

EPRI

BATTERY ENERGY STORAGE ROADMAP



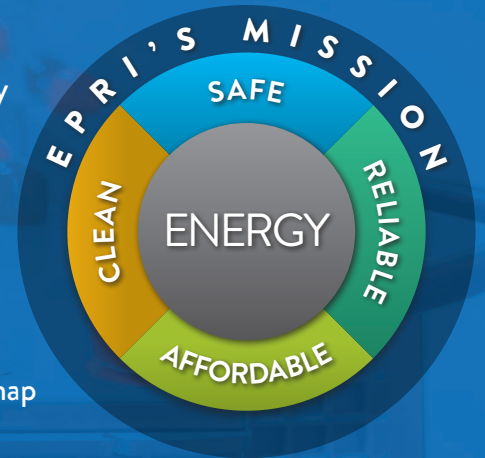
2024

EXECUTIVE SUMMARY

This EPRI Battery Energy Storage Roadmap charts a path for advancing deployment of **SAFE**, **RELIABLE**, **AFFORDABLE**, and **CLEAN** battery energy storage systems (BESS) that also cultivate equity, innovation, and workforce development.

Energy storage is integral for realizing a clean energy future in which a decarbonized electric system is reliable and resilient. Global installed energy storage capacity is expected to grow more than 650% by 2030 to enable more renewable energy resources and support grid modernization.*

EPRI’s Energy Storage and Distributed Generation Program uses this Roadmap as a planning guide for strategizing the direction and alignment of its BESS collaborations and applied research priorities to foster the needs of its Members and EPRI’s mission of “advancing safe, reliable, affordable, and clean energy for society.”



COLLABORATIVE ROADMAP DEVELOPMENT

EPRI’s Battery Energy Storage Roadmap was developed collaboratively with its subject matter experts and Member Advisors, who represent diverse international and domestic utility, energy developer, and government agency perspectives. EPRI’s the original Energy Storage Roadmap and current Battery Energy Storage Roadmap were developed using the process shown below:



Originally published in 2020, EPRI’s Energy Storage Roadmap envisioned a path to 2025 in which energy storage enhances safe, reliable, affordable, and environmentally responsible electric power. Fifteen distinct Future States were described and associated gaps identified to realize the energy storage future vision.

In 2022, the Roadmap was enhanced to include detailed descriptions of the gaps and describe the research activities underway to address those gaps.

This Battery Energy Storage Roadmap revises the gaps to reflect evolving technological, regulatory, market, and societal considerations that introduce new or expanded challenges that must be addressed to accelerate deployment of safe, reliable, affordable, and clean energy storage to meet capacity targets by 2030. The EPRI Battery Energy Storage Roadmap is the product of a series of working group meetings attended

by EPRI Member Advisors and staff to review and assess the relevance of gaps identified in 2020 and compile new gaps that have since emerged. The compilation of gaps included in this document represent challenges that are collectively regarded as high-priority by EPRI Members. To facilitate use of the Roadmap as a strategic planning guide, Future State Pillar gaps have been reorganized by:

- ➔ **Energy storage project life cycle** – Gaps were sorted by the project life cycle phase they are aligned with most. This facilitates proactive planning and coordination of project activities across the life cycle.
- ➔ **EPRI’s Energy Storage and Distributed Generation Program project sets** – Gaps were sorted by project set to facilitate focused, long-term research planning that incorporates projects and activities to close the gaps.

* Excludes pumped storage hydro capacity and includes capacity for both front-of-the-meter and behind-the-meter energy storage system installations. Source: “Global Energy Storage Market Update Q2 2024,” Wood Mackenzie, Jun. 2024



BATTERY ENERGY STORAGE FUTURE STATE PILLARS

This EPRI Battery Energy Storage Roadmap contains four Future State Pillars, each representing an aspect of EPRI’s mission to advance **SAFE**, **RELIABLE**, **AFFORDABLE**, and **CLEAN** energy. Innovation, community support of BESS adoption, and a trained workforce are considered foundational to the planning, procurement, deployment and integration, operations and maintenance (O&M), and decommissioning of BESS projects.



SAFE battery energy storage minimizes safety risks and hazard impacts on workers, communities, the public, and property.



RELIABLE battery energy storage assets are dependable and used for grid reliability and resilience.



AFFORDABLE battery energy storage meets grid operator and customer needs cost effectively.



CLEAN battery energy storage supports a decarbonized grid using equitable and responsible life cycle practices.

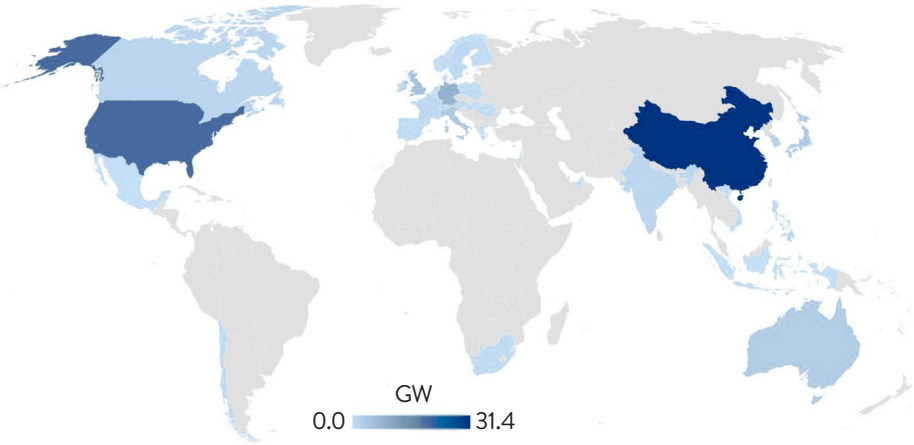


Advancing **EQUITABLE** energy storage with a **TRAINED WORKFORCE** and cross-cutting **INNOVATION**.

EPRI’s **Battery Energy Storage Roadmap** takes a simplified approach compared to its 2020 and 2022 predecessors based on EPRI Member and subject matter expert feedback on the Future States. This Roadmap defines a singular vision for each Future State Pillar. The following pages include “aspects” that supplement the vision. These are non-exhaustive lists that will lead the deployment of safe, reliable, affordable, and clean battery energy storage.

Removing the boundaries of discrete future states allows EPRI flexibility in its applied research activities to address BESS gaps and challenges, which are interdisciplinary and have multi-faceted impacts across diverse stakeholder interests. This Battery Energy Storage Roadmap can also be used by others to help develop their energy storage future.

2023, INSTALLED ENERGY STORAGE CAPACITY (GW)[†]



INSTALLED ENERGY STORAGE CAPACITY (GW) [†]		
2023 COUNTRIES WITH THE MOST INSTALLED CAPACITY	2030, EXPECTED	GROWTH
GLOBAL	681	653%
China	312	893%
US	133	554%
Germany	36.4	345%
UK	21.5	304%
Italy	23.6	511%
Australia	28.4	726%
Japan	10.7	177%

Energy storage is integral to achieving electric system resilience and reducing net greenhouse gases by 45% before 2030 compared to 2010 levels, as called for in the Paris Agreement. China and the United States led energy storage deployments in 2023 and are expected to maintain the majority share of installed energy storage system capacity in 2030. Regions with the largest expected growth in energy storage capacity by 2030 include Latin America (+1,374%), the Middle East (+1,147%), and the Asia-Pacific (+778%), based on data from Wood Mackenzie’s Global Energy Storage Market Update Q2, 2024.[†]

The United States has set a national decarbonization target of 50 – 52% greenhouse gas emissions reduction from 2005 levels by 2030, with the goal of reaching a net-zero carbon economy in 2050. As of 2023, the United States reported nearly 16.5 GW of operable energy storage assets with a capacity greater than 1 MW.[‡] United States forecasts that consider state goals, utility integrated resource plans (IRPs), and industry expectations estimate energy storage capacity will more than double by 2030, much of which is expected to be contributed to BESS deployments. This EPRI Battery Energy Storage Roadmap is a planning tool for EPRI and its Members that identifies gaps in accelerating significant deployment of BESS capacity and prioritizes the applied research activities that EPRI and its Members will undertake.

UNITED STATES REGIONAL ENERGY STORAGE CAPACITY (GW)				
UNITED STATES REGION	2023, OPERATIONAL [†]	2030, EXPECTED BASED ON		
		STATE POLICIES ^{††}	IRPs ^{††}	INDUSTRY ESTIMATE ^{††}
UNITED STATES TOTALS	16.5	19.0	48.2	120
MIDWEST	0.21	2.50+	5.34+	12.9
NORTHEAST	0.72	10.0+	7.82+	10.3
<i>New York</i>	0.22	6 GW state target		5.15
SOUTH	4.67	4.16+	5.76+	43.2
<i>Texas</i>	3.71	No defined target		26.4
WEST	10.9	2.30+	29.3+	54.1
<i>California</i>	8.00	13.5+ GW of BESS & 1 GW of LDES		27.2

LDES: long duration energy storage

[†] Excludes pumped storage hydro (PSH), includes front-of-the-meter (FTM) and behind-the-meter (BTM) energy storage systems. Source: “Global Energy Storage Market Update Q2 2024,” Wood Mackenzie, Jun. 2024.

[‡] Excludes PSH, includes FTM systems with a rated capacity > 1MW. Source: *Annual Electric Generator Report (Form EIA-860, 2023 Early Release)*, US Energy Information Administration.

^{††} Some values have been linearly interpolated to estimate 2030 capacity.

^{††} Excludes PSH, excludes BTM energy storage systems. Source: “US Grid-Scale Energy Storage Outlook 2023,” Wood Mackenzie, Jul. 2023

Energy Storage at EPRI

EPRI performs applied energy storage research across its Programs. Listed below are EPRI's three programs with a dedicated energy storage focus. These programs collaborate together and with other EPRI programs to develop industry-leading resources that unlock the value of energy storage.

→ ENERGY STORAGE AND DISTRIBUTED GENERATION (PROGRAM 94)

EPRI's Energy Storage and Distributed Generation (ES&DG) program leads in the applied research for integration and use of safe, reliable, affordable, clean, and equitable energy storage, as well as fueled distributed generation and microgrids. Program Members work with world-class technical experts to better understand how to overcome barriers to implementation, manage risks, and maximize benefits from this new class of varied technologies.

APPROACH:

The ES&DG program is aimed at providing practical tools, resources, and guides that can be applied in day-to-day processes. It is built on the foundation of EPRI's collaborative model that brings together utilities, industry stakeholders, national laboratories, and academics to share experiences and align on common approaches. Advanced tools and analytical methods are developed and applied to accurately assess energy storage resource potential and its impacts to the grid, utility business models, the customer, and the environment. Field demonstration and deployments enable performance and reliability benchmarking, validation of emerging technologies, and development of leading practices for safe implementation and operation. Education and training help to support the development of new utility staff skills and inform external stakeholders from regulators to the public.

VALUE:

The knowledge acquired through the ES&DG program will support Members with the following:

Up-to-date intelligence to aid decision making: Up-to-date information and unbiased analysis on the fast-evolving energy storage and distributed generation technologies, products, markets, environmental justice, and regulatory advancements.

Informed planning and analysis: Development of methods and tools to guide use case, siting, sizing, environmental justice, and technology selection of energy storage, distributed generation, and microgrids, which support value maximization.

Technology evaluation: Field demonstrations, data, and analytical approaches to support accurate performance and reliability assessments for commercial and emerging technologies. Evaluation of supply chain, sustainability, safety, and life cycle assessments.

Project life cycle practices and risk mitigation: Convene stakeholders to document and share leading practices on siting and permitting, procurement, commissioning, operations and maintenance, decommissioning, environmental compliance, and sustainability practices. Risk mitigation strategies for operations, worker safety, public safety, and environmental impact.

Accurate information for public stakeholders: Places the environmental and safety benefits and challenges of energy storage into a broader context to utilities, nonutility distributed generation owners and operators, the energy storage industry, regulators, first responders, and the public.

→ HYDROPOWER GENERATION (PROGRAM 208)

The Hydropower Generation program focuses on conventional and pumped storage hydropower asset management, performance optimization, and technology development. The Program's work aims to understand the impacts of operational flexibility and the economic value hydropower may provide to markets to develop of modernization strategy frameworks needed to grow role hydropower within the electric power system. Existing and planned EPRI research projects intend to provide the industry with actionable technological and operational solutions to balance performance, reliability, and economics in meeting the world's energy needs.

→ BULK ENERGY STORAGE (PROGRAM 221)

The Bulk Energy Storage program performs research on bulk energy storage technologies including chemical, mechanical, and thermal types. The Program uses both technology and economic assessments of commercial and emerging technologies to understand and determine the applicability and potential benefits of bulk energy storage to support energy delivery. Research on these technologies includes technoeconomic assessments, evaluation of use cases, laboratory- and pilot-scale field testing, and development of operational and maintenance guidelines for available commercial technologies.



FUTURE STATE & ASPECTS

The **FUTURE STATE** vision for safe battery energy storage is defined with support from its **ASPECTS**.

The **CURRENT STATE** of safety related to each project life cycle phase gives context to the identified **GAPS** that EPRI and others can address to advance deployment of safe battery energy storage.

SAFE battery energy storage uses proven hazard mitigations and leading practices across the project life cycle that address safety risks and comply with codes to uphold public and worker health and safety, environmental justice, and equity.

A future in which battery energy storage is **SAFE** requires:

- Hazard characterization, including research in material safety at various operating conditions, for commercial and emerging BESS technologies for improved risk assessment and implementation of safety strategies that consider all project stakeholders.
- Innovation upon existing fire and explosion prevention and protection knowledge to develop applicable monitoring and modeling tools, effective technology solutions, and relevant emergency action plans.
- Collaboration and sharing of experiences to advance common leading practices across the industry and enhance the development of sensible and comprehensive codes, standards, and regulations.
- Community authorities (authorities having jurisdiction) to be equipped with the necessary resources and tools to ensure battery energy storage upholds public health, safety, environmental justice, and equity.
- Engagement, education, and effective communication with the public to share safety strategies that consider BESS benefits, risks, and community concerns.

CURRENT STATE	GAPS
PLANNING	
Potential opposition from agencies and communities that may be unaware or misinformed about the environmental, health, and safety (EH&S) attributes of BESS creates challenges in facility siting and permitting.	<ul style="list-style-type: none"> • Community engagement strategies, including targeted communication resources, that justify a social license to operate • Community engagement costs to inform project planning • EH&S data and modeling of system failure impacts for siting
PROCUREMENT	
Overall BESS safety can be improved with uniform system designs but is delayed by inconsistent jurisdictional requirements and underdeveloped safety guidance for emerging technology hazards and risk.	<ul style="list-style-type: none"> • Common safety requirements specified in requests for proposal for utility, customer-sited, and microgrid systems • Common hazard assessment frameworks for comparison and selection of BESS technologies
DEPLOYMENT & INTEGRATION	
Discordant development schedules for battery energy storage technologies and the codes, standards, and regulations needed to enforce safety are a cyclic obstacle that slows mutually beneficial advancements needed to accelerate and bolster safety in BESS deployments.	<ul style="list-style-type: none"> • Safety-informed deployment strategies that apply technology-specific safety considerations, equipment, and practices throughout deployment and integration planning and activities • Characterization of EH&S hazards and risks that inform engineering design and deployment practices • Common safety checklists of issues for which a jurisdiction can look for mitigations in the design/plans
OPERATIONS & MAINTENANCE	
Maintaining safe operation that does not compromise system reliability and profitability requires improved monitoring, data, and documentation of existing systems.	<ul style="list-style-type: none"> • Safety-informed operation strategies, such as the impact of state-of-charge limitations on system use case and profitability, to inform asset management and technoeconomic analyses • Safety system O&M guidelines for utility, customer-sited, and microgrid systems
DECOMMISSIONING	
Safe BESS decommissioning practices are not well characterized nor developed, especially for damaged energy storage systems, and guidance is lacking as few systems have yet reached end-of-life (EOL).	<ul style="list-style-type: none"> • Decommissioning protocols informed by EH&S hazard characterizations of technologies near EOL and include guidance on de-energization and safe handling • De-energization technologies for decommissioning damaged and failed systems



EPRI'S ROLE

EPRI is engaged in applied research and project activities for BESS safety. These projects are a representative sample from the breadth of EPRI's activities related to this Future State Pillar.

FEATURED PROJECTS & PRIORITIES

Battery Energy Storage Fire Prevention & Mitigation (Supplemental, [3002028531*](#))

This project develops new research, guidance, and tools to support safety deployment of lithium ion battery energy storage systems (BESS) across the project lifecycle. The current Phase III of the project is focused on thermal runaway characterization, failure incident response, safe O+M practices among other topics.

Case Studies for Energy Storage Decommissioning (PS94I)

This research priority details lessons learned from real-world decommissioning scenarios, such as the Cedartown BESS ([3002029744*](#)), and applies updated decommissioning cost methodologies to a wider range of energy storage technologies and facility designs.

Qualitative Risk Assessment (QRA) for Stationary BESS (PS94I)

This project combines data and insights from EPRI's portfolio of hazard assessment, system reliability, and environmental/health impacts research to create QRA case studies.

EPRI's BESS Failure Incident Database

EPRI tracks and collates BESS failure incidents around the globe. The database was created to inform stakeholders and the public on BESS failures. Failure incidents included in the database are classified as Stationary Energy Storage Failure Incidents or Other Storage Failure Incidents, which includes failures that are related to the manufacture, transportation, storage, and recycling of battery energy storage. EPRI uses the database to track trends in failure incidents and provide failure root cause insights ([3002030360](#)).

EPRI REPORTS

Product ID	TITLE (Year Published)	Planning	Procurement	Deployment & Integration	Operation & Maintenance	Decommissioning
3002030586	Lessons Learned from Air Plume Modeling of Battery Energy Storage System Failure Incidents (2024) *	■		■	■	
3002030360	Insights from EPRI's Battery Energy Storage Systems Failure Incident Database: Analysis of Failure Root Cause (2024) *	■		■		■
3002028522	Safety Implications of Lithium Ion Chemistries (2023) *		■	■	■	
3002028521	The Evolution of Battery Energy Storage Safety Codes and Standards (2023) *	■	■	■		
3002026399	Residential Energy Storage System Safety Guidelines (2023) *			■	■	
3002026396	Carnegie Road Energy Storage System Failure Response, Recovery, and Rebuild Lessons Learned (2023) *	■				■
3002027974	Battery Energy Storage Thermal Management Performance Testing (2023)				■	
3002019219	Energy Storage Safety Lessons Learned: Fire Prevention and Mitigation (2020)		■			

* Indicates the resource is Free to the Public



FUTURE STATE & ASPECTS

The **FUTURE STATE** vision for reliable battery energy storage is defined with support from its **ASPECTS**.

The **CURRENT STATE** of reliability related to each project life cycle phase gives context to the identified **GAPS** that EPRI and others can address to advance deployment of reliable battery energy storage.

RELIABLE, utility-grade battery energy storage assets and fleets are dependably dispatched, fortified for field deployment, designed with common monitoring, control, and communication systems, and optimized by data-informed asset management strategies.

A future in which battery energy storage is **RELIABLE** requires:

- A comprehensive understanding of BESS asset life that informs technology and system development while considering energy equity, utility operations, and customer needs.
- The support of a skilled workforce that assures reliable BESS deployment, integration, operation, and maintenance.
- Leading practices for data collection and evaluation of performance and reliability to enable simple and effective BESS benchmarking and technology comparisons to bolster asset and fleet reliability.
- Innovative, automated methods for real-time operational performance analysis and accurate state-of-health projections to facilitate intelligent and cost-effective asset O&M strategies.
- Development of dependable and integrated monitoring and control technologies that use common communication protocols across utility controls, BESS assets, fleets, and technology solution providers.

CURRENT STATE	GAPS
PLANNING	
Long-term BESS asset and fleet reliability is not well understood due to the relative nascence of the technology as an electric power system component.	<ul style="list-style-type: none"> • Trained analysis and grid planning personnel for improved BESS and electric system reliability • Common data collection and analysis methodologies that enable consistent performance and reliability assessments used to develop improved technoeconomic models
PROCUREMENT	
Establishing common data-informed procurement requirements applicable to all energy storage technologies and use cases is challenging because the landscape of energy storage products, solution providers, and applications is constantly evolving.	<ul style="list-style-type: none"> • Performance characterization for understanding reliability, availability, and longevity • Common system reliability requirements specified in requests for proposal for utility, customer-sited, and microgrid systems • Derisked technology selection considers battery technology and solution provider evaluation and qualification for all system components
DEPLOYMENT & INTEGRATION	
The quantity and quality of system performance and related non-performance data available for reliability analysis is limited and impacting development and improvement of BESS reliability standards and regulations.	<ul style="list-style-type: none"> • Inventory of component reliability and failure rates based on deployed system data to improve system design and reliability • Common design, data collection, and analysis guidelines, including outage reporting, alarms, monitoring, control, and communication systems
OPERATIONS & MAINTENANCE	
Asset management strategies are underdeveloped in how they balance reliability and risk because of the scarcity of installed system operations data needed to development technology-specific operational practices and maintenance plans.	<ul style="list-style-type: none"> • Data-informed asset management strategies to optimize operations and augmentation plans, extend life, increase uptime, and improve provisioning and storage of spare parts. • Integrated, real-time monitoring and control technologies that indicate emerging issues and enable preventative maintenance planning and activities
DECOMMISSIONING	
Reliability is not often associated with EOL, therefore energy storage reliability as it pertains to system decommissioning is not well understood.	<ul style="list-style-type: none"> • Data-informed definition of EOL for consistent determination of residual asset value used in planning and asset management • Circular economy practices that strengthen an internal provision of refurbished or reused spare parts



EPRI'S ROLE

EPRI is engaged in applied research and project activities for BESS reliability. These projects are a representative sample from the breadth of EPRI's activities related to this Future State Pillar.

FEATURED PROJECTS & PRIORITIES

Energy Storage Reliability *forthcoming* (Supplemental)

This project builds upon the current *Energy Storage Performance and Reliability Foresight* supplemental (3002020038*), which developed a sophisticated, secure platform to analyze past energy storage system performance and project overall reliability. The forthcoming project will address some of the gaps identified in a recent report, *Pathways to Improved Energy Storage Reliability* (3002030387*), which also provides a framework for EPRI's energy storage reliability assessment.

Emerging Energy Storage Technology *forthcoming* (Supplemental)

This project builds upon the current *Emerging Energy Storage Technology Testing and Demonstration* supplemental (3002019070*), which tests, demonstrates, and analyzes data from pre-commercial, non-lithium energy storage technologies. Participants benefit from an enhanced understanding of emerging battery technologies that can support eventual planning, deployment, and operation of these systems.

EPRI's Energy Storage Technology Database (Joint, PS94J & P221)

This database contains technical overviews of candidate energy storage technologies and is a singular source for information about energy storage products. The database can be used in various ways, from simple technology development tracking to project planning and technology selection support. The technologies included in the database generally have an identified developer and have achieved a technology readiness level (TRL) of TRL-3 or have real prospects of attaining this level in the near-to-intermediate future.

EPRI REPORTS

Product ID	TITLE (Year Published)	Planning	Procurement	Deployment & Integration	Operation & Maintenance	Decommissioning
3002030387	Pathways to Improved Energy Storage Reliability (2024) *	■		■	■	
3002025977	Electrical Energy Storage Data Submission Guidelines (2023) *	■	■	■		
3002025961	ESIC Energy Storage Data Calculator v1.0 (2023) *	■	■	■		
3002027899	Energy Storage Relocation and Decommissioning Project Lesson Learned (2023)		■			■
3002023124	Optimized Integration of Large-Scale Energy Storage into Microgrids: Energy Security for Military Installations (2021) *	■		■	■	
3002021898	Performance and Reliability Impacts on Modeling, Planning, and Operations (2021)	■			■	
3002019781	Energy Storage Performance and Reliability Foresight (2020) *				■	■
3002018968	Assessing Non-Wires Alternative's Impact on System Reliability: Guidance on Energy Storage Applications (2020)	■		■	■	

* Indicates the resource is Free to the Public



The **FUTURE STATE** vision for affordable battery energy storage is defined with support from its **ASPECTS**.

The **CURRENT STATE** of affordability related to each project life cycle phase gives context to the identified **GAPS** that EPRI and others can address to advance deployment of affordable battery energy storage.

FUTURE STATE & ASPECTS

AFFORDABLE battery energy storage encompasses economically viable technologies and deployment practices represented in planning models and proven to provide value to grid operators and customers.

A future in which battery energy storage is **AFFORDABLE** requires:

- Value propositions, costs, and benefits of various BESS technologies are understood, accurately represented in planning models, and effectively communicated to industry and community stakeholders
- Consideration of equity and environmental justice in technoeconomic analyses based on BESS demonstration learnings that include community engagement activities and their costs and benefits.
- Advanced and reliable monitoring and control system technologies that maximize BESS asset value.
- Established, well-informed, and transparent regulatory and market structures that encourage BESS deployment and drive monetization of multiple value propositions.
- A trained workforce to accelerate the economic viability of battery energy storage by advancing innovative and cost-effective technology solutions and streamlining common procurement and deployment practices.

CURRENT STATE	GAPS
PLANNING	
Properly estimating costs and benefits of multi-use energy storage is difficult given locational dependencies, unknown assumptions, forecasting challenges, interconnection uncertainties, and market and regulatory reforms.	<ul style="list-style-type: none"> • Common definitions and valuation of qualitative benefits used in project planning and analysis • Data-informed planning models that economically optimize single- and multi-use operation implement common, realistic, and well-communicated constraints • Common analysis frameworks with an established set of assumptions and cost bases that enable more accurate and relevant comparisons • Interconnection processes streamlined to mitigate timelines and related costs
PROCUREMENT	
Energy storage project costs vary widely due to differences in locational impacts, labor rates, ambient conditions, jurisdictional requirements, timing, and market forces.	<ul style="list-style-type: none"> • Specified project assumptions and locations for consistent and more accurate cost estimates • Life cycle assessments of commercial and emerging technologies to leverage environmental considerations in project cost justifications
DEPLOYMENT & INTEGRATION	
Project capital expenditures include contingency for cost uncertainties that could arise during engineering design and construction.	<ul style="list-style-type: none"> • Integration strategies that include technology-specific guidance to accelerate deployment timelines and reduce contingency and balance of plant costs • Case-specific costs understood early in the planning process
OPERATIONS & MAINTENANCE	
BESS operation and maintenance cost information is inadequate for fleet management.	<ul style="list-style-type: none"> • Monetization strategies for emerging technologies and novel use cases informed and documented by field testing and demonstrations • Augmentation strategies optimized with operational system data analysis • Trained operations and maintenance workforce to reduce system downtime, improve availability, and minimize associated costs
DECOMMISSIONING	
BESS asset value and liability at EOL is recognized but not well understood or documented.	<ul style="list-style-type: none"> • EOL costs and residual asset values applied to technoeconomic analyses during project planning



EPRI'S ROLE

EPRI is engaged in applied research and project activities for BESS affordability. These projects are a representative sample from the breadth of EPRI's activities related to this Future State Pillar.

FEATURED PROJECTS & PRIORITIES

Solar PV + Energy Storage Technoeconomic Analysis (Supplemental, [3002029087*](#))

The current Phase II of this project investigates the optimization and tradeoffs of different solar PV + energy storage configurations to support resource planning. The study analyzes the levelized cost of electricity (LCOE), capacity value, capital costs, and performance of several energy storage technologies paired with a solar photovoltaic (PV) plant.

Utility Battery Energy Storage System (BESS) Handbook (PS94L, [3002026792](#))

This handbook is a practical reference guide for a utility-connected BESS. It supports project cost reductions, risk minimization, schedule adherence, and revenue optimization. The handbook outlines the many facets of the complete project life cycle that need to be recognized for effective implementation of a utility-connected BESS, including the people and practices necessary for successful, safe, and reliable deployments.

EPRI's Distributed Energy Resource Value Estimation Tool (DER-VET*)

DER-VET™ provides a free, publicly accessible, open-source platform for calculating, understanding, and optimizing the value of energy storage and other distributed energy resources (DER) based on their technical merits and constraints. DER-VET uses load and other data to determine optimal system characteristics for maximizing benefits based on site-specific conditions and the value that can be extracted from targeted use cases. Industry stakeholders can apply this tool to inform project-level decisions based on sound technical understanding and unbiased cost-performance data.

EPRI REPORTS

Product ID	TITLE (Year Published)	Planning	Procurement	Deployment & Integration	Operation & Maintenance	Decommissioning
3002029466	Storage as a Transmission Asset: Stacking Market and Transmission Services (2024)	■				
3002026729	Energy Storage Valuation 2023: Functions, Methods, Tools, Lessons Learned, and Examples (2024)	■		■	■	
3002026999	State of Electric Storage in US Wholesale Electricity Markets (2023)	■			■	
3002026734	Technoeconomic Analysis of Centralized and Distributed Storage as a Non-Wires Alternative (2023)			■	■	
3002025178	Seasonal Energy Storage: A Technical and Economic Framework (2022) *			■	■	
3002024311	Design and Cost Basis for Bulk Energy Storage Study: Bulk Energy Storage Costs and Performance Supplemental Project (2022)		■		■	
3002025718	Circular Economy Metrics for the Electric Power Industry: Overview and Grounding Discussion (2022)	■			■	■
3002020594	Guidelines for Assessing End-of-Life Management Options for Renewable and Battery Energy Storage Technologies (2021) *	■				■

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The **FUTURE STATE** vision for clean battery energy storage is defined with support from its **ASPECTS**.

The **CURRENT STATE** of clean related to each project life cycle phase gives context to the identified **GAPS** that EPRI and others can address to advance deployment of clean battery energy storage.

FUTURE STATE & ASPECTS

CLEAN battery energy storage supports a decarbonized grid using equitable and responsible life cycle practices and stakeholder engagement, considering both environmental and human health impacts.

A future in which battery energy storage is **CLEAN** requires:

- Environmental and human health considerations that are reviewed during long-term energy resource planning.
- Decisions informed by systematic evaluations that quantify and compare the life cycle environmental and human health impacts of various battery energy storage technologies.
- Applied measurement, tracking, and valuation methods that include community benefits and equity during siting and permitting processes.
- Focus on reducing greenhouse gas emissions, critical mineral use, and waste that considers fair labor and environmentally responsible practices throughout the BESS technology supply chain.
- Technology and facility management strategies that are environmentally responsible, supported by a trained workforce in quality jobs, and demonstrated to be economically viable across various BESS technologies.

CURRENT STATE	GAPS
PLANNING	
Measurement and valuation of clean BESS benefits for communities lacks guidance and attention.	<ul style="list-style-type: none"> • Ecological impacts on communities to support engagement strategies and resource development • Determination of clean benefits, which considers the identification and quantification of BESS benefits to the environment and human health, to inform siting and planning decisions
PROCUREMENT	
“Clean” has been historically overshadowed by the electric power sector’s requirements for safety, reliability, and affordability.	<ul style="list-style-type: none"> • Clean resource planning frameworks informed by BESS life cycle assessments used in decision-making • Equitable procurement processes that consider technology-specific environmental and human health benefits and challenges
DEPLOYMENT & INTEGRATION	
Characterizing the environmental and human health impacts of BESS operation is an active area of research, and therefore related system designs and deployment practices that mitigate adverse impacts are not well-established.	<ul style="list-style-type: none"> • Characterization of clean energy storage considers technology-specific impacts of normal and abnormal system operation on the environment, human health, and community well-being to inform system design, deployment practices, and emergency preparedness • Clean measurement technology solutions that are system integrated to enable measurement and tracking of clean benefits and impacts
OPERATIONS & MAINTENANCE	
BESS operations impact on the environment, human health, and community well-being have not yet been monitored nor guidance developed.	<ul style="list-style-type: none"> • Common environmental reporting guidelines that include leading data collection practices for improving and supporting decarbonization strategies • Community benefits plan evaluation guidelines for optimizing operation strategies
DECOMMISSIONING	
Regulatory uncertainty and limited recycling options due to underdeveloped infrastructure and market fluctuations create unreliable estimates for EOL value.	<ul style="list-style-type: none"> • EOL regulatory and industry development awareness to develop actionable and streamlined decommissioning strategies that are socially and environmentally just



EPRI'S ROLE

EPRI is engaged in applied research and project activities for clean battery energy storage. These projects are a representative sample from the breadth of EPRI's activities related to this Future State Pillar.

FEATURED PROJECTS & PRIORITIES

Environmental Health and Safety Aspects of Advanced Lithium and Non-Lithium Storage (PS94I)

This work conducts a literature review and detailed interviews to compile and compare the EH&S aspects associated with novel and developing energy storage technologies. The resulting scorecard is intended to be an ongoing work, updated as new developments and research results arise, that serves as an educational tool for considering benefits and challenges of a technology at the planning stage as well as providing guidance for vendor discussions and RFP elements during procurement.

Lessons Learned from Battery Energy Storage System Permitting (PS94I)

The evolution of siting and permitting considerations are reviewed with the objective of helping stakeholders deliver project benefits and overcome deployment barriers at local, regional, and national levels. It is based on interviews with project developers and reviews of publicly available information resources, including permitting dockets and prior reports.

Community Engagement, Perception and Benefits for Energy Storage Projects (TI)

Energy storage technologies, operations, and benefits to electricity systems and the public are not well-understood by many people. This can result in confusion and misinformation which can derail deployment and operations. This work will survey public knowledge and perceptions of energy storage technologies and their features to assist with developing educational tools for the public, new workers to the field, jurisdictional authorities and policy-makers. The insights will inform all project life cycle phases.

EPRI REPORTS

Product ID	TITLE (Year Published)	Planning	Procurement	Deployment & Integration	Operation & Maintenance	Decommissioning
3002028618	Second Life for Large-Format Lithium Ion Batteries (2023)	■	■	■		
3002023723	Environmental Impacts of Battery Recycling: A Summary of Recent Environmental Life Cycle Assessment Results (2022)					■
3002025142	Evaluating Environmental Impacts of Firefighting Water Releases at Lithium Ion Battery Energy Storage System Facilities (2022)				■	■
3002025849	Novel Battery Module Designs to Enhance Sustainability (2022)		■	■		■
3002019811	Sustainability Aspects of the Lithium Ion Battery Supply Chain (2021) *	■	■			■
3002021604	Modeling Greenhouse Gas Emissions in Energy Storage and Distributed Energy Resource Decision-Making Frameworks (2021)	■	■			
3002016593	Environmental Health and Safety Comparison Across Multiple Utility-Scale Energy Storage Technologies (2020) *	■	■			
3002014157	Air Quality Impacts of Fueled Distributed Generation (2018) *	■			■	

* Indicates the resource is Free to the Public



The table below (page 1 of 2) organizes Future State Pillar gaps by project life cycle phases and EPRI’s Energy Storage and Distributed Generation Program project sets (PS). The gaps are printed in their respective future state pillar color:

SAFE	RELIABLE	AFFORDABLE	CLEAN
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This organization of gaps facilitates EPRI’s strategic planning and future program activities. This list is non-exhaustive; gaps and activities may overlap. Collaboration and communication across project sets, project life cycle activities, and stakeholders is paramount for advancing battery energy storage deployment.

GAPS	PLANNING	PROCUREMENT	DEPLOYMENT & INTEGRATION
Safety, Environment, & Community Engagement (PS94I)	Community engagement strategies	Common safety requirements	Safety-informed deployment strategies
	Community engagement costs	Common hazard assessment frameworks	Characterization of EH&S hazards
	EH&S data and modeling	Life cycle assessments	Common safety checklists
	Trained analysis and grid planning personnel	Clean resource planning frameworks	Characterization of clean energy storage
	Common definitions and valuation of qualitative benefits	Equitable procurement processes	Clean measurement technology solutions
	Ecological impacts		
	Determination of clean benefits		
Technology Evaluation (PS94J)	Common data collection and analysis methodologies	Common safety requirements	Safety-informed deployment strategies
	Ecological impacts	Common hazard assessment frameworks	Characterization of EH&S hazards
	Common analysis frameworks	Performance characterization	Inventory of component reliability and failure rates
		Derisked technology selection	Integration strategies
		Life cycle assessments	Characterization of clean energy storage
Planning & Economic Analysis (PS94K)	Community engagement costs	Performance characterization	Integration strategies
	Common data collection and analysis methodologies	Specified project assumptions	Case-specific costs
	Common definitions and valuation of qualitative benefits	Life cycle assessments	Characterization of clean energy storage
	Data-informed planning models	Clean resource planning frameworks	
	Common analysis frameworks		
Deployment & Operations (PS94L)	EH&S data and modeling	Common safety requirements	Safety-informed deployment strategies
	Trained analysis and grid planning personnel	Performance characterization	Common safety checklists
	Common data collection and analysis methodologies	Common system reliability requirements	Inventory of component reliability and failure rates
	Interconnection processes	Specified project assumptions	Common design, data collection, and analysis guidelines
		Clean resource planning frameworks	Integration strategies
			Clean measurement technology solutions
Customer Energy Storage, Microgrids, & Distributed Generation (PS94M)	Common data collection and analysis methodologies	Common safety requirements	Safety-informed deployment strategies
	Common definitions and valuation of qualitative benefits	Performance characterization	Common safety checklists
	Data-informed planning models	Common system reliability requirements	Inventory of component reliability and failure rates
	Life cycle assessments	Specified project assumptions	Case-specific costs
	Common analysis frameworks	Equitable procurement processes	
	Determination of clean benefits		



The table below (page 2 of 2) organizes Future State Pillar gaps by project life cycle phases and EPRI’s Energy Storage and Distributed Generation Program project sets (PS). The gaps are printed in their respective future state pillar color:

SAFE	RELIABLE	AFFORDABLE	CLEAN
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This organization of gaps facilitates EPRI’s strategic planning and future program activities. This list is non-exhaustive; gaps and activities may overlap. Collaboration and communication across project sets, project life cycle activities, and stakeholders is paramount for advancing battery energy storage deployment.

GAPS	OPERATION & MAINTENANCE	DECOMMISSIONING
Safety, Environment, & Community Engagement (PS94I)	Safety-informed operation strategies	Decommissioning protocols
	Trained O&M workforce	De-energization technologies
	Common environmental reporting guidelines	Data-informed definition of EOL
	Community benefits plan evaluation guidelines	Circular economy practices
		EOL costs and residual asset values
		EOL regulatory and industry development awareness
Technology Evaluation (PS94J)	Safety-informed operation strategies	Decommissioning protocols
	Data-informed asset management strategies	Data-informed definition of EOL
	Monetization strategies	
Planning & Economic Analysis (PS94K)	Safety-informed operation strategies	Data-informed definition of EOL
	Monetization strategies	Circular economy practices
	Augmentation strategies	EOL costs and residual asset values
		EOL regulatory and industry development awareness
Deployment & Operations (PS94L)	Safety-informed operation strategies	Decommissioning protocols
	Safety system O&M guidelines	Data-informed definition of EOL
	Data-informed asset management strategies	Circular economy practices
	Integrated, real-time monitoring and control technologies	
	Augmentation strategies	
	Trained O&M workforce	
	Common environmental reporting guidelines	
Customer Energy Storage, Microgrids, & Distributed Generation (PS94M)	Safety system O&M guidelines	Decommissioning protocols
	Data-informed asset management strategies	De-energization technologies
	Integrated, real-time monitoring and control technologies	Data-informed definition of EOL
	Monetization strategies	Circular economy practices
		EOL costs and residual asset values

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, nonprofit, public benefit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

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