-world experiences working with energy storage technology solutions. This information can inform the greater community and help shape future technology innovations.

Appendix E.3 offers representative examples of DOE's demonstration and deployment at scale activities. These examples include long-duration lithium-ion storage deployments in remote communities and military housing and long-duration energy storage demonstrations using a variety of innovative technologies including second life electric vehicle (EV) batteries, flow batteries, zinc batteries, and iron batteries.

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[7] In this context, validation refers to the practice of analyzing and demonstrating the economic and technical viability of energy storage technologies to end users, including through the use of energy storage system tools and models.

3.1.4 Modeling, Analysis, and Technical Assistance

DOE supports cutting-edge modeling tools and analytical insight to inform decision-making across the energy ecosystem. Access to R&D datasets, modeling tools, and analysis can unlock additional value and enable discovery of new materials, designs, and methods to further advance technologies and identify process efficiencies. This aggregation of information takes many forms across DOE's energy storage portfolio, from studies exploring the value of energy storage as the power system evolves, to dialogues between innovator communities, to technology cost and performance databases. The suite of resources and analytical capabilities available through DOE and its National Laboratories provides a wealth of information and a variety of platforms through which lessons learned can be shared.

One important way that DOE translates modeling and analysis learnings to the broader energy community is through technical assistance activities. Technical assistance activities match providers of technical expertise and capabilities with recipients who have timely challenges to address. Examples of technical assistance can include providing valuation modeling tools for project developers, aiding remote communities with energy planning, building capacity through trainings and workforce activities, and informing regulators about potential impacts of new policies. Crucially, the particular challenge addressed by a technical assistance project should be replicable and scalable to other recipients, so that DOE funding has broader impact beyond that project. While the DOE National Laboratories serve as providers for numerous technical assistance programs across DOE, new mechanisms are under exploration to expand the capabilities available to potential recipients.

Appendix E.4 offers representative examples of DOE's modeling, analysis, and technical assistance efforts. These examples include technical assistance programs supported by various DOE programs, cost and performance analysis, and long-duration storage technology strategy assessments and other efforts reviewing potential pathways to long-duration storage technology commercialization.

3.2 Foundational and Crosscutting Efforts

Foundational and crosscutting efforts support DOE's RDD&D efforts through a variety of ways and complement the innovative activities described in Section 3.1. As shown in Figure 5, the foundational and cross-cutting efforts embedded in the RDD&D continuum, also benefit from lessons learned through implementation over time. The sections that follow provide brief descriptions of foundational and cross-cutting activities that support DOE's SRM. Appendix E.5 offers representative examples of DOE's basic and applied research activities. These examples include social equity initiatives, various workforce development programs, entrepreneurship training, technology commercialization and adoption resources, and supply chain analyses.

3.2.1 Diversity, Equity, Inclusion, and Accessibility (DEIA)

Diversity, equity, inclusion, and accessibility (DEIA) is a cornerstone to effectively advancing the U.S. research and scientific innovation enterprise. Stewardship and promotion of diverse and inclusive workplaces that value and celebrate a diversity of people, ideas, cultures, and educational backgrounds is foundational to delivering on DOE's mission. Additionally, fostering local job opportunities for people in disadvantaged communities is essential to creating a fairer and more just economy.

3.2.2 Workforce Development

Workforce development is a planned approach to enhance and broaden the skills of individuals outside the workforce seeking employment, entry-level workers looking for job growth, and experienced workers in changing industries. The aim of workforce development is to foster prosperity for individuals, communities, and businesses. In practice, workforce development means providing individuals with training, continuing education, and professional development opportunities to maximize their job success and career pathway.

Successful approaches to workforce development engage multiple stakeholders from the community, educational institutions, and potential employers. Initiatives should consider areas of the clean energy industry most in need of trained workers and be designed to lead successful participants to quality jobs.

The emerging and growing energy storage industry involves workers with different roles, responsibilities, skills, and areas of expertise to design, develop, manufacture, specify, sell, install, maintain, repair, and inspect energy storage systems. Key themes of workforce needs throughout the energy storage industry span technical topics, hands-on trade and manufacturing skills, energy storage business matters, and regulatory processes. Safety related to energy storage systems is also of paramount concern for those that manufacture, design, install, operate, inspect, and otherwise deal with physical battery infrastructure.

3.2.3 Technology Transition

Federal R&D should yield new products and services, new industries and jobs, new policies and regulations, and new standards and practices that address the greatest challenges of our time. In order to do so, translational research is needed to convert discoveries into innovations that can be deployed at scale.

DOE supports efforts to promote translational research through programs that catalyze partnerships, facilitate proof-of-concept, and support prototyping and demonstration of commercial potential. The Federal Government has taken steps to speed applied R&D and accelerate the technology transfer process. As an example, DOE's Adoption Readiness Level (ARL) framework [12] serves as a conceptual framework for understanding technology commercialization risks and opportunities. The ARL framework is being adopted across DOE to assess key adoption risks (e.g., product-market fit, demand pull, supply chain, workforce, siting & permitting, etc.) that can impede commercialization.

Through the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs [13], technical challenges and prizes, and cost sharing programs, many agencies foster the transition of research from laboratories to startup companies and small enterprises that can bring innovations to market.

3.2.4 Supply Chain Access/Resilience

More recently, this Administration has required that federally funded inventions be manufactured in America whenever feasible and consistent with applicable law. On July 28, 2023, the President signed Executive Order (EO) 14104, "Federal Research and Development in Support of Domestic Manufacturing and United States Jobs" [14]. This EO ensures that federal taxpayer's investments in R&D support the nation's national security and economic competitiveness, domestic manufacturing capacity, and U.S. workers and communities.

3.3 Stakeholder Engagement

In additional to RDD&D activities, federal agencies also, in partnership with state, local, and Tribal governments and other stakeholders, take action to develop and deploy energy storage technologies across the marketplace. DOE's research enterprise leverages universities and national labs, as well as external partnerships with private sector entities. Several actions are already in progress, supported by existing activities and initiatives across DOE.

Appendix E.6 offers representative examples of DOE's basic and applied research activities. These examples include industry and academia partnerships and coordination efforts to help with exchange of ideas, generation of innovative solutions, and education of system and consumer needs.

4 Technology Portfolio

Public research, development, and demonstration investments play a critical role in fostering technological progress in all sectors, including energy. Over the past several decades, DOE has funded or supported dozens of energy storage technologies spanning electrochemical, electromechanical, thermal, flexible generation, and controllable loads, as well as power electronics. While lithium-ion batteries have historically received the most research and development (R&D) funding, reflecting their applicability to the missions of multiple DOE offices, other technologies, including flow batteries and hydrogen storage, have also received significant DOE support. This SRM is intended to lay out the path forward for DOE's strategic investment over the next 10+ years to achieve broader market deployment of energy storage technologies to reliably meet a variety of electricity needs and applications, at an affordable cost, using sustainable designs and manufacturing processes (both in terms of materials and workforce).

4.1 Use Cases

Energy storage is becoming competitive across a broad range of applications and markets across multiple sectors. For this SRM, DOE identified use cases based on outcomes, not applications, of energy storage, and considered that different energy storage technologies could achieve the same outcome. This approach to identifying use cases enables the role of energy storage and the service (or outcome) it provides to inform DOE's energy storage activities more broadly and helps align energy storage technology solutions with potential market opportunities. Additionally, as Table 2 illustrates, several applications can benefit from a similar outcome.

Table 2. Energy storage SRM outcome-based Use Cases

Use Case (UC)	Description/Role of Energy Storage	Example Applications[8]
UC.1: Improved Power Quality and Supply Reliability	Energy storage may be leveraged to provide regulating and contingency reserves for power system stability (e.g., inertia, frequency regulation) or to address short-term (e.g., <1 hour) capacity gaps, enhancing grid flexibility to ensure the continued reliability, resilience, and security of the electric power system.	• Operating reserve • Storing and smoothing renewable electricity generation • Utility resource planning
UC.2: Energy Load Management	Energy storage may be leveraged to ensure sufficient electricity supply is available to meet demand, whether for planned capacity requirements or due to dynamic changes in customer demand, as well as stresses from weather, physical, and cyber threats.	• Peak shaving and/or demand response resource • Demand changes (e.g., seasonal, week/weekend) • Integrated long-term energy planning (e.g., balancing VRE) • Facility flexibility, efficiency, and value enhancement • Resource adequacy
UC.3: Access to Electricity for Isolated Locations	Energy storage may be deployed in grid-disconnected locations (e.g., island, coastal, and remote communities) to provide access to electricity and the ability to leverage local energy supplies (e.g., wind, solar, hydropower, geothermal), and to mitigate against challenges with transported fuel supply disruptions.	• Island black start • Islanded microgrids

[8] The example applications identified do not reflect an exhaustive list; they are identified for illustrative purposes only.

UC.4: Outage Mitigation/Management	Energy storage may be used to mitigate against electricity supply disruptions across the electricity system by providing backup power and or uninterrupted power supply capabilities during unplanned and extended outages, thereby enabling facilities and/or systems to resume and/or maintain operations.	• Microgrid resilience/islanding • Storm preparedness • Backup power • Uninterruptible power supply • Continued operation of critical services and or interdependent infrastructure during extended power outages
UC.5: Infrastructure Investment Alternatives	Energy storage may be strategically deployed within the bulk power system or local distribution systems to off-set the need for costly, long-term asset or system upgrades.	• Deferring electricity infrastructure (e.g., substations, transmission and distribution lines) investments • Offering a non-wires alternative to new transmission or distribution capacity • Lower cost alternatives to upgrading or expanding existing electricity infrastructure
UC.6: Reduced Electricity Supply Costs	Energy storage can play a role in shifting electricity from times of high supply and lower cost to times of high demand and higher cost, allowing consumers to meet demand during system peak; additionally, energy storage, in conjunction with renewable energy, can provide reliable access to lower cost energy supplies.	• Price arbitrage opportunities • Reducing end-user demand and demand charges • Time of use support • Renewable power purchase agreements
UC.7: Mass Electrification	Energy storage can help enable mass electrification of, e.g., heating, transportation, and manufacturing systems by facilitating use of intermittent energy sources and distributed charging system infrastructure.	• Electrified mobility – enabling large-scale adoption of electric vehicles (EVs) while maximizing beneficial coordination with the power grid • Electrified heating – enabling broader adoption of electric heating across the manufacturing and buildings sectors

The above outcome-based use case list comes from review of several references that identify various use cases compilations and/or provide context for the role of energy storage in Table 2.[9]

[9] See “Storage Innovations (SI) 2030” presentations at https://www.energy.gov/oe/energy-storage-grand-challenge-summit-agenda; and references [18] [20] [21] [81] [82] [83] [84] [85] [86].

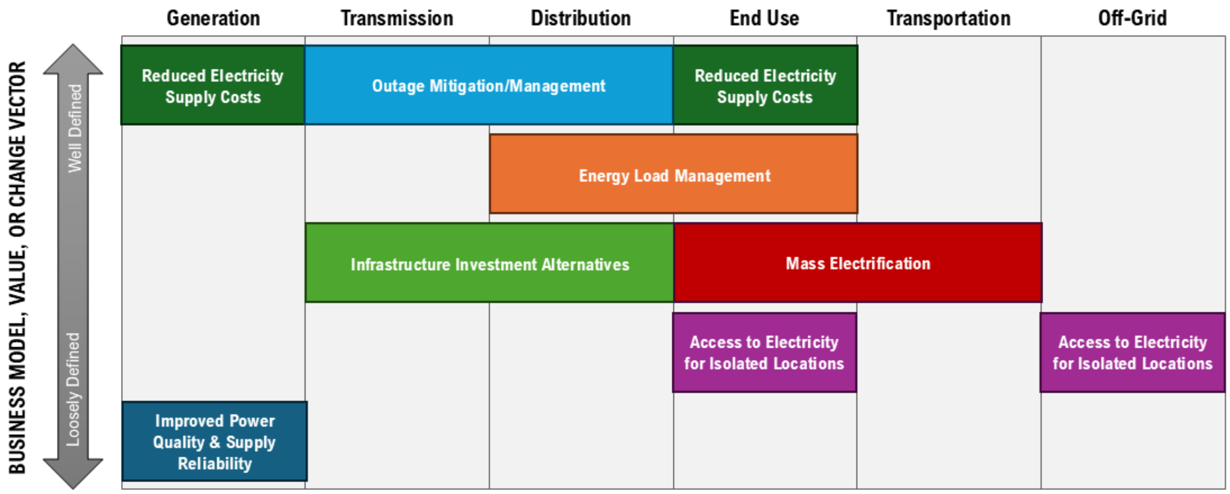

Figure 6. Illustration of the SRM use cases across the electricity system.

Figure 6 shows each use case described in Table 2 mapped to the electricity system and the degree to which the anticipated benefits are easy to quantify or define. Consistent with the ESGC 2020 Roadmap, the electricity system here comprises generation, transmission, distribution, end use, and transportation as connected system elements while off-grid refers primarily to those locations that are geographically isolated (e.g., island communities) and/or electrically isolated (e.g., limited and unstable grid connectivity). While some anticipated benefits of energy storage technologies, such as energy arbitrage and demand charges may be more well-defined, others such as resilience are less well-defined. DOE continues its efforts to better define and quantify these benefits through its RDD&D efforts, both currently and through future activities.

4.2 Technology Landscape

The energy system has become increasingly complicated with the proliferation of renewable generation and demand for grid flexibility services. Energy storage has an important role to play as we reevaluate and reengineer how we ensure reliability, resiliency, security, and affordability in this increasingly complex and dynamic environment. DOE is working to advance energy storage technologies at all scales and to meet different temporal needs (e.g., short-, medium-, and long-duration). As shown in Section 4.1, energy storage has the potential to play many roles in the electricity system and for other applications, such as transportation, buildings, and industry. In order to fulfill these roles, energy storage technologies are evaluated against certain characteristics, performance standards, and readiness levels (see Section 4.2.2) to align with market-based applications. Understanding the status of energy storage technologies provides insights into the current energy storage landscape and may also reveal critical data and knowledge gaps in the energy storage technology and application landscape. DOE routinely considers these evaluations when identifying appropriate activities to advance the energy storage sector and meet the variety of roles and applications across the market sector.

4.2.1 Technologies

Energy storage includes a broad range of technologies that fall into two basic categories: potential energy and kinetic energy. Potential energy is stored energy and the energy of position, and includes chemical, mechanical, and gravitational energy. Kinetic energy is the motion of waves, electrons, atoms, molecules, substances, and objects, and includes thermal, motion, and electrical energy. [15]

As shown in Figure 1 (page 17), DOE has supported a large number of technologies across these categories, as well as complementary technologies and system components (e.g., power electronics, power conversion equipment). These technologies support the use cases described in Section 4.1 and have sufficient flexibility to support future use cases as well. Research efforts across the energy storage ecosystem, not solely those funded by DOE, have the potential to expand the portfolio of technologies as different materials, chemistries, and designs are investigated, evaluated, and demonstrated. Together, energy storage innovations across the ecosystem will provide the portfolio of solutions that enable broader market participation to advance sustainable, affordable, reliable, and secure energy systems for customer applications at all scales and locations.

4.2.2 Readiness Levels

DOE employs several readiness level metrics to evaluate the maturing and adoptability of technologies. Table 3 describes three metrics employed by this SRM to help align technology solutions with appropriate DOE opportunities.

Table 3. Readiness levels describing technology maturity and adoptability.

Readiness Level	Definition
Technology Readiness Level (TRL)	A metric used for describing technology maturity. It is a measure used by many U.S. government agencies to assess maturity of evolving technologies (materials, components, devices, etc.) prior to incorporating that technology into a system or subsystem. [16]
Manufacturing Readiness Level (MRL)	A metric used for describing the maturity of a technology, component, or system from a manufacturing perspective. It is a measure used by some U.S. government agencies to assess the maturity of manufacturing readiness. [17]
Adoption Readiness Level (ARL)	A metric used for assessing the adoption risks of a technology and its readiness to be adopted by the ecosystem. [12]

As DOE evaluates opportunities for their potential and anticipated impact on the energy storage sector, understanding the trajectory of the metrics in Table 3 for different technologies and identifying appropriate activities and investments accordingly is paramount. As illustrated by Figure 7, engagement by DOE and other members of the energy storage ecosystem can help increase the maturity of a technology (TRL), its manufacturability (MRL), and its adoptability (ARL).

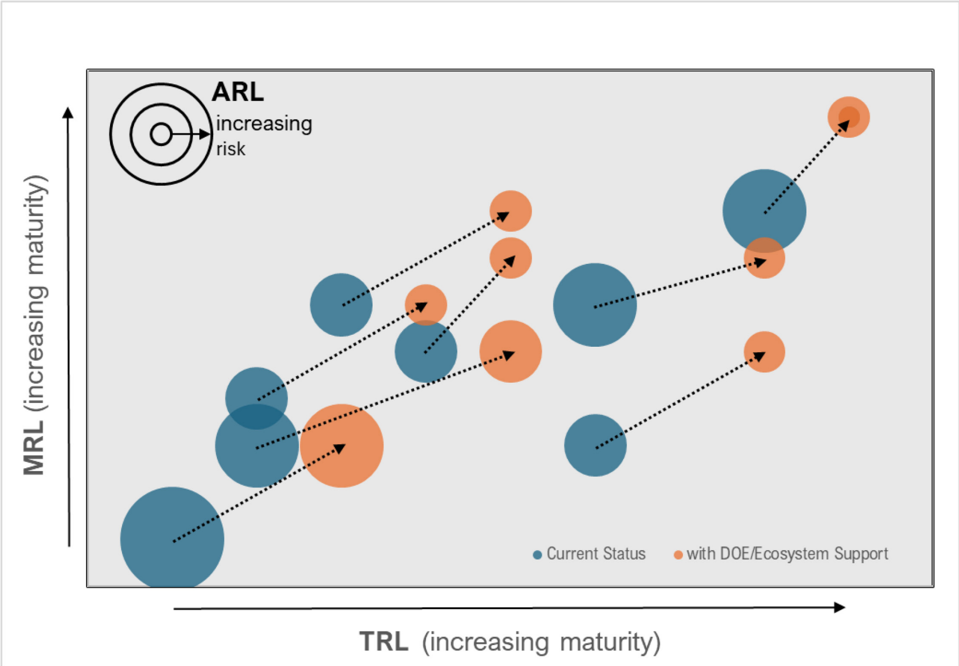

Figure 7. Illustrative impact of DOE and the energy storage ecosystem effort to advance energy storage.

Targeted DOE interventions that leverage DOE's activities (see Section 3) can support technologies advancing their respective TRLs and MRLs as well as derisk their adoption (increase their respective ARLs). Such investments can accelerate the timeline to achieving desired TRLs, MRLs, and ARLs, which can result in earlier than expected commercialization and market adoption, enabling more energy storage technology solutions to meet customer needs. Section 5 identifies several pathways through which DOE can intervene and support advancing energy storage solutions in alignment with the mission and vision of this SRM, and to achieve the strategic objectives (SOs) in Section 2.1 over the 2024-2035 horizon.

4.2.3 Cost and Performance Metrics

In addition to readiness levels, establishing and tracking cost and performance metrics provides valuable insights into the effectiveness with which energy storage technologies will participate in various markets (e.g., stationary, mobile, facility).

- DOE activities stimulate progress addressing innovations aimed at reducing storage capital, interconnection, balance of plant, and soft costs associated with stationary energy storage. Since the publication of the ESGC 2020 Roadmap [18], DOE has targeted advancements in new storage technologies at scale while building tools to facilitate cost and validation analyses to better understand barriers to stationary energy storage deployment.
- DOE aims to address urgent needs for electrified mobility by encouraging a broad and comprehensive research landscape, spanning from fundamental materials to manufacturing and scale-up. DOE has invested in research to advance state-of-the-art batteries in enhanced lithium-ion, next-generation lithium-ion, and beyond lithium-ion chemistries across the supply chain. Since the publication of the ESGC 2020 Roadmap [18], battery innovations have focused on reducing the use of cobalt and other critical materials, investing in new lithium-ion chemistries with the potential to reach higher energy densities, addressing safety concerns with investments in solid-state electrolytes, and investing in advances in battery manufacturing.
- To address facility flexibility and efficiency, and enhance the value of commercial, residential, and energy-intensive facilities, DOE is engaged in activities to facilitate building integration and improve

efficiency through waste-heat recovery and other forms of storage. Supporting a changing industrial landscape with energy storage represents an expansive opportunity for industrial decarbonization. DOE is actively engaging with stakeholders to identify energy storage areas and solutions, such as thermal and hydrogen storage, that can decarbonize industrial processes contributing to nearly 25% of all greenhouse gas (GHG) emissions.

The ESGC 2020 Roadmap (Figure 3 in [18]) provides an illustrative example of performance functional framework, looking across use cases (as defined by the ESGC 2020 Roadmap) and the different classes of energy storage technologies in comparison to functional goals that the technology's performance might be considered to support. The trends observed in the ESGC 2020 Roadmap help identify opportunities for DOE (and broader ecosystem) engagement, but also may help understand why technologies may be limited in their applicability and functionality. DOE-supported RDD&D activities continue to seek and achieve cost reductions and performance improvements across the energy storage technology portfolio. Additionally, DOE continues to develop and update tools to provide insights on cost and performance analysis for a variety of energy storage technologies to accelerate their development and deployment (e.g., PNNL's Energy Storage Cost and Performance Database [19], NREL's Storage Futures Studies [20], DOE's Pathways to Commercial Liftoff report [21], DOE's Storage Innovations 2030 (SI 2030) initiative [22]).

4.3 Aligning Technology RDD&D Opportunities

DOE's RDD&D investments can accelerate technology innovations as well as infuse new solutions into the marketspace. To be effective, these investments need to be properly aligned to what's needed by the current state of the industry for different technologies in order to increase a technology's readiness level or decrease the risk associated with adopting a technology (see Section 4.2.2). DOE activities (see Section 3) and guiding principles (see Section 2.3) shape the opportunities DOE offers to advance the technology landscape, inform the customer base, and expand the marketspace. DOE relies on a variety of data sources to scope its engagements across the energy storage ecosystem (examples provided in Appendix E), whether to provide a forum for exchange of information or to boost innovation or demonstrations. Aligning technologies based on their maturity levels with appropriate opportunities allows DOE to strategically de-risk innovation and market adoption, enabling the energy storage ecosystem to thrive and technologies to provide the much-needed services and functions in support of the energy sector transition underway.

The strategies described in Section 2.2 will help DOE achieve its vision for energy storage innovations to enable resilient, flexible, affordable, and secure energy systems and supply, for everyone, everywhere. Leveraging DOE's resources and expertise, activities designed to de-risk technologies and clarify their value can incentivize increased engagement across the energy storage ecosystem as well as expand options to meet customer needs. Figure 8 (left) draws connections between the technology lifecycle and DOE's activities (e.g., funding opportunity announcements (FOAs), requests for information (RFIs), fundamental science research) and expertise (e.g., DOE National Laboratories, technical assistance, modeling & analysis). In addition, DOE activities can help advance not just technology development, but also impact how technologies engage in the marketspace. Achieving market adoption balances the ability of a technology to enter the market and expand its market base for both existing and new technology applications (see Figure 8 (right)).

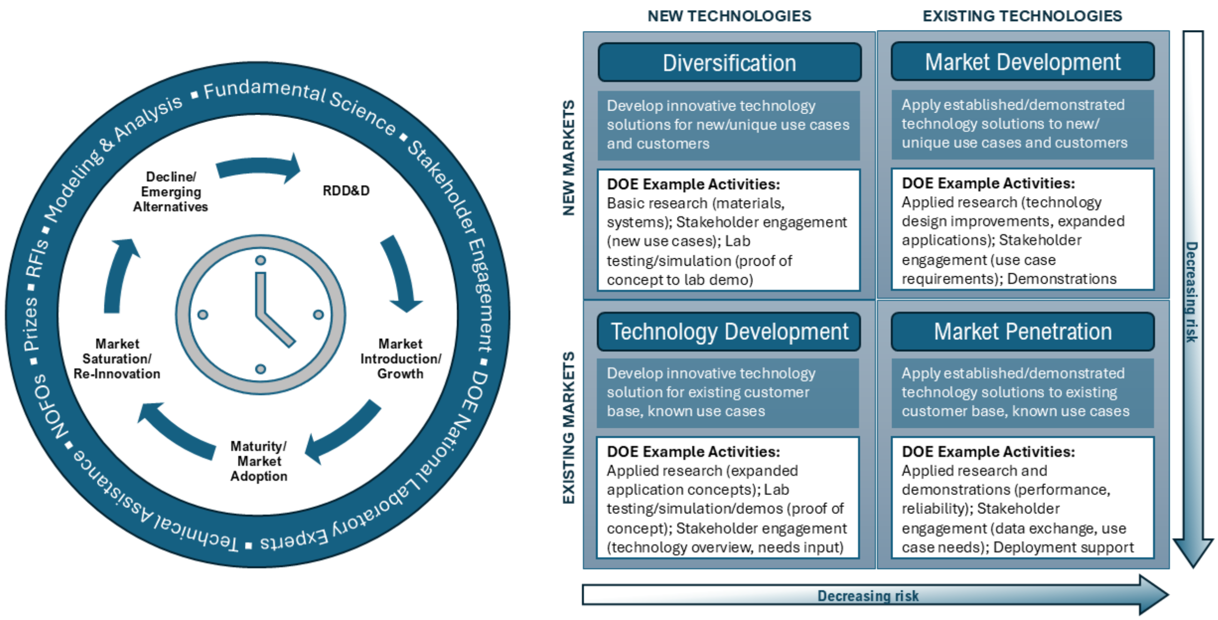

Figure 8. DOE activities to support transition from RDD&D to commercial deployment and market adoption.

DOE's technical and analytical RDD&D efforts not only align with the strategic direction outlined in Section 2, but also address identified knowledge gaps and opportunities to explore and grow nascent technologies to diversify the portfolio of energy storage technologies in the market. For example, more established technologies that have an existing market base might seek to broaden that base through innovation, resulting in the emergence of alternative technologies or system designs that can then meet a broader set of customer needs. A funding opportunity, a partnership with a DOE National Laboratory, or engagement in a DOE-industry collaboration could boost the innovation timeline by leveraging DOE resources and expertise. Similarly, a more nascent technology needing to establish its potential to meet customer needs in the market might benefit from technical assistance, fundamental science research collaborations, and broader stakeholder engagement to learn more about the market opportunities and relevant, complementary research efforts from materials and system design to manufacturing and supply chain. Technologies and their innovators may find themselves at different levels of the RDD&D continuum and the technology lifecycle. Understanding the needs of not only the end use customers, but also the challenges individual technologies face to participate in the energy storage market is paramount for the success of the energy storage ecosystem, as well as for DOE's engagements to advance the SRM's mission and vision. This further echoes the need to balance the SOs outlined in Section 2.1: technology innovation and deployment, empowering decision-makers, and strengthening collaboration throughout the energy storage ecosystem. Section 5 offers a summary of the pathways to achieve these SOs, consistent with the broader strategy described in Section 2.

5 The Path Forward

R&D roadmaps are strategic tools that help align research and development activities with business goals, customer needs, and market opportunities. They provide a clear vision of the desired outcomes, the key milestones, the required resources, and the potential risks and challenges along the way. The sections that follow lay out DOE's path toward achieving the strategic objectives (SOs) in Section 2.1 over the 2024-2035 horizon. These pathways inform DOE's trajectory toward achieving the energy storage vision and aligning with the mission (Section 1). [10] The activities identified support the strategies described in Section 2.2 and, as a result, may have similar or overlapping titles. The tables below provide a snapshot of the flow of activity that address each SO; several of these activities are initiated and completed on a rolling horizon based on DOE's ongoing evaluation of technologies and opportunities to advance innovative solutions in support of the energy storage mission and vision presented in this SRM.

5.1 Technology Innovation and Deployment

Strategic Objective 1 focuses on technology innovation and deployment. Table 4 describes the 10+-year pathways to facilitate the safe, beneficial, and timely deployment of energy storage to successfully do this. Given the diversity of storage technologies and continually evolving deployment landscape, many of these activities are ongoing or will continue beyond the 10+-year horizon discussed in this roadmap. Sections 5.1.1 through 5.1.8 discuss each of the pathways and the associated activities in more detail.

Table 4. DOE technology innovation and deployment pathways and activities, 2025-2035.

Strategic Objective 1	**To facilitate the safe, beneficial, and timely deployment of energy storage technologies and accelerate the development of new technologies that address current and emerging consumer needs.**		
PATHWAY	**DOE ACTIVITY TIMELINE**		
	0-2 years	**3-6 years**	**7-10+ years**
Establish a use case discovery and validation cycle.	▪ Engage stakeholders* ▪ Scenario development, demonstration, and business case validation for foreseeable use cases	▪ Engage stakeholders* ▪ Establishment of capabilities to rapidly evaluate low probability use cases	▪ Engage stakeholders* ▪ Continue to establish feedback loops to align use case evaluation with anticipated technology improvements and past use case results
De-risk new technology through R&D investments.	▪ Elevate early-stage concepts that match emerging use cases ▪ Reduce time to market as well as manufacturing costs through modeling and collaborative testbed facilities ▪ Evaluate market adoption risks (ARLs) that impact commercialization early in R&D	▪ Link to financial metrics during later R&D phases ▪ Continue to evaluate market adoption risks (ARLs) that impact commercialization early in R&D ▪ Inform relevant operational and safety standards	▪ Facilitate bringing bankable technologies to market that are backed by multiple years of high-quality operational experience and performance data ▪ Inform relevant operational and safety standards

[10] The activities identified in this SRM, unless already funded with FY2024 or earlier appropriations are subject to the availability of future appropriations.

	▪ Inform relevant operational and safety standards		
Develop and demonstrate innovative technology solutions.	▪ Engage R&D partners ▪ Support demonstration opportunities for innovative, pre-commercial technologies	▪ Incorporate core DOE capabilities and new techniques (e.g., artificial intelligence) into discovery and validation ▪ Achieve key targets such as <$.05/kWh LCOS for LDES ▪ Support demonstration opportunities for innovative, pre-commercial technologies	▪ Successfully validate that one or more storage technologies can achieve key targets such as <$.05/kWh LCOS for LDES
Develop a secure, domestic, diversified supply chain.	▪ Map and identify emerging trends in material flows ▪ Assess domestic supply chain availability to meet current/emerging material and component needs ▪ Invest in materials and components manufacturing to enable effective system integration.	▪ Map and identify evolving trends in material flows* ▪ Expand domestic material and component use in technology development* ▪ Support reshoring of manufacturing and recycling capabilities*	▪ Map and identify evolving trends in material flows* ▪ Expand domestic material and component use in technology development* ▪ Support reshoring of manufacturing and recycling capabilities*
Foster domestic manufacturing.	▪ Evaluate unmet needs to facilitate higher MRLs ▪ Elevate early-stage concepts that complement domestic materials and manufacturing capacity ▪ Establish collaborative pilot manufacturing production lines for energy storage manufacturers and developers	▪ Identify manufacturing platform technologies that improve performance, manufacturability, and scalability* ▪ Improve manufacturing and scalability of system materials and components* ▪ Advance sustainable manufacturing processes*	▪ Identify manufacturing platform technologies that improve performance, manufacturability, and scalability* ▪ Improve manufacturing and scalability of system materials and components* ▪ Advance sustainable manufacturing processes*
Enhance workforce capabilities and capacity.	▪ Identify required skillsets for industry growth and target relevant industries for workforce development ▪ Utilize collegiate competitions to spur interest and promote diversity*	▪ Inform K-12 and college curriculum ▪ Train/upskill industry ▪ Utilize collegiate competitions to spur interest and promote diversity*	▪ Utilize collegiate competitions to spur interest and promote diversity*
Accelerate commercialization.	▪ Identify market risks to commercialization (i.e., ARLs), including areas that slow pace to commercialization	▪ Communicate learnings from early deployments quickly and efficiently within the energy storage sector	▪ Support adoption of best practices ▪ Communicate learnings from mid-stage deployments quickly and efficiently

	▪ Engage relevant stakeholders to address identified barriers	▪ Socialize best-practice for project implementation	within the energy storage sector
Improve attractiveness and affordability of adopting energy storage technologies.	▪ Advance R&D toward achieving the ESGC 2030 cost and performance targets[11]	▪ Achieve ESGC 2030 cost and performance targets[12]	▪ Achieve applicable DOE/Administration cost targets[13]

* Ongoing activity during the timeline presented.

