MPSC
MICHIGAN PUBLIC SERVICE COMMISSION

Study of Long-Duration and Multi-Day Energy Storage

February 27, 2025

Dan Scripps, Chair
Alessandra Carreon, Commissioner
Katherine Peretick, Commissioner

LARA
LICENSING AND REGULATORY AFFAIRS

Contents

Executive Summary i

Acknowledgements 1

1. Introduction 2

2. Energy Storage in Michigan 4

DOE Report on Best Practices for Modeling Energy Storage 7

3. A National Perspective 9

State-level LDES Policies and Deployments 9

Other Relevant LDES Pilots 13

4. Costs and Specifications 19

Challenges to Finding Data 19

Other Potential Data Sources 21

5. Modeling LDES 23

Data Collection and Model Inputs 23

Grid Planning Modeling with LDES 26

Accurate Representation of Technologies: 27

Long-term Grid Planning: 29

Challenges of Modeling LDES 32

6. LDES as a Replacement Resource 35

Generation Replacement Analysis 35

Fossil Generation Replacement Optimization Using Analytical Software 38

Replacement Analysis Methodology 41

Sample Analysis 43

7. Grid Impacts and Considerations 46

Transmission System Impacts 46

Resilience Impacts 50

8. Environment and Community Impacts 54

Resource Siting Impacts 54

EJ Community Mapping 56

Conclusion 62

Appendices A-1

Appendix A: List of Tables & Figures A-1
Appendix B: Advanced Modeling Tools & Software B-1
Appendix B.1: Sources of data for LDES modeling B-1
Appendix B.2: Grid planning tools for LDES modeling B-3
Appendix C: QuEST Equity Karn Unit 1 Sample Analysis C-1

Executive Summary

In November 2023, Governor Gretchen Whitmer signed into law a broad package of legislation focused on energy policy. The new laws, Public Acts 229 through 235 of 2023, establish clean and renewable energy standards and a statewide energy storage target, among other requirements. 2023 PA 235, Section 101, establishes a statewide energy storage target of 2500 megawatts (MW) of capacity and directs the Commission to develop a study on long-term energy storage systems and multi-day energy storage (MDES) systems by February 27, 2025.[1]

On February 8, 2024, the Commission issued an Order in Case No. U-21571, which clarified two components of the study directed by the Legislature. First, long-term energy storage systems are synonymous with long-duration energy storage (LDES) systems. Second, the study will be provided to the Legislature no later than February 27, 2025. The Commission's order directed Staff to create a report focused on long-duration and multi-day storage resources that:

1. Includes details of foundational energy storage work that resulted from the Staff's engagement with the US Department of Energy (DOE) throughout 2022 and 2023.
2. Includes recent utility announcements and regulatory approvals from state public utility commissions relating to the deployment of long-duration and multi-day storage.
3. Provides utilities and interested persons with information about publicly available data and resources that includes the technical and cost specifications necessary to create generic storage resources, including long-duration and multi-day storage, which can be selected by a capacity expansion model.
4. Outlines recommended modeling practices and provides guidelines for long-duration and multi-day energy storage modeling and best practices to ensure that capacity expansion modeling captures the full value of long-duration and multi-day storage.
5. Provides an analysis of the aggregated capacity of existing fossil resources in each regulated utility service territory within Michigan that utilities should analyze for replacement with storage resources in their next IRP after the issuance of the report.
6. To the extent practicable, provides indications of what capacity may be better suited to be replaced with long-duration or multi-day storage or guidelines for how utilities should perform this assessment.
7. To the extent practicable, identifies high-level grid characteristics that may impact the decision-making process and recommendations for how to incorporate in utility modeling.

[1] PA 235 of 2023, Section 101(7).

8. Provides an analysis, as set forth above and to the extent practicable, with mapping to indicate resource location and identifying locations within environmental justice communities.