5.1.1 Establish a use case discovery and validation cycle.

While energy storage technologies have experienced rapid innovation, markets that would fully utilize their new functionality have been slower to develop. In order to facilitate the "market pull" that powers a durable storage ecosystem, this pathway would accelerate the process of discovering, demonstrating, and validating new high-impact uses of energy storage.

In order to support use case identification, stakeholder engagement should take place over the entirety of the 2024-2035 timeframe, enabling DOE to continually learn about emerging opportunities. These efforts will adhere to DOE's strategy described in Section 2.2.7 to specifically ensure that collaboration and coordination are taking place across different parts of DOE as well as with external groups that focus on identifying use cases across different mission spaces and representing a diverse set of stakeholders.

In the near-term (0-2 years), this pathway will focus on foreseeable use cases, including those identified in Section 4.1. In the mid-term (3-6 years), this pathway will explore more financially or quantitatively challenging use cases, especially those that depend on low-probability exogenous events or technological improvements. In the longer-term (7-10+ years), this pathway would build the capability to both self-calibrate based on prior results and better anticipate the range of future technological improvements.

In each of these time horizons, key activities will include efforts to define future scenarios that impact storage's deployment potential; quantifying the overall market potential; demonstrations of energy storage technologies in progressively more novel use cases; and validation of a clear and replicable value proposition.

Through this pathway, DOE will adhere to the following guiding principles to carry out this strategic objective:

- Enable affordability and versatility by supporting identification, analysis, and validation of high impact use cases that show energy storage's value proposition and diversity of services it can provide (2.3.4)
- Facilitate the energy transition through strategic, high-impact uses by showing storage can be a high performing, cost effective, and safe solution that can be commercially deployed to serve different use cases across commercial, industrial, residential, mobility, and grid services market spaces (2.3.8)

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[11] See Appendix D.2.

[12] See Appendix D.2.

[13] From the U.S. National Clean Hydrogen Strategy and Roadmap, 2023 [75]: Lower costs of fuel-flexible stationary fuel cells to $900/kW and 40,000-hr durability.

5.1.2 De-risk new technology through R&D investments.

As DOE makes technology R&D investments to advance early stage, innovative storage solutions, targeted activities to de-risk such investments and the associated work must be considered so that the technology can eventually be used safely and effectively.

In the near-term (0-2 years), activities that will support this pathway include elevating early-stage storage concepts that match emerging use cases and reducing manufacturing costs through modeling efforts and leveraging testbed capabilities that can enable early-stage collaboration to tackle manufacturing challenges. These activities will bolster DOE's strategies for making longer-term investments in energy storage technology research outlined in Strategy 1 (Section 2.2.1) by increasing the ability for technologies to address barriers such as manufacturing cost and use-case alignment from an early stage if development.

In the near- (0-2 years) and mid-terms (3-6 years), activities will include evaluating market adoption risks (ARLs) starting in early stages of R&D, which will ensure that the longer-term R&D investment strategy (Section 2.2.1) will take into account the extent to which deployment and commercialization risks can be reduced as technologies are developed.

Additionally in the mid-term, activities should link technology development to financial metrics during later R&D phases that will support DOE's strategy 3 to improve energy storage implementation cost and valuation assessments (Section 2.2.3) by giving end users and investors interested in pre-commercial technologies early indicators on key cost and performance aspects that will dictate what markets and use cases the technology is best suited to support.

In the longer-term (7-10+ years), to sufficiently show that investments have led to de-risk technologies, DOE should support activities that facilitate bankability of technologies that have gained operational experience from demonstrations started in the near- and mid-terms, which will align with strategy 3 (Section 2.2.3) which ensures DOE is improving understanding of implementation costs and strategy 4 (Section 2.2.4) focused on improving valuation of storage systems based on empirical evidence.

In the near-, mid-, and longer-terms, DOE should support activities that keep relevant operational and safety standards up to date with the latest information and best practices concerning use of new technologies and use cases to de-risk their implementation. These activities will support DOE's strategy 5 to enhance safety and reliability of energy storage technologies (Section 2.2.5) by ensuring stakeholders can have the latest information and documentation on safety, integration, and other aspects needed to safely deploy and operate emerging storage technologies as they become ready for deployment.

Through this pathway, DOE will adhere to the following guiding principles to carry out this strategic objective:

- Catalyzing RDD&D innovation and investment by encouraging forward looking early-stage R&D investments (2.3.5).
- Ensuring safety, reliability, and resilience by de-risking technology across all stages of development and supporting updated safety and operational standards (2.3.7).

5.1.3 Develop and demonstrate innovative technology solutions.

DOE will continue to support activities to develop and demonstrate innovative technology solutions in which objectives of these efforts are informed by how these technologies will meet certain characteristics informed by needs of potential consumers.

In the near-term (0-2 years), relevant activities include engaging partners to inform R&D opportunities and priorities as well as tracking progress in innovation for different storage technologies. This will support DOE's strategy 1 to make longer-term investments in fundamental and responsible energy storage technology research (Section 2.2.1) by ensuring DOE R&D investments are informed well informed by stakeholder groups that are involved in carrying out this work.

In the mid-term (3-6 years), key activities include achieving key targets such as the LCOS goal of < $.05/kWh, incorporating core DOE capabilities and new techniques (e.g., artificial intelligence) into discovery and validation to develop and deploy technologies at an accelerated pace supporting DOE's strategy to invest in capabilities that will facilitate responsible energy storage technology research (Section 2.2.1).

Additionally, to bolster strategy 1 in both the near- and mid-terms, DOE should support activities that create demonstration opportunities for innovative, pre-commercial technologies in order to help novel technologies overcome barriers to deployment and continue progression towards commercialization.

In the longer-term (7-10+ years), key activities include those that provide successful validation that technologies have met key cost and performance targets such as achieving the LCOS goal of < $.05/kWh.

Through this pathway, DOE will adhere to the following guiding principles to carry out this strategic objective:

- Catalyzing RDD&D investment by fostering partnerships with industry, academia, national laboratories, and other stakeholders to invest in innovation and identify key opportunities for DOE support (2.3.5)

5.1.4 Develop a secure, domestic, diversified supply chain.

Developing a secure, domestic, and diversified supply chain is an essential component of Strategic Objective 1, as this pathway plays a key role in achieving timely and secure energy storage deployment to meet current and projected demand. DOE's near-, mid-, and longer-term activities that support this pathway involve developing analytical strengths, expanding domestic markets, and standing up critical infrastructure.

Near-term activities (0-2 years) that help realize a secure, domestic, and diversified supply chain include mapping and identifying emerging trends in material flows that are pertinent to energy storage technologies and assessing the domestic supply chain availability to meet current and emerging needs of energy storage technology materials and components. It is imperative that this analysis is a robust, systematic, and holistic evaluation of the domestic supply chain and includes consideration of critical minerals and materials. This will help inform DOE's supporting programs that will bolster investments in materials and components manufacturing to enable effective system integration of energy storage technologies. Investments in materials and components manufacturing must occur quickly and be made strategically.

Further down the timeline, mid-term (3-6 years) and longer-term (7-10+ years) activities that advance this pathway include mapping and identifying evolving trends in material flows that are pertinent to energy storage technologies. Similar to the approach in the near-term timeframe, coupling the development of analytical tools with physical impacts on markets and infrastructure will have the greatest impact on developing a secure, domestic, and diversified supply chain. The mid- and longer-term activities that carry tangible impacts include expanding domestic material and component use in technology development and supporting reshoring of manufacturing and recycling capabilities.

Through this pathway, DOE will adhere to the following guiding principles to carry out this strategic objective:

- Secure critical energy storage supply chains (2.3.6).
- Ensure safety, reliability, and resilience (2.3.7).

5.1.5 Foster domestic manufacturing.

Though the activities that support the pathway for developing a secure, domestic, and diversified supply chain touch on manufacturing, improving domestic manufacturing is so critical to Strategic Objective 1's success that it merits its own dedicated pathway. The activities that support expansion of domestic manufacturing capabilities are a mix of analytical and technological advancements. These activities also support the existing target for industry to achieve a domestic energy storage manufacturing capacity target of 3 GW per year, as identified in the Pathways to Commercial Liftoff: Long Duration Energy Storage Report released in March 2023 [21].

In the near-term (0-2 years), DOE will evaluate unmet needs of domestic energy storage manufacturing capabilities. Gaining this understanding will facilitate technologies in achieving higher MRLs. Additional DOE activities in this timeframe include elevating early-stage concepts that complement domestic materials and manufacturing capacity, as well as offering grants to support construction of facilities enabling onshoring of manufacturing.

In the near-term (0-2 years), DOE will also establish a collaborative pilot to address manufacturing production lines for energy storage manufacturers and developers. This will provide relevant stakeholders with the opportunity to help address identified manufacture and supply challenges.

In the mid-term (3-6 years) and longer-term (7-10+ years), DOE's activities to facilitate this pathway include identifying manufacturing platform technologies that improve performance, manufacturability, and scalability of energy storage technologies. Further advancements to expand domestic manufacturing including improving manufacturing and scalability of system materials and components as well as advancing sustainable manufacturing processes.

Through this pathway, DOE will adhere to the following guiding principles to carry out this strategic objective:

- Enable affordability and versatility (2.3.4).
- Catalyze RD&D innovation and investment (2.3.5).
- Secure critical energy storage supply chains (2.3.6).

5.1.6 Enhance workforce capabilities and capacity.

Timely deployment of energy storage technologies requires enhancing workforce capabilities to design, install, operate, and integrate energy storage technologies and scaling workforce capacity. Energy storage technologies may require honing specific skills or reskilling the current workforce. Additionally, competing or complementary technologies may draw from the same pool of workers, requiring the workforce size to increase overall to ensure timely deployment. As identified in the Pathways to Commercial Liftoff: Long Duration Energy Storage Report [21], increasing domestic energy storage manufacturing will require active planning to prevent workforce gaps—such as expansion of on-the-job training and registered apprenticeship programs, project hybridization and modular project deployment. Enhancing workforce capabilities and capacity in the near-, mid-, and longer-terms is critical to enabling smooth industry growth.

In the near-term (0-2 years), DOE will identify required skills for energy storage sector growth and target relevant industries for workforce development. Advancing strategy 8 through collaboration across DOE (Section 2.2.8), needed skills will be identified across RDD&D activities. Collegiate competitions will also be used to generate interest in the energy storage sector and promote diversity across the country. With thoughtful implementation, competitions targeting a range of academic institutions will advance strategy 6 providing equitable access to energy storage technologies across the country (Section 2.2.6).

In the mid-term (3-6 years), the DOE's key activities will include continuing to use collegiate competitions to widen the workforce pool but will also include informing K-12 and college curriculums to access a wider audience and potential workforce pool. Activities will also include training and upskilling industry to transition workers from other sectors or entering the workforce to the energy storage sector.

In the longer-term (7-10+ years), there will be a continuation of collegiate competitions in the field, focused on any lingering skillsets that have been underdeveloped.

This pathway adheres to the following guiding principles to carry out this strategic objective:

- Grow quality jobs and workforce (2.3.2)
- Advance diversity, equity, inclusion and accessibility (2.3.3)

5.1.7 Accelerate commercialization.

Accelerating commercialization of technically viable energy storage technologies as well as earlier stage technologies advanced the strategic objective of safe, beneficial, and timely deployment of energy storage by increasing the pace of getting technologies to the market, where their benefits can be felt. Rapid commercialization requires understanding market barriers (e.g., ARLs) and ties into several other pathways, such as identifying use cases, demonstrating technologies, and de-risking technologies across all stages of the RDD&D continuum.

In the near-term (0-2 years), relevant activities include identifying current market risks delaying the pace of commercialization as well as engaging relevant stakeholders who can address these challenges.

In the mid-term (3-6 years), activities will focus on communicating lessons learned from early deployments across the energy storage industry to reduce investor and customer uncertainty. Additionally, best practices for project implementation will be shared transparently.

In the longer-term (7-10+ years), DOE's activities will provide support for adoption of best practices and communicating learnings from mid-stage deployments quickly and efficiently with the energy storage sector. Sharing of this information will not only benefit the sector, bust also help facilitate broader exchange of ideas to further continued innovation and improvement to meet energy storage needs.

This pathway relies on identifying and targeting strategic, high impact use cases for energy storage technologies in alignment with strategy 2 (Section 2.2.2) and strategy 4 focused on improving energy storage implementation cost and valuation assessments to uncover potential cost savings (Section 2.2.4). It requires strategic implementation of solutions, whether through direct DOE investment or DOE recommendations for private sector or regulatory action.

This pathway adheres to the following guiding principles:

- Cultivate a holistic approach (2.3.1)
- Catalyze RD&D innovation and investment (2.3.5)

5.1.8 Improve attractiveness and affordability of adopting energy storage technologies.

Taking steps to improve the attractiveness and affordability adopting energy storage technologies will be needed to facilitate the safe, beneficial, and timely deployment of these technologies and accelerate the development of new technologies that address current and emerging consumer needs.

In the near-term (0-2 years), key activities in the initial stages of this pathway include supporting development of new and improvement of existing tools accessible to stakeholders that analyze different cost, operational, and economic aspects of energy storage in order to show potential benefits from using these technologies especially to model scenarios, technologies, and use cases that do not have real world examples to reference. These activities will support DOE's strategy 4 to improve energy storage implementation cost and valuation assessments (Section 2.2.4) by giving stakeholders tools that can help them understand costs and valuation with accurate assumptions built in and initial information on where key barriers might be when considering actual deployment opportunities.

In the mid-term (3-6 years), key activities to continue support of this pathway include conducting techno-economic analyses (TEA) that show costs and benefits of emerging technologies and value provided in novel use-cases. This can leverage tools developed in the near-term that have the latest functionalities and information to help stakeholders understand different cost, performance, and value aspects before actual deployment which will further support DOE's strategy 4 to improve energy storage implementation cost and valuation assessments (Section 2.2.4).

In the longer-term (7-10+ years), key activities building off short- and mid- terms efforts include validating results of TEA and similar efforts conducted in the mid-term by highlighting successful field demonstrations and commercial deployments that support the findings of those analyses in the real world. This will support DOE's strategy 4 to inform value proposition by validating use of tools and TEA with real world examples so that others can use these methods to further their development and deployment efforts (Section 2.2.4). Additionally, longer-term efforts should identify analyses and real-world projects that show key DOE targets such as the long duration storage shot goals have been achieved.

Through this pathway, DOE will adhere to the following guiding principles to carry out this strategic objective:

- Cultivating a holistic approach by developing comprehensive tools and analysis methods that improve understanding of technology and ultimately make them more attractive for deployment (2.3.1)
- Enabling affordability and versatility by providing transparency on cost, performance, and valuation for technologies and use cases (2.3.4)

5.2 Empowering Decision-Makers

Strategic Objective 2 focuses on empowering decision-makers. DOE engages with decision-makers in a variety of ways that contribute to this SO. Pathways are identified to inform DOE's trajectory toward achieving the energy storage vision and aligning with the mission (Section 1). Empowering decision-makers is an ongoing process of learning, adapting, and continuous improvement. In the energy sector, the portfolio of solutions is ever-evolving as new technologies, policies, and customer applications arise and existing technologies, policies, and customer applications must be flexible and adapt. Table 5 describes the different pathways to achieve Strategic Objective 2 and the different activities DOE will undertake over the next 10+ years in support of this SO. DOE's activities will remain flexible and responsive to accommodate technology and policy innovations, as well as changing customer needs. Scope and timing of the various planned activities represent a logical sequence based on the current landscape; however, DOE has a history of engaging in such activities and some of those identified are part of ongoing efforts. Sections 5.2.1 through 5.2.5 discuss each of the pathways and the associated activities in more detail.

Table 5. DOE decision-maker empowerment pathways and activities, 2025-2035.

Strategic Objective 2	**To empower decision-makers by providing unbiased and fact-based information and analysis to enhance their energy storage-related investments, policies, and goals.**		
PATHWAY	**DOE ACTIVITY TIMELINE**		
	0-2 years	**3-6 years**	**7-10+ years**
Strengthen communication channels with decision-makers.	▪ Develop engagement strategy	▪ Implement engagement strategy and identify gaps	▪ Implement refined engagement strategy
Expand tools and resources available to decision-makers.	▪ Explore currently available tools/resources ▪ Invest in user-friendly resource development	▪ Invest in resource user-friendly development ▪ Socialize standardized valuation models and technical assistance tools	▪ Assess need for updates to existing tools (e.g., data, capabilities) and plan for implementation
Facilitate access to needed data/tools.	▪ Educate/inform PUCs and other regulators/policy-makers (data/tools)*	▪ Educate/inform PUCs and other regulators/policy-makers (data/tools)*	▪ Educate/inform PUCs and other regulators/policy-makers (data/tools)*
Improve awareness of current status of industry, including key market barriers and solutions.	▪ Educate/inform PUCs and other regulators/policy-makers (general)* ▪ Assess adoption risks for energy storage technologies ▪ Expand dissemination of information*	▪ Educate/inform PUCs and other regulators/policy-makers (general)* ▪ Address key adoption risk areas ▪ Expand dissemination of information* ▪ Identify and de-risk revenues	▪ Educate/inform PUCs and other regulators/policy-makers (general)* ▪ Assess outcomes of DOE activities on addressing market barriers ▪ Expand dissemination of information*
Embed energy storage into routine planning and investment.	▪ Inform ISO/RTO proceedings* ▪ Translate academic model expertise into industry practice* ▪ Facilitate full compensation of storage functions*	▪ Inform ISO/RTO proceedings* ▪ Translate academic model expertise into industry practice* ▪ Facilitate full compensation of storage functions*	▪ Inform ISO/RTO proceedings* ▪ Translate academic model expertise into industry practice* ▪ Facilitate full compensation of storage functions*

* Ongoing activity during the timeline presented.

5.2.1 Strengthen communication channels with decision-makers.

Effective communication can help decision makers gather information, understand different perspectives, and make informed decisions. DOE has a long history of engaging with energy sector decision-makers, including those across the energy storage ecosystem. Strengthening communication channels with decision-makers enhance the conduit through which DOE can share its expertise and knowledge, and through which DOE can learn more about the information and decision-support tools that will help decision-makers (strategy 8, Section 2.2.8).

In the near-term (0-2 years), establishing a more formal engagement strategy will help coordinate DOE's engagement to better align with DOE's current organizational structure and help facilitate alignment of decision-maker requests and inquiries with the appropriate DOE organization(s). A robust strategy will complement ongoing engagement activities and improve the efficiency and effectiveness of DOE's future engagements on various energy storage topics, including informing use case scope (strategy 2, Section

2.2.2), cost and valuation (strategies 3-4, Sections 2.2.3-2.2.4), safety and reliability (strategy 5, Section 2.2.5), equitable access (strategy 6, Section 2.2.6), and supply chains (strategy 7, Section 2.2.7).

In the mid- (3-6 years) and longer-term (7-10+ years), DOE will implement the more formal engagement strategy, identify gaps, and refine the strategy in parallel with its broader planned and ongoing activities. Additionally, DOE will revisit its engagement strategy to update and adapt it to the evolving needs of the decision-makers and the energy storage ecosystem, overall.

DOE's guiding principles will inform DOE's implementation of this pathway. Specifically,

- DOE will cultivate a holistic approach by looking across the energy storage ecosystem to engage decision-makers, technical experts, and decision-support tool developers to learn what decision-makers need and address those needs. (2.3.1)
- DOE will focus on preserving and growing quality jobs through meaningful impacts with the energy storage workforce by providing needed information and offering training expertise to help decision-makers promote relevant opportunities. (2.3.2)
- DOE will pursue a comprehensive, systemic approach to advance equity, including delivering energy and environmental justice by fulfilling the Justice 40 Initiative and striving to support stewardship and promotion of diverse and inclusive workplaces that value and celebrate a diversity of people, ideas, cultures, and educational backgrounds. (2.3.3)
- DOE will target affordability and versatility by provide transparency around technology costs and performance, use cases, and valuation benefits, among other relevant topics, for decision-makers. (2.3.4)
- DOE will foster partnerships with industry, academia, national laboratories, and other stakeholders to invest in innovation. DOE will engage with decision-makers to accelerate market recognition of the value of energy storage technologies for emerging and known use cases and services. (2.3.5)
- DOE activities will support U.S. re-shoring, skilling, and scaling of U.S. manufacturing, to ensure robust, secure, and resilient supply chains. DOE will engage decision-makers in the development of analytical tools to characterize, identify gaps, vulnerabilities, and other needs across U.S. supply chains for energy storage. (2.3.6)

DOE will provide expertise to decision-makers seeking to address energy storage safety concerns, supporting early adoption by improving storage reliability and safety. DOE also engage with decision-makers addressing workforce development to implement safety practices and reduce risk. (2.3.7)

- DOE engages with decision-makers to provide information and expertise in support of the energy transition through targeted deployments of energy storage in sectors where its application has the most impact, including commercial, industrial, residential, mobility, and grid services. (2.3.8)

5.2.2 Expand tools and resources available to decision-makers.

In parallel with developing and implementing an engagement strategy, using the information exchanged through those engagement will help scope the expansion of existing tools and resource as well as identify the need for new user-friendly tools and resources to inform decision-making. DOE's role as a neutral broker of information has been foundational to the success of its portfolio of decision support and analytical tools. Expanding this portfolio to meet evolving needs of decision-makers will continue to be an ongoing effort. Similar to Section 5.2.1, the portfolio of tools offers resources that address various energy storage topics, including cost and valuation (strategies 3-4, Sections 2.2.3-2.2.4), safety and reliability (strategy 5, Section 2.2.5), equitable access (strategy 6, Section 2.2.6), supply chains (strategy 7, Section 2.2.7).

In the near-term (0-2 years), DOE will assess the current portfolio of tools and resources to determine whether and what gaps may exist that would benefit decision-makers. Additionally, DOE will determine its investment strategy in resource and tool development.

In the mid- (3-6 years) and longer-term (7-10+ years), DOE will continue advancing needed resource and tool investments for the benefit of decision-makers while also working to socialize the availability of such resources and tools through technical assistance and other engagements.

DOE's guiding principles will inform DOE's implementation of this pathway. Specifically,

- DOE will cultivate a holistic approach by looking across the energy storage ecosystem to learn what decision-makers need and address those needs by aligning DOE's technical experts and tool developers accordingly. (2.3.1)
- DOE will focus on preserving and growing quality jobs through meaningful impacts with the energy storage workforce by providing needed data and analysis resources and offering training resources to educate broader groups of decision-makers. (2.3.2)
- DOE will pursue a comprehensive, systemic approach to advance equity, including delivering energy and environmental justice by fulfilling the Justice 40 Initiative and striving to address diversity of people, ideas, cultures, and educational backgrounds while providing equitable access to the tools and resources needed by decision-makers. (2.3.3)
- DOE will target affordability and versatility by provide transparency around technology costs and performance, use cases, and valuation benefits analysis, among other relevant topics, to support decision-makers. (2.3.4)
- DOE will foster partnerships with industry, academia, National Laboratories, and other stakeholders to invest in innovation an exchange cost and performance data to support needed modeling and analysis tools. (2.3.5)
- DOE will engage decision-makers through the development of analytical tools to characterize, identify gaps, vulnerabilities, and other needs across U.S. supply chains for energy storage. (2.3.6)

DOE will provide expertise, through tools, resources, and technical assistance, to decision-makers seeking to address energy storage safety concerns, supporting early adoption by improving storage reliability and safety, including workforce development to implement safety practices and reduce risk. (2.3.7)

- DOE engages with decision-makers to provide information and expertise in support of the energy transition through targeted deployments of energy storage in sectors where its application has the most impact, including commercial, industrial, residential, mobility, and grid services. (2.3.8)

5.2.3 Facilitate access to needed data/tools.

Alone, expanding the availability of needed tools and resources to support decision-making isn't enough; these tools and resources need to be accessible to the decision-makers who need them. DOE will leverage prior experience to engage decision-makers (e.g., PUCs, other regulators/policy makers) and provide appropriate training and education about the information and functionality of the tools and resources such that decision-makers may access and apply these DOE resources to support their decision-making. This has been and will continue to be an important on-going DOE effort throughout the 10+ year horizon of this SRM (strategy 8, Section 2.2.8), supporting energy storage decision-making across several areas of the energy storage ecosystem, including cost and valuation (strategies 3-4, Sections 2.2.3-2.2.4), safety and reliability (strategy 5, Section 2.2.5), equitable access (strategy 6, Section 2.2.6), supply chains (strategy 7, Section 2.2.7).

DOE's guiding principles will inform DOE's implementation of this pathway. Specifically,

- DOE will cultivate a holistic approach by looking across the energy storage ecosystem to learn what decision-makers need and address those needs by aligning DOE's technical experts and tool developers accordingly. (2.3.1)

- DOE will focus on preserving and growing quality jobs through meaningful impacts with the energy storage workforce by providing needed data and analysis resources and offering training resources to educate broader groups of decision-makers. (2.3.2)
- DOE will pursue a comprehensive, systemic approach to advance equity, including delivering energy and environmental justice by fulfilling the Justice 40 Initiative and striving to address diversity of people, ideas, cultures, and educational backgrounds while providing equitable access to the tools and resources needed by decision-makers. (2.3.3)
- DOE will target affordability and versatility by provide transparency around technology costs and performance, use cases, and valuation benefits analysis, among other relevant topics, to support decision-makers. (2.3.4)
- DOE will foster partnerships with industry, academia, national laboratories, and other stakeholders to invest in innovation an exchange cost and performance data to support needed modeling and analysis tools. (2.3.5)
- DOE will engage decision-makers through the development of analytical tools to characterize, identify gaps, vulnerabilities, and other needs across U.S. supply chains for energy storage. (2.3.6)

DOE will provide expertise, through tools, resources, and technical assistance, to decision-makers seeking to address energy storage safety concerns, supporting early adoption by improving storage reliability and safety, including workforce development to implement safety practices and reduce risk. (2.3.7)

- DOE engages with decision-makers to provide information and expertise in support of the energy transition through targeted deployments of energy storage in sectors where its application has the most impact, including commercial, industrial, residential, mobility, and grid services. (2.3.8)

5.2.4 Improve awareness of current status of industry, including key market barriers and solutions to these barriers.

As a complement to facilitating access to needed data and tools (Section 5.2.3), DOE also develops activities to help improve decision-maker awareness of the current status of the industry, including key market barriers and solution opportunities. This enables decision-makers to better understand the energy storage ecosystem, technology market maturity challenges, and how to address those challenges to enable broader application of energy storage technologies. DOE's ongoing, broad education campaign will continue to provide information about the current industry landscape throughout the 10+ years of this SRM horizon, and well beyond. The specific scope and breadth of the campaign will adapt to changes in the industry landscape and knowledge gaps to support decision-makers in several strategic areas, including cost and valuation (strategies 3-4, Sections 2.2.3-2.2.4), safety and reliability (strategy 5, Section 2.2.5), equitable access (strategy 6, Section 2.2.6), supply chains (strategy 7, Section 2.2.7).

In addition to the ongoing education campaign, in the near-term (0-2 years), DOE will also work to support better understanding of the adoption risks of different energy storage technologies. Through the development of tools, and exchange of information across the energy storage ecosystem, DOE is well-positioned to aggregate market perspectives and technology barriers such that they can be effectively shared with decision-makers seeking to better understand the energy storage ecosystem.

In the mid-term (3-6 years), DOE will consider appropriately scoped funding opportunities that help address key adoption risk areas. Through such opportunities, DOE can continue to learn about the relevant challenges, apply that knowledge to support decision-makers, and help de-risk revenue investment opportunities.

In the longer-term (7-10+ years), DOE's expanded knowledge base will serve as a foundation for further engagement with decision-makers to help ensure they are aware of the ever-changing energy storage landscape. Outcomes from DOE activities, including funding opportunities, will be an invaluable resource to provide key insights into progress made and progress still needed.

DOE's guiding principles will inform DOE's implementation of this pathway. Specifically,

- DOE will cultivate a holistic approach by looking across the energy storage ecosystem to inform decision-makers and provide increased awareness by aligning DOE's technical experts and analysis accordingly. (2.3.1)
- DOE will focus on preserving and growing quality jobs through meaningful impacts with the energy storage workforce by providing needed data and analysis resources with respect to energy storage industry workforce needs to educate broader groups of decision-makers. (2.3.2)
- DOE will pursue a comprehensive, systemic approach to advance equity, including delivering energy and environmental justice by fulfilling the Justice 40 Initiative and striving to address diversity in the energy storage industry by providing equitable access to relevant tools and resources needed by decision-makers. (2.3.3)
- DOE will target affordability and versatility by provide transparency around the current technology landscape, including technology costs, performance validation, and valuation benefits analysis, among other relevant topics, to support decision-makers. (2.3.4)
- DOE will foster partnerships with industry, academia, national laboratories, and other stakeholders to aggregate and exchange cost and performance data to support needed modeling and analysis tools. (2.3.5)
- DOE will engage decision-makers through the development of analytical tools to characterize, identify gaps, vulnerabilities, and other needs across U.S. supply chains for energy storage. (2.3.6)

DOE will provide expertise, through tools, resources, and technical assistance, to decision-makers seeking to address energy storage safety concerns, supporting early adoption by improving storage reliability and safety, including workforce development to implement safety practices and reduce risk. (2.3.7)

- DOE engages with decision-makers to provide information and expertise in support of the energy transition through targeted deployments of energy storage in sectors where its application has the most impact, including commercial, industrial, residential, mobility, and grid services. (2.3.8)

5.2.5 Embed energy storage into routine planning and investment.

DOE's research has already informed past proceedings about the benefits of energy storage, e.g., ISO/RTO rules. Enabling such proceedings, and others, to more quickly incorporate improvements to energy storage can expand the portfolio of options and open the opportunity for energy storage to serve more roles and customer applications in the market.

Throughout the 10+ year horizon, and leveraging DOE's past engagements with decision-making proceedings, DOE activities will provide energy storage data and evidence as inputs to decision-makers. As energy storage inclusion becomes routine, DOE activities will engage decision-makers to help inform decisions about full compensation of energy storage for the different roles it plays in the electricity system.

DOE's guiding principles will inform DOE's implementation of this pathway. Specifically,

- DOE will cultivate a holistic approach by looking across the energy storage ecosystem to learn what decision-makers need and address those needs by aligning DOE's expertise and analytical capabilities accordingly. (2.3.1)
- DOE will pursue a comprehensive, systemic approach to advance equity, including delivering energy and environmental justice by fulfilling the Justice 40 Initiative and striving to address diversity of people, ideas, cultures, and educational backgrounds while providing equitable access to the tools and resources needed by decision-makers. (2.3.2)

- DOE will target affordability and versatility by provide transparency around technology costs and performance, use cases, and valuation benefits analysis, among other relevant topics, to support decision-makers. (2.3.4)
- DOE will foster partnerships with industry, academia, national laboratories, and other stakeholders to invest in innovation an exchange cost and performance data to support needed modeling and analysis tools. (2.3.5)
- DOE will engage decision-makers through the development of analytical tools to characterize, identify gaps, vulnerabilities, and other needs across U.S. supply chains for energy storage. (2.3.6)

DOE will provide expertise, through tools, resources, and technical assistance, to decision-makers seeking to understand energy storage safety concerns, including workforce development requirements to implement safety practices and reduce risk. (2.3.7)

- DOE engages with decision-makers to provide information and expertise in support of the energy transition through targeted deployments of energy storage in sectors where its application has the most impact, including commercial, industrial, residential, mobility, and grid services. (2.3.8)

5.3 Strengthening Collaboration Throughout the Energy Storage Ecosystem

Strategic Objective 3 focuses on collaboration throughout the energy storage ecosystem (Figure 2). DOE engages across the ecosystem in a variety of ways that support this SO. Pathways are identified to inform DOE's trajectory toward achieving the energy storage vision and aligning with the mission (Section 1). Sections 5.3.1 through 5.3.4 discuss each of the pathways and the associated activities in more detail.

Table 6. DOE strengthening collaboration pathways and activities, 2025-2035.

Strategic Objective 3	**To leverage DOE's global leadership in the energy storage community and accelerate the path from innovation to commercialization that benefits all Americans by effective and durable engagement throughout the innovation ecosystem.**		
PATHWAY	**DOE ACTIVITY TIMELINE**		
	0-2 years	**3-6 years**	**7-10+ years**
Catalyze stakeholder engagement.	▪ Expand stakeholder engagement channels ▪ Align and coordinate across DOE offices to maximize stakeholder engagement* ▪ Increase awareness of DOE-wide energy storage activities	▪ Expand/maintain stakeholder engagement channels ▪ Align and coordinate across DOE offices to maximize stakeholder engagement*	▪ Transition stakeholder engagement to self-sustaining models ▪ Align and coordinate across DOE offices to focus engagement on long-term or high-risk areas*
Communication with the public.	▪ Increase public opportunity to engage.	▪ Socialize/increase awareness of publicly available tools and data* ▪ Track usage rates and adjust communication approach as needed*	▪ Socialize/increase awareness of publicly available tools and data* ▪ Track usage rates and adjust communication approach as needed*
Collaborate with other government agencies (local, state, federal).	▪ Disseminate high-level energy storage activity information (e.g., ESGC annual report, technology fact sheets, strategy)*	▪ Disseminate high-level energy storage activity information (e.g., ESGC annual report, technology fact sheets, strategy)*	▪ Disseminate high-level energy storage activity information (e.g., ESGC annual report, technology fact sheets, strategy)*

Engage with international collaborations.	▪ Strategically expand international partnerships, leveraging past/current practices	▪ Maintain/expand international partnerships*	▪ Maintain/expand international partnerships*

* Ongoing activity during the timeline presented.

5.3.1 Catalyze stakeholder engagement.

DOE is well-known for its convening role, often gathering stakeholders from across the energy storage ecosystem to discuss key challenges and opportunities, and potential solutions. Stakeholder engagement is paramount to DOE's efforts to modernize the electricity system, including advancing the development and use of next-generation energy storage technologies to meet customer needs. Additionally, DOE has set aggressive goals toward developing and manufacturing energy storage technologies that can meeting all market demands by 2030. Together, DOE's stakeholder engagement and aggressive goals shape DOE activities to sustain its role as a global leader in energy storage.

DOE will continue to be a leader in the global energy storage ecosystem throughout the 10+ year horizon of this SRM by expanding and maintaining effective stakeholder engagement channels to share knowledge, expertise, and resources toward common objectives. Internally, DOE will continue to align and coordinate across DOE programs and offices to maximize the value of stakeholder engagement opportunities.

In the mid- (3-6 years) and longer-term (7-10+ years), it is anticipated that many stakeholder activities could transition to an industry-led, self-sustaining model. However additional activities may continue to be scoped based on stakeholder needs to help DOE better understand emerging, longer-term, or high-risk challenges and opportunities.

DOE's guiding principles will inform DOE's implementation of this pathway. Specifically,

- DOE will cultivate a holistic approach by looking across the energy storage ecosystem to inform decision-makers and provide increased awareness by aligning DOE's technical experts and analysis accordingly. (2.3.1)
- DOE will focus on preserving and growing quality jobs through meaningful impacts with the energy storage workforce by providing needed data and analysis resources with respect to energy storage industry workforce needs to educate broader groups of decision-makers. (2.3.2)
- DOE will pursue a comprehensive, systemic approach to advance equity, including delivering energy and environmental justice by fulfilling the Justice 40 Initiative and striving to address diversity in the energy storage industry by providing equitable access to relevant tools and resources needed by decision-makers. (2.3.3)
- DOE will target affordability and versatility by provide transparency around the current technology landscape, including technology costs, performance validation, and valuation benefits analysis, among other relevant topics, to support decision-makers. (2.3.4)
- DOE will foster partnerships with industry, academia, national laboratories, and other stakeholders to aggregate and exchange cost and performance data to support needed modeling and analysis tools. (2.3.5)
- DOE will engage decision-makers through the development of analytical tools to characterize, identify gaps, vulnerabilities, and other needs across U.S. supply chains for energy storage. (2.3.6)
- DOE will provide expertise, through tools, resources, and technical assistance, to decision-makers seeking to address energy storage safety concerns, supporting early adoption by improving storage reliability and safety, including workforce development to implement safety practices and reduce risk. (2.3.7)

- DOE engages with decision-makers to provide information and expertise in support of the energy transition through targeted deployments of energy storage in sectors where its application has the most impact, including commercial, industrial, residential, mobility, and grid services. (2.3.8)

5.3.2 Communication with the public.

DOE is a valuable resource for information about the electricity system and its components, including energy storage. Sharing this information with the public not only helps improve awareness of DOE activities and build relationships, but it can also help improve general understanding about options and decisions made regarding the electricity system and energy storage technologies that will likely impact the public.

In the near-term (0-2 years), DOE will identify and implement means to increase public opportunities to engage with DOE, about DOE activities, or use DOE resources and information. Increasing awareness and access to information will help broaden public participation in DOE's RDD&D activities and help DOE ensure that its research investments are aligned to benefit the American public.

In the mid- (3-6 years) and longer-term (7-10+ years), DOE will continue to socialize and increase public awareness of the data and tools, and other research work products, that arise from its investments. Complementary to this, DOE will seek ways to understand how the public can benefit from the R&D resources, how to improve communication to more effectively inform the public, and how to adjust the resources' availability and usability for a broader user group (including non-technical users).

While engagement with the public is an element in much of DOE's energy storage work, this SRM highlights opportunities to improve that engagement over the 10+ year horizon of this SRM. DOE's long history of public engagement is foundational to the path forward, providing lessons learned and best practices that can be adapted for the public members of the energy storage ecosystem.

DOE's guiding principles will inform DOE's implementation of this pathway. Specifically,

- DOE will pursue a comprehensive, systemic approach to advance equity, including delivering energy and environmental justice by fulfilling the Justice 40 Initiative and by providing the public equitable access to relevant tools and resources. (2.3.3)
- DOE will foster partnerships with industry, academia, national laboratories, and other stakeholders to ensure usability of relevant tools and resources. (2.3.5)

5.3.3 Collaborate with other government agencies (local, state, Federal).

Collaboration can be beneficial for R&D organizations, generally, but the benefits are even more compounding when considered for collaboration with other government agencies. Government agencies at all levels are making decisions and investing tax-payer dollars to address the needs of the Nation, state, and locality, as well as the various consumers across each of these jurisdictions. Sharing information not only helps improve the decision-making process, but it also helps inform investment decisions to avoid duplication of effort. Recognizing that energy storage is increasingly part of the regulatory and planning discussions happening across these jurisdictions, DOE can offer its expertise, analytical capabilities, tools, and data to support other government decision-makers. Further, recognizing that other government agencies may be focused on specific applications for energy storage, and may also be researching similar cost, performance, reliability, etc. aspects of the different energy storage technologies available, DOE would benefit from a similar exchange of information to help guide its own decision-making and research investments. DOE's engagement with other government agencies is well-established. Over the 10+ year horizon of this SRM, DOE will focus on ways to broaden that engagement and more effectively disseminate information about DOE's energy storage activities and work products to improve its participation in the broader energy storage ecosystem.

DOE's guiding principles will inform DOE's implementation of this pathway. Specifically,

- DOE will cultivate a holistic approach by looking across the energy storage ecosystem to inform decision-makers and provide increased awareness by aligning DOE's technical experts and analysis accordingly. (2.3.1)
- DOE will pursue a comprehensive, systemic approach to advance equity, including delivering energy and environmental justice by fulfilling the Justice 40 Initiative and striving to address diversity in the energy storage industry by providing equitable access to relevant tools and resources needed by decision-makers. (2.3.3)
- DOE will target affordability and versatility by provide transparency around the current technology landscape, including technology costs, performance validation, and valuation benefits analysis, among other relevant topics, to support decision-makers. (2.3.4)
- DOE will foster partnerships with industry, academia, national laboratories, and other stakeholders to aggregate and exchange cost and performance data to support needed modeling and analysis tools. (2.3.5)
- DOE will engage decision-makers through the development of analytical tools to characterize, identify gaps, vulnerabilities, and other needs across U.S. supply chains for energy storage. (2.3.6)

DOE will provide expertise, through tools, resources, and technical assistance, to decision-makers seeking to address energy storage safety concerns, supporting early adoption by improving storage reliability and safety, including workforce development to implement safety practices and reduce risk. (2.3.7)

DOE engages with decision-makers to provide information and expertise in support of the energy transition through targeted deployments of energy storage in sectors where its application has the most impact, including commercial, industrial, residential, mobility, and grid services. (2.3.8)

5.3.4 Engage with international collaborations.

DOE's engagement with international collaborations has been long-standing for several energy focus areas. Energy storage is garnering increased attention across the globe and DOE has been identified as a resource, both in terms of expertise and experience, from which other nations around the world wish to learn. Appendix H highlight several recenter international efforts in which DOE serves in different capacities. As international efforts related to energy storage continue to ramp up, over the 10+ year horizon of this SRM, DOE seeks to strategically expand and maintain its international partnerships to continue to share expertise and learn from other countries' experiences with advancing energy storage innovations and integrating energy storage into the electricity system and market. This will leverage successes across the SOs of this SRM.

DOE's guiding principles will inform DOE's implementation of this pathway. Specifically,

- DOE will cultivate a holistic approach by looking across the energy storage ecosystem to inform decision-makers and provide increased awareness by aligning DOE's technical experts and analysis accordingly. (2.3.1)
- DOE will focus on preserving and growing quality jobs through meaningful impacts with the energy storage workforce by providing needed data and analysis resources with respect to energy storage industry workforce needs to educate broader groups of decision-makers. (2.3.2)
- DOE will pursue a comprehensive, systemic approach to advance equity, including delivering energy and environmental justice by fulfilling the Justice 40 Initiative and striving to address diversity in the energy storage industry by providing equitable access to relevant tools and resources needed by decision-makers. (2.3.3)
- DOE will target affordability and versatility by provide transparency around the current technology landscape, including technology costs, performance validation, and valuation benefits analysis, among other relevant topics, to support decision-makers. (2.3.4)

- DOE will foster partnerships with industry, academia, national laboratories, and other stakeholders to aggregate and exchange cost and performance data to support needed modeling and analysis tools. (2.3.5)
- DOE will engage decision-makers through the development of analytical tools to characterize, identify gaps, vulnerabilities, and other needs across U.S. supply chains for energy storage. (2.3.6)
- DOE will provide expertise, through tools, resources, and technical assistance, to decision-makers seeking to address energy storage safety concerns, supporting early adoption by improving storage reliability and safety, including workforce development to implement safety practices and reduce risk. (2.3.7)
- DOE engages with decision-makers to provide information and expertise in support of the energy transition through targeted deployments of energy storage in sectors where its application has the most impact, including commercial, industrial, residential, mobility, and grid services. (2.3.8)

6 Conclusion

This Energy Storage Strategy and Roadmap (SRM) represents the strategic direction of DOE's energy storage activities over a 10+-year horizon, driving towards a future where energy storage innovations enable resilient, flexible, affordable, and secure energy systems and supply, for everyone, everywhere. To achieve this vision, three strategic objective focus on technology innovation and deployment, empowering decision-makers, and strengthening collaboration throughout the energy storage ecosystem for the benefit of all Americans. Eight strategies and eight guiding principles establish the framework though which DOE will engage across the ecosystem to accomplish these objectives. They are foundational to the pathways that DOE may follow to implement this SRM an recognize the various roles that DOE plays in support of executing this SRM's mission to empower a self-sustaining energy storage ecosystem that develops, delivers, and deploys breakthrough solutions to meet a range of real-world applications, across multiple time horizons.

DOE supports a broad energy storage technology portfolio by designing activities and initiatives to advance the maturing of the technologies to meet customer needs. DOE's activities span the RDD&D continuum from basic and applied research to systems integration to demonstrations and deployment, as well as modeling, analysis, and technical assistance. DOE's research activities are complemented by other DOE foundational and crosscutting initiatives such as DEIA, workforce development, technology transition, supply chain access/resilience, and stakeholder engagement. Additionally, DOE activities help de-risk investment advanced R&D as well as support the transition from RDD&D to commercial deployment and market adoption of energy storage technologies.

Successfully advancing energy storage technology solutions is a collaborative endeavor across the energy storage ecosystem. The pathways captured in this SRM will guide DOE's contributions to the ecosystem, making progress toward affordable, reliable, flexible, and secure energy storage solutions that meet system and customer needs. DOE's research agility enables it to adapt to changing dynamics across the ecosystem while still progressing toward its strategic objectives and vision. DOE's expertise and leadership within the energy storage ecosystem will help facilitate innovative technology solutions and broader collaborations across the ecosystem, adding value beyond the 10+-year horizon of this SRM.

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Appendix A. DOE Offices Engaged in Energy Storage RDD&D

Since a broad range of technologies—electrochemical, electromechanical, thermal, flexible generation, controllable loads, and power electronics—can provide and enable energy storage, several DOE offices have the authority and scope to work on different energy storage systems and applications. While DOE offices have individual roles and responsibilities, they coordinate to target their funding more effectively to the highest-priority areas while integrating RDD&D capabilities and expertise across program portfolios. Below is a summary of roles and responsibilities for each DOE office:

A.1 Office of Electricity (OE)

Accelerates bi-directional electrical energy storage technologies as a key component of a reliable, resilient, and affordable future-ready grid. OE's energy storage research, demonstration, and deployment efforts accelerate the development of grid storage technologies, including long-duration energy storage, through increasing performance, reducing technology costs, de-risking technologies to ensure safe long-term reliability, developing analytic models to uncover technical and economic benefits, and demonstrating how storage provides clean and equitable energy access for consumers and communities.

A.2 Office of Energy Efficiency and Renewable Energy (EERE)

Supports energy storage R&D for stationary and mobility applications. This includes leading DOE's applied R&D on lithium-ion batteries, pumped storage hydropower (PSH), hydrogen and fuel cell technologies, and increased power system flexibility by thermal storage, renewable energy generation, and controllable loads, as well as next generation technologies including flow batteries, sodium-ion batteries and hydrogen. EERE also supports manufacturing research to lower manufacturing costs and improve performance of storage technologies. In addition, EERE supports analytical efforts to examine the role of storage in the power system and provides storage-related technical assistance to policymakers and facility owners. This includes leading Vehicle Technology Offices's (VTO) fundamental and applied R&D on new battery materials including sodium-ion and solid-state electrolytes. In the near-term, the cathode and anode consortia focused on earth abundant cathode materials (no cobalt and nickel) and silicon anode, respectively, support R&D on next generation lithium-ion batteries. In the longer-term, the Battery500 consortium focuses on lithium metal anode to develop very high specific energy battery technologies (e.g., 500 Wh/kg).

A.3 Office of Science (SC)

Supports basic research that underpins a wide range of current and potential technologies for energy storage. The office also supports various user facilities, such as light and neutron sources, supercomputers, and advanced synthesis capabilities that provide insight into the operation of energy storage systems from the atomic scale to operating prototypes. One important capability is the Materials Project that includes the electrolyte genome and other data and computation capabilities for predictive design of energy storage materials and chemistries.

A.4 Office of Technology Transitions (OTT)

Expands the public impact of the DOE's RDD&D investments and enables technology commercialization that supports the DOE's mission. OTT serves a multi-faceted role to support the transition of technologies to the market by providing public-private partnering assistance, technology transfer policy leadership, market-informed analytics, commercial adoption risk assessments, and Departmental expertise in the use of prizes and partnership intermediary agreements. OTT collaborates across DOE Program Offices to manage lab-to-market and other technology commercialization activities that can support energy storage technologies. These include the statutory Technology Commercialization Fund (TCF), the Energy I-Corps, the Energy Program for Innovation Clusters (EPIC), Energy Technology University Prize, the Partnership Intermediary Agreement Voucher Program, and the Lab Partnering Service. OTT, in coordination with Program Offices, stewards DOE technology transition activities, including policy reform, data collection and analysis, industry stakeholder convenings, and strategic communication and amplification of DOE technology transfer success stories across the DOE.

A.5 Office of Fossil Energy and Carbon Management (FECM)

Leads work in integrating advanced thermal, chemical, hydrogen, and battery energy storage technologies with energy assets to improve asset flexibility, grid reliability, and environmental performance. FECM also supports analysis and stakeholder engagement to define technology requirements, metrics, and barriers to energy storage deployment. FECM engages with stakeholders and government agencies to repurpose energy assets that have closed or are closing to determine the use of integrated energy systems, including long-term energy storage solutions, at these locations. Additionally, FECM supports the development of domestic critical mineral and material supply chains (e.g., Li, Ni, Co, V, REE, graphite) needed for advanced energy storage technologies.

A.6 Office of Nuclear Energy (NE)

Supports integrated energy systems R&D, which explores coupling electrical, thermal, and chemical storage systems with nuclear power and other generation types to enable clean, affordable, reliable, and resilient energy systems. The NE system modeling, simulation, and technology development efforts seek to optimize technical and economic performance in commercial applications.

A.7 Advanced Research Projects Agency – Energy (ARPA-E)

Advances energy storage technologies by focusing on early-stage, high-risk and high-impact technologies, as well as activities to bring those technologies to market. The research activities are typically accompanied by techno-economic analysis, stakeholder outreach, and technology-to-market plans. Current activities include Duration Addition to electricitY Storage (DAYS), Electric Vehicles for American Low-carbon Living (EVs4ALL), Pioneering Railroad, Oceanic and Plane ELectrification with 1K energy storage systems (PROPEL-1K), Catalyzing Innovative Research for Circular Use of Long-lived Advanced Rechargeables (CIRCULAR),and ARPA-E's OPEN Funding Opportunity Announcements (OPEN FOA).

A.8 Office of Clean Energy Demonstration (OCED)

Delivers clean energy and industrial decarbonization demonstration projects at scale in partnership with the private sector to launch or accelerate market adoption and deployment of technologies, as part of an equitable transition to a decarbonized energy system and economy. OCED was established in December 2021 and first authorized and funded through the IIJA, which includes $505 million for long duration energy storage pilots and demonstrations.

A.9 Loan Programs Office (LPO)

Provides high-impact, flexible financing to help innovative technologies in a variety of clean energy sectors reach full market acceptance, overcoming key barriers to bankability at all stages of commercialization. Through loan guarantees and direct loans, LPO helps innovative projects address challenges faced at first and subsequent commercial deployments, barriers to reaching scale, and commercial debt market acceptance. To date, LPO has issued more than $35 billion for more 30 projects and has a proven track record of accelerating U.S. EV battery manufacturing. Through existing lending authorities, LPO can finance a range of storage technologies, including battery supply chain; energy storage technologies for residential, industrial, transportation, and power generation applications; distributed battery storage and thermal storage that promote demand dexterity and grid stability; EV charging plus storage; clean hydrogen storage; and long-duration storage technologies.

A.10 Office of Manufacturing and Energy Supply Chains (MESC)

Responsible for strengthening and securing manufacturing and energy supply chains needed to modernize the nation's energy infrastructure and support a clean and equitable energy transition. MESC catalyzes the development of an energy sector industrial base through targeted investments that establish and secure domestic clean energy supply chains and manufacturing, and by engaging with private-sector companies, other federal agencies, and key stakeholders to collect, analyze, respond to, and share data about energy supply chains to inform future decision making and investment. The office manages programs that develop clean domestic manufacturing and workforce capabilities, with an emphasis on opportunities for small and medium enterprises and communities in energy transition. MESC coordinates across all of DOE's programs on manufacturing and supply chain issues and covers a range of technologies including battery manufacturing.

A.11 Office of Cybersecurity, Energy Security, and Emergency Response (CESER)

Leads the nation's efforts to enhance the security and resilience of the U.S. energy sector from all hazards—physical or cyber attacks, or natural causes like hurricanes, wildfires, and the impacts of climate change. CESER manages DOE's responsibilities as the Sector Risk Management Agency, identifying and mitigating risks to the energy sector in collaboration with government and industry partners and through research, development, and deployment of tools and technologies. Under the National Response Framework, CESER carries out DOE's Emergency Support Function 12 (ESF-12) role, working alongside public and private sector partners during any incidents affecting the energy sector to restore power and fuel efficiently and effectively. CESER ensures that cybersecurity, energy security, and resilience priorities are embedded in early-stage R&D and in the deployment of clean energy systems. This includes supporting capacity building and planning with industry and the states and informing resilience investments in partnership with other DOE offices, including the Grid Deployment Office (GDO), Office of State and Community Energy Programs (SCEP), Office of Energy Efficiency and Renewable Energy (EERE), and Office of Electricity (OE).

A.12 State and Community Energy Program (SCEP)

Partners with state and local organizations to significantly accelerate the deployment of clean energy technologies, create jobs, reduce energy costs, and avoid pollution through place-based strategies involving a wide range of government, community, and business stakeholders. Key activities include formula grants to support the core capabilities of state energy offices and a weatherization provider network that assists low-income families through provision of home energy retrofits; competitive awards to support innovative state and local high-impact and self-sustaining clean energy projects; and technical assistance to facilitate clean energy programs and practices through "best practice" tools, "lead-by-example" methods, peer-to-peer forums, and strategic partnerships, which may include supporting energy storage applications. SCEP was established in January 2022 and is funded through annual appropriations and the IIJA.

A.13 Grid Deployment Office (GDO)

Works to catalyze the development of new and upgraded electric infrastructure across the country by maintaining and investing in critical generation facilities; developing and upgrading high-capacity electric transmission lines nationwide; and deploying transmission and distribution technologies. GDO acts as a partner with states, Tribes, territories, industry, communities, and other energy sector stakeholders to deploy solutions to lower energy costs and improve grid reliability and resilience. GDO is investing over $22 billion in generation, transmission, and distribution infrastructure including energy storage.

Appendix B. List of Acronyms

AFL-CIO	American Federation of Labor and Congress of Industrial Organizations
AMMTO	Advanced Materials and Manufacturing Technologies Office
AMO	Advanced Manufacturing Office
ANL	Argonne National Laboratory
ARIES	Advanced Research on Integrated Energy Systems
ARL	Adoption Readiness Level
ARPA-E	Advanced Research Projects Agency-Energy
BAU	business as usual
BES	Office of Basic Energy Sciences
BEST	Better Energy Storage Technology
BIG-DIG	BIG Decadal Idea Generator
BIL	Bipartisan Infrastructure Law
BIL TCF	Bipartisan Infrastructure Law TCF
BNL	Brookhaven National Laboratory
BTO	Building Technologies Office
BWI	Battery Workforce Initiative
CAPEX	capital expenditure
CARAT	Commercial Adoption Readiness Assessment Tool
CEC	California Energy Commission
CEM	Clean Energy Ministerial
CEQ	Council on Environmental Quality
CESER	Office of Cybersecurity, Energy Security, and Emergency Response
CFR	Code of Federal Regulations
CHP	Combined Heat and Power
CMI	Critical Materials Institute
CO2	carbon dioxide
COP28	2023 United Nations Climate Change Conference or Conference of the Parties of the United Nations Framework Convention on Climate Change (UNFCCC)
CRADA	Cooperative Research and Development Agreement
CSP	concentrating solar-thermal power
DAYS	Duration Addition to electricitY Storage program
DC	direct current
DEGREES	DEGradation Reactions in Electrothermal Energy Storage
DEIA	diversity, equity, inclusion & accessibility

DER	distributed energy resource
DOE	Department of Energy
EPSCoR	Established Program to Stimulate Competitive Research
DOL	U.S. Department of Labor
DR	Demand Response
EAC	Electricity Advisory Committee
EERC	Energy Earthshot Research Center
EERE	Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
EO	Executive Order
EPRI	Electric Power Research Institute
EPSA	Office of Energy Policy and Systems Analysis
ERCOT	Electric Reliability Council of Texas
ES4SE	Energy Storage for Social Equity Initiative
ESF	Emergency Support Function
ESGC	Energy Storage Grand Challenge
ESIB	Energy Sector Industrial Base
ESS	energy storage system
ESTF	U.S.-India Energy Storage Taskforce
EU	European Union
EV	electric vehicle
FCAB	Federal Consortium for Advanced Batteries
FECM	Office of Fossil Energy and Carbon Management
FERC	Federal Energy Regulatory Commission
FOA	Funding Opportunity Announcement
FY	fiscal year
GB	Governing Board
GDO	Grid Deployment Office
GHG	greenhouse gas(es)
GMI	Grid Modernization Initiative
GMLC	Grid Modernization Laboratory Consortium
GRIDS	Grid-scale Rampable Intermittent Dispatchable Storage
GSL	Grid Storage Launchpad
GTO	Geothermal Technologies Office
GW	gigawatt
HFC	hydrofluorocarbon

HFTO	Hydrogen and Fuel Cell Technologies Office
HPC	High Performance Computing
HydroWIRES Initiative	Hydro Water Innovation for a Resilient Electricity System Initiative
IA	Office of International Affairs
IBR	inverter-based resource
IEA	International Energy Agency
IEDO	Industrial Efficiency and Decarbonization Office
IESA	India Energy Storage Alliance
IIJA	Infrastructure Investment and Jobs Act
INL	Idaho National Laboratory
IONICS	Integration and Optimization of Novel Ion-Conducting Solids
IP	intellectual property
IRA	Inflation Reduction Act of 2022
IRP	integrated resource plan
IRS	Internal Revenue Service
ISO	independent system operator
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelized cost of energy
LCOS	levelized cost of storage
LDES	Long-Duration Energy Storage
LDSS	Long Duration Storage Shot™
LDV	light-duty vehicle
LEEP	Lab-Embedded Entrepreneurship Program
LFP	lithium iron phosphate
LPO	Loan Programs Office
MEF	Major Economies Forum on Energy and Climate
MESC	Office of Manufacturing and Energy Supply Chains
MHDV	medium- and heavy-duty vehicle
MOU	memorandum of understanding
MRL	Manufacturing Readiness Level
MSC	manufacturing and supply chain
MW	megawatt
MWh	megawatt-hour
MYPP	Multi-Year Program Plan

NASA	National Aeronautics and Space Administration
NCA	nickel cobalt aluminum
NCSL	National Conference of State Legislatures
NE	Office of Nuclear Energy
NEPA	National Environmental Policy Act
NERC	North American Electric Reliability Corporation
NRTLs	Nationally Recognized Testing Labs
NSF	National Science Foundation
NWA	Non-Wires Alternatives
NYSERDA	New York State Energy Research and Development Authority
O&M	operations and maintenance
OCED	Office of Clean Energy Demonstrations
OE	Office of Electricity
OMB	Office of Management and Budget
OPEX	operational expenditure
ORNL	Oak Ridge National Laboratory
OSD	Department of Defense Office of the Secretary of Defense
OTT	Office of Technology Transitions
PNNL	Pacific Northwest National Laboratory
PSH	pumped storage hydropower
PUC	public utility commission
PV	photovoltaic
QC	Quality Control
QER	Quadrennial Energy Review
QTR	Quadrennial Technology Review
R&D	research and development
RADIANCE	Resilient Alaskan Distribution System Improvements Using Automation, Network Analysis, Control, and Energy Storage
RD&D	research, development, and demonstration
RDD&D	research, development, demonstration, and deployment
RENEW	Reaching a New Energy Sciences Workforce
RFI	request for information
ROI	Return on Investment
ROVI	Rapid Operational Validation Initiative
RTE	round-trip efficiency
RTIC	Research Technology Investment Committee

RTO	regional transmission organization
SBIR	Small Business Innovation Research
STTR	Small Business Technology Transfer
SC	Office of Science
SCEP	Office of State and Community Energy Program
SETO	Solar Energy Technologies Office
SI 2030	Storage Innovations 2030
SI Liftoff	Storage Innovations 2030: Technology Liftoff
SNL	Sandia National Laboratories
SOs	strategic objectives
SPP	Strategic Partnership Project
SRM	Strategy and Roadmap (current document)
TA	technical assistance
TCF	Technology Commercialization Fund
TCIP	Technology Commercialization Internship
TCP	Technology Collaboration Programmes
TD	technology development
TEA	techno-economic analyses
TES	thermal energy storage
TRL	Technology Readiness Level
TT	technology transition
UC	use case
URL	Uniform Resource Locator
V2X	Vehicle-to-Everything
VGI	vehicle-grid integration
VRE	variable renewable energy
VTO	Vehicle Technologies Office
WETO	Wind Energy Technologies Office
WHEJAC	White House Environmental Justice Advisory Council
WPTO	Water Power Technologies Office

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Appendix C. Key Terms

This Appendix lists terms and includes descriptions of the specific connotation/context in which the terms are used in this document.

In this SRM, some terms that are used may have either different contexts, depending on the industry or scientific field, or definitions that lack the specificity with which they are used outside of this document. Therefore, we provide specific descriptions of these terms, for clarity to the reader.

1. **Grid service** – when a grid operator remunerates an individual action taken by a generator to provide power or increase the stability and reliability of the electric grid. There are three main types of grid services: capacity, energy, and essential reliability services. [23] Some grid services are currently monetized, while others are not monetized.
    a. **Capacity** – instantaneous power, measured in kilowatts (kW), MW, etc.
    b. **Energy** – power generated over a unit of time, measured in kilowatt-hours (kWh), megawatt-hours (MWh), etc.
    c. **Other grid services** – enable the grid to handle interruptions and power changes over various durations in different locations.
        i. **Operating reserves** – while there is no common definition, the North American Electric Reliability Corporation (NERC) defines operating reserves as “a capability above firm system demand required to provide for regulation, load forecasting error, equipment forced and scheduled outages, and local area protection.” [24]
        ii. **Black start** – capacity that can be started without either external power or a reference grid frequency, and then provide power to start other generators.
        iii. **Voltage control** – used to maintain voltage within tolerance levels and provided by local resources.
2. **System-level** – aspects that have to do with complex interactions between multiple components and sub-systems. System-level challenges or innovations deal with entire energy storage systems, or full operational systems (such as microgrids and hybrid systems) of which an energy storage system is a subsystem. System-level aspects are differentiated from aspects that have to do with individual components.
3. **Energy storage performance metrics** – energy storage cost and performance metrics are used to assess energy storage technologies’ ability to meet the technical and economic requirements of specific use-case applications. Due to the nascent nature of energy storage technologies, a standardized list of cost and performance metrics has yet to become universal. The list of metrics below comes from several detailed reports and highlights key cost and performance metrics, but it is not intended to be comprehensive.[14]
    a. **Load response** – able to respond to frequency needs of the grid or user. There are three classifications of load response:

[14] See Mongrid, K., V. Viswanathan, P. Balducci, J. Alam, V. Fotedar, V. Koritarov, and B. Hadjerioua. 2019. *Energy Storage Technology Cost Characterization Report* (Technical Report). PNNL – 28866. Pacific Northwest National Laboratory. https://energystorage.pnnl.gov/pdf/PNNL-28866.pdf; IRENA. 2017. *Electricity Storage and Renewables: Cost and Markets to 2030.* https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf; Connover DR., AJ Crawford, J. Fuller, SN Gourisetti, V Viswanathan. SR. Ferreira, DA. Schoenwald, and DM Rosewater. 2016. *Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems* (Technical Report). PNNL-22010/SAND2016-3078. Pacific Northwest National Laboratory and Sandia National Laboratories. https://energystorage.pnnl.gov/pdf/PNNL-22010Rev2.pdf.

i. **Short-duration** – able to respond to frequency needs of the grid or user (frequency regulation, frequency response, etc.)

ii. **Mid-duration** – able to respond to shifting capacity needs of the grid or user over the course of a few (1–18) hours (load shifting, arbitrage, spinning/non-spinning reserves, transmission congestion relief, etc.)

iii. **Long-duration** – able to provide services over several days or weeks to meet needs of grid or user (energy and operating reserves, long-term buybacks, resilient VRE integration, etc.)

iv. Performance metrics, defined in Appendix 5 of the ESGC 2020 Roadmap, that assess progress towards this goal include *Duration*, *Response Time Constrained by Power Conversion Systems*, and *Theoretical Response Time*.

b. **Black start capable** – can provide other systems with the initial power input required for them to start up, usually after a black-out (also known as “Grid Forming”).

c. **Power quality** – provides smooth electricity supply without variations in voltage, frequency, harmonics, unexpected interruptions of any duration, etc.

i. Performance metrics, defined in Appendix 5 of the ESGC 2020 Roadmap, that assess progress toward this goal include *Discharge Voltage Variability*.

d. **Reliable** – can provide power, even after long inactive periods.

i. Performance metrics, defined in Appendix 5 of the ESGC 2020 Roadmap, that assess progress towards this goal include *Calendar Life*.

e. **Robust** – able to withstand extreme use conditions (mechanical distress, cold temperatures, extreme weather) and not fail.

i. Performance metrics, defined in Appendix 5 of the ESGC 2020 Roadmap, that assess progress towards this goal include *Maximum Operating Temperature* and *Minimum Operating Temperature*.

f. **Scalable** – possible to cost-effectively build large-scale (MW) systems.

i. Assessing progress towards this goal would involve comparing how cost metrics (defined in Appendix 5 of the ESGC 2020 Roadmap) associated with energy ($/kWh) or power ($/kW) change with system size. Systems with a lower (or more negative) size to cost metric correlation would be more scalable.

ii. **Long lifetime** – able to perform (e.g., <20%) capacity degradation. Often used in the context of extending storage lifetimes to match renewable power purchase agreement terms. Performance metrics, defined in Appendix 5 of the ESGC 2020 Roadmap, that assess progress towards this goal include *Operational Life*, *Cycle Life*, *Cycles Per Day*, *Cycles Per Year*, and *Degradation Factor*.

g. **Compact** – has the energy density and total system characteristics to cost effectively meet requirements for systems with size and weight restrictions (AVs, UAVs, mobile stationary units, etc.).

i. Performance metrics, defined in Appendix 5 of the ESGC 2020 Roadmap, that assess progress toward this goal include *Energy Density*, *Footprint*, *Power Density*, and *Weight*.

h. **Safe** – presents low or no safety risks either in operation or in end-of-life disposal/recycling.

i. Performance metrics, defined in Appendix 5 of the ESGC 2020 Roadmap, that assess progress towards this goal include *Limited Oxygen Index*, *Percent Environmentally-Sensitive Material*, *Recyclability*, and *Self-Extinguishing Time*.

i. **Efficient** – achieves a high enough conversion efficiency to cost-effectively integrate with necessary energy sources.

i. Performance metrics, defined in Appendix 5 of the ESGC 2020 Roadmap, that assess progress towards this goal include *Ramp Rate* and *Round-Trip Efficiency*.

j. **Flexible**[15] – able to easily integrate and operate with existing generation systems and infrastructure.

k. **Modular**[16] – can be configured to easily combine with other storage systems to achieve precise capacity targets (“plug-n-play”).

15 See Enel Green Power, Energy Vault, Form Energy Inc, GE Research, IEEE, Redstone Technology Integration ESCG 2020 Roadmap RFI Responses

16 See ABB Inc., Enel Green Power, Energy Vault, Form Energy Inc, GE Research, IEEE ESCG 2020 Roadmap RFI Responses

Appendix D. ESGC 2020 Roadmap

In December 2020, DOE released the ESGC Roadmap, the Department's first comprehensive energy storage strategy. The ESGC seeks to create and sustain American leadership in energy storage. In addition to concerted research efforts, the ESGC 2020 Roadmap's approach includes accelerating the transition of technologies from the lab to the marketplace, focusing on ways to competitively manufacture technologies at scale in the U.S., and ensuring secure supply chains to enable domestic manufacturing. The ESGC 2020 Roadmap includes an aggressive but achievable goal: to develop and domestically manufacture energy storage technologies that can meet all U.S. market demands by 2030.

For more information about the ESGC 2020 Roadmap, please visit: https://www.energy.gov/energy-storage-grand-challenge/articles/energy-storage-grand-challenge-roadmap.

D.1 Status of Action Items

The ESGC 2020 Roadmap identified a suite of actions to position the U.S. for global leadership of the energy storage technologies of the future. Relevant DOE activities to each of these action items are identified below.

Appendix Table 1. ESGC 2020 Roadmap Action Items and Relevant DOE Activities (as of [final SRM date])

Action Items by Track	Relevant DOE Activities
Technology Development	
Maintain a set of Use Cases that describe long-term stakeholder objectives.	
Develop standardized metrics and tools that facilitate technology-agnostic cost and performance evaluations. Develop functional performance targets to inform a long-term R&D strategy that incorporates the Manufacturing and Supply Chain Track's goals of domestic manufacturability (in coordination with Policy and Valuation Track).	AMMTO has developed an analytics lab call that addresses manufacturing costs and commercialization timelines and pathways. DE-LC-0000120 EERE eXCHANGE: Funding Opportunity (energy.gov) 2022 Grid Energy Storage Technology Cost and Performance Assessment (2022)
Accelerate technology development pathways through:	AMMTO has developed an analytics lab call that addresses manufacturing costs and commercialization timelines and pathways. DE-LC-0000120 EERE eXCHANGE: Funding Opportunity (energy.gov) AMMTO *Platform Technologies for Transformative Battery Manufacturing* FOA DE-FOA 0003236 (2024) (announcement) (EERE eXCHANGE: Funding Opportunity (energy.gov)) *Phase I Release 2 SBIR/STTR C58-11. B. Energy Technology: Eco-friendly Innovations in Manufacturing of Lithium Metal for Batteries* (2024)*:* (https://science.osti.gov/-/media/sbir/pdf/funding/2024/FY24-Phase-I-Release-2-TopicsV701182024.pdf) AMMTO *National Laboratory Call for Proposals Strengthening Domestic Capabilities in Solid-State and Flow Battery Manufacturing,* DE-LC-000027 (2023) EERE eXCHANGE: Funding Opportunity (energy.gov)

Action Items by Track	Relevant DOE Activities
	SBIR/STTR topic C56-20 b. Chemistry-Level Electrode Quality Control (QC) for Battery Manufacturing (2023) (SBIR/STTR FY 2023 Phase I Funding Opportunity | Department of Energy) AMMTO Microbattery Design Prize Phase I Selections | Department of Energy (2023) AMMTO-BTO and OE FY22 Multi-Topic FOA: Subtopic 3.1: *Advanced Process Manufacturing of Electric Vehicle Cathode Active Materials at Volume* (2022): (announcement) (https://eere-exchange.energy.gov/Default.aspx#FoaId2e455119-5dd2-4824-876d-f803cea5696c) AMO *Flow Battery System Manufacturing FOA*, DE-FOA-0002453 (2021) (https://eere-exchange.energy.gov/Default.aspx#FoaIdfe9c1382-3bf1-48c4-bfdb-8fabd798d342) AMO-VTO battery manufacturing lab call (2020) (Energy Department Selects National Laboratories to Establish Industry Partnerships for Battery Manufacturing Innovation | Department of Energy) OE Storage Innovations 2030: Long-Duration Storage Shot Technology Strategy Assessments (July 2023) WPTO selected 2 innovative PSH concepts for $6M in funding (Quidnet, RCAM): Biden-Harris Administration Invests More Than $13 Million to Enhance Continued Deployment of Hydropower | Department of Energy (the Georgia Power award was later canceled)
Maintaining basic and early-stage R&D for a variety of technologies	
Investing in capabilities that reduce the cost and time to validate new concepts	
Developing methods and validating data to confirm commercial viability.	
Manufacturing and Supply Chain	
Develop a deep understanding of technical barriers in production and manufacturing for a wide range of energy storage technologies, identifying key technical metrics.	AMMTO has developed an analytics lab call that addresses manufacturing costs and commercialization timelines and pathways. DE-LC-0000120 EERE eXCHANGE: Funding Opportunity (energy.gov) OE Manufacturability Pre-Production Design Implications on Energy Storage Technologies RFI (May 2024) OE Storage Innovations 2030: Long-Duration Storage Shot Technology Strategy Assessments (July 2023)
Support innovations to lower manufacturing cost and overcome technical barriers.	AMMTO has developed an analytics lab call that addresses manufacturing costs and commercialization timelines and pathways. DE-LC-0000120_EERE eXCHANGE: Funding Opportunity (energy.gov) OE Manufacturability Pre-Production Design Implications on Energy Storage Technologies RFI (May 2024)

Action Items by Track	Relevant DOE Activities
	AMMTO *Platform Technologies for Transformative Battery Manufacturing* FOA DE-FOA 0003236 (2024) (announcement) (EERE eXCHANGE: Funding Opportunity (energy.gov)) *Phase I Release 2 SBIR/STTR C58-11. B. Energy Technology: Eco-friendly Innovations in Manufacturing of Lithium Metal for Batteries* (2024)*:* (https://science.osti.gov/-/media/sbir/pdf/funding/2024/FY24-Phase-I-Release-2-TopicsV701182024.pdf) AMMTO *National Laboratory Call for Proposals Strengthening Domestic Capabilities in Solid-State and Flow Battery Manufacturing,* DE-LC-000027 (2023) EERE eXCHANGE: Funding Opportunity (energy.gov) SBIR/STTR topic C56-20 b. Chemistry-Level Electrode Quality Control (QC) for Battery Manufacturing (2023) (SBIR/STTR FY 2023 Phase I Funding Opportunity | Department of Energy) AMMTO Microbattery Design Prize Phase I Selections | Department of Energy (2023) AMMTO-BTO and OE FY22 Multi-Topic FOA: Subtopic 3.1: *Advanced Process Manufacturing of Electric Vehicle Cathode Active Materials at Volume* (2022): (announcement) (https://eere-exchange.energy.gov/Default.aspx#FoaId2e455119-5dd2-4824-876d-f803cea5696c) AMO *Flow Battery System Manufacturing FOA*, DE-FOA-0002453 (2021) (https://eere-exchange.energy.gov/Default.aspx#FoaIdfe9c1382-3bf1-48c4-bfdb-8fabd798d342) AMO-VTO battery manufacturing lab call (2020) (Energy Department Selects National Laboratories to Establish Industry Partnerships for Battery Manufacturing Innovation | Department of Energy)
Accelerate scale-up of emerging manufacturing processes through partnerships with industry, and expand U.S. capabilities for testing/validating manufacturing innovations at commercial-scale.	AMMTO has developed an analytics lab call that addresses manufacturing costs and commercialization timelines and pathways. DE-LC-0000120 EERE eXCHANGE: Funding Opportunity (energy.gov) AMMTO *Platform Technologies for Transformative Battery Manufacturing* FOA DE-FOA 0003236 (2024) (announcement) (EERE eXCHANGE: Funding Opportunity (energy.gov)) *Phase I Release 2 SBIR/STTR C58-11. B. Energy Technology: Eco-friendly Innovations in Manufacturing of Lithium Metal for Batteries* (2024)*:* (https://science.osti.gov/-/media/sbir/pdf/funding/2024/FY24-Phase-I-Release-2-TopicsV701182024.pdf)

Action Items by Track	Relevant DOE Activities
	AMMTO *National Laboratory Call for Proposals Strengthening Domestic Capabilities in Solid-State and Flow Battery Manufacturing,* DE-LC-000027 (2023) (EERE eXCHANGE: Funding Opportunity (energy.gov)) SBIR/STTR topic C56-20 b. Chemistry-Level Electrode Quality Control (QC) for Battery Manufacturing (2023) (SBIR/STTR FY 2023 Phase I Funding Opportunity | Department of Energy) AMMTO Microbattery Design Prize Phase I Selections | Department of Energy (2023) AMMTO-BTO and OE FY22 Multi-Topic FOA: Subtopic 3.1: *Advanced Process Manufacturing of Electric Vehicle Cathode Active Materials at Volume* (2022): (announcement) (https://eere-exchange.energy.gov/Default.aspx#FoaId2e455119-5dd2-4824-876d-f803cea5696c) AMO *Flow Battery System Manufacturing FOA*, DE-FOA-0002453 (2021) (https://eere-exchange.energy.gov/Default.aspx#FoaIdfe9c1382-3bf1-48c4-bfdb-8fabd798d342) AMO-VTO battery manufacturing lab call (2020) (Energy Department Selects National Laboratories to Establish Industry Partnerships for Battery Manufacturing Innovation | Department of Energy) The Manufacture of Advanced Key Energy Infrastructure Technologies (MAKE IT) Prize Facilities Track developed by OTT, OCED, and EERE, awarded three prizes to projects focused on the manufacture of LDES-related components. (2024).[17]
Standardize systems design and testing protocols to streamline integration of manufacturing innovations for emerging storage technologies.	AMMTO *Platform Technologies for Transformative Battery Manufacturing* FOA DE-FOA 0003236 (2024) (announcement) (EERE eXCHANGE: Funding Opportunity (energy.gov)) OE Manufacturability Pre-Production Design Implications on Energy Storage Technologies RFI (May 2024)
Deepen understanding and pursue innovation to improve domestic supply chain resilience, and advance processing and separations to diversify critical materials sourcing and improve recycling.	AMMTO Lab Call for Li-ion battery rejuvenation, recycling, and reuse (2023): (DOE Invests $2 Million to Advance Li-Ion Battery Recycling and Remanufacturing Technologies | Department of Energy) DOE Response to Executive Order 14017, "America's Supply Chains" report: America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition (2022)

[17] Ref: DOE Awards $5 Million Towards Clean Energy Manufacturing Development Through MAKE IT Prize | Department of Energy

Action Items by Track	Relevant DOE Activities
	DOE Response to Executive Order 14017, "America's Supply Chains" report: Grid Energy Storage – Supply Chain Deep Dive Assessment (2022)
Establish a domestic battery manufacturing ecosystem.	AMMTO has developed an analytics lab call that addresses manufacturing costs and commercialization timelines and pathways. DE-LC-0000120_EERE eXCHANGE: Funding Opportunity (energy.gov) AMMTO *Platform Technologies for Transformative Battery Manufacturing* FOA DE-FOA 0003236 (2024) (announcement) (EERE eXCHANGE: Funding Opportunity (energy.gov)) *Phase I Release 2 SBIR/STTR C58-11. B. Energy Technology: Eco-friendly Innovations in Manufacturing of Lithium Metal for Batteries* (2024)*:* (https://science.osti.gov/-/media/sbir/pdf/funding/2024/FY24-Phase-I-Release-2-TopicsV701182024.pdf) AMMTO *National Laboratory Call for Proposals Strengthening Domestic Capabilities in Solid-State and Flow Battery Manufacturing,* DE-LC-000027 (2023) (EERE eXCHANGE: Funding Opportunity (energy.gov)) SBIR/STTR topic C56-20 b. Chemistry-Level Electrode Quality Control (QC) for Battery Manufacturing (2023) (SBIR/STTR FY 2023 Phase I Funding Opportunity | Department of Energy) AMMTO Microbattery Design Prize Phase I Selections | Department of Energy (2023) AMMTO-BTO and OE FY22 Multi-Topic FOA: Subtopic 3.1: *Advanced Process Manufacturing of Electric Vehicle Cathode Active Materials at Volume* (2022): (announcement) (https://eere-exchange.energy.gov/Default.aspx#FoaId2e455119-5dd2-4824-876d-f803cea5696c) AMO *Flow Battery System Manufacturing FOA*, DE-FOA-0002453 (2021) (https://eere-exchange.energy.gov/Default.aspx#FoaIdfe9c1382-3bf1-48c4-bfdb-8fabd798d342) AMO-VTO battery manufacturing lab call (2020) (Energy Department Selects National Laboratories to Establish Industry Partnerships for Battery Manufacturing Innovation | Department of Energy)
Technology Transition	
Enhance external partner access to lab experts, facilities, and intellectual property (IP) to accelerate moving technical innovations to market.	Example of the AMMTO-LEEP success Cuberg's Ribbon Cutting with Secretary Jennifer M. Granholm Tickets, Mon, Feb 26, 2024 at 9:00 AM | Eventbrite LEEP Lab-Embedded Entrepreneurship Program | Department of Energy

Action Items by Track	Relevant DOE Activities
	A hub for ESGC-focused topics was added to the Lab Partnering Service website, administered by OTT, to provide direct access to national lab experts.[18]
Develop real-world projects to generate data for validation and standardization and reduce technology risk.	15 LDES demonstrations totaling up to $325 million (Office of Clean Energy Demonstrations) were announced as selected for negotiations in September 2023. These projects span 17 states and one tribal nation, capturing a variety of technologies and diverse regulatory environments.[19] Two LDES projects received $19 million in DOE funding (Office of Electricity) to demonstrate two distinct use cases—LDES for remote communities and microgrid resilience for military housing.[20]
Pursue industry collaboration and interagency engagement to inform the ESGC strategy to accelerate commercialization and deployment of energy storage technologies.	The Long Duration Energy Storage National Consortium,[21] launched in January 2024, brings together national labs, industry, academics, utility commissions, and other stakeholders to identify and work to address core issues facing LDES commercialization. OE Storage Innovations 2030: Long-Duration Storage Shot Technology Strategy Assessments (July 2023)
Provide industry and market analysis to support investment, market formation, and policymaking activities.	AMMTO has developed an analytics lab call that addresses manufacturing costs and commercialization timelines and pathways. DE-LC-0000120_EERE eXCHANGE: Funding Opportunity (energy.gov) Published *Pathways to Commercial Liftoff: Long Duration Energy Storage* in March 2023 which serves as a common fact base for energy storage stakeholders, identifying key action areas to accelerate commercialization of LDES technologies.
Expand data collection and analysis activities to connect DOE funded activities with commercialization opportunities.	OE Energy Storage Valuation: A Review of Use Cases And Modeling Tools (2022)
Policy and Valuation	
Identify and assess federal, state, and local policies and regulations with significant impacts on the deployment, operation, and value of both stationary and transportation related energy storage technologies.	
Develop cutting-edge data, tools, and analyses to address policy and valuation issues and needs.	WPTO Pumped Storage Valuation Guidebook and Online Tool developed, supporting technical assistance opportunity with 10 new projects selected (PSH Valuation Tool (anl.gov))
Deliver these products to stakeholders through a coordinated, systematic, and reoccurring engagement program.	

[18] Energy Storage Grand Challenge | LPS (labpartnering.org)

[19] Biden-Harris Administration Announces $325 Million For Long-Duration Energy Storage Projects to Increase Grid Resilience and Protect America's Communities | Department of Energy

[20] Energy Department Awards $19 Million for Long-Duration Energy Storage in Remote Communities and Military Housing | Department of Energy

[21] LDES National Consortium – Sandia National Laboratories

Action Items by Track	Relevant DOE Activities
Ultimately, help stakeholders make informed decisions that maximize the utility and value of energy storage technologies for both the energy system and end users.	WPTO study of PSH opportunities in Alaska (https://www.energy.gov/sites/default/files/2024-01/The-Prospects-for-Pumped-Storage-Hydropower-in-Alaska.pdf)
Workforce Development	
Strengthen and broaden the relevance of existing programs through increased stakeholder input across the breadth of the ESGC.	BWI is a partnership with Vehicles Technology Office and the Office of Energy Jobs. It is an effort that was started to address the workforce needs of a high growth industry (cell Battery manufacturing). Battery Workforce Challenge (2023) Energy storage focused fellows sponsored by ESGC DOE offices in the AMMTO Lab Embedded Entrepreneurship Program (LEEP) Training the next generation of energy storage researchers in the BES Reaching a New Energy Sciences Workforce (RENEW) program
Conduct a Needs Assessment/Skills Assessment at all education levels and target audiences and include assessment and evaluation of effectiveness of these programs.	BWI is a partnership with Vehicles Technology Office and the Office of Energy Jobs. It is an effort that was started to address the workforce needs of a high growth industry (cell Battery manufacturing). Battery Workforce Challenge (2023)
Look for opportunities to enhance or develop programs across DOE that will enable the development of the workforce of the future in energy storage at all stages of education and skill sets.	AMO DE-LC-0000011 CHP and workforce development support (2021) EERE eXCHANGE: Funding Opportunity (energy.gov) ESGC Workforce Development Track's Listening Sessions (2020) Summary of Energy Storage Grand Challenge Workshop: Manufacturing and Workforce Needs in the Energy Storage Industry (2021)

D.2 Status of Use Case Targets

The ESGC 2020 Roadmap identified drivers and target for each use case identified in that roadmap. Relevant DOE activity examples are identified for each target.

Appendix Table 2. ESGC 2020 Roadmap Targets: Relevant DOE Activities (as of [final SRM date])

ESGC 2020 Roadmap Use Case [18]	ESGC 2020 Roadmap Drivers [18]	ESGC 2020 Roadmap Target [18]	Relevant DOE Activities (Examples)
Facilitating an Evolving Grid	Increasing the adoption of variable resources and dynamic changes in customer demand	$0.03–$0.05/kWh levelized cost of storage	▪ Long-Duration Storage Shot™ (E.1.1) ▪ Interconnection Innovation e-Xchange (i2x) [25] ▪ NREL's Storage Future Studies [20] ▪ ROVI Demonstration and Validation FOA (3036) ▪ Storage Innovations Technology Liftoff FOA (3020)

Serving Remote Communities	Electricity premium due to fuel logistics and maintenance Fuel supply disruptions	$65/MWh delivered energy	▪ Energy Storage for Social Equity (see Section E.5.1.2)
Electrified Mobility	Lower EV battery manufacturing costs and improved performance Distribution delivery capacity for fast charging	$80/kWh manufactured cost for a battery backup $104/kW-year storage capital expenditures	▪ EV Battery Target (see Section G.4.2) ▪ EV@Scale Consortium [26] ▪ Vehicle-to-Everything (V2X) MOU [27] ▪ EVGrid Assist [28]
Interdependent Network Infrastructure	Grid interdependencies mean that a loss of function and services within these infrastructures can have far-reaching costs and impacts	$77/kW-year storage capital expenditures	▪ PNNL's Embedded Storage [29] research ▪ North American Energy Resilience Model ▪ Power Grid and Communications Interdependencies
Critical Services	Disaster-related and other power outages	$77/kW-year for reliability applications $1,392/kW-year for backup generator offset	▪ OCED demonstration FOAs (2867-LDES, 3139-DES) ▪ Energy Storage for Social Equity (see Section E.5.1.2) ▪ PNNL's Embedded Storage [29] research ▪ OE Critical Facility Energy Resilience FOA 3384
Facility Flexibility, Efficiency, and Value Enhancement: Commercial and Residential Buildings	Enhancing the overall facility value to the owner, operator, and end consumer	$85/kWh, $52/kW-year for commercial and residential buildings	▪ Pathways to Commercial Liftoff: Long-Duration Energy Storage [21] ▪ Thermal Energy Storage in Buildings
Facility Flexibility, Efficiency, and Value Enhancement: Energy-Intensive Facilities		$20–$52/kW-year for energy-intensive facilities	▪ Pathways to Commercial Liftoff: Long-Duration Energy Storage [21] ▪ Industrial Energy Storage System Prize

D.3 Transitions from the ESGC 2020 Roadmap

The ESGC 2020 Roadmap was developed to align DOE's energy storage activities toward a common goal of developing new energy storage technologies to help tackle challenges associated with our evolving electricity grid's ability to accommodate increasingly diverse energy sources to meet consumer needs. The ESGC 2020 Roadmap provided strategic direction to DOE's program activities related to energy storage based on the state of the industry and the R&D community at that time. Since 2020, DOE has determined that certain changes to its ESGC 2020 Roadmap are warranted to help improve the effectiveness and efficiency with which it executes its energy storage activities. The subsections that follow identify high-level changes that are reflected in this SRM.

D.3.1 Tracks

The ESGC 2020 Roadmap identified a five-track structure for its holistic approach to energy storage, starting with fundamental R&D for storage technologies and following through to production and deployment:

- The **Technology Development Track** will focus DOE's ongoing and future energy storage R&D around user-centric Use Cases and long-term leadership.

- The **Manufacturing and Supply Chain Track** will develop technologies, approaches, and strategies for U.S. manufacturing that support and strengthen U.S. leadership in innovation and continued at-scale manufacturing.
- The **Technology Transition Track** will work to ensure that DOE's R&D transitions to domestic markets through field validation, demonstration projects, public-private partnerships, bankable business model development, and the dissemination of high-quality market data.
- The **Policy and Valuation Track** will provide data, tools, and analysis to support policy decisions and maximize the value of energy storage.
- The **Workforce Development Track** will educate the workforce, who can then research, develop, design, manufacture, and operate energy storage systems.

In 2023, the ESGC revised this structure into four tracks:

- The **Investment, Commercialization, and Scale-Up Track** works to ensure that DOE's R&D investments transition to domestic markets through field validation, demonstration projects, public-private partnerships, and bankable business model development.
- The **Manufacturing and Supply Chain Innovations, Workforce Track** develops technologies, approaches, and strategies for U.S. manufacturing that support and strengthen American leadership in innovation and increase production across the supply chain; utilizes energy storage to support industrial decarbonization and resilience; and, educates members of the workforce, who can then research, develop, design, manufacture, and operate energy storage systems.
- The **Markets and Valuation Track** disseminates data, tools, and analysis to support planning, regulatory, market, and policy decision-making in order to maximize the benefits energy storage can provide to the entire system.
- The **Technology Development Track** develops strategies for DOE's ongoing and future energy storage R&D around user-centric goals and long-term leadership. It also coordinates execution of storage R&D activities and outreach to the innovation community.

DOE revised the structure of the ESGC to better strategize, coordinate, and maintain awareness of the ever-expanding universe of storage activities across DOE and its national laboratories. As part of this revision, DOE also created a more formalized working group structure.

D.3.2 Use Cases

As described in the ESGC 2020 Roadmap Use Case Framework, a "Use Case" describes a set of broad or related future applications that could be enabled by much higher performing or lower cost energy storage. Each Use Case can contain multiple specific instances that represent scenarios ranging from early high-value projects to high-quantity mass adoption. The Use Cases (see Appendix Table 3) were intended as guidepost examples to facilitate stakeholder discussions that envision future (i.e., 2030 and beyond) ways in which energy storage can benefit end users.

Appendix Table 3. ESGC 2020 Roadmap Use Cases (adapted from [18]).

Use Case	Scope
1. Facilitating an Evolving Grid	The ability of the U.S. electric power system (i.e., the electric grid) to reliably meet customer demand is crucial to our economy and national security. The increasing adoption of variable renewable energy (VRE) and dynamic changes in customer demand, as well as stresses from weather, physical, and cyber threats, highlight how enhanced grid flexibility can ensure the continued reliability, resilience, and security of the electric power system.
2. Serving Remote Communities	Up to a billion people in the world do not have access to electricity. Island, coastal, and remote communities that are disconnected from the bulk power system pay a premium for electricity due to fuel

	logistics and maintenance associated with diesel generation. In remote communities subject to extreme weather conditions, fuel supply disruptions are a major risk factor.
3. Electrified Mobility	Increasing electrification in in the transportation sector can be facilitated with large-scale, reliable, high-power, and cost-effective charging infrastructure that enables charging times equivalent to that of refueling at a traditional gas station. Because high-power DC fast charging can stress the delivery capacity of the local distribution grid, this new charging infrastructure should minimize any negative grid impact and optimize operations with the grid and other end uses, including buildings. Beyond charging infrastructure, energy storage systems will also be necessary for the electric vehicles themselves. Lower manufacturing costs and improved performance of domestically produced electric vehicle batteries can facilitate widespread adoption and further establish American leadership in energy storage.
4. Interdependent Network Infrastructure	The operation of the electric grid depends on other infrastructure sectors, including natural gas, communications, information technology, water, and financial services. Loss of function and service within this infrastructure due to energy delivery disruption can have far-reaching impacts and costs for end users. These interdependencies elevate the importance of sustaining the normal operations of critical infrastructure amidst short-term disruption of energy inputs.
5. Critical Services	Sectors that provide critical services include the defense industrial base sector, emergency services sector, government facilities sector, and health care and public health sector. An extended loss of power to facilities in these sectors could lead to unacceptable public health and safety risks, especially following disaster-related power outages. Similarly, many companies or manufacturers require the ability to resume and maintain operations in the event of an extended outage. The importance of these services reinforces the importance of sufficient energy supplies to these facilities during an extended outage.
6a. Facility Flexibility, Efficiency, and Value Enhancement: Commercial and Residential Buildings	This Use Case seeks to leverage opportunities to optimize energy production and usage in facilities, especially commercial and residential buildings. Optimized integrated processes can utilize high-performance, low-cost energy storage technologies to enhance the overall facility value to the owner, operator, and ultimately, the end consumer.
6b. Facility Flexibility, Efficiency, and Value Enhancement: Energy Intensive Facilities	This Use Case seeks to leverage opportunities to integrate energy storage within a range of electric power generation and energy-intensive industrial facilities. This sub-family is characterized by significantly higher energy flows than the commercial/residential buildings sector. The nature of how energy is converted and transported in the processes associated with energy-intensive facilities optimization offers potential opportunities for improvement in economics, flexibility, and market diversity.
Table Note: For more details, see ESGC 2020 Roadmap [18], Appendix 1.	

For this SRM, DOE reconsidered its approach to identifying use cases. The revised use cases are based on outcomes, not applications, of energy storage, and consider that different energy storage technologies could be selected to achieve the same outcome. This new approach to identifying use cases enables the role of energy storage and the service (or outcome) it provides to inform DOE's energy storage activities more broadly and helps align energy storage technology solutions with potential market opportunities. Section 4.1 describes the use cases for this Energy Storage SRM.

Appendix E. DOE Energy Storage Activities

This appendix offers representative activities illustrating the types of activities DOE undertakes along the RDD&D continuum, and as foundational/crosscutting. Structure aligns with Section 3.

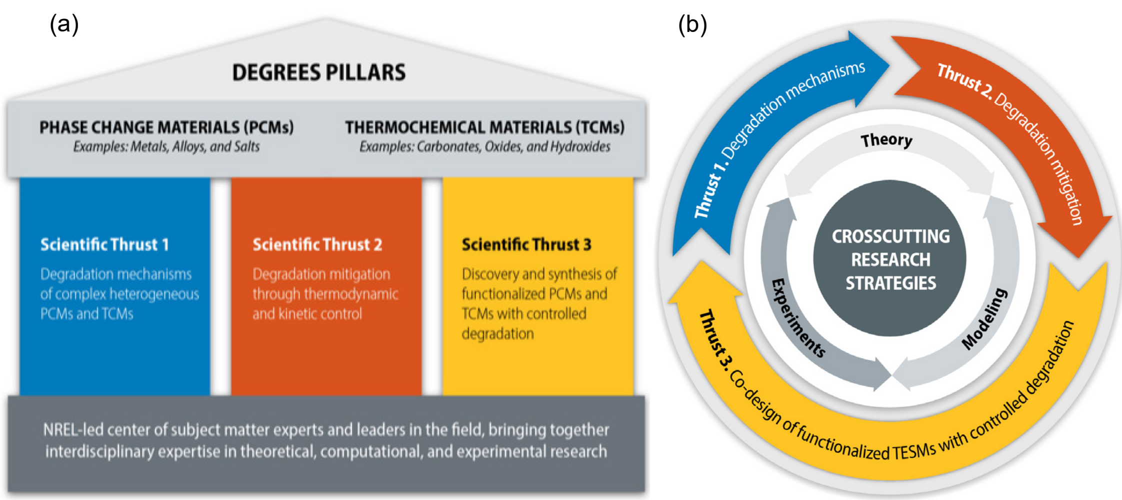
Summary Index

E.1 Basic & Applied Research

E.1.1 Long Duration Storage Shot™ Energy Earthshot™ Research Centers

DOE's Office of Science is supporting 11 new Energy Earthshot™ Research Centers (EERC) led by DOE National Laboratories addressing one or more of the Energy Earthshots™. The Energy Earthshots™ connect DOE's basic science and energy technology offices to accelerate innovations toward more abundant, affordable, and reliable clean energy solutions. These efforts seek to revolutionize many sectors across the United States and will rely on fundamental science and innovative technology to be successful. DEGradation Reactions in Electrothermal Energy Storage (DEGREES) is the EERC addressing long-duration energy storage and is managed by the Office of Basic Energy Sciences (BES). Highlights of this initiative are provided below.

DEGREES: DEGradation Reactions in Electrothermal Energy Storage



(a) Overview of objectives and scientific thrusts of EERC DEGREES. (b) A crosscutting methodology—applying theory, modeling, and experiment—is applied across all three research thrusts.

Appendix Figure 1. Energy Earthshot™ Research Centers DEGradation Reactions in Electrothermal Energy Storage (DEGREES) project concept.

Director: Dr. Judith Vidal

Lead: National Renewable Energy Laboratory

Partners: BNL, ANL, The University of Texas – Dallas, Georgia Institute of Technology, Auburn University, University of Chicago, University of New Mexico, University of Arizona

Estimated Funding: $19 million over four years (pending appropriations)

Highlights:

- The Center aims to understand and overcome coupled degradation mechanisms in thermal energy storage materials
- A goal is to predict and control performance from atomic/molecular to exascale levels to increase the longevity, reliability, and dispatchability of grid-scale clean energy storage
- The deployment of advanced cost-effective and reliable materials will enable lower cost energy by dramatically reducing the operation and maintenance costs

Ref. DOE Announces $264 Million for Basic Research in Support of Energy Earthshots | Department of Energy (https://www.energy.gov/articles/doe-announces-264-million-basic-research-support-energy-earthshotstm)

E.1.2 Science Foundations for the Energy Earthshots™ – LDES

DOE's Office of Science is funding researchers at 18 different universities across 14 states that will, for example, investigate hydrogen arc plasmas to make steelmaking carbon-free and how to make clean energy systems more resilient using exascale computer simulations and observations. Four projects underpinning the Long Duration Storage Shot were selected:

Appendix Table 4. Science Foundations for the Energy Earthshots™ - Selected LDES Projects.

Principal Investigator	Title	Lead Institution
Sarah Tolbert	Center for STrain Optimization for Renewable Energy (STORE)	University of California, Los Angeles
Akanksha Menon	Understanding Thermo-Chemo-Mechanical Transformations in Thermal Energy Storage Materials and Composites	Georgia Institute of Technology
Thomas Mallouk	Proton and Ion Management in Bipolar-Membrane-Based Electrochemical Systems	University of Pennsylvania
Kelsey Stoerzinger	Molecular and Atomic EngineeRing of Interfacial Electro-catalytic Environments (MARIE)	University of Minnesota

Highlights:

- Crosscutting discovery science to build fundamental scientific understanding, seed innovations, and address knowledge gaps that limit achievement of the Energy Earthshot™ goals.
- Targeted at the academic community, complementing the EERC Lab Call.

Ref. DOE Announces $264 Million for Basic Research in Support of Energy Earthshots™ | Department of Energy (https://www.energy.gov/articles/doe-announces-264-million-basic-research-support-energy-earthshotstm)

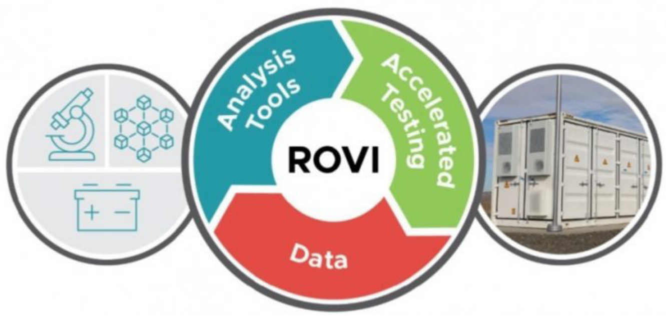
E.1.3 Basic Science Underpinning Energy Storage

Aside from research focused on the Long Duration Storage Shot™, the BES research priorities focus on fundamental science underpinning batteries for transportation and grid energy storage such as using advanced synthesis to tailor structures, tuning functionality of materials and chemistry, reducing detrimental chemistries that degrade performance, and utilizing advanced analytical and modeling tools to probe reactions across a wide range of temporal and spatial scales. BES supports energy-storage related singleinvestigator and small group research projects in several BES programs, plus larger group research efforts funded as Energy Frontier Research Centers.

E.2 Applied RD&D and Systems Integration

E.2.1 Rapid Operational Validation Initiative (ROVI)

The focus of Office of Electricity's Rapid Operational Validation Initiative (ROVI) is to greatly reduce time required for emerging energy storage technologies to go from lab to market by developing new tools that will accelerate the testing and validation process needed to ensure commercial success. To develop these tools, ROVI will employ innovative data science methods such artificial intelligence and machine learning that will leverage large sets of energy storage performance data at different scales to facilitate generating lifetime performance predictions for new technologies with minimal real-time testing required. [30]



Appendix Figure 2. DOE's Rapid Operational Validation Initiative (ROVI) bridges data, analysis, and testing.

Ref. https://www.energy.gov/oe/rapid-operational-validation-initiative-rovi

E.2.2 Grid Storage Launchpad (GSL) Facility at PNNL

The Grid Storage Launchpad (GSL) is the first dedicated energy storage facility in the DOE national lab system. DOE's Office of Electricity selected Pacific Northwest National Laboratory (PNNL) in Richland, Washington, as the site for a national grid energy storage research and development (R&D) facility that includes investments from the State of Washington, Battelle, and PNNL.

The GSL will expand on existing and add new capabilities in the areas of:

- Independent testing and validation for next generation energy storage materials, devices, and prototype systems under grid operating conditions;
- Characterization abilities focused on technologies with grid applications; and
- Integration of existing materials development and collaboration with industry and universities.

Through independent testing and validation, the GSL will develop and promulgate rigorous grid performance standards and requirements that span the entire energy storage R&D development cycle — from basic materials synthesis to advanced prototyping. The GSL will focus on three outcomes to advance grid energy storage development:

- **Collaboration:** Bringing DOE, multidisciplinary researchers, and industry together at the facility will lower the barriers to innovation and deployment of grid-scale energy storage.
- **Validation:** The facility will enable independent testing of next generation grid energy storage materials and systems under realistic grid operating conditions.
- **Acceleration:** From bench top to systems, the facility will de-risk and speed the development of new technologies by propagating rigorous performance requirements.

The GSL will help ensure DOE succeeds in strengthening the resilience of the grid to withstand the tests and challenges of the future, while ensuring that Americans continue to enjoy the benefits of our Nation's energy abundance.

The GSL also supports DOE's Energy Storage Grand Challenge, which draws on the extensive research capabilities of the DOE National Laboratories, universities, and industry to accelerate the development of energy-storage technologies and sustain American global leadership in the energy storage technologies of the future with a secure domestic manufacturing supply chain. Additionally, the facility will provide opportunities for training and development of the next generation workforce, from skilled labor to first responders and safety officials, to utility planners and regulators.

Appendix Figure 3. Newly constructed Grid Storage Launchpad (GSL) at Pacific Northwest National Laboratory is the home to groundbreaking energy storage research spanning materials and systems through validated safety and reliability (photo courtesy of PNNL).

Ref. https://www.energy.gov/oe/grid-storage-launchpad; https://www.pnnl.gov/grid-storage-launchpad-pnnl

E.3 Demonstrations and Deployments at Scale

E.3.1 Long-Duration Storage Demonstrations

The Long Duration Energy Storage Demonstrations FOA (DE-FOA-0002867) and Long Duration Energy Storage Demonstrations Lab Call (DE-LC-000L001) represents the largest DOE investment to date to translate applied energy storage research for LDES into near-commercial demonstration projects. This FOA (from the Office of Clean Energy Demonstrations and the Office of Electricity) and Lab Call (from the Office of Clean Energy Demonstrations) implements the energy storage demonstration program enacted in the Energy Act of 2020 and provides $344 million to innovative technologies capable of delivering electricity for 10-24 hours or longer to support a low-cost, reliable, carbon-free electric grid. LDES demonstration projects are encouraged to have substantial engagement with local and regional stakeholders to ensure that they generate local, regional, and national benefits.

- $19M announced by OE for innovative lithium-ion long-duration energy storage – August 2023
    - 2 projects in remote communities (VT) and military housing (KS)
- $325M announced for long-duration energy storage demonstrations by OCED – September 2023

- 15 projects across 17 states and one tribal nation to accelerate the development of long-duration energy storage (LDES) technologies
- Projects selected will feature a range of intraday (10 to 36 hours) and multiday (36 to 160+ hours) storage solutions
- Innovative technologies including second life EV batteries, flow batteries, zinc batteries, and iron air batteries

Refs. Energy Department Awards $19 Million for Long-Duration Energy Storage in Remote Communities and Military Housing | Department of Energy (https://www.energy.gov/oe/articles/energy-department-awards-19-million-long-duration-energy-storage-remote-communities-and); Biden-Harris Administration Announces $325 Million For Long-Duration Energy Storage Projects to Increase Grid Resilience and Protect America's Communities | Department of Energy (https://www.energy.gov/articles/biden-harris-administration-announces-325-million-long-duration-energy-storage-projects)

E.4 Modeling, Analysis, and Technical Assistance

E.4.1 Storage Innovations 2030

The DOE Energy Storage Grand Challenge launched Storage Innovations 2030 (SI 2030) at the ESGC Summit in September 2022. The objective of SI 2030 is to develop specific and quantifiable RD&D pathways to achieve the targets identified in the Long-Duration Storage Shot™, which seeks to achieve 90% cost reductions for technologies that can provide 10 hours or longer duration of energy storage by 2030.

DOE has supported or currently supports over 30 distinct energy storage technologies including electrochemical, electromechanical, thermal, and chemical storage. Many of these energy storage technologies have the potential to enable the Long-Duration Storage Shot™ targets. Achieving these aggressive targets will require resolution of key barriers throughout value chain, from basic and applied research through analysis, demonstration, manufacturing, and full integration into the power and end-use sectors.

Through Storage Innovations 2030, DOE is seeking to understand the specific innovations required to unlock the potential for long-duration applications in a variety of these technologies. To obtain community input, SI 2030 has launched four thrusts: SI 2030 Framework, SI 2030 Prize, SI 2030 Flight Paths, and SI Liftoff (see section E.4.3 for SI Liftoff).

SI Framework: This pillar is creating an industry-aware R&D "framework," aiming to project and estimate the impact of R&D activities on future storage cost targets. This approach is aimed at guiding the highest impact R&D investments by facilitating one-on-one conversations around the future of the 10 energy storage technologies [22]. The primary goals of the Framework are to stochastically model the future outcomes of potential investment portfolios on storage technology LCOS and craft strategies around the highest impact investments and technology suitability across different use cases.

SI Prize [31]: While the Framework targets established or mid-stage technologies, the Prize invited the storage community to propose early-stage, emerging, and innovative energy storage ideas that may be disruptive to industry in the future. The competition closed in December 2022 and the winners were announced on February 27, 2023 [32].

SI Flight Paths: SI Flight Paths complements the Framework by providing a collaborative forum to discuss technology R&D opportunities and the potential for pre-commercial R&D pathways. The Flight Paths effort was composed of nine industry listening sessions held January through March

2023, bringing together industry representatives to take part in technology-focused discussions about specific technology areas.

Ref. https://www.energy.gov/oe/storage-innovations-2030

E.4.2 Long-Duration Storage Shot Technology Strategy Assessments

On July 19, 2023, DOE released a series of technical reports summarizing and analyzing the results from the SI 2030 stakeholder engagement process, including SI Flight Paths and SI Framework, as detailed in the Methodology report. The objective of SI 2030 is to develop specific and quantifiable research, development, and deployment (RD&D) pathways toward achieving the targets identified in the Long-Duration Storage Shot™, which seeks to achieve 90% cost reductions for technologies that can provide 10 hours or longer of energy storage within the coming decade. These reports (listed below) are opportunities to explore promising RD&D pathways to substantially lower the costs of long-duration energy storage.

- **Methodology Report**
- **Lithium-ion Batteries Technology Strategy Assessment**
- **Lead-acid Batteries Technology Strategy Assessment**
- **Flow Batteries Technology Strategy Assessment**
- **Zinc Batteries Technology Strategy Assessment**
- **Sodium Batteries Technology Strategy Assessment**
- **Pumped Storage Hydropower Technology Strategy Assessment**
- **Compressed-Air Energy Storage Technology Strategy Assessment**
- **Thermal Energy Storage Technology Strategy Assessment**
- **Supercapacitors Technology Strategy Assessment**
- **Hydrogen Storage Technology Strategy Assessment**

Ref. https://www.energy.gov/oe/storage-innovations-2030

E.4.3 Storage Innovations 2030: Technology Liftoff (SI Liftoff)

The SI Liftoff FOA aims to leverage the Flight Paths listening session conversations and analytical Framework results, both described in the Technology Strategy Assessments (see section E.4.2) to accelerate partnerships and enable pre-competitive R&D projects that have the potential to benefit entire technology industries. The selected technology or technologies must have a pathway to cost-effective, grid-scale, long-duration energy storage.

The partnerships developed in response to this funding opportunity will collaborate with two primary objectives: [33]

1. *Partnership development:* Entities will organize by coordinating with each other, engaging in meetings and discussions, and setting up durable channels of communication to effectively collaborate through this award period and afterwards. Entities are encouraged to think creatively to develop lasting partnerships.
2. *Pre-competitive R&D:* Partnerships will receive funding to perform “pre-competitive R&D” projects at a research institution, such as (but not limited to) a DOE National Laboratory. “Pre-competitive R&D” includes activities that are of interest to multiple or all entities in the partnership. Such activities should propel an entire technology industry forward, and the outputs of this work should provide value to all participating members of the partnership.

Ref. https://www.energy.gov/oe/storage-innovations-2030-technology-liftoff

E.4.4 2022 Grid Energy Storage Technology Cost and Performance Assessment

DOE tracks the progress of its energy storage strategy, in part, through the Cost and Performance Report. The report series, which released its second edition in 2023, provides a standardized approach to analyzing the cost elements of storage technologies, engages industry to identify current cost elements, and projects 2030 costs based on each technology's current state of development.

The 2022 Cost and Performance Assessment (second edition) helped provide a standardized approach to analyzing the cost elements of storage technologies, engaging industry to identify theses various cost elements, and projecting 2030 costs based on each technology's current state of development. This data-driven assessment of the current status of energy storage technologies is essential to track advances in technology and inform the decision-making of a broad range of stakeholders. The 2022 Cost and Performance Assessment includes five additional features comprising of additional technologies & durations, changes to methodology such as battery replacement & inclusion of decommissioning costs, and updating key performance metrics such as cycle & calendar life.

Key highlights of this effort include:

- The 2020 Cost and Performance Assessment provided installed costs for six energy storage technologies: lithium-ion (Li-ion) batteries, lead-acid batteries, vanadium redox flow batteries, pumped storage hydro, compressed-air energy storage, and hydrogen energy storage. The assessment adds zinc batteries, thermal energy storage, and gravitational energy storage.
- The 2020 Cost and Performance Assessment provided the levelized cost of energy. The 2022 Cost and Performance Assessment provides the levelized cost of storage (LCOS). The two metrics determine the average price that a unit of energy output would need to be sold at to cover all project costs inclusive of taxes, financing, operations and maintenance, and others. However, shifting toward LCOS as a separate metric allows for the inclusion of storage-specific components and terminology that can be more accurately defined when compared to the levelized cost of energy calculation. This includes the cost to charge the storage system as well as augmentation and replacement of the storage block and power equipment. The LCOS offers a way to comprehensively compare the true cost of owning and operating various storage assets and creates better alignment with the Long-Duration Storage Shot™.
- This report incorporates an increase in Li-ion iron phosphate and nickel manganese cobalt Li-ion cycle life and calendar life based on input from industry partners.
- Recycling and decommissioning are included as additional costs for Li-ion, redox flow, and lead-acid technologies.
- The 2020 Cost and Performance Assessment analyzed energy storage systems from 2 to 10 hours. The 2022 Cost and Performance Assessment analyzes storage system at additional 24- and 100-hour durations. This analysis of longer duration storage systems supports the Long-Duration Storage Shot™.

The 2024 Cost and Performance Assessment (third edition) is underway.

Ref. https://www.energy.gov/eere/analysis/2022-grid-energy-storage-technology-cost-and-performance-assessment

E.4.5 Energy Storage Technical Assistance to States

Policy initiatives that impact the energy storage sector can emerge from legislative or regulatory bodies, or directly from the governors in individual states. Sandia and PNNL engage directly with state and federal policymakers to obtain and share perspectives on best practices in energy storage policymaking, providing independent, objective, and neutral analysis on industry best practices, lessons learned from specific regulatory and legislative proceedings, and cross-state comparisons.

In addition, the team conducts educational Energy Storage Webinars for state policymakers across the country. These workshops, free for all attendees and funded by the DOE Office of Electricity, help regulatory commissions and related institutions around the United States develop the expertise they need to more quickly and efficiently integrate energy storage into their regional operations.

E.4.6 HydroWIRES Technical Assistance (EERE)

The $7M HydroWIRES technical assistance (TA) program is designed to assist the hydropower industry with decisions to develop hydropower hybrids and pumped storage hydropower (PSH). This 2024 opportunity follows a 2023 technical assistance call that utilized a similar structure. General objectives are twofold:

- Provide hybrid and PSH developers and other stakeholders with National Lab expertise and capabilities to address specific, timely challenges they face.
- Disseminate results, outcomes, and lessons learned from the selected TA projects so that the broader hydropower community can utilize them to achieve expanded impact beyond the individual selected projects.

In addition, this call will emphasize increasing the diversity of research staff, increasing diversity of voices in research design, and increasing quantification and emphasis on supporting underserved communities.

Ref. PSH Valuation Tool (https://pshvt.egs.anl.gov/ta)

E.5 Foundational and Crosscutting Efforts

While the following activities do not support the R&D activities above in Appendices E.1-E.4 directly, they are important to the development of energy storage systems and the mission of DOE. Moreover, they are paramount to DOE successfully achieving the vision of this Energy Storage Strategy and Roadmap.

E.5.1 Diversity, Equity, Inclusion, and Accessibility

E.5.1.1 Justice40 Initiative

The Biden-Harris Administration has made it a priority to support disadvantaged communities disproportionally impacted by air and water pollution and vulnerable to extreme weather events. Executive Order 14008 created the Justice40 Initiative, a plan to deliver 40% of the overall benefits of climate investments to disadvantaged communities and inform equitable research, development, demonstration, and deployment within DOE. [7]

In addition to supporting the transition to a decarbonized energy system, energy storage can also support energy justice and equity objectives. For example, non-wire alternatives, aggregated behind-the-meter batteries, or new utility-scale long-duration storage technologies can reduce localized fossil-fuel generation in the low-income communities where fossil fuel generation disproportionately occurs. Energy storage can also provide reliable power, increase resilience, reduce price shocks, and enhance energy security for remote and Tribal communities. DOE's efforts to develop a robust and sustainable domestic supply chain can also promote international energy justice by decreasing the need to extract raw materials in foreign locations with lax environmental and/or human rights oversight.

E.5.1.2 Energy Storage for Social Equity Initiative

Innovation and energy justice are at the forefront of DOE's mission. As part of that effort, on September 23, DOE launched its Energy Storage for Social Equity Initiative (ES4SE) to help underserved and frontline communities leverage energy storage as a means of increasing resilience and maximizing energy flexibility. The funding available through this initiative will promote an equitable clean energy transition, advance more affordable and reliable electricity, and support the Biden Administration's Justice40 goals.

Nationally, more than 65% of low-income households face a high energy burden and more than 30% of all households experienced some form of energy insecurity, sometimes even foregoing food, medicine, and heating or cooling comfort to pay an energy bill. [34]

ES4SE, a program managed by Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (SNL), is designed to empower communities to consider energy storage technologies and applications as a viable path towards community prosperity, well-being, and resilience.

The initiative will be organized into two phases, with the first working to help communities better assess their energy challenges, evaluate solutions, and find partners to support the community in meeting its energy goals. Selected urban, rural, and tribal communities will receive technical assistance, equity assessments, and workforce analysis. Technical assistance may include energy, economic, and spatial analysis, as well as assistance to complete grant and funding applications.

The second phase will focus on energy storage project development and deployment, where up to six communities from the 10-15 chosen from the initial Technical Assistance phase will be selected to begin installing and commissioning their projects. Engineering support may include equipment sizing, identifying utility connections, identifying safety concerns, installation support, and measurement, and validation to ensure project performance meets the original goals.

ES4SE is designed around easy access and eligibility is linked to need.

Ref. https://www.energy.gov/oe/energy-storage-social-equity-initiative

E.5.1.3 Established Program to Stimulate Competitive Research (EPSCoR) Awards

The U.S. Department of Energy's Established Program to Stimulate Competitive Research (DOE EPSCoR) is a federal-state partnership program designed to enhance the capabilities of designated states and territories to conduct sustainable and nationally competitive energy-related research. DOE EPSCoR addresses this mission by fostering competitions for scientific and engineering research in states and territories that have demonstrated a commitment to develop their research bases and to improve the quality of science and engineering research conducted at their universities and colleges.

Ref. https://ess.science.energy.gov/epscor/

E.5.2 Workforce Development

E.5.2.1 Long-Duration Energy Storage for Everyone, Everywhere Initiative – Workforce Development Listening Session

In January of 2021, the ESGC Workshop on Manufacturing and Workforce Needs in the Energy Storage Industry identified several need areas, including: working with community colleges and 4-year universities to develop new curricula; working with industries and the national labs to provide internship opportunities to excite the next-generation workforce; need for federal/state codes to protect the safety of both communities and first responders; and, need for municipal personnel, such permit approvers to be properly trained to understand the magnitude of ESS risks.

Ref. ESGC, "Summary of Energy Storage Grand Challenge Workshop: Manufacturing and Workforce Needs in the Energy Storage Industry", Workshop Report DOE/PA-0023 (https://www.energy.gov/energy-storage-grand-challenge/articles/summary-esgc-workshop-manufacturing-and-workforce-needs)

E.5.2.2 Reaching a New Energy Sciences Workforce (RENEW)

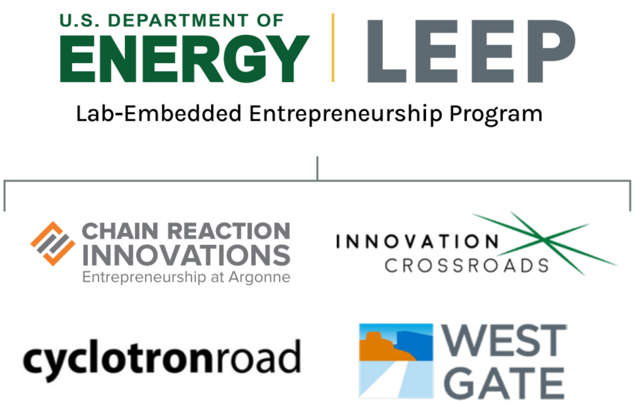
Reaching a New Energy Sciences Workforce (RENEW) aims to build foundations for Office of Science (SC) research at institutions historically underrepresented in the SC research portfolio. RENEW leverages SC's unique national laboratories, user facilities, and other research infrastructures to provide training opportunities for undergraduate and graduate students, postdoctoral researchers, and faculty at academic institutions not currently well represented in the U.S. science and technology ecosystem. The hands-on experiences gained through the RENEW initiative will open new career avenues for the participants, forming a nucleus for a future pool of talented young scientists, engineers, and technicians with the critical skills and expertise needed for the full breadth of SC research activities. Principal investigators, key personnel, postdoctoral researchers, and students of RENEW awards will be invited to participate in program research meetings and/or SC-wide professional development events.

Ref. https://science.osti.gov/Initiatives/RENEW

E.5.2.3 Lab-Embedded Entrepreneurship Program (LEEP)

New innovations, derived from investments in basic and applied energy research at universities and national labs, are critical to building a clean energy economy. The mission of DOE's Lab-Embedded Entrepreneurship Program (LEEP) is to enable the most promising clean tech entrepreneurs to develop game-changing technologies for a clean energy future.

Each LEEP "node" recruits clean energy's best and brightest minds through a national call for a two-year funded fellowship that will help move their emerging technology into the market. Early-stage startups embed at their respective national lab and are mentored by a lab scientist. The programs also provide local, regional, and national ecosystem support including business entrepreneurship training to eliminate the hurdles traditionally faced by early-stage clean tech startups.



Appendix Figure 4. Four "nodes" of the LEEP program.

These innovators are our future. The program supports the revolutionary technologies that may save the planet.

Ref. https://www.energy.gov/eere/ammto/lab-embedded-entrepreneurship-program

E.5.2.4 Battery Workforce Initiative

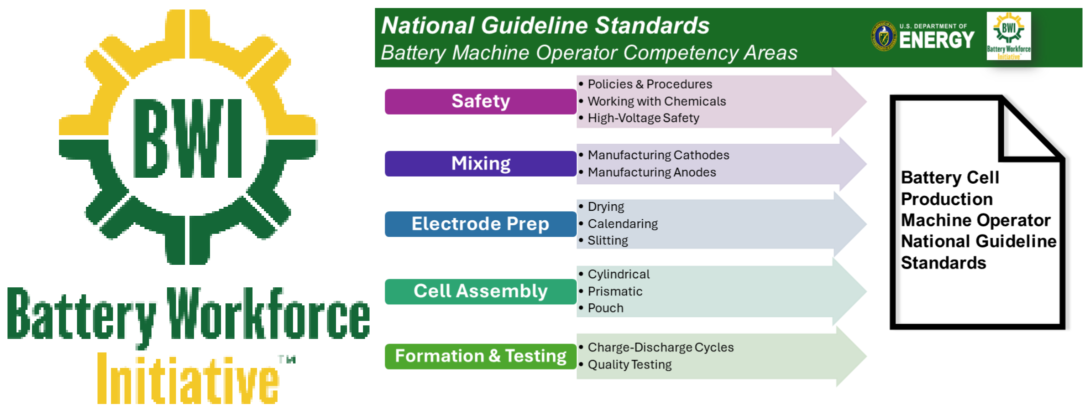
The U.S. Department of Energy (DOE) is establishing a team of experts and stakeholders from the advanced battery industry to rapidly develop training and materials for key occupations (as defined by industry) in a manner that complements ongoing workforce development efforts. DOE is coordinating the Battery Workforce Initiative (BWI) with the U.S. Department of Labor (DOL), American Federation of Labor and Congress of Industrial Organizations (AFL-CIO) Working for America Institute, Li-Bridge alliance members, and other organizations.

The purpose of this industry-driven, government-facilitated initiative is to speed up the development of high-quality training, starting with existing examples to develop consensus on core training needs, and then develop training for use by companies and local training providers. The initiative will:

- Convene battery industry organizations to cooperate in the development of training by sharing non-proprietary requirements for high-demand occupations.
- Engage training experts from manufacturers, labor, education, government, and other organizations to participate in facilitated workshops that quickly distill common skills and abilities needed in each industry segment and accelerate decision making.
- Translate those needs into educational and on-the-job training requirements, forming the basis for training materials and guides.

The initiative includes employer-based testing and validation programs that will test the effectiveness of draft training for high-priority job positions/responsibilities identified by the initiative.

The initiative will result in draft training for each job position/responsibility tested and improved upon during the employer-based testing and validation programs. The draft training will be used to develop a DOL-approved credential and shared with community colleges and other training providers.



Appendix Figure 5. The Battery Workforce Initiative recently finalized a key tool to help aide in the development of a skilled workforce for the nation's competitive domestic battery industry.

Ref. https://netl.doe.gov/bwi

E.5.2.5 Entrepreneurship Trainings and Talent Development

The Office of Technology Transitions administers a variety of technology transfer activities focused on increasing knowledge of market risks and opportunities, Energy I-Corps is a commercialization training program linking lab researchers with industry mentors to define technology value propositions, conduct stakeholder discovery interviews, and develop viable market pathways for their technologies. The Energy Tech University Prize provides student teams with the opportunity to explore business opportunities for lab-developed or other high-potential energy technologies, assess commercialization opportunities through market analysis, and develop a viable business plan with the support of mentors and educational materials.

The Technology Commercialization Internship (TCIP) is an internship opportunity for undergraduate students to experience the Department of Energy's world-class National Lab system, boost entrepreneurial thinking, and explore market opportunities.

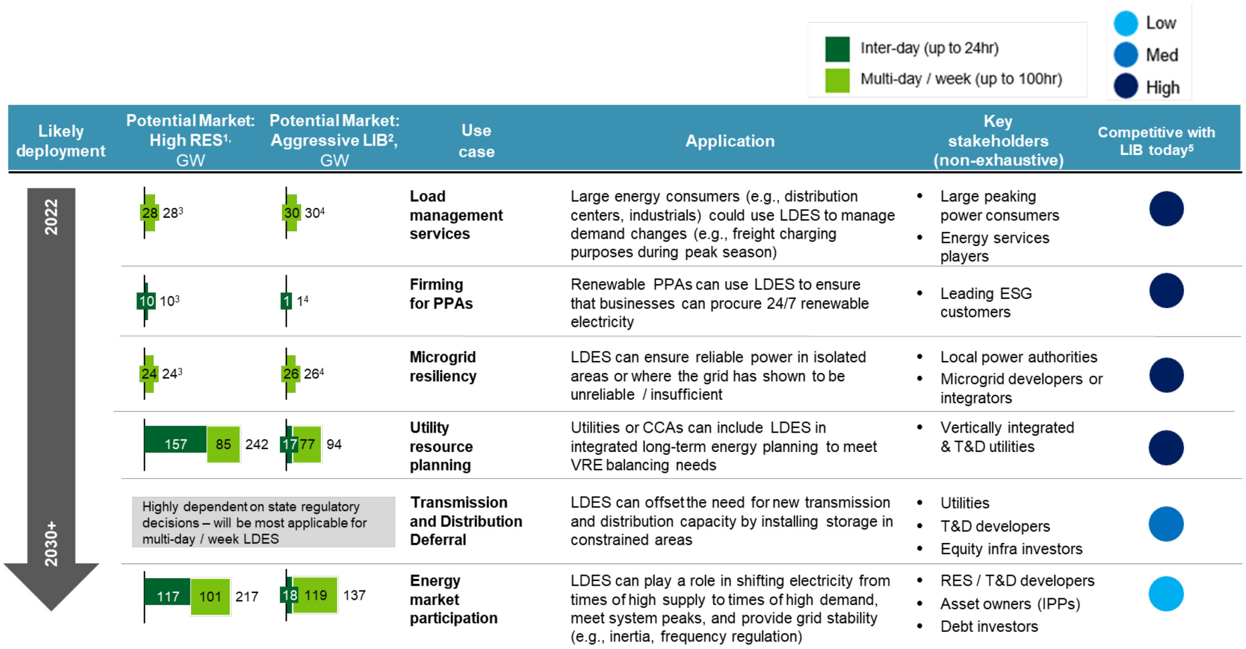
Ref. https://www.energy.gov/technologytransitions/talent-development

E.5.3 Technology Transition

E.5.3.1 Pathways to Commercial Liftoff: Long-Duration Energy Storage

The Department of Energy (DOE) plays a critical role in accelerating the commercialization of clean energy technologies and enabling the nation's broader industrial strategy – creating high quality American jobs, strengthening domestic supply chains and global competitiveness, and facilitating an equitable energy transition. DOE's Pathways to Commercial Liftoff provide public and private sector capital allocators with a perspective as to how and when various technologies could reach full-scale commercial adoption– including a common analytical fact base and critical signposts for investment decisions. Given the constantly and rapidly evolving market, technology, and policy environment, the Liftoff Reports are designed to be "living documents" – and will be updated as the commercialization outlook on each technology evolves.

The LDES report focuses on the application of LDES systems for electricity purposes (e.g., energy is stored and then dispatched in the form of electricity at a later time). To evaluate the commercial feasibility of LDES within the U.S., this effort consulted a wide range of existing research1 and modeled a U.S.-power-sector decarbonization pathway with varied decarbonization and technical scenarios to assess LDES's role in the power sector and factors influencing LDES deployment pathways for electricity needs. "Liftoff" is defined as the point where the LDES industry became a largely self-sustaining market that does not depend on significant levels of public capital and instead attracts private capital with a wide range of risk. "Liftoff" is characterized by significant improvement in technology and operating parameters, market recognition of LDES's full value, and realization of industrial-scale manufacturing and deployment capacity. These improvements are needed for LDES to compete with alternative technologies. This analysis helps to understand potential LDES use case scenarios and how they correspond to market segments and duration requirements (Appendix Figure 6).



Appendix Figure 6. Competition landscape for LDES use cases (adapted from [21]).

The insights and takeaways found in these Liftoff Reports were developed through extensive stakeholder engagement and a combination of system-level modeling and project-level financial modeling. Taken together, these sources of insight shed light on a set of common themes and expose the interplay between the technologies of focus. They do not reflect DOE official policy or strategic plans;[22] they are a resource intended to inform decision making across industry, investors, and the broader stakeholder community.

[22] The Liftoff Report initiative does not represent a policy position for DOE or the U.S. Government; nor does it reflect intentions for DOE program execution or funding.

Ref. Long Duration Energy Storage - Pathways to Commercial Liftoff (https://liftoff.energy.gov/long-duration-energy-storage/)

E.5.3.2 Technology Commercialization Fund

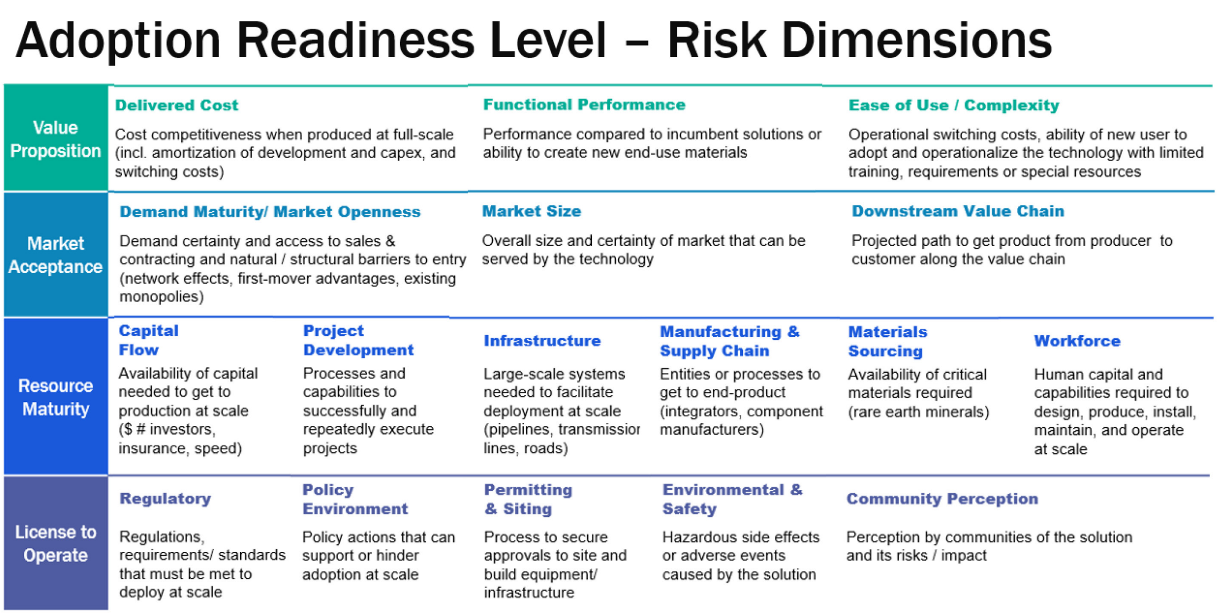
The Technology Commercialization Fund (TCF) leverages applied energy program funding to mature promising and potentially high impact energy technologies. TCF Base is an estimated $40 million annual program that supports the commercialization of National Lab, plant, and site developed technologies and the build out of the National Lab commercialization ecosystem.

The Bipartisan Infrastructure Law TCF (BIL TCF), part of the Bipartisan Infrastructure Deal (see Appendix G.2.1) provided more than $275 million of additional funding over five years for programming that supports the commercialization of promising energy technologies while simultaneously enhancing and supporting BIL provision activities.

Ref: https://www.energy.gov/technologytransitions/funded-programs

E.5.3.3 Adoption Readiness Levels

OTT developed the Adoption Readiness Level (ARL) framework as a tool to determine market deployment barriers beyond technical readiness. This framework serves to complement TRLs by capturing technology commercialization risk factors that can impede technology commercialization. ARLs were developed in partnership with other DOE and industry stakeholders to assess the market risks impacting scaled commercial deployment of a technology. There are 17 ARL dimensions (shown in Appendix Figure 7 below), which are quantified in in the associated Commercial Adoption Readiness Assessment Tool (CARAT).[23] CARAT can be used to develop an 1-9 adoption readiness score, representing the readiness of a technology to be adopted by the commercial ecosystem.

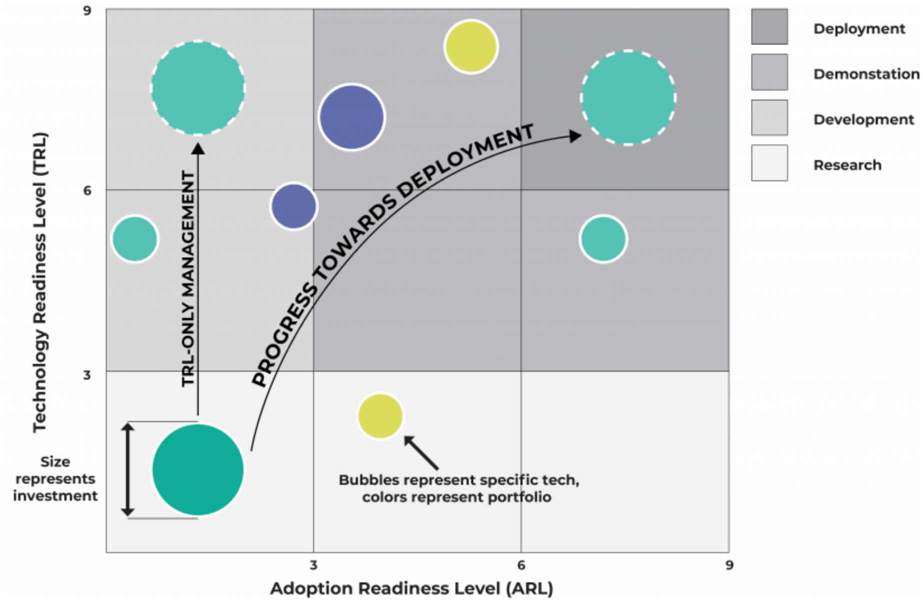


Appendix Figure 7. Risk dimensions of the Adoption Readiness Level framework.

Considering adoption risks is critical to achieving commercial success. As shown in Appendix Figure 8 below, technologies can reach a high TRL and still fail to gain market traction. Proactively assessing

[23] The CARAT tool is available for download here: https://www.energy.gov/media/297882.

technology value proposition, market acceptance, resource maturity, and societal license to operate can assist to de-risk technologies.



Appendix Figure 8. Relationship of technology readiness and adoption readiness to commercial deployment.

Uptake of the ARL framework is growing across the DOE and with external partners. ARLs are being used in thought leadership, entrepreneurial trainings, national lab technology evaluations project prioritization and planning, and in funding selection criteria.

Ref. Adoption Readiness Levels (ARL): A Complement to TRL | Department of Energy (https://www.energy.gov/technologytransitions/adoption-readiness-levels-arl-complement-trl)

E.5.4 Supply Chain Access/Resilience

E.5.4.1 DOE Supply Chain Analysis of Incumbent Technologies for Grid Energy Storage

To meet growing demand for long duration energy storage, domestic manufacturing will have to increase significantly. The use of renewables is rapidly increasing, and the adaption of electric vehicles is on the rise, which will require the national grid to not only produce and deliver electricity, but also store it reliably and cost-effectively.

In February 2021, President Biden signed Executive Order (EO) 14017, America's Supply Chains, directing four executive agencies to evaluate the resilience and security of the nation's critical supply chains and craft strategies for seven industrial bases that underpin America's economic and national security. As part of the one-year response to EO 14017, the U.S. Department of Energy (DOE), through the National Laboratories, conducted evaluations of the supply chains that encompass the Energy Sector Industrial Base (ESIB), with a particular focus on technologies required to decarbonize by 2050. In February 2022, DOE released the Grid Energy Storage: Supply Chain Deep Dive Assessment as response to Executive Order 14017, "America's Supply Chains". This report provides an overview of the supply chain resilience associated with several grid energy storage technologies.

Strategies to address key vulnerabilities in the grid storage supply chain include developing domestic, sustainable manufacturing and recycling capabilities along the energy storage supply chain; maximizing the use of domestic resources by focusing on second-life and recycling technologies; and enabling the diversification and deployment of grid storage technologies through targeted research activities.

The report identified key challenges that contribute to vulnerabilities to the supply chain. The challenges include reliance on other countries for components and products for lithium-ion batteries; environmental and climate impacts of material refining, battery manufacturing, and recycling industries; increasing transportation electrification needs that decrease an already limited market; and limited adoption of alternative inexpensive and abundant materials.

Ref. https://www.energy.gov/sites/default/files/2022-02/Energy%20Storage%20Supply%20Chain%20Report%20-%20final.pdf

E.6 Stakeholder Engagement

E.6.1 DOE Energy Storage Systems Program

The goal of the ESS program is to develop advanced energy storage technologies and systems, in collaboration with industry, academia, and government institutions that will increase the reliability, performance, and competitiveness of electricity generation and transmission in the electric grid and in standalone systems.

The DOE Energy Storage Systems program collaborates with industry, academia, and other government institutions to develop advanced energy storage technologies, demonstrate the effectiveness of storage technologies and analyze policy options that will increase the reliability, performance, and competitiveness of electricity generation and transmission in utility-tied and off-grid systems. The program goals include the education and dissemination of information on electrical energy storage systems by increasing the collective knowledge of energy storage systems, their operations, uses, benefits and potential issues.

ESS has been instrumental in the research & development of energy storage technologies and applications since the 1970s, especially as storage relates to electric utilities, renewables, and grid security.

Ref. https://www.sandia.gov/ess/

E.6.2 Long-Duration Energy Storage Memorandum of Understanding

Signed in March 2023, the LDES MOU establishes a coordination mechanism to further accelerate the commercialization of LDES. Parties involved include the U.S. Department of Energy Office of Technology Transitions (OTT), the Edison Electric Institutes' Institute for the Energy Transition, Electric Power Research Institute (EPRI), and the Long Duration Energy Storage Council (LDES Council). Signed in March 2023, the MOU will result in several key actions: create opportunities to leverage the key findings from DOE's Pathways to Commercial Liftoff: LDES report; initiate engagements with industry stakeholders to share insights and expertise, and then to outline collective ideas to address barriers; highlight and map LDES technologies that are moving from innovation and pilot to market maturity and scale; and, host an industry-focused LDES technical summit in 2024. The 2-year MOU aimed at accelerating the commercialization of long-duration energy storage will focus on the following areas:

- Support the development and domestic manufacture of energy storage technologies that can meet all U.S. market demands by 2030, including the DOE's Long Duration Storage Shot, which establishes a target to reduce the cost of grid-scale energy storage by 90% for systems that deliver 10+ hours of duration within the decade.
- Facilitate the understanding and dissemination of knowledge about the technological, economic, and resilience benefits afforded by long-duration energy storage.
- Provide access to specific DOE and national lab core competencies in energy storage and energy infrastructure integration for supporting research, development, demonstration, and deployment purposes.

- Convene regulators, electric companies, technology vendors, and the financial community to identify barriers to LDES deployment and potential solutions to those barriers.

Ref. Department of Energy Announces Partnership to Accelerate Commercialization of Long-Duration Energy Storage | Department of Energy (https://www.energy.gov/technologytransitions/articles/department-energy-announces-partnership-accelerate-commercialization); https://www.energy.gov/technologytransitions/articles/department-energy-and-partners-sign-landmark-agreement-accelerate

E.6.3 National Consortium for the Advancement of Long-Duration Energy Storage Technologies

The National Consortium for the Advancement of LDES technologies is funded through an OTT/OCED Collaborative Alignment for Critical Technology Industries Lab Call Award, September 2023. The Consortium will enable, facilitate, and coalesce collaborative efforts between public and private entities to address the core issues facing LDES commercialization, including investor confidence, market planning, interconnection, standardization, safety, economic evaluation, and more. Sandia National Laboratories, in partnership with Argonne National Laboratory, Idaho National Laboratory, the National Renewable Energy Laboratory, Oak Ridge National Laboratory, and Pacific Northwest National Laboratory, will stand up this consortium. More than 120 external partners have committed to the project, including local government agencies, utilities, and non-profits. The Consortium launched its website on 16 Jan 2024: https://LDESconsortium.sandia.gov.

Ref. DOE Announces Over $15 Million Towards Two Projects to Support Industry Engagement and Alignment for Clean Energy Solutions | Department of Energy (https://www.energy.gov/technologytransitions/articles/doe-announces-over-15-million-towards-two-projects-support-industry)

E.6.4 Energy Program for Innovation Clusters (EPIC)

The Energy Program for Innovation Clusters (EPIC) is a $50-million program comprising a two-part funding opportunity (Prize and FOA) to encourage the robust growth of regional energy innovation ecosystems across the United States. In FY2021, the prize awarded $50,000 each to 20 incubators focused on developing strong regional innovation clusters. The EPIC FOA awarded $9.5 million—in partnership with the DOE Buildings Technologies Office, Arctic Energy Office, and Office of Electricity—to 10 incubators across the country that recognized innovation-accelerating organizations focused on stimulating energy hardware development and related supportive ecosystems.

Ref. https://www.energy.gov/technologytransitions/articles/ott-announces-epic-program-energy-incubator-prize; https://www.energy.gov/technologytransitions/energy-program-innovation-clusters;

Appendix F. Grid Modernization Initiative – Relevant Activities

The Grid Modernization Initiative (GMI) [35] works across DOE to create the modern grid of the future. Our extensive, reliable power grid has fueled the nation's growth since the early 1900s; however, the grid we have today does not have the attributes necessary to meet the demands of the 21st century and beyond. DOE is working with public and private partners to develop the concepts, tools, and technologies needed to measure, analyze, predict, protect, and control the grid of the future. DOE's portfolio of work will help integrate all sources of electricity better, improve the capability of our nation's grid, solve challenges of energy storage and distributed generation, and provide a critical platform for U.S. competitiveness and innovation in a global energy economy. The grid of the future will deliver resilient, reliable, flexible, secure, sustainable, and affordable electricity.

F.1 2015 Multi-Year Program Plan (MYPP)

In 2015, DOE issued its Grid Modernization Multi-Year Program Plan (MYPP) [36] to guide DOE activities in support of GMI [32]. This MYPP defines a vision for the modern grid and identifies key challenges and opportunities. The direction and priorities outlined in the 2015 MYPP draw upon DOE's ongoing work on the Quadrennial Energy Review (QER) [33] and the Quadrennial Technology Review (QTR) [34], as well as DOE program activities and numerous private sector inputs over the previous years. It describes the RD&D activities DOE expected to focus on over the next five years, including opportunities for public-private partnerships. This plan also laid the foundation for coordination across DOE, linking key programs within the Office of Science (SC), Office of Electricity Delivery and Energy Reliability (OE), Office of Energy Efficiency and Renewable Energy (EERE), Office of Fossil Energy (FE), Office of Nuclear Energy (NE), Advanced Research Projects Agency - Energy (ARPA-E), Office of Energy Policy and Systems Analysis (EPSA), and others. DOE recognized, however, that this intra-DOE coordination and collaboration is only the prelude to broader collaborative efforts that are needed with and among other federal agencies, regulators, legislators, utilities, vendors, consumer groups, and others.

With respect to energy storage, the 2015 MYPP recognized the following:

> Advances to the electric grid must enhance the robustness and resilience of the electricity delivery system. Energy storage does this by improving the operating capabilities of the grid, enhancing reliability, and deferring or reducing infrastructure investments. Storage is also valuable for emergency preparedness, providing backup power as well as grid stabilization services. DOE's Energy Storage Program performs R&D on a wide variety of storage technologies, conducts analytical studies on the technical and economic performance of storage technologies, and collaborates with industry and states to test storage installations. [36]

The 2015 MYPP was structured around six technical areas, each including elements of energy storage. The descriptions of each technical area are adapted from the 2015 MYPP to provide context for the Energy Storage SRM. The subsections that follow highlight how activities within each technical area aligns with this Energy Storage SRM. Additional details are available in the 2015 MYPP [36].

F.1.1 Devices and Integrated Systems Testing

New distributed devices and systems will help deliver the flexibility required by the future grid for managing variable generation, engaging consumer, and enhancing reliability and resiliency while keeping electricity affordable. This technical area develops devices and integrated systems, coordinates integration standards and test procedures, and evaluates the grid characteristics of both individual devices and integrated systems to provide grid-friendly energy services.

Appendix Table 5. Energy storage-related activities and technical achievements for Devices and Integrated System Testing, 2015 MYPP.

Activity/Technical Achievements by 2020, assuming adequate funding levels[24]	Alignment with Energy Storage SRM
1. Develop Advanced Storage Systems, Power Electronics and other Grid Devices • Develop power electronics-based converters for renewable, distributed energy and energy storage systems that can provide grid services, self-optimize around the market and energy environment and meet specific DOE applications' targets.[25] • Decrease the system costs of deployed grid-scale, energy storage system to under $300/kWh by establishing grid-scale storage systems' metrics for safety, reliability and performance, and through new energy storage technologies development.	[high overlap with ESGC] [link to SC, AR, OE, AMMTO battery and storage work] [link to OE, SETO, AMMTO power conversion work] [overlap with LDSS and SI 2030]
2. Develop Standards and Test Procedures • Updated standards and test procedures that characterize the ability of devices (50% of building loads and all new generation and storage) to provide a full range of grid services and accelerate the uptake of these devices in the market. Codes and standards are also necessary to ensure deployed technologies are safe and effective. • Development of standards and test procedures for microgrids, storage and other systems that reduce customer outages by 10%.	[high overlap with ESGC] [link to OE codes and standards, GSL]
4. Conduct Multi-scale Systems Integration and Testing • Validated transactive control constructs that coordinate distributed generation, storage, and controllable loads to reduce reserve margins by 33%. • Field demonstrations of energy storage providing multiple grid services cost effectively.	[high overlap with ESGC] [link to OE GSL, LDES demos (especially the multi-location projects)]

Appendix Table 6. Devices and Integrated Systems Testing tasks identified in the 2015 MYPP.

2015 MYPP Tasks[26]	Alignment with Energy Storage Strategy and Roadmap
Power Electronics	
Task 2.1.1: Develop and demonstrate new materials that enable increased switching frequencies and power densities of power electronics-based devices by a factor of 2-4. [FY16-20]	[moderate overlap with ESGC] [link to OE inverter/power electronics work]
Task 2.1.2: Develop power electronics-based converters for renewable, distributed energy and energy storage that can provide grid services, self-optimize around the market and energy environment, and meet specific DOE applications' targets. [FY16-20]	[high overlap with ESGC] [link to OE inverter/power electronics work]

[24] This information is captured from Table 1. Activities and technical achievements for devices and integrated system testing of the 2015 MYPP [36].

[25] For specific goals around power electronics, see DOE Office reference documents located in footnotes of Section 2.1 of the 2015 MYPP [36].

[26] Task numbers adhere to their enumeration in the MYPP, where the second digit corresponds to the activity number in Appendix Table 5 [36].

2015 MYPP Tasks[26]	Alignment with Energy Storage Strategy and Roadmap
Energy Storage	
Task 2.1.3: Decrease the system cost of deployed grid-scale energy storage to under $300/kWh by FY20 by establishing metrics for safety, reliability, and performance storage systems and through new energy storage technologies. Demonstrate deployment and usage models that provide a return on investment (ROI) of under three years. [FY16-FY20]	[high overlap with ESGC] [link to SC, AR, OE, AMMTO battery and storage work] [link to OE storage valuation models]
Interconnection Standards and Testing Procedures	
Task 2.2.2: Facilitate establishment of risk evaluation protocols, safety standards, and performance testing methodologies for energy storage [FY16-19]	[high overlap with ESGC] [link to OE ROVI]
Grid Services Standards and Testing Procedures	
Task 2.2.10: Establish and test methodologies for enabling optimal dispatch of energy storage to serve multiple grid services [FY16-19]	[high overlap with ESGC] [link to OE ROVI]
Improved Standards and Testing Procedures for Emerging Technologies to Improve Customer Reliability	
Task 2.2.13: Demonstrate enhanced customer reliability through use of energy storage in conjunction with coordinated grid and customer dispatch. Establish and validate reliability of energy storage systems. [FY16-20]	[high overlap with ESGC] [link to OE ROVI, OCED/OE LDES Demos]
Device Modeling and Simulation Library	
Task 2.3.6: Develop models for generation, transmission, distribution, storage, and loads and populate library based on testing results. [FY17-FY20]	[moderate overlap with ESGC]
Reduces Outages	
Task 2.4.10: Evaluate current microgrids'[27] ability to reduce customer outages and integrate clean energy resources with and without energy storage. Provide feedback to Initiative activities to improve device development (Activity 1) and testing procedures (Activity 2). [FY16-17]	[low/moderate overlap with ESGC]
Energy Storage Field Demonstration	
Task 2.4.14: Facilitate the establishment of field demonstrations of a suite of grid energy storage technologies being applied to multiple use cases. [FY16-19]	[high overlap with ESGC] [link to OCED/OE LDES Demos]
Task 2.4.15: Collaboratively monitor the application of grid energy storage for multiple use cases both for functionality and performance, but also for reliability and economic optimization under regional pricing considerations. [FY16-20]	[high overlap with ESGC] [link to OCED/OE LDES Demos, OE ROVI]
Task 2.4.16: Develop optimization and control algorithms for energy storage operation that maximize the grid benefit, especially for the case of providing multiple simultaneous grid services. Utilize the field demonstration projects to illustrate the improvement in performance with these algorithms. [FY16-20]	[high overlap with ESGC]

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[27] See [92].

F.1.2 Sensing and Measurements

Measuring and monitoring vital parameters throughout the electric power network is necessary to assess the health of the grid in real time, predict its behavior, and respond to events effectively. Lack of visibility and accurate device- or facility-level information makes it difficult to operate the electricity system efficiently and has contributed to large-scale power disruptions and outages. Additionally, next- generation sensors will allow energy management systems to integrate buildings, EVs, and distributed systems. This technical area focuses on tools and strategies to determine the type, number, and placement of sensors to improve system visibility from individual devices to feeders, distribution systems, and regional transmission networks.

Appendix Table 7. Energy storage-related activities and technical achievements for Sensing and Measurements, 2015 MYPP.

Activity/Technical Achievements by 2020, assuming adequate funding levels[28]	Alignment with Energy Storage Strategy and Roadmap
2. Enhance Sensing for Distribution System • Development of low cost, multi-purpose sensors (under $100 per sensor or two-year payback) and ability to effectively deploy these technologies to operate in normal and off-normal operations. • Development of “visibility strategy” using visualization techniques and tools to define sensor type, number, location, and data management. Optimize sensor allocation for a given feeder.	[low overlap with ESGC]
3. Enhance Sensing for the Transmission System • Development of advanced synchrophasor technology that is reliable during transient events as well as steady state measurement and can be upgraded remotely if sensor function needs to be modified. • Development of low cost, multi-purpose sensors for electric grid components to monitor realtime health status, stress accumulation leading to component Loss of Life, and real time loading that takes local environmental conditions into account.	[low overlap with ESGC]
4. Develop Data Analytic and Visualization Techniques • Real-time data management for the ultra-high velocities and volumes of grid data from T&D systems and the ability to identify and compensate for inaccuracies and errors. • Establish the appropriate visibility of generation, loads, and system parameters across the electric infrastructure through the development of visualization techniques and software tools incorporating measures for secure access and privacy/confidentially. • Development of measurement and modeling techniques for estimating and forecasting renewable generation both for centralized and distributed generation for optimizing buildings, transmission, storage, and distribution systems.	[low/moderate overlap with ESGC]
6. Regional & Cross-cut Initiatives • Provide real-time information of solar and wind generation and building loads at high spatial and temporal resolution. • Provide forecasts from minutes to days ahead of solar and wind generation and loads. • Incorporate environmental sensors that identify and predict weather-related effects (e.g., ice buildup on power lines, thermal imbalance, and increased stresses from high velocity winds), thereby mitigating impacts on	[low/moderate overlap with ESGC]

[28] This information is captured from Table 1. Activities and technical achievements for devices and integrated system testing of the 2015 MYPP [36].

the infrastructure or preventing widespread disturbances.	

Appendix Table 8. Sensing and Measurements tasks identified in the 2015 MYPP.

2015 MYPP Tasks[29]	Alignment with Energy Storage Strategy and Roadmap
New Sensing Capabilities	
Task 3.2.4: Develop and demonstrate new, low-cost sensors for distribution-level electrical state and asset condition monitoring for new assets such as storage and power electronics based devices including parameters such as temperature, chemistry, and pressure, as well as very high frequency power quality effects. [FY16-20].	[high overlap with ESGC] [suggested activities: OE ROVI]
Asset Monitoring Tools	
Task 3.3.3: Develop novel inexpensive sensors for component health monitoring and low-cost grid state monitors. This will include sensing and measurement of advanced components such as energy storage devices and power electronics. As advanced manufacturing techniques and diagnostic and prognostic tools are developed, an integrated sensor with multi-parameter sensing, onboard diagnostic, and prognostic as well as built-in communication elements will become possible. [FY16-18]	[moderate overlap with ESGC]
Environmental Forecasting	
Task 3.6.9: Improve and optimize current forecasting methods at test sites and incorporate into existing system operations with a focus on probabilistic forecasts. Integrate the forecasts for grid integration studies to improve demand response, ancillary services from distributed resources, energy storage operations, dispatch, reserve margin requirements and unit commitment. [FY17-FY18]	[moderate overlap with ESGC] [suggested activities: any of the storage valuation and operational models inventoried on the model selection platform]

F.1.3 System Operations, Power Flow, and Control

The existing grid control systems were developed over several decades using a set of 20th century design characteristics: centralized dispatchable generation connected to transmission, relatively slow system dynamics that permitted manual control, no significant grid energy storage, passive loads, one-way flow of real power at the distribution level, operation for reliability, and generation-following load for balancing. Several of these design parameters have become outmoded by new technologies, changing economics, and shifting customer expectations. This technical area focuses on new control technologies to support new generation, load, and storage technologies.

[29] Task numbers adhere to their enumeration in the MYPP, where the second digit corresponds to the activity number in Appendix Table 5.

Appendix Table 9. Energy storage-related activities and technical achievements for System Operations, Power Flow, and Control, 2015 MYPP.

Activity/Technical Achievements by 2020, assuming adequate funding levels[30]	Alignment with Energy Storage Strategy and Roadmap
4. Develop Enhanced Power Flow Control Device Hardware • Low-cost, efficient and reliable power flow control devices that enable improved controllability and flexibility of the grid.	[low overlap with ESGC]

Appendix Table 10. System Operations, Power Flow, and Control tasks identified in the 2015 MYPP.

2015 MYPP Tasks[31]	Alignment with Energy Storage Strategy and Roadmap
Low-Cost Power Flow Control Technologies	
Task 4.4.4: Enhance capabilities of inverter-coupled technologies (wind, solar, energy storage) through the development of control strategies for coordinated control of distributed resources to accomplish global system objectives such as power flow control and provision of ancillary services to the grid. [FY17-19]	[high overlap with ESGC] [suggested activities: OE, SETO inverter work]

F.1.4 Design and Planning Tools

Sound long-term planning and design yields smart capital investment. Electric power grid modeling and simulation applications are fundamental to the successful design, planning, and secure operation of power systems with billions of dollars in capital investments and operations costs. However, existing planning and modeling tools have not kept pace with the complex technology, policy, economics, and outcomes demanded for the electric grid. This technical area develops the next generation of modeling and simulation tools needed for power system planning.

Appendix Table 11. Energy storage-related activities and technical achievements for Design and Planning Tools, 2015 MYPP.

Activity/Technical Achievements by 2020, assuming adequate funding levels[32]	Alignment with Energy Storage Strategy and Roadmap
1. Scaling Tools for Comprehensive Economic Assessment • Enhance performance of stochastic production cost modeling from 100 to 10,000 transmission nodes; expand to include distribution system. • Easy-to-use decision support tools based upon complex high-performance computing (HPC) results that incorporate new technologies such as demand response and energy storage and enable cost-benefit analysis for policy and regulatory analysis. • Improve scaling of stochastic tools to model electric and gas system inter-dependencies from 1,000 to 60,000 electric and 100 to 1,000 gas nodes.	[moderate overlap with ESGC]
2. Developing and Adapting Tools for Improving Reliability and Resilience	[moderate overlap with ESGC] [link to ESGC UC4]

[30] This information is captured from Table 1. Activities and technical achievements for devices and integrated system testing of the 2015 MYPP [36].

[31] Task numbers adhere to their enumeration in the MYPP, where the second digit corresponds to the activity number in Appendix Table 5.

[32] This information is captured from Table 1. Activities and technical achievements for devices and integrated system testing of the 2015 MYPP [36].

• Scalable simulation framework that couples transmission, distribution, and communications systems for integrated modeling at regional scale. • Data-driven tools to automate construction and validation of models of devices, loads, generation, and customer behavior. • Improve performance of contingency analysis tools by 500x to capture extreme events; enable automated analysis of cascading events.	

Appendix Table 12. Design and Planning Tools tasks identified in the 2015 MYPP.

2015 MYPP Tasks[33]	Alignment with Energy Storage Strategy and Roadmap
Scalable transmission and distribution planning with uncertainty	
Task 5.1.2: Develop methods for integrating distribution into system-wide planning, including data management, integration of balanced and unbalanced power-flow, retail market models, models of load, validation methodologies and distributed energy resources—including distributed generation, demand response, electric vehicles, and energy storage. [FY16-19]	[moderate overlap with ESGC] [link to UC5]
Model development and valuation	
Task 5.1.5: Develop valuation methods and mathematical models for new energy technologies such as energy storage, customer behaviors and communications. [FY17-18]	[high overlap with ESGC] [link to all policy and valuation track work]
Dynamic Modeling of Integrated Transmission, Distribution, and Communications	
Task 5.2.2: Scale modeling framework to the regional level. Develop associated models for load, distributed generation, energy storage, and controls to enable the design and evaluation of future Energy Management System/Distribution Management System/Building Management System (EMS/DMS/BMS) architectures and novel wide-area sensor-control networks. [FY18-20]	[moderate overlap with ESGC] [link to UC5]

F.1.5 Security and Resilience

There are ever increasing natural and man-made threats to the electric grid, including high-impact and low-frequency events, severe storms, fuel delivery failures, and more frequent physical and cyber threats. This technical area aims to meet physical and cybersecurity challenges, analyze asset criticality, assess ways to minimize risk, address supply chain risks (specifically for transformers), and provide situational awareness and incident support during energy-related emergencies.

Appendix Table 13. Energy storage-related activities and technical achievements for Security and Resilience, 2015 MYPP.

Activity/Technical Achievements by 2020, assuming adequate funding levels[34]	Alignment with Energy Storage Strategy and Roadmap
2. Increase Ability to Protect Against Threats and Hazards	[high overlap with ESGC] [link to UC1/4]

[33] Task numbers adhere to their enumeration in the MYPP, where the second digit corresponds to the activity number in Appendix Table 5.

[34] This information is captured from Table 1. Activities and technical achievements for devices and integrated system testing of the 2015 MYPP [36].

• Standards, methods, testing and evaluation procedures for physical and cybersecurity enabled designs. • Development, demonstration, and field validation of novel energy device (e.g., energy storage), communications, and control system models and logistical optimization techniques. • Grid components which are inherently protective of grid services to all-hazards (e.g., energy storage).	[link to recent LDES demos, especially the multi-location projects]
4. Improve Ability to Respond to Incidents • Methodologies and architecture frameworks that assess system degradation to all hazards, provide diverse attack recognition, and mixed-initiative response on multiple timescales, and optimize operational efficiencies/priorities to reduce incident response time for the power grid.	[high overlap with ESGC] [link to UC4]
5. Improve Recovery Capacity/Time • Advanced substation, transformer and support technology (e.g., energy storage) designs and standards that facilitate improved portability and rapid substation recovery from storms and natural disasters. • Hardened fail-safe and wireless communications capabilities and devices for grid control systems that resist impacts from cyber, geomagnetic disturbance, and electromagnetic pulse events.	[high overlap with ESGC] [link to UC1/4]

Appendix Table 14. Security and Resilience tasks identified in the 2015 MYPP.

2015 MYPP Tasks[35]	Alignment with Energy Storage Strategy and Roadmap
Develop resilient architectures	
Task 6.4.4: Formulate an adaptive and agile OT framework and demonstrate/vet/deploy prototypes, that optimize stability and efficiencies of operation while accommodating high penetration of distributed, renewables generation, smart loads and energy storage [FY16-20]	[moderate overlap with ESGC] [link to UC1/4]

F.1.6 Institutional Support

Technical assistance to key decision-makers is important so that they can address the high-priority grid modernization challenges and needs identified by electric power industry stakeholders. It gives particular emphasis to working with state policymakers and regional planning organizations, with support for both analysis of issues and creation of information for stakeholders. Analytic, non-prescriptive workshops and facilitator-led dialogues among stakeholders can build agreement around the value of transforming the grid and the best ways to do that using technology, regulatory, and market tools that meets the unique needs of every region. In addition to technical assistance, this technical area will develop new analytic frameworks for key grid modernization issues.

Appendix Table 15. Energy storage-related activities and technical achievements for Institutional Support, 2015 MYPP.

Activity/Technical Achievements by 2020, assuming adequate funding levels[36]	Alignment with Energy Storage Strategy and Roadmap

[35] Task numbers adhere to their enumeration in the MYPP, where the second digit corresponds to the activity number in Appendix Table 5.

[36] This information is captured from Table 1. Activities and technical achievements for devices and integrated system testing of the 2015 MYPP [36].

1. Provide Technical Assistance to States and Tribal Governments • Technical assistance to all states and tribes to inform their electricity policy decision making and that accelerate policy innovation in at least 7 states (e.g., DR programs and resources in a post-FERC order 745 world, innovative strategies to acquire all cost-effective efficiency, policy, regulations and market designs that facilitate deployment of energy storage technologies). • Technical analysis results to at least 10 states that allows them to establish formal processes to review utility distribution system plans, including guidance on how to consider Non-Wires Alternatives (NWAs),[37] distributed energy resources, and advanced grid components and systems. • At least 10 other states have developed comprehensive energy system plans.	[high overlap with ESGC] [link to UC1/4/5] [link to supercharged initiative, ES4SE]
2. Support Regional Planning and Reliability Organizations • Regional planning & reliability organizations develop institutional frameworks, standards, and protocols for integrating new grid-related technologies, supported by DOE funding. • Facilitated long-term regional planning in each U.S. interconnection (e.g., conduct studies of potential clean energy zones in Eastern Interconnection; analyze impacts of market design changes in a region, such as Energy Imbalance Market in the West). • Coordinated regional long-term planning process in states that uses standardized, publicly available databases of transmission and regional resource data and planning assumptions.	[moderate overlap with ESGC] [link to UC5]
3. Develop Methods and Resources for Assessing Grid Modernization: Emerging Technologies, Valuation, and Markets • New methods for valuation of DER technologies (including energy storage) and services that are defined and clearly understood by stakeholders and enable informed decisions on grid investments and operations. • Analysis tools and methods that facilitate states' and tribes' integration of emerging grid technologies into decision-making, planning, and technology deployment. • New Grid Modernization performance and impact metrics and data collection methods, which are used by states and tribes to track Grid Modernization progress.	[high overlap with ESGC] [link to UC5, valuation work]

Appendix Table 16. Institutional Support tasks identified in the 2015 MYPP.

2015 MYPP Tasks[38]	Alignment with Energy Storage Strategy and Roadmap
State Institutional Support for Reliability and Assurance Planning	

[37] Non-Wires Alternatives (NWAs) can be defined as any action or strategy that could help defer or eliminate the need to construct or upgrade a transmission system and/or distribution system sub-stations and include, but are not limited to, demand response, dynamic retail pricing, distributed generation, energy efficiency, alternative power dispatch options, and application of technologies to expand the capacity of the system. [93]

[38] Task numbers adhere to their enumeration in the MYPP, where the second digit corresponds to the activity number in Appendix Table 5.

2015 MYPP Tasks[38]	Alignment with Energy Storage Strategy and Roadmap
Task 7.1.2: Administer and implement a new program that will provide grants to states, localities, and tribal entities for electricity transmission, storage, and distribution reliability and resilience plans. [FY16-FY18]	[high overlap with ESGC] [link to supercharged, GDO GRIP, ES4SE]
Expanded Technical Assistance	
Task 7.1.3: Provide technical support to at least ten states to allow them to establish formal processes to review utility distribution system plans, including guidance on how to consider non-wires alternatives, distributed energy resources (including energy storage), and advanced grid components and systems. [FY16-FY20]	[moderate overlap with ESGC] [link to UC5, OE storage state TA]
Assist regional planning and reliability organizations in developing institutional frameworks, standards and protocols for integrating emerging technologies as well as for the physical and cybersecurity of the grid	
Task 7.2.5: Provide technical support for developing design requirements for enhancing existing tools or for developing new analytical tools to model and simulate integrating emerging smart grid and DER technologies (including energy storage) in the grid at the interconnection level. [FY17-FY19]	[moderate overlap with ESGC] [link to OE state TA]
Valuation of DER	
Task 7.3.1: Develop an analytical framework and tools for valuing potential benefits, costs, and impacts of distributed energy resources on grid functions and services that are well-defined and clearly understood by stakeholders to enable informed decisions on grid investments and operations. [FY16-FY18]	[high overlap with ESGC] [link to UC5, valuation work]
Task 7.3.2: Develop and implement informational activity targeted at regulators, policy makers, consumers and utilities on valuation of DER technologies: annual workshops, periodic reports, and ongoing TA. [FY17-FY20]	[moderate overlap with ESGC] [link to OE state TA]
Mitigate market barriers	
Task 7.3.3: Perform two to three focused analyses per year of emerging technologies to characterize the barriers posed by existing market structures and identify options to reduce market entry impediments. [FY16-FY20]	[moderate overlap with ESGC]

F.2 2020 Updated Strategy

The GMI released a revised strategy in 2020 [37]. The GMI Updated Strategy 2020 focuses on program strategy and vision. The updated MYPP explains the current set of goals and expected technical achievements while providing examples of projects that will help achieve those goals. It also provides an organizing framework so that projects and partnerships, in the future as new needs and goals evolve, are aligned and focused toward the GMI vision of a modernized grid. The structure of the document follows eight specific technical areas: (1) Generation; (2) Devices and Integrated Systems; (3) Systems Operations, Power Flow, and Control; (4) Sensing and Measurement; (5) Planning and Design Tools; (6) Resilience; (7) Security; and (8) Institutional Support. Energy storage is recognized in seven areas; highlights are provided below (adapted from [37]), including projects from the Grid Modernization Laboratory Consortium (GMLC).

1 Appendix Table 17. GMI Updated Strategy 2020 energy storage highlights.

Technical Area	Energy Storage Highlights
Generation	
Challenges	Multilevel Interdependencies: higher reliance on information technology systems for operating the generation power fleet, growing complexity of planning for new generation assets to mee new load from EVs, and power-to-gas technologies that require large amounts of power and storage to be strategically located.
Ongoing/Proposed Future Activities	Investigate the deployment and operation of hybrid generation portfolios that include all power generation technologies, including advanced thermal technologies, advanced large-scale and distributed renewable technologies, storage technologies, especially integrated with generating assets and applications of combined heat and power. Asses the cost and value of various generation mixes and supply-side technology innovations that consider state laws and how they impact regional reliability and national-level grid operations. Study strategic allocation of advanced power plants and cost-effective deployment of storage capacity that enhances cleaner delivered electricity.
GMLC Projects	▪ Clusters of Flexible Photovoltaic (PV)-Wind-Storage Hybrid Generation (2019 GMLC Project 6.1.1) ▪ Design and Optimization Infrastructure for Tightly Coupled Hybrid Systems (2019 GMLC Project 6.1.2)
Devices and Integrated Systems	
Challenges	Some device technologies (including distributed generation, storage, power electric interfaces, and grid-interactive efficient building loads or demand flexibility) are not yet capable of securely communicating, coordinating, and transacting with the electrical grid to provide a wide range of grid services (e.g., energy, capacity, voltage and frequency regulation, inertial response, and black start) that benefit both the device owner and the grid.
Ongoing/Proposed Future Activities	Integrate Advanced Storage Systems, Power Electronics Interfaces, Controllable Loads, and other Grid Devices: ▪ Increase the value of deployed grid-scale energy storage systems by improving performance, lowering costs, and enabling new capability. An energy storage system consists of the energy storage technology and balance of plant. ▪ Develop power electronics-based interfaces for a variety of generation (e.g., turbines, engines, fuel cells, renewable, distributed energy), energy storage (battery, thermal, hydrogen, and others), and loads (EVs, electrolyzers, and building loads) that can provide grid services and self-optimize around market and energy environment. Harmonize Standards and Grid Codes for Providing Interoperability, Interconnection, and Grid Services: ▪ Update standards and grid codes that characterize the ability of device technologies (generation, storage, and loads) to provide a full range of grid services and accelerate the uptake of these technologies in the market and integrated into distribution systems. ▪ Develop standards and test procedures for microgrids, storage, and other energy management systems that reduce customer outages and improve resilience. Conduct Validation of Individual Devices and Integrated Systems at Multiple Scales: ▪ Characterize the ability of individual device technologies (distributed generation, storage, loads) to provide a range of grid services at the distribution system. ▪ Validate multiscale (microgrids and distribution systems), integrated energy systems that improve grid reliability, resilience, and affordability through integrated sensing and advanced control constructs that coordinate generation, storage, and controllable loads.
GMLC Projects	▪ Energy Storage Demonstrations (2019 GMLC Project GM0008)
System Operations, Power Flow, and Control	
Challenges	The system is becoming more complex with the integration of a range of new generation technologies, new and more flexible transmission and distribution equipment, and a myriad of new opportunities to manage demand. Under this new paradigm, potentially millions of intelligent devices will need to be coordinated with legacy control systems to support the power system across the electricity supply, delivery, and end-use ecosystem.
Ongoing/Proposed Future Activities	Coordinated System Controls: ▪ These systems must provide interoperability and autonomous coordination between bulk generation (including fuel delivery infrastructure and/or carbon capture controls as

	applicable), transmission, distribution, and DERs including generation, storage, and demand response. Enabling Flexible Generation: ▪ Develop and deploy control schemes to enable the portfolio of generators (and hybrid generation schemes) to operate in a comprehensive manner enabling overall system objectives associated with resilience and flexible operations while maximizing efficiency and maintaining security for bulk generation, autonomous individual generating facilities, storage, and DER assets (coordinate with the generation and the device and integrated systems technical areas).
GMLC Projects	▪ Vermont Regional Partnership Enabling the use of DER (2019 GMLC Project 1.3.10) ▪ Resilient Alaskan Distribution System Improvements Using Automation, Network Analysis, Control, and Energy Storage (RADIANCE) (2019 GMLC Project 1.5.02) ▪ Virtual Battery-based Characterization and Control of Flexible Building Loads using VOLTTRON (2019 GMLC Project GM0061 ▪ Validation, Restoration, and Black Start Testing of Sensing, Controls, and DER Technologies at Plum Island (2020 GMLC Project 2.3.1)
Sensing and Measurement	
Challenges	<u>Communication constraints and data framework:</u> Data transfer characteristics and data storage must match current and anticipated application requirements to enable both analytics and power grid operation in centralized, distributed, and fragmented modes. To reduce data transfer exchanges, analyses can be executed locally to quantify measurement uncertainty during transient and abnormal conditions. Distributed sensing and data architectures that support application decoupling can help improve system resiliency.
Ongoing/Proposed Future Activities	Working with the generation technical area team, develop planning tools to understand the system benefits and impacts of new hybrid generation concepts (e.g., coordinated nuclear and megawatt-scale storage), improve the accuracy of generation models, and assess the value of generation fleet flexibility to affordability, resilience, etc..
GMLC Projects	(no storage-specific projects listed)
Resilience	
Challenges	As the engine of our industrial and economic growth, the electric grid has grown and evolved over the past century with emphasis on providing reliable power at all times and has become a critical element of our national security and defense infrastructure. Today, the grid faces ever-increasing and complex threats, including intensifying cyber and physical attacks, severe weather, wildfires, and fuel delivery failures. Coupled with factors such as managing some legacy infrastructure while increasing reliance on digital and communications technologies, these threats can cause devastating large-area, long-duration outages. Our standard measures of reliability and today's accepted planning and operational practices do not sufficiently address these threats. The technological transformation of the grid, including renewables, DERs, and smart grid, presents both new vulnerabilities as well as opportunities for resilience.
Ongoing/Proposed Future Activities	Multiscale, self-healing grid control methodologies and processes that implement graceful degradation over wide areas. Advancements to improve resilience to disruptive events including coordination of grid components that add protective grid services to all hazards (e.g., component hardening, parts inventory, energy storage, and adaptable transmission and distribution architectures), fuel switching capabilities, and emergency preparedness measures.
GMLC Projects	(no storage-specific projects listed)
Security	
Challenges	Understanding and securing the physical-cyber nexus where digitally initiated attacks result in physical consequences in the power grid. One area of interest is evolution of the grid attack surface due to infrastructure interdependencies and the addition of new technologies at the grid edge, including DERs, energy storage, small modular reactors, EVs, and other technologies.
Ongoing/Proposed Future Activities	(no storage-specific activities listed)
GMLC Projects	(no storage-specific projects listed)
Institutional Support	
Challenges	Rapid changes in the power system including the growth in potentially disruptive technologies (e.g., distributed generation, storage, smart grid, grid-interactive efficient buildings, small modular generation units under development, offshore wind) in conjunction with slowing growth in energy demand, aging infrastructure, customer desires for more choice and innovative services, and increasing cyber and physical threats highlight issues

	regarding the roles and functions of electric utilities and other service providers. In some cases, utility integrated resource planning processes are challenged in their attempts to incorporate new, emerging technologies (e.g., carbon capture, utilization, and storage; small modular nuclear reactors).
Ongoing/Proposed Future Activities	Energy Storage and Flexible Generation and Demand: ▪ Valuation of grid services provision, non-monetized benefits, and compensation mechanisms for emerging technology solutions (e.g., including energy storage, flexible generation, buildings that provide demand flexibility, and hybrid energy systems) for specific use cases; systems and electricity market designs inform planning and operations in leading jurisdictions. ▪ Analytical approaches to characterize the current and potential future cost and performance characteristics of storage and other flexible generation and demand technologies are established and implemented.
GMLC Projects	(no storage-specific projects listed)

Appendix G. Policy and Regulatory Landscape for Energy Storage

This appendix describes the landscape for energy storage and identifies representative policies, goals, regulations, and incentives that are relevant to this Energy Storage SRM since the ESGC 2020 Roadmap was released. This Appendix does not provide an exhaustive list, but it illustrates the breadth of actions that are considered in the Department of Energy's (DOE) strategic direction and execution of energy storage activities. The annual federal appropriations process is not specifically addressed in the below subsections, but it is a key consideration for DOE's energy storage activities.

G.1 Administration Goals and Policies

G.1.1 Clean Electricity

Recognizing the key role of the power sector in overall decarbonization and other key benefits, the U.S. has set a goal of 100% carbon pollution-free electricity by 2035 [38] [39] [40]. Additionally, the U.S. has set an economy-wide target of reducing U.S. net greenhouse gas emissions by 50-52 percent below 2005 levels in 2030 [39]. Investing in clean electricity[39] propels us into a safer future that supports our health, our economy, and our climate. In May 2023, DOE published the "On the Path to 100% Clean Electricity" report that outlines the key actions that the U.S. can take to accelerate the safe and rapid expansion of clean electricity throughout the economy [41]. The ten actions outlined in this report provide a framework to support coordination of activities that can unlock the benefits of 100% clean electricity while maintaining or enhancing reliability and affordability. See Section G.1.3.1 for more context.

Ref. https://www.energy.gov/policy/articles/path-100-clean-electricity#:~:text=%E2%80%9COn%20the%20Path%20to%20100,clean%20electricity%20throughout%20the%20economy.

G.1.2 Clean Vehicles

Executive Order 14037, issued on August 5, 2021, directed federal agencies to set clear standards, expand key infrastructure, spur critical innovation, and invest in the American autoworker to lead the world on clean and efficient cars and trucks. The EO also established that 50 percent of all new passenger cars and light trucks sold in 2030 be zero-emission vehicles, including battery electric, plug-in hybrid electric, or fuel cell electric vehicles to bolster the domestic market.

Ref. https://www.federal register.gov/documents/2021/08/10/2021-17121/strengthening-american-leadership-in-clean-cars-and-trucks

G.1.3 Climate Action

On April 20, 2023, President Biden convened leaders of the Major Economies Forum on Energy and Climate (MEF) to galvanize efforts needed to tackle the climate crisis and keep a 1.5°C limit on warming within reach, with a focus on four specific areas:

- **Decarbonizing energy:** Announcing steps to drive down emissions in the power and transportation sectors, including scaling up of clean energy, setting ambitious 2030 zero-emission vehicle goals, and decarbonizing international shipping.

[39] In this report, "clean electricity", "clean generation," "clean power," and "clean energy" include wind, solar, geothermal, hydropower, nuclear, biomass with and without carbon capture and sequestration, and fossil energy with carbon capture and sequestration. [41]

- **Ending deforestation of the Amazon and other critical forests:** Working through the Forest and Climate Leaders' Partnership to mobilize public, private, and philanthropic support.
- **Tackling potent, non-CO_2 climate pollutants:** Launching a Methane Finance Sprint to cut methane emissions and accelerating hydrofluorocarbon (HFC) phasedown under the Kigali Amendment.
- **Advancing carbon management:** Partnering with countries to accelerate carbon capture, removal, use, and storage technologies through the COP28 United Nations Climate Change Conference Carbon Management Challenge to deal with emissions that can't otherwise be avoided.

Targeted goals were established for key energy-related sectors, such as electric power and transportation. The following subsections highlight those goals that are relevant to this Energy Storage Strategy and Roadmap.

Refs. https://www.whitehouse.gov/briefing-room/statements-releases/2023/04/21/chairs-summary-of-the-major-economies-forum-on-energy-and-climate-held-by-president-joe-biden-2/; https://www.whitehouse.gov/briefing-room/statements-releases/2023/04/20/fact-sheet-president-biden-to-catalyze-global-climate-action-through-the-major-economies-forum-on-energy-and-climate/#:~:text=Putting%20the%20Power%20Sector%20on%20a%20Path%20to%20Net%20Zero%20Emissions&text=President%20Biden%20has%20set%20an,by%20no%20later%20than%202050

G.1.3.1 Putting the Power Sector on a Path to Net Zero Emissions

President Biden set an ambitious U.S. goal of achieving a carbon pollution-free power sector by 2035 and net zero emissions economy by no later than 2050. The U.S. released a new National Innovation Pathway Report [42], highlighting the Administration's strategy for accelerating key clean energy technology innovations. The Administration is advancing a three-pronged approach that prioritizes innovation, demonstration, and deployment to scale the technologies the U.S. needs to achieve its goals of a carbon pollution-free electricity sector by no later than 2035 and a net-zero emissions economy by no later than 2050.

G.1.3.2 Reducing Emissions and Fossil Fuel Use by Accelerating Zero-Emission Vehicle Deployment

President Biden invited world leaders to join the U.S. in a collective goal aiming to ensure that by 2030 over 50 percent of light-duty vehicles (LDVs) and at least 30 percent of medium- and heavy-duty vehicles (MHDVs) sold globally will be zero-emissions vehicles (e.g., battery electric, fuel cell electric, and plug-in hybrid vehicles).

G.1.4 Environmental Justice

G.1.4.1 Justice40 Initiative

In Executive Order 14008, the President directed the Director of the Office of Management and Budget (OMB), the Chair of the Council on Environmental Quality (CEQ), and the National Climate Advisor, in consultation with the White House Environmental Justice Advisory Council (WHEJAC), to jointly publish guidance on how certain federal investments might be made toward a goal that 40 percent of the overall benefits of such investments flow to disadvantaged communities – the Justice40 Initiative. The Justice40 Initiative is a critical part of the Administration's whole-of-government approach to advancing environmental justice.

Refs. Tackling the Climate Crisis at Home and Abroad, 86 Fed. Reg., 7619 (February 1, 2021); https://www.whitehouse.gov/wp-content/uploads/2021/07/M-21-28.pdf; Advancing Racial Equity and Support for Underserved Communities Through the Federal Government, 86 Fed. Reg., 7009 (January 25, 2021).

G.2 Congressional Actions

Since 2020, Congress has enacted several laws that have helped shape the landscape for DOE's energy storage activities.

G.2.1 Infrastructure Investment and Jobs Act (2021)

The Bipartisan Infrastructure Deal is a long-overdue investment in our nation's infrastructure, workers, families, and competitiveness. The Bipartisan Infrastructure Investment and Jobs Act will create good jobs for workers across the country, including workers in rural areas, hard-hit energy workers, historically disadvantaged workers, and workers in distressed areas. This historic investment will accelerate the economic recovery, put Americans back to work, and boost wages for workers across the country.

The infrastructure deal includes more than $62 billion for DOE to deliver a more equitable clean energy future for the American people by doing the following:

- Investing in American manufacturing and workers.
- Expanding access to energy efficiency and clean energy for families, communities and businesses.
- Delivering reliable, clean, and affordable power to more Americans.
- Building the technologies of tomorrow through clean energy demonstrations.

Refs. Pub. L. No. 117-58, Div. J., Tit. III, 135 Stat. 429, 1376-77 (2021). These energy storage demonstration projects were initially authorized under the Energy Act of 2020, Pub. L. No. 116-260, Div. Z, § 3201, 134 Stat. 2418, 2517-25. FACT SHEET: The Bipartisan Infrastructure Investment and Jobs Act Creates Good-Paying Jobs and Supports Workers | The White House (https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/03/fact-sheet-the-bipartisan-infrastructure-investment-and-jobs-act-creates-good-paying-jobs-and-supports-workers/); DOE Fact Sheet: The Bipartisan Infrastructure Deal Will Deliver For American Workers, Families and Usher in the Clean Energy Future | Department of Energy (https://www.energy.gov/articles/doe-fact-sheet-bipartisan-infrastructure-deal-will-deliver-american-workers-families-and-0); Bipartisan Infrastructure Law Frequently Asked Questions | Department of Energy (https://www.energy.gov/infrastructure/articles/bipartisan-infrastructure-law-frequently-asked-questions); Bipartisan Infrastructure Law | Department of Energy (https://www.energy.gov/gdo/bipartisan-infrastructure-law); Investing in American Energy: Significant Impacts of the Inflation Reduction Act and Bipartisan Infrastructure Law on the U.S. Energy Economy and Emissions Reductions | Department of Energy (https://www.energy.gov/policy/articles/investing-american-energy-significant-impacts-inflation-reduction-act-and)

G.2.2 Inflation Reduction Act (2022)

The Inflation Reduction Act of 2022 (IRA) marks the largest investment in clean energy in our nation's history. Along with its signature companion laws the CHIPS and Science Act and the Bipartisan Infrastructure Law of 2022, the United States is well positioned to reshape its economy for the future and rewire the energy sector that powers it to position the United States to lead the global clean energy market.

The Inflation Reduction Act is aimed squarely at building a better America and delivering on President Biden’s vision to make sure the United States—powered by American workers— remains the global leader in clean energy technology, manufacturing, and innovation. The Inflation Reduction Act’s $370 billion in investments will lower energy costs for families and small businesses, accelerate private investment in clean energy solutions in every sector of the economy and every corner of the country, strengthen supply chains for everything from critical minerals to efficient electric appliances, and create good-paying jobs and new economic opportunities for workers.

By 2030, the IRA will:

- double the clean energy workforce to employ nearly 1 million Americans
- provide enough clean energy to power every American home
- GHG emissions will be 40% lower than 2005 levels
- save the average American taxpayer $1,000 a year in energy costs
- deliver a range of tax incentives and rebates that provide direct, material benefits to ordinary Americans.

The IRA includes some two dozen tax provisions that will save families money on their energy bills and accelerate the deployment of clean energy, clean vehicles, clean buildings, and clean manufacturing. For example, the IRA provides a 30% tax credit for families investing in clean energy systems like solar electricity, solar water heating, wind, geothermal heat pumps, fuel cells, and battery storage for their homes. [43]

The IRA also provides billions of dollars in grant and loan programs and other investments for clean energy and climate action. The law advances President Biden's Justice40 Initiative, which commits to delivering 40 percent of the overall benefits of climate, clean energy, infrastructure, and other investments to disadvantaged communities, including Tribes, communities with environmental justice concerns, rural areas, and energy communities.

With the passage of the Inflation Reduction Act—in combination with the Bipartisan Infrastructure Law and other actions—the Department of Energy (DOE) estimates that the United States will achieve a 40 percent reduction in economywide greenhouse gas emissions below 2005 levels by 2030, positioning the United States to realize the President's goal with additional executive branch, state, local, and private sector action. DOE estimates that the clean energy provisions of the Inflation Reduction Act and the Bipartisan Infrastructure Law together could reduce emissions by more than 1,000 million metric tons of CO2e in 2030, equivalent to the combined annual emissions released from every home in the United States. [44] [45]

In 2022 (updated in 2023), the White House released a guidebook to help navigate the opportunities available under the IRA. Relevant agency opportunities across the Federal Government are highlighted; readers are directed to cleanenergy.gov for up-to-date information. [45] For energy storage, relevant opportunities include Department of Treasury's tax credits and DOE's Loan Programs Office activities.

Refs. Inflation Reduction Act of 2022 - What it Means for You | Department of Energy (https://www.energy.gov/energysaver/articles/inflation-reduction-act-2022-what-it-means-you); Investing in American Energy: Significant Impacts of the Inflation Reduction Act and Bipartisan Infrastructure Law on the U.S. Energy Economy and Emissions Reductions | Department of Energy (https://www.energy.gov/policy/articles/investing-american-energy-significant-impacts-inflation-reduction-act-and); https://www.whitehouse.gov/wp-content/uploads/2022/12/Inflation-Reduction-Act-Guidebook.pdf

G.3 Regulatory Considerations

G.3.1 Federal Energy Regulatory Commission (FERC) Actions

There have been several recent FERC actions relevant to energy storage. The table below summarizes some of these actions, with URLs to learn more about them.

Appendix Table 18. FERC regulatory actions relevant to energy storage (2018+)

FERC Action	Description
Order 841: Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators (Issued 15 Feb 2018) (Upheld by DC Circuit, July 2020)	Amends FERC's regulations to facilitate the participation of electric storage resources in the capacity, energy, and ancillary service markets operated by regional transmission organizations/independent system operators (RTOs/ISOs) (excluding ERCOT). Ref: https://www.ferc.gov/media/order-no-841
Order 841-A (Issued 16 May 2019)	Affirms FERC's determinations in Order No. 841, amending its regulations under the Federal Power Act to remove barriers to the participation of electric storage resources in the capacity, energy, and ancillary service markets operated by Regional Transmission Organizations and Independent System Operators. Ref: https://www.ferc.gov/sites/default/files/2020-06/E-1_15.pdf
Order 901: Reliability Standards to Address Inverter-Based Resources (Issued 19 Oct 2023)	Helps ensure reliability of the grid by accommodating the rapid integration of new power generation technologies, known as inverter-based resources (IBRs), that include solar photovoltaic, wind, fuel cell and battery storage resources and comprise a significant portion of new generating capacity projected to come online over the next decade. Directs the North American Electric Reliability Corporation (NERC) to develop a suite of new or modified reliability standards that

	comprehensively address IBR data sharing, model validation, planning and operational studies, and performance requirements. Ref: https://www.ferc.gov/media/e-1-rm22-12-000
Order 2222: Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators (Issued 17 Sep 2020)	Seeks to facilitate participation and competition in any of the RTO markets as long as qualifications are met. DER aggregations would have the opportunity to earn the same compensation as other types of resources that participate in RTO markets, such as power plants. Ref: https://www.ferc.gov/sites/default/files/2020-09/E-1_0.pdf; *Participation of Distributed Energy Res. Aggregations in Mkts. Operated by Reg'l Transmission Orgs. & Indep. Sys. Operators*, Order No. 2222, 172 FERC ¶ 61,247 (2020), *order on reh'g*, Order No. 2222-A, 174 FERC ¶ 61,197 (2021), *order on reh'g*, Order No. 2222-B, 175 FERC ¶ 61,227 (2021).
Order 2222-A: Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators Order Addressing Arguments Raised on Rehearing, Setting Aside in Part and Clarifying in Part Prior Order (Issued 18 Mar 2021)	In this order, FERC addresses arguments raised on rehearing, sets aside in part, and clarifies in part its final rule amending its regulations to remove barriers to the participation of distributed energy resource aggregations in the capacity, energy, and ancillary service markets operated by Regional Transmission Organizations and Independent System Operators (RTOs/ISOs). Ref: https://www.ferc.gov/media/e-1-rm18-9-002
Order 2222-B: Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators Order Addressing Arguments Raised on Rehearing, Setting Aside in Part and Clarifying in Part Prior Order (Issued 17 Jun 2021)	In this order, FERC addresses arguments raised on rehearing, sets aside in part and clarifies in part Order No. 2222-A. Ref: https://www.ferc.gov/media/e-4-061721
Order 2023: Improvements to Generator Interconnection Procedures and Agreements (Issued 28 Jul 2023)	Adopts reforms to FERC's *pro forma* Large Generator Interconnection Procedures, *pro forma* Small Generator Interconnection Procedures, pro forma Large Generator Interconnection Agreement, and *pro forma* Small Generator Interconnection Agreement to address interconnection queue backlogs, improve certainty, and prevent undue discrimination for new technologies. The reforms are intended to ensure that the generator interconnection process is just, reasonable, and not unduly discriminatory or preferential. Ref: https://www.ferc.gov/media/e-1-order-2023-rm22-14-000
Order 1920: Building for the Future Through Electric Regional Transmission Planning and Cost Allocation (Issued 13 May 2024)	Requires transmission providers to conduct Long-Term Regional Transmission Planning that will ensure the identification, evaluation, and selection, as well as the allocation of the costs, of more efficient or cost-effective regional transmission solutions to address Long-Term Transmission Needs. Directs other reforms to improve coordination of regional transmission planning and generator interconnection processes, require consideration of certain alternative transmission technologies in regional transmission planning processes, and improve transparency of local transmission planning processes and coordination between regional and local transmission planning processes. Ref: https://ferc.gov/media/e1-rm21-17-000

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G.3.2 Regulatory Reviews

G.3.2.1 National Environmental Policy Act

NEPA is the National Environmental Policy Act, which requires federal agencies to assess the environmental impact of all major federal actions significantly affecting the quality of the human environment. The White House Council on Environmental Quality (CEQ) has promulgated NEPA implementing regulations (40 CFR Parts 1500-1508) that are applicable to all agencies. DOE Policy Directive 451.1 (National Environmental Policy Act Compliance Program) establishes Agency roles, responsibilities, and expectations for implementing the procedural provisions of the CEQ regulations and DOE's NEPA implementing regulations (10 CFR Part 1021).

With some limited exceptions, all federal agencies in the executive branch have to comply with NEPA before they make final decisions about federal actions that could have environmental effects. Thus, NEPA applies to a very wide range of federal actions that include, but are not limited to, federal construction projects, plans to manage and develop federally-owned lands, and federal approvals of non-federal activities such as grants, licenses, and permits. Analyses and documentation prepared to comply with NEPA may include a Categorical Exclusion, Environmental Assessment, or an Environmental Impact Statement.

In 2023, DOE proposed changes to its categorical exclusions to add a categorical exclusion for certain energy storage systems, revise categorical exclusions for upgrading and rebuilding transmission lines and for solar photovoltaic systems, and make conforming changes to related sections of DOE's regulations regarding implementation of the National Environmental Policy Act (NEPA). On April 30, 2024, DOE published a notice of final rulemaking reflecting these new categorical exclusions (89 FR 34074).

Ref. DOE NEPA Categorical Exclusion Rulemaking (2024) | Department of Energy
(https://www.energy.gov/nepa/doe-nepa-categorical-exclusion-rulemaking-2024)

G.3.2.2 National Historic Preservation Act

The National Historic Preservation Act requires that DOE assess the effects of proposed actions on historic and archeological resources, and sites of religious and cultural significance to Tribes. DOE must consult with state historic preservation officials and Tribes to determine if an action adversely affects any historic properties.

G.3.2.3 Other environmental federal laws

Other federal laws, regulations and Executive Orders concerning wetlands and floodplains may require consultation with U.S. Army Corps of Engineers or Federal Emergency Management Agency. Other laws apply to both federal and private projects, such as the Clean Air Act, Clean Water Act, and hazardous waste management laws. The Endangered Species Act requires that DOE assess the impact of proposed actions on Federally-listed threatened and endangered species and their critical habitat; DOE must consult with the U.S. Fish and Wildlife Service if endangered species are affected by a project.

G.4 Technology Targets

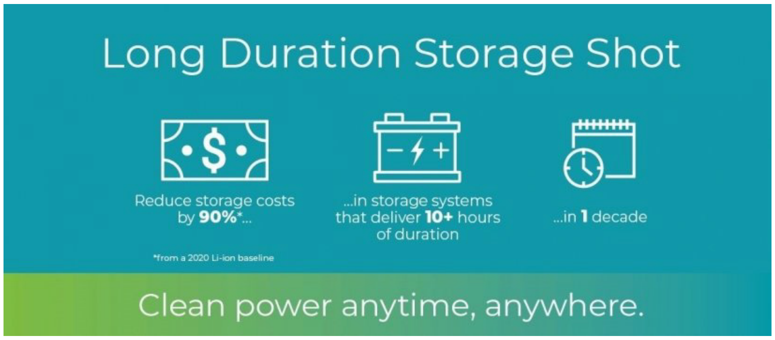
DOE programs have also established technology targets to drive technology advancements and meet various application needs. Examples of these technology targets relevant to the time horizon of this strategy and roadmap document are provided below.

G.4.1 The Long-Duration Storage Shot™

Launched in July 2021, the Long-Duration Storage Shot™ (LDSS) [46] is the second Earthshot™ announced as part of DOE's Energy Earthshots™ Initiative. The Energy Earthshots™ Initiative aims to accelerate breakthroughs of more abundant, affordable, and reliable clean energy solutions within the decade.[40] LDSS seeks to achieve

[40] Achieving the DOE Energy Earthshots will help America tackle the toughest remaining barriers to addressing the climate crisis, and more quickly reach the Biden-Harris Administration's goal of net-zero carbon emissions by 2050 while creating good-paying union jobs and growing the clean energy economy.

affordable long-duration grid storage for clean power anytime, anywhere. The LDSS elevates and extends selected elements of DOE's ESGC to achieve the established environmental, energy, equity, and other goals.[41] The LDSS establishes a target to reduce the cost of grid-scale energy storage by 90% for systems that deliver 10+ hours of duration within the decade (Appendix Figure 9).



Appendix Figure 9. Long-Duration Storage Shot™ (LDSS) goals.

Energy storage has the potential to accelerate full decarbonization of the electric grid. While shorter duration storage is currently being installed to support today's level of renewable energy generation, longer duration storage technologies are needed as more renewables are deployed on the grid. Cheaper and more efficient storage will make it easier to capture and store renewable clean energy for use when energy generation is unavailable or lower than demand – for instance, so renewable sources generated during the daytime like solar-generated power can be used at night or nuclear energy generated during times of low demand can be used when demand increases. LDSS will consider all types of technologies – whether electrochemical, mechanical, thermal, chemical carriers, or any combination that has the potential to meet the necessary duration and cost targets for grid flexibility.

LDSS incorporates two ways of measuring progress toward affordable long-duration grid storage: upfront costs and per-usage costs. The upfront cost, or the capital expenditure cost (CAPEX), is the purchase price for the storage resource. It is analogous to the sale price of an automobile. In contrast, the per-usage cost incorporates all the upfront and operating costs and averages those costs over the lifetime of the storage resource. This usage cost, also known as the levelized cost of storage (LCOS), is analogous to the standard mileage rate the IRS uses to approximate the per-mile costs of driving a car.[42]

Note that upfront costs are typically reported as dollars per kilowatt-hour ($/kWh), while usage costs can be reported as dollars or cents per kilowatt-hour-cycle ($/kWh-cycle). Upfront costs measure the "purchase" cost to buy a storage system, which has a size measured in kilowatt-hours. Per-usage costs measure the cost of using the battery to store and deliver one kilowatt-hour of electricity.

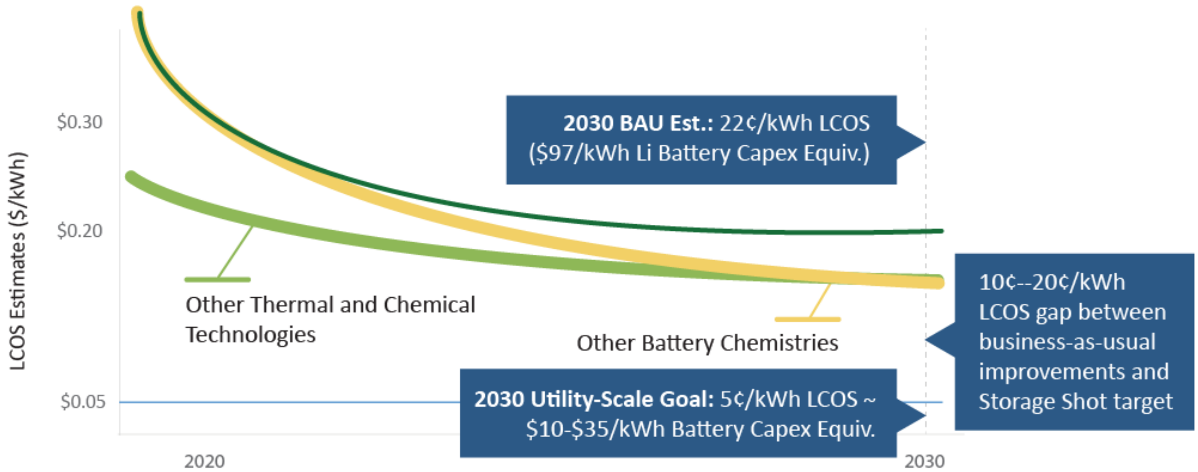
G.4.1.1 Upfront Cost Target: 90% Reduction from 2020 Levels

For LDSS to achieve the objectives outlined above, storage CAPEX needs to decrease to approximately $10–$35/kWh, relative to the 2020 lithium-ion battery baseline cost of $162/kWh.[43] The specific percentage reduction will vary, as other technologies (such as flow batteries or thermal storage) have different starting points, as shown in Appendix Figure 10. The target range represents an 80%–95% decrease in upfront costs, which LDSS highlights as the 90% reduction goal. LDSS provides a wide target range because, in addition to technology, other costs such as efficiency losses or soft costs affect the total cost of using a storage resource.

[41] The LDSS establishes a major (though not the sole) technology target that is coordinated by the ESGC.

[42] The IRS standard mileage rate in 2020 was 57.5 cents per mile and is meant to account for expenses such as the upfront purchase price (via depreciation), maintenance, repairs, fuel, insurance, and registration fees [89].

[43] This 2020-dollar figure reflects the estimated price of the storage block component of a 10-hour lithium-ion battery cost, as documented in DOE's 2020 Grid Energy Storage Technology Cost and Performance Assessment [90].



Appendix Figure 10. Business as usual (BAU) technology cost expectations for various storage technology categories.

G.4.1.2 Per-Usage Cost Target: $0.05 Levelized Cost of Storage

Similarly, the LCOS for 10-hour systems needs to decline to approximately $0.05/kWh-cycle from $0.20–$0.35/kWh-cycle in 2020. LDSS does not provide a range for the LCOS because this target includes all major costs of using a storage resource. The upfront cost range represents the variety of ways in which technologies with different upfront costs can achieve the $0.05/kWh-cycle target, which is the more significant metric in determining storage competitiveness for a given use case. This price target is relevant to both LDSS focal areas: remote communities and grid decarbonization.

Focal Area 1: Remote Communities: Many grid-connected schools, hospitals, and neighborhoods that experience frequent outages have installed backup generators that run on natural gas or diesel. Many remote communities are not connected to the larger grid but instead obtain electricity from portable generator sets (“gensets”), which often use diesel fuel. The levelized cost of energy (LCOE) from diesel gensets can range from $0.192-$0.20/kWh, while the LCOE from natural-gas gensets can range from $0.105-$0.111/kWh [47]. The DOE Solar Energy Technologies Office (SETO) has a residential solar photovoltaic LCOE target of $0.05/kWh. If long-duration storage can be available for $0.05/kWh-cycle or less, then the combination of residential-scale storage and renewables would become the most affordable option for remote and off-grid electricity.

Focal Area 2: Grid Decarbonization: The U.S. Energy Information Administration’s (EIA) *Annual Energy Outlook 2021* reference case identifies several types of dispatchable generation that could be built through 2030 [48]. These generators have an anticipated LCOE ranging from $35/MWh to $108/MWh, with a midpoint at $71/MWh, or $0.071/kWh. SETO revised its utility-scale solar LCOE target to $0.02/kWh [49]. Experts predict the LCOE of onshore wind energy to continue declining, with lower-end estimates approaching $0.02/kwh or less by 2035 [50]. If long-duration storage can be available for $0.05/kWh-cycle or less, then enabling dispatchability through the combination of utility-scale storage and renewables would approach competitiveness with a variety of dispatchable thermal generators.

G.4.2 Electric Vehicle (EV) Battery Target

Executive Order 14037 (August 5, 2021) set an aggressive goal that 50 percent of all new passenger cars and light trucks sold in 2030 be zero-emission vehicles, including battery electric, plug-in hybrid, or fuel cell electric vehicles.[44] To help support this goal, DOE has established a related R&D target, the Electric Vehicles (EV) Battery Target, to reduce EV battery cell cost to $75/kWh, (based on rated energy) manufactured cost for a battery cell for a 300-mile

[44] 86 FR 43583, https://www.federalregister.gov/documents/2021/08/10/2021-17121/strengthening-american-leadership-in-clean-cars-and-trucks.

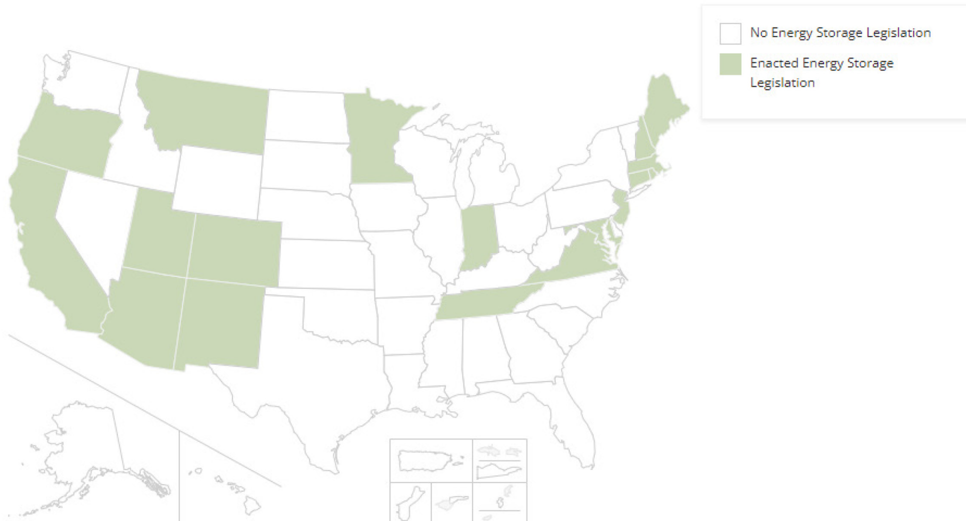
range electric vehicle.[45] Advances in battery production for transportation applications are anticipated to continue benefitting production, performance, and safety of similar technologies used in batteries for stationary applications.

G.5 Deployment Targets

As energy storage becomes more readily available, affordable, and reliable, polices are being established that set deployment targets for energy storage, whether broadly or for a specific technology. State organizations such as the National Conference of State Legislatures' (NCSL) track and share these trends. Section G.5.1 describe an example of NCSL's recent efforts to map the energy storage deployment target landscape.

G.5.1 State Legislative Energy Storage Trends

State-level policies and goals are also contributing to the energy storage landscape. In 2021, the National Conference of State Legislatures provided a snapshot of legislative activity related to energy storage, identifying just under 300 measures, of which 60 became law. Most of these actions encouraged energy storage capacity development through financial incentives or regulatory changes (e.g., easing the burden on energy storage developers). Some states have also established mandates and targets for energy storage development, as well as to capitalize on the benefits of energy storage (e.g., community resilience projects).



Appendix Figure 11. States with Energy Storage Legislation (as of 2021) [51]

Ref. https://www.ncsl.org/energy/2021-legislative-energy-trends#storage

G.6 Others

In 2023, the Government Accountability Office (GAO) issued a report on Utility Scale Energy Storage [52]. The report focuses on policy issues and offers a limited scope of technology assessments. While this SRM does not address policy options, it does consider relevant existing policies to the extent they can inform DOE's energy storage activities. Additionally, DOE activities since the GAO report's release provide more granularity with respect to different energy storage technologies (e.g., see Appendix E.4.2) and provides a stronger foundation for DOE's strategy and roadmap.

Ref. GAO report on Utility Scale Energy Storage (March 2023), https://www.gao.gov/assets/gao-23-105583.pdf.

[45] 2022 VTO Annual Progress Report on Battereis, https://www.energy.gov/sites/default/files/2023-10/VTO_2022_APR_Batteries_FINAL_Compliant_-min.pdf.

Appendix H. International Efforts

While DOE engages across several domestic stakeholder groups, international engagements within DOE's energy storage portfolio are an important component to facilitate technology acceleration and adoption. This appendix highlights representative engagements; it is not an exhaustive list.

H.1 International Energy Agency (IEA)

DOE, with the U.S. Department of State, oversees governance of the IEA and advances U.S. interests through participation in various committees that guide the IEA's policy and programs. DOE's Office of International Affairs (IA) leads DOE's interaction with IEA. IA's Assistant Secretary serves as a Vice Chair of IEA's Governing Board (GB). The GB is responsible for overall management of the Agency, mainly through its budget and work plan. DOE and its national labs also engage actively in multilateral science and technology cooperation through IEA. IEA's platform for cooperation on energy technology R&D accesses 6,000 technical experts and enables a series of Technology Collaboration Programs (a.k.a., Implementing Agreements). The U.S. participates in 37 of 40 TCPs, including the Hydropower TCP and the Energy Storage TCP. DOE's energy storage experts have presented and attended various IEA workshops and meetings to exchange ideas and general energy storage knowledge.

Additional information about DOE's engagement with IEA is available on the DOE website: https://www.energy.gov/ia/international-energy-agency-iea#:~:text=The%20U.S.%20Department%20of%20Energy,leads%20DOE's%20interaction%20with%20IEA.

H.2 US-India Energy Storage Taskforce (ESTF)

Launched on 13 Dec 2023, the ESTF will work to advance the goals of the U.S.-India Strategic Clean Energy Partnership (SCEP), including to develop and deploy emerging clean energy technologies to decarbonize the energy sector. The ESTF's objective is to facilitate an ongoing and meaningful dialogue among U.S. and Indian government officials, industry representatives, and other stakeholders to scale up and accelerate the deployment of Energy Storage technologies.

The ESTF comprises six working groups focused on:

- Technology
- Market Design, Business Models and Projects
- Manufacturing and Supply Chain
- R&D, Skill Development
- Finance
- Safety, Code and Standards

It is co-chaired by India and the US. Additional information about the ESTF's organization and activities can be found on the India Energy Storage Alliance website: https://indiaesa.info/initiatives/us-india-estf.

H.3 US-India Energy Storage Webinar Series

Under the auspices of US-India Strategic Clean Energy Partnership, US-DOE and India Energy Storage Alliance (IESA) launched a monthly webinar series on Energy Storage with active participation from government officials, key industry players, national labs, and stakeholders. The inaugural webinar was held 23 June 2023; webinars are held on the third Thursday of the month and comprise a presentation and moderated discussion. Topics have ranged from the Energy Storage Landscape and Best Practices to Policy and LDES Technologies.

Additional information about the webinar series can be found on the India Energy Storage Alliance website: https://indiaesa.info/initiatives/us-india-partnership.

H.4 Certified Energy Storage Professional

On 8 Jan 2024, an advisory board including experts from India, U.S., Japan, and Germany was announced to support certification of energy storage professionals. OE's Dr. Imre Gyuk was among the selected experts. This certification effort will address emerging energy storage industry needs across the globe and bridge the skill gap by focusing on skilling, re-skilling, and capacity building of current workforce and future personnel. The effort will be led by the India Energy Storage Alliance but will benefit all nations. It will aim to serve as a uniform baseline for industry to evaluate energy storage professionals. A website is currently being developed to provide additional information for this effort.

H.5 Clean Energy Ministerial (CEM)

A new initiative, "Supercharging Energy Storage" was launched with support from the U.S., Canada, Australia, and the EU. The new CEM initiative will aim to boost stationary battery storage development and deployment and reduce technology cost, through international cooperation and alignment as appropriate, to build a diversified, sustainable, responsible, secure, and transparent supply chain, to promote grid stability and reliability and to support the integration of renewable energy globally. The new CEM Initiative was launched at COP 28 in Dubai on December 6th, 2023. Work continues with the intention of involving other international partners.

Additional information about this initiative can be found on the Clean Energy Ministerial's website: https://www.cleanenergyministerial.org/supercharging-battery-storage-initiative-launch/.

H.6 Australia-U.S. Net-Zero Technology Acceleration Partnership

In 2022, the U.S. Secretary of Energy and Australia's Minister for Climate Change and Energy signed the Australia-United States Net-Zero Technology Acceleration Partnership to accelerate the development and deployment of zero emissions technology and cooperate on critical minerals supply chains to reduce greenhouse gas emissions while supercharging economic growth. The Partnership builds on long-standing cooperation between the two countries, which share many of the same challenges in decarbonising our economies. Cooperation will be practical, inclusive of industry, research and private sector to drive investment, trade, and development of commercial opportunities between our countries in low and zero emissions technologies and critical material that will drive them. Initial areas for cooperation under the Partnership include the development of long duration energy storage technology, as well as digital electricity grids and technology to support the integration of variable renewable energy, hydrogen, and carbon dioxide removal, including direct air capture. The MOU may be viewed through DOE's website: https://www.energy.gov/articles/australia-and-us-join-forces-path-net-zero.

Appendix I. Electricity Advisory Committee 2022 Biennial Storage Review

Ref. Electricity Advisory Committee (EAC), 2022 Biennial Storage Review report [3]; DOE Response to 2022 Biennial Storage Review [53]

The EAC Biennial Storage Review fulfills the duties allocated to the Energy Storage (Technologies) Subcommittee (the Subcommittee) of the Electricity Advisory Committee (EAC) by the Energy Independence and Security Act (EISA) of 2007 related to assessing the U.S. Department of Energy's (DOE) activities in energy storage technologies. Title VI, Section 641(e) of EISA requires the formation of a council to serve in an advisory role to DOE and the Subcommittee was formed in March 2008 to serve that function. Specifically, EISA Section 641(e)(4) states that every 5 years "the Council, in conjunction with the Secretary [of Energy], shall develop a 5-year plan for integrating basic and applied research so that the United States retains a globally competitive domestic energy storage industry for electric drive vehicles, stationary applications, and electricity transmission and distribution." EISA Section 641(e)(5) states further that "the Council shall (A) assess, every two years, the performance of the Department in meeting the goals of the plans developed under paragraph (4); and (B) make specific recommendations to the Secretary on programs or activities that should be established or terminated to meet those goals." The 2022 Biennial Energy Storage Review serves the purpose defined in EISA Section 641(e)(5) and presents the Subcommittee's and EAC's findings and recommendations for DOE.

The table below provides the list of EAC recommendations from the 2022 Biennial Storage Review, DOE's response to those recommendations, and additional updates since DOE issued its response. For more details, please see the full EAC report and DOE response (cited above).

Appendix Table 19. 2022 Biennial Storage Review recommendations, response, and updates

EAC REPORT [3]:	**DOE RESPONSE (18 May 2023)** [53]:	**Additional Updates (final SRM date)**
1. Macro-energy storage analysis	**1. Conduct macro-energy storage analysis.**	Status = in Progress ESGC Track = Policy & Valuation
DOE should conduct a macro-energy storage analysis to determine the power and duration of energy storage needed and where it is needed. This should be compared with the projected availability to assess whether it satisfies the needs and evaluates the cost associated with the needs. The analysis should include 24/7 capacity, reserve margin, energy, and resilience needs, as well as load growth and distributed storage potential associated with EVs and other electrification loads. The analysis should consider the timeframe for the transition from fossil fuel power generation and assess whether energy storage will be available to ensure a reliable and resilient electric grid throughout the transition. This analysis should be communicated to policymakers and regulators to reduce the risk of becoming overly	DOE agrees with the EAC and will continue to holistically examine the evolution of the energy system and its impact on the value, quantity, and location of energy storage needs. DOE has done work in the past and will continue to do work in the future that incorporates improved energy cost and performance, new technologies including energy storage, and additional policy considerations into system-level/macro-market analyses. Examples include: ▪ The National Renewable Energy Laboratory's (NREL) Storage Future Studies [20] is a series of analyses that: (1) developed energy storage cost and performance projections, (2) assessed the economic potential of diurnal storage out to 2050, (3) examined distributed solar and storage adoption, and (4)	▪ ESGC; $30M announced in July 2023 to help enable the LDSS [57] ○ $15M - Storage Innovations Technology Liftoff FOA ○ $15M - ROVI Demonstration and Validation FOA

EAC REPORT [3]**:**	**DOE RESPONSE (18 May 2023)** [53]**:**	**Additional Updates (final SRM date)**
dependent on energy storage if it is not available on the needed timeline.	the operational impacts of widespread energy storage on the grid. ▪ NREL's Standard Scenarios [54] is an annual product that examines 50+ scenarios of power sector evolution. All the underlying data and model is publicly available. ▪ NREL's 100% Clean Electricity by 2035 [55] report examined five pathways to achieve the Administration's 100% clean electricity goal and found the U.S. could need as much as 120-350 GW of diurnal storage and 100-650GW of long-duration/seasonal storage by 2035 in order to meet resource adequacy and reliability needs. ▪ NREL's Evaluating the Impacts of the Inflation Reduction Act and Bipartisan Infrastructure Bill on the U.S. Power System [56] report assesses the impact of new tax credits including the new investment tax credit for standalone storage systems and estimates the law will spur 50-100 GW of storage by 2030. ▪ DOE's Pathways to Commercial Liftoff: Long-Duration Energy Storage [21], conducts techno-economic analysis of existing Long-Duration Energy Storage (LDES) technologies, identifies cost reduction and compensation improvements for LDES technologies to be commercially viable, and proposes solutions to existing market barriers.	
2. Market efficiency	**2. Coordinate with industry to promote efficient markets for energy storage.**	Status = in Progress ESGC Track = Policy & Valuation
DOE should coordinate the development of high-level ownership rules and intrinsic value propositions for energy storage systems. These rules should facilitate investments by utilities, third-party developers, and customers that fairly compensate the storage investments while delivering the multiple technical and market	DOE welcomes the recommendation and agrees that the Department should continue to support work that promotes strong energy storage markets. ▪ Examples of previous work now being used by the storage industry include the ESGC Market Report [58] and the	▪ LDES MOU - landmark agreement to accelerate LDES [60]; first LDES conference, Apr 2024

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value streams. This coordination will need to involve the Federal Energy Regulatory Commission, National Association of Regulatory Utility Commissioners/state regulators, independent system operators, market developers, third-party developers, and utilities. The goal should be to optimize the use of energy storage to benefit end-use customers while balancing a highly reliable electric grid with reasonable cost and equitable opportunities for ownership. The value of storage should be based not only on the immediate siting and reliability benefits but also the avoided long-term transmission costs. Flexible rate design and ownership models are required. A change in systems thinking from a central push of power model paradigm to a push/pull network resource model is critical.	ESGC Cost and Performance Assessment [59]. ▪ DOE is also facilitating bankable and replicable storage solutions by creating new performance prediction capabilities through the performance data collection and data science efforts of the Rapid Operational Validation Initiative (ROVI) [30]. ▪ Finally, DOE is supporting deployment projects that target unique use cases and unlock new market opportunities through activities such as the Office of Clean Energy Demonstration's (OCED) LDES Funding Opportunity Announcement (FOA)[46] [47] and the Office of Electricity's (OE) Storage Demonstration Program. [48]	
3. Market barriers	**3. Support local efforts by states and regulators to remove barriers to facilitate markets and remove disincentives for energy storage.**	Status = in Progress & Complete ESGC Track = Policy & Valuation
Many local policymakers are continually advised that long-duration storage technologies are "just around the corner." It is imperative and productive to redouble efforts to help policymakers, regulators, and utilities understand the critical interdependence of energy storage in facilitating VRE resources, such as wind and solar, and the limitations on how much energy storage and VRE resources can be integrated into a grid without compromising reliability. Federal guidance on best practices and standards for integrating energy storage can assist state regulators in facilitating the highest and best value of energy storage integration and remove regulatory and structural barriers and disincentives.	DOE agrees with the EAC. DOE has an existing portfolio of work to boost capacity in state energy offices and regulatory commissions which will continue to be supported and augmented into the future. DOE will continue to work with decision-makers to help them understand how grid evolution will drive diurnal, long-duration, and seasonal storage needs to maintain resource adequacy, reliability, resilience, and affordability. ▪ OE's activities that augment institutional capabilities around storage analysis include: ○ Energy Storage Technical Assistance [61] [62] ○ Energy Storage for Social Equity [63]	OE Storage Program Peer Review - Annual Meeting and Peer Review assembled researchers from across the DOE landscape – national laboratories, industry, government, and academia – to summarize the state of the art in energy storage research, development, and application. Program reviews solicit feedback from formal peer reviewers and attendees to ensure that program activities remain centered in high-impact focus areas, thereby optimizing the use of federal resources to fill critical R&D gaps. Big Decadal Idea Generator (BIG DIG): Through the BIG DIG, OE is funding the development of project plans that will then be evaluated for execution. One of the selected

[46] https://www.energy.gov/oced/funding-notice-long-duration-energy-storage-demonstrations

[47] https://www.energy.gov/oced/funding-notice-distributed-energy-systems-demonstrations-program

[48] https://www.energy.gov/oe/rapid-operational-validation-initiative-rovi

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	▪ In addition to storage-specific activities, DOE funds activities that generally support decision-makers (without being specific to storage), such as: ○ Grid Modernization Lab Consortium Technical Assistance for Public Utility Commissions [64] ○ Grid Modernization Lab Consortium Technical Assistance for ISO/RTOs [65] ○ EERE & OE Grid Solutions Program [66] ○ Water Power Technologies Office – Hydrowires Technical Assistance [67]	project plans in the *Markets and Valuation* track is focused on developing an energy storage deployment toolkit aimed at assisting regulators in navigating energy storage deployment.
4. Critical services	**4. Improve the resilience of critical services by supporting the deployment of energy storage at critical services and interdependent network infrastructure.**	Status = in Progress ESGC Track = Technology Transition
Recognition of the interdependencies of electric supply and a wide range of other critical infrastructure services is an important next step in ensuring the resiliency of both the grid and those important services. DOE can play a leadership role in helping to define those interdependencies and evaluate the potential consequences of a failure of each element in those relationships. With support from the industry, this information can then be used to create potential roadmaps for integrating energy storage to facilitate mutual improvements to key elements for the public good. These roadmaps can then be used to prioritize storage-related improvements to each critical infrastructure that improve the overall interdependent system for the benefit of public safety and the resilience of those services.	▪ DOE is increasing its interagency coordination with Department of Defense and Department of Homeland Security to leverage energy storage to support critical infrastructure such as military installations and community lifeline facilities. ▪ Ongoing activities, such as Energy Storage for Social Equity, provides technical assistance and project development support for communities to implement storage that serves resilience needs such as supporting community shelter operations during power outages. ▪ Anticipated at scale LDES deployments may support resiliency objectives through OE/OCED demonstration programs, with technologies that can provide 24 hours or more of duration.	▪ OCED demonstration FOAs (2867-LDES, 3139-DES)

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5. Mobility	**5. Increase the resilience of the grid and support customer, critical services, and grid-level resilience by facilitating the bidirectional storage capacity of electrified mobility.**	Status = in Progress ESGC Track = Technology Development
Electrified mobility through EVs and emerging electrification of marine and aviation transportation should be acknowledged and quantified in the macro-energy storage analysis (see recommendation 1). The high value of portable energy has been demonstrated for decades in the form of consumer-scale disposable batteries for cordless tools and devices, which can feasibly exceed $50/kWh, underscoring the exponentially higher feasibility of rechargeable batteries. The high-energy storage capacity of EVs can be relocated, coordinated, and deployed to assist with grid-level peak shifting, load balancing, spinning reserve, and emergency power supply needs to support critical segments of the grid or island to support critical industries, critical services, and home-scale resilience. DOE can assist with removing the regulatory barriers for deploying portable storage assets via electrified mobility. DOE can play an essential role in removing the barriers to grid-to-vehicle interconnectivity and portability. The industry needs signals and incentives to promote interconnection standards, interoperability capabilities, and control platforms for coordinated control of fleets of mobile storage assets. Department outreach can assist utilities and regulators in recognizing the role of electrified mobility as a potential grid-moderating asset rather than destabilizing the grid by growing the magnitude and timing variability of grid peaks. DOE should lead in ensuring that electrified mobility supports grid stability and contributes to the macro storage needs of the grid and not contribute to peaking magnitude and variability that undermines and competes with fixed storage.	▪ EV@Scale Consortium [26] - brings together National Laboratories and key stakeholders to conduct infrastructure research and development to address challenges and barriers for high-power EV charging infrastructure that enable greater safety, grid operation reliability, and consumer confidence. ▪ V2X MOU [27] - brings together cutting-edge resources from DOE, DOE national labs, state and local governments, utilities, and private entities to evaluate technical and economic feasibility as we integrate bidirectional charging into energy infrastructure. The MOU will also advance cybersecurity as a core component of V2X charging infrastructure. ▪ EVGrid Assist [28] - provide technical assistance and inform research and development on vehicle-grid integration (VGI) to facilitate the rapid deployment of electric vehicles and the associated charging infrastructure by minimizing the impacts to the electric grid and helping electric utilities and regulators make planning and policy decisions.	

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6. Standards development	**6. Facilitate the cost-effective deployment and interoperability of fixed and mobile storage assets by promoting standards that support consistent best practices among the industry and user groups.**	Status = in Progress ESGC Track = Technology Transition
DOE should play a leadership role in promoting the development of standards for the entire spectrum of the energy storage industry, including the compatibility of communications and controls, regulatory consistency, siting and safety considerations, obsolescence, disposal and recycling, reliability, and cyber and physical security. The role of standards is particularly crucial in the aggregation and dispatch of fixed storage assets at the grid level during both blue sky (normal) grid operations and dark sky (degraded) grid cases. Standards that support the aggregation of electrified mobile assets can prove to be particularly valuable by leveraging their portability to locate and aggregate to critical sites to enhance resiliency at key grid nodes or critical islanded microgrids.	▪ DOE will continue its ongoing energy storage R&D work on codes and standards and leverage this recommendation to continue and expand upon this important work. Examples of standards development work include: ○ Energy Storage Reliability Codes and Standards Activities Update [68] ○ IEEE Std 1547.9-2022 [69] ○ Battery Management System Standards [69] ○ Energy Storage Safety Collaborative Codes and Standards Report [70]	▪ Energy Storage Device (MESA-DER) Interoperability standards and device (PNNL)[49]
7. Interconnection and integration issues	**7. Address barriers and develop use cases for the industry and end users to facilitate timely and efficient interconnection and accelerate the integration of storage assets to maintain stability and promote resilience as the grid transitions.**	Status = in Progress ESGC Track = Technology Transition
DOE can assist in accelerating the deployment of storage assets by promoting a two-pronged approach of showcasing successful use cases and best practices, and by assisting state and federal regulators, end users, and industry in recognizing and confronting the barriers to energy storage integration. The barriers include regulatory rigidity in siting, deploying, operating, and the cost recovery of storage assets; financing storage assets; addressing real and perceived technical	▪ Activities to demonstrate emerging use cases include: ○ Pathways to Commercial Liftoff: Long-Duration Energy Storage [21] ○ PNNL's Embedded Storage [29] research - Improving grid infrastructure with embedded storage will improve transmission-level and distribution-level resilience, support critical lifeline capabilities for emergencies	

[49] See, e.g., https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-33302.pdf.

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readiness deficiencies; and creating visibility with regard to performance characteristics and asset life, including end-of-life repurposing or disposal.	such as critical load outage ride-through and generator black-start, and improve joint operating characteristics of natural gas/electric generation systems ○ Long-Duration Storage Shot [46] ○ Energy Storage Grand Challenge Roadmap [18] ○ Puerto Rico Grid Resilience and Transitions to 100% Renewable Energy Study [71] ▪ Activities that help states better understand use cases and reduce barriers include: ○ Interconnection Innovation e-Xchange (i2x) [25] - enables a simpler, faster, and fairer interconnection of clean energy resources all while enhancing the reliability, resiliency, and security of our electric grid. ○ Rapid Operational Validation Initiative (ROVI) [30] will facilitate bankable and replicable storage solutions by creating new performance prediction capabilities.	

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