Commission Staff enlisted the DOE to aid in gathering data, understanding analysis tools and modeling best practices, and guiding Staff in completing portions of the report that can be used as a foundation for energy storage work. Staff appreciates the engagement and efforts of the DOE representatives who were instrumental in furthering the Commission's knowledge of energy storage as it works to ensure Michigan's 2,500 MW statewide storage target is achieved.

RECOMMENDATIONS

As a result of its work developing this report, Staff has identified the following recommendations as useful to advance the future consideration of long-duration and multi-day energy storage:

Section 2-1: Utilities should continue to improve the evaluation and modeling of all energy storage in long-term resource planning, including adopting best practices such as hourly/sub-hourly optimizations, advanced market dynamics (imperfect foresight, advanced cycling, impact to ancillary market prices), and consideration of multiple value streams.

Section 4-1: Utilities should use public data to source cost and technology information for the modeling of energy storage in IRPs. If adequate public data is not available, utilities should use data that can be shared with Staff and intervening parties through nondisclosure agreements to allow the review of sensitive information.

Section 5-1: To ensure that LDES technologies are adequately represented in utility modeling, the following best practices related to the sourcing and application of data should be adopted to the extent feasible:

- Use high-resolution data in the spatial and temporal dimensions to capture detailed geographic and operational characteristics.
- Use public data sources to promote an open and transparent planning process.
- Use actual operational data from deployments and pilots to validate sources when available.

Section 5-2: Utilities should investigate the use of advanced tools and techniques, such as those identified in Section 5, and work to incorporate LDES modeling best practices resulting from that section as necessary to accurately model the operations of LDES and MDES technologies, their participation in markets, and their support of the reliability and resilience of the system. A focus should be on practical

application to current planning practices, including applying or supplementing current modeling software and tools.

Section 6-1: Electric providers in the UP should consider coordinating storage planning efforts, where possible, to evaluate candidate resources identified in this analysis and provide any results from this effort in their respective IRPs.

Section 6-2: Each electric provider with candidate resource capacity identified in the example study included in Section 6 of this report should conduct a full analysis of its existing fleet, considering the replacement of existing generation with LDES, MDES, or other solutions, in at least the capacity amount identified in this report and using the best practices identified in Sections 4 through 8 of this report.

Section 7-1: Utilities, regulators, and other interested persons who participate in RTO/ISO system planning activities should proactively request that the RTO/ISO investigate storage alternative solutions as transmission planning solutions during the transmission planning process to ensure they are adequately considered.

Section 7-2: The Commission should encourage RTOs/ISO to develop specific metrics and objectives for resilience planning to incorporate these metrics/objectives into existing transmission planning processes. The Commission should direct Staff to develop specific metrics and objectives related to resilience as part of the distribution planning process to encourage consideration of resilience alongside traditional reliability metrics when analyzing regulated utility investment.

Section 8-1: As part of future IRP filings and consistent with the requirements in MCL 460.6t, utilities should develop and include maps using tools such as MiEJScreen or the EPA EJ Screen that identify the location of proposed and existing power plants in Environmental Justice (EJ) communities and further detail how EJ communities were considered when making decisions about existing resource retirements and future resource investment. This information should be used to inform the analysis required by MCL 460.6t of the impact of the proposed course of action on EJ communities and support this plan as the most reasonable and prudent in comparison to alternatives.

Acknowledgements

This report was created by the Staff of the MPSC's Energy Resources Division in consultation with and assisted by researchers at the US DOE's Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (Sandia) and researchers from the nonprofit Clean Energy State Alliance (CESA). The Commission would like to thank all its Staff who contributed to the development of this report, as well as persons outside of the organization who contributed to its development, and specifically the following group members:

Jon DeCooman, MPSC

Jesse Harlow, MPSC

Cody Matthews, MPSC

Naomi Simpson, MPSC

Cody Jack Newlun, Sandia

Tu Nguyen, Sandia

Jeremy Twitchell, PNNL

Todd Olinsky-Paul, CESA

Austin Glass, MPSC

Zack Heidemann, MPSC

Megan Mix, MPSC

Karsten Szajner, MPSC

Will McNamara, Sandia

David Rosewater, Sandia

Olivia Tym, CESA

Organizations

MPSC
MICHIGAN PUBLIC SERVICE COMMISSION

The Michigan Public Service Commission's mission is to serve the public by ensuring safe, reliable, and accessible energy and telecommunications services at reasonable rates.

Sandia National Laboratories

Sandia National Laboratories began with a focus on nuclear technologies and has since evolved into a multidisciplinary laboratory focused on matters of national security.

Pacific Northwest
NATIONAL LABORATORY

The Pacific Northwest National Laboratory is a national laboratory under the Department of Energy that focuses on innovations that advance sustainable energy and transition new technologies to market.

CleanEnergy States Alliance

Clean Energy States Alliance is a bipartisan coalition of US state energy agencies working together to advance the rapid expansion of clean energy technology and is managed by the nonprofit Clean Energy Group.

1. Introduction

In November 2023, Governor Gretchen Whitmer signed into law a broad package of legislation focused on energy policy. The new laws, Public Acts 229 through 235 of 2023, establish clean and renewable energy standards and a statewide energy storage target, among other requirements. Among these new laws, 2023 PA 235 establishes a statewide energy storage target of 2500 megawatts (MW) of capacity and directs the Commission to develop a study on long-term energy storage systems and multi-day energy storage systems by February 27, 2025.

In the order, the Commission clarified two components of the study directed by the Legislature. First, long-term energy storage systems are synonymous with long-duration energy storage systems. Second, the study will be provided to the Legislature no later than February 27, 2025.

This report is the result of the study efforts of Commission Staff (Staff) with assistance from experts at the Department of Energy (DOE)'s national laboratories to provide a foundational assessment of long-duration energy storage (LDES) and multi-day energy storage (MDES) technologies and how they may contribute to meeting the energy needs of the state while achieving decarbonization and other environmental targets both statewide and nationally. For the purposes of this report, LDES and MDES will be defined as stated in MCL 460.1007 (g) and (k), respectively:

- "Long-duration energy storage system" means an energy storage system capable of continuously discharging electricity at its full rated capacity for more than 10 hours.
- "Multi-day energy storage system" means an energy storage system capable of continuously discharging electricity at its full rated capacity for more than 24 hours.

Therefore, these groups of technologies will be referred to collectively as "LDES" when discussing LDES and MDES technologies generally in this report, without the need to distinguish between the discharge duration capabilities of the two different technology groups.

The purpose of this report is to provide information on LDES technologies and their applications and to serve as a guide on the best practices for incorporating these technologies into utility planning functions, such as capacity expansion modeling for IRPs. This report will discuss the following topics in its sections:

- A foundational background of energy storage evaluation and development both in the state and nationally, as well as a review of a previous report on the best practices for modeling energy storage resources developed by the DOE for the Commission.
- Identifying sources of cost and technical specifications for LDES and the best practices for the modeling of LDES in utility planning functions.

- A presentation of an example replacement evaluation of the state's existing fossil-fueled generating fleet with energy storage of different durations and identification of additional factors that must be considered as part of a complete replacement analysis, such as grid and Environmental Justice impacts.

The report concludes with final recommendations on how LDES technologies can best be used to serve Michigan, given the focus on the transition to a grid running on clean and renewable energy.

2. Energy Storage in Michigan

Between 2017 and 2021, energy storage gained attention in Michigan as utilities recognized its potential to support clean energy goals and improve resource adequacy. With growing pressure to reduce greenhouse gas emissions and integrate more renewable energy, utilities identified the potential for storage to manage the variability of wind and solar while enhancing grid flexibility. Both DTE Energy and Consumers Energy, the state's largest utilities, included storage in their integrated resource plans (IRPs), which are long-term resource strategies. However, the role of storage in these plans was initially limited due to various challenges in modeling its performance and accounting for its different potential value streams, which limited its cost-effectiveness. Consumers Energy's 2018 IRP, filed in Case No. U-20165, proposed 450 MW of energy storage by 2040 but included only small-scale pilot projects in the near term.[2] DTE's 2020 IRP, filed in Case No. U-20471, similarly included storage but at a modest scale, emphasizing its potential while acknowledging uncertainties that limited its selection as a resource solution.[3]

In the following round of IRPs, Consumers Energy committed to deploying 75 MW of storage by 2027, with a more ambitious goal of 475 MW by 2040.[4] The modeling in DTE's IRP had a focus on better identifying the potential value of energy storage outside of capacity and energy markets. DTE used a tool, Distributed Energy Resource-Valuation Estimation Tool (DER-VET), separate from its long-term capacity expansion model to identify the potential value a storage asset would provide in the ancillary service and frequency regulation markets. Although Staff and interested parties identified additional areas of improvement, DTE's more robust modeling resulted in the selection of 240 MW of storage by 2027 and 1,810 MW by 2042.[5] This IRP also included a proposal for a battery energy storage resource, the Trenton Channel Battery Energy Storage System (BESS). At 220 MW, this facility will be the largest battery storage resource in the state once it reaches commercial operation in 2026.

Historically, utilities faced difficulties in quantifying the full range of storage capabilities and ancillary benefits using traditional modeling techniques. Traditional IRP models were designed for large, baseload power plants, and adapting these models to capture the nuanced, time-sensitive operations of energy storage requires significant advancements. These modeling challenges, coupled with the technical challenge of determining the capacity value of storage for reliability purposes, led to a cautious approach in which storage's inclusion in the near-term was often limited to pilots or as a supplemental resource rather than a core component of Michigan's future resource strategy. Efforts to improve the robustness of the utilities' consideration of storage, such as DTE's use of the DER-VET modeling tool to account

[2] Exhibit A-2, p. 166, Case No. U-20165.
[3] Exhibit A-3, p. 156, Case No. U-20471.
[4] Exhibit A-2, p. 165, Case No. U-21090.
[5] Exhibit A-3.1, p. 123, Case No. U-21297.

for additional value streams in Case No. U-21297, have just begun to be employed. However, even the relatively limited expansion of energy storage modeling seen in the state thus far has resulted in additional storage being selected as a resource option due to a better accounting of its costs and value.

Michigan's current energy storage landscape includes a small mix of large-scale and small-scale facilities. The Ludington pumped storage plant, one of the nation's largest pumped hydro facilities, provides 2,292 MW of capacity through its six turbine generators. The Ludington pumped storage plant provides its co-owners, DTE Electric and Consumers Energy, with a unique depth of experience operating an LDES facility in the MISO market for decades. On a smaller scale, several utilities operate battery energy storage facilities, which are summarized in **Table 2.1**.

Table 2.1

Small-scale Utility-owned Energy Storage in Michigan[6, 7]

Facility Name	**Utility**	**Installed Capacity (MW)**	**Energy (MWh)**	**Commercial Operation Date**
Airpark	Consumers Energy	2	8	2025
Cadillac Solar + BESS	Consumers Energy	0.5	1	2021
Circuit West	Consumers Energy	0.5	0.5	2021
Parkview	Consumers Energy	1	1	2018
Innovation Center	Consumers Energy	0.1	0.35	2021
The 200 Building	Consumers Energy	0.25	0.5	2021
Star of the West	Consumers Energy	0.25	0.5	2021
Bissell	Consumers Energy	0.25	0.5	2021
Battery Trailer (Westland)	DTE Electric	1	4	2023
Ford Industrial site	DTE Electric	0.125	0.506	2021
Total		**5.975**	**16.856**	

In addition to these utility installations, residential and nonresidential distributed generation programs supported the installation of 28.6 MW of energy storage, as of the publication of the MPSC's 2024 report on renewable energy and distributed

[6] 2024 Consumers Energy Company Electricity Storage Systems Report.
[7] 2024 DTE Electric Company Storage Report.

generation.[8] In addition to these energy storage facilities currently in operation, numerous other storage resources are currently under development with pilots testing various technologies and use cases, as well as an additional 709 MW of storage being developed under Commission-approved contracts or proposals, as summarized in **Table 2.2**.

Table 2.2

Commission-approved Energy Storage Projects Currently in Development

Facility Name	**Utility**	**Installed Capacity (MW)**	**Energy (MWh)**	**Expected Commercial Operation Date**
Tibbits Energy Storage[9]	Consumers Energy	100	400	2025
Iosco Battery Storage	Consumers Energy	30	120	2026
Weadock Battery Storage	Consumers Energy	45	180	2026
Century Oaks Battery Storage[10]	Consumers Energy	200	800	2026
Voyager Energy Storage[11]	Consumers Energy	100	400	2027
Slocum Battery Storage[12]	DTE Electric	14	56	2026
Trenton Channel Battery Storage[13]	DTE Electric	220	880	2026
Total		**709**	**2,836**	

These storage projects represent a critical first step toward achieving Michigan's goal of incorporating more renewable energy in the state's energy portfolio while maintaining grid stability.

[8] Status of Renewable Energy, Distributed Generation, and Legacy Net Metering in Michigan.
[9] 4/11/24 Order in MPSC Case No. U-21090.
[10] 5/13/24 Order in MPSC Case No. U-21090.
[11] 9/27/24 Order in MPSC Case No. U-21090.
[12] 11/18/22 Order in Case No. U-20836.
[13] 3/15/24 Order in MPSC Case No. U-21566.

DOE Report on Best Practices for Modeling Energy Storage

In 2023, the MPSC sought to enhance its understanding of the best practices for integrating energy storage in utility IRPs with support from the US DOE. Through federal grant funding, the MPSC received technical assistance from Argonne National Laboratory and the National Renewable Energy Laboratory (NREL) as part of the US DOE's grid modernization lab consortium.[14] This effort aimed to address the complexities utilities face in modeling energy storage technologies, particularly as rapid cost declines and the unique performance capabilities of energy storage make it challenging for utilities to accurately assess its value in IRPs and distribution planning.

As part of the technical assistance, the national labs provided a series of educational presentations to MPSC Commissioners and Staff to enhance their knowledge of energy storage systems, valuation tools, and operational characteristics. The workshops focused on how storage could be modeled to optimize its role in meeting capacity needs, improving grid reliability, and serving as a non-wires alternative (NWA) to traditional grid investments. In particular, the Staff was introduced to tools like DER-VET and the Energy Storage Evaluation Tool, which help utilities analyze and balance an energy storage asset's participation in nontraditional value streams, such as frequency regulation, voltage support, and transmission deferral to optimize its economics. This technical assistance helped the MPSC evaluate lagging pricing data and other challenges to perform this analysis in IRPs, ensuring that storage technologies were better considered in long-term utility planning.

The associated DOE storage best practices report first reviewed the dramatic cost reductions in lithium-ion batteries and other storage technologies, which dropped by as much as 89% from 2010 to 2021, making storage more economically viable. The report also discussed the broad value of energy storage to the bulk energy, ancillary services, and capacity markets, as well other nontraditional use cases like NWAs and local reliability benefits. The report noted that challenges in accurately capturing these benefits in IRPs persist, as many existing models struggle with optimizing storage's flexible operations to maximize these value streams. Additionally, lessons from other states provided insights into best practices for integrating storage into utility planning, highlighting the need for continued regulatory support and advanced modeling tools to fully unlock storage's potential in Michigan.

The report suggested several critical changes to energy storage modeling in IRPs to improve the accuracy and comprehensiveness of its evaluation. One key recommendation was the need for models that can account for sub-hourly operational flexibility. Many current models rely on hourly time resolution, or the even less granular representative weeks, which fail to capture the dynamic capabilities of storage systems in real-time grid operations, such as frequency regulation and rapid response to grid fluctuations. Additionally, the report calls for more advanced tools to supplement traditional long-term capacity expansion

[14] The United States' Department of Energy's Grid Modernization Lab Consortium: https://www.energy.gov/doe-grid-modernization-laboratory-consortium-gmlc-awards.

modeling that can accurately capture value stacking. Value stacking is a term for operating energy storage to provide multiple services simultaneously, such as energy arbitrage, capacity, and ancillary services. This would allow utilities to better assess the economic benefits of storage in multiple markets and levels of grid connection.

The report recommended improving the integration of the degradation of storage systems into modeling, as many tools do not adequately account for how frequency of cycling (the charging and discharging of energy stored in the energy storage system) impacts the long-term performance and lifecycle costs of storage systems. The report also suggested adopting models that can better handle uncertainty in pricing and market conditions, as storage revenues and costs are influenced by fluctuating energy prices, evolving market rules, and decarbonization efforts. Lastly, utilities are encouraged to adopt a flexibility-first approach in modeling, where storage is evaluated as a core asset capable of both short-term and long-term grid services, rather than as a peripheral or backup resource. These enhancements would help utilities optimize the deployment of energy storage and better integrate it into future grid planning.

Due to the timing of its release, there have not been any utility IRPs filed since the national labs provided this report to Staff. Given the complexity of energy storage modeling, the nascency and rapid development of storage technology, and the complexity in achieving some of the more aspirational recommendations, it is reasonable to expect improvements to energy storage modeling within utility IRPs to be incremental. Due to the difficulty of achieving some of the initial report's recommendations, utilities should continue to work closely with Staff when developing their IRP. For example, DTE provided Staff the interim results of its storage modeling prior to filing their IRP application in Case No. U-21193. This helped to inform Staff's review of energy storage modeling in that proceeding. Building upon the learnings from that case, additional industry research, and assistance from the DOE, this current report further refines previous recommendations to ensure they remain relevant to the proper evaluation of LDES.

Section Recommendation:

2-1: Utilities should continue to improve the evaluation and modeling of all energy storage in long-term resource planning, including adopting best practices such as hourly/sub-hourly optimizations, advanced market dynamics (imperfect foresight, advanced cycling, impact to ancillary market prices), and consideration of multiple value streams.

3. A National Perspective

State-level LDES Policies and Deployments

Efforts to achieve decarbonization (i.e., reducing reliance on fossil fuels and replacing them with renewable and clean energy resources) are advancing in regulatory and policymaking proceedings at both the national and state levels. The US has adopted a national target of 100% carbon-free electricity by 2035 and net-zero emissions by 2050, with similar goals being adopted in numerous states.[15, 16] Meeting these goals will require significant deployment of renewables and other carbon-free forms of generation. Research also shows, however, that the most economically advantageous approach to decarbonization includes deployment of significant energy storage resources. The optimal role of LDES in each state's decarbonization pathway can vary significantly. However, a review of state-level policymaking across the nation has revealed that LDES technology is less mature and, as a result, is often subject to significantly less intensive and accurate study than other forms of generation or storage. Success stories from some states suggest that proper evaluation of LDES projects will likely be facilitated by the existence of enabling policies at the state level and, in contrast, hindered by the nonexistence or inadequacy of such policies.

Policymaking related to energy storage deployment has begun to develop in states over the last decade. Since 2010, 15 states have adopted policies addressing energy storage deployment. As of October 2024, 12 states (including Michigan) have established a procurement target, goal, or mandate for energy storage deployment.[17] States have also established other enabling policies for energy storage, such as providing financial incentives/subsidies (California, Maryland, New Jersey, New York); sanctioning energy storage demonstration projects (Massachusetts, Maryland, New York, Utah, and Washington); and requesting or requiring the inclusion of energy storage considerations in utility-integrated resource plans (Nevada, New Mexico).[18] In each case where a state's policies do not contain specific requirements for LDES resource development, the state policies are generally applicable to all storage technologies, including, but not limited to, LDES.

The development of state policies specific to LDES remains a nascent undertaking. In general, there is little consensus across the US electricity sector about the specifics of when, where, and how LDES should be deployed. Although research and experience, including the operation of the Ludington pumped storage facility in Michigan, agree that there are grid benefits to LDES technologies, regulators may be

---

[15] "Pathways to Commercial Liftoff: Long Duration Energy Storage." US Department of Energy, May 2023.
[16] Clean Energy Collaborative, Clean Energy States Alliance (CESA).
[17] The 11 states that have adopted an energy storage procurement target, goal or mandate are California, Oregon, Nevada, Illinois, Virginia, New Jersey, New York, Connecticut, Massachusetts, Maine, Rhode Island, and Michigan.
[18] "State Level Policy: Building Markets for Long Duration Energy Storage." Will McNamara. Sandia National Laboratories. October 23, 2023.

inclined to enact policies to address more near-term needs for energy storage that can be fulfilled by short-duration technologies. Without well-designed policies and evaluation methods, it will be difficult to establish incentives and market mechanisms that are uniquely tailored to LDES technologies, perpetuating conditions in which shorter-term solutions with shorter-term goals are the only viable options. Legislators and regulators can address the existing policy gap regarding LDES by maintaining an awareness of approaches that have enabled LDES development in other states and by considering action across the following policy pathways:

- Consider policies that can be developed to enable the known best use-case scenarios for LDES.
- Require the evaluation of LDES in long-term system planning, particularly within the framework of established decarbonization goals.
- Revise existing energy storage procurement practices and targets to require specific amounts of LDES to be deployed.
- Support the early deployment of LDES through incentives to developers and/or ensuring cost recovery for utility pilot programs.
- Develop supportive market designs that begin to capture the full value of LDES, allowing it to play a greater role in meeting resource adequacy requirements, providing resilience and other ancillary services.

There are multiple examples available from states where policymaking specific to LDES or projects intended to develop and assess the potential of LDES technologies have advanced.

In 2016, the California Legislature expressed support for long-duration bulk storage, which resulted in state-sanctioned modeling to quantify the amount of LDES that would be required in the state to achieve California's interim goal of 60% renewable penetration by 2030. The modeling concluded that capacity additions of around 2 GW of LDES technologies with durations of at least 10 hours would be needed. This led to a regulatory action (R.20-05-003) in August 2024 by the California Public Utilities Commission (CPUC) which established a centralized procurement strategy through which the statewide energy office will be tasked with procuring up to 1 GW of LDES with at least a 12-hour discharge period and up to 1 GW of MDES. These resources are scheduled to be in place between 2031 and 2037 to support the state's decarbonization goal of 100% carbon-free electricity by 2045.[19]

In addition to these planned procurements, the California Energy Commission's (CEC) LDES program has been established to invest $330 million in projects that accelerate the implementation of LDES solutions to increase the resiliency and reliability of the state's energy infrastructure and meet the state's energy and climate goals. A major focus of the program is to support development of non-

[19] California Public Utilities Commission. https://www.cpuc.ca.gov/news-and-updates/all-news/cpuc-advances-clean-energy-with-centralized-procurement-strategy.

lithium-ion energy storage technologies to foster diversity and competition in the market.[20] The CEC awarded a $30 million grant to Form Energy to build a 5 MW / 500 MWh iron-air battery storage project at a Pacific Gas & Electric substation in Mendocino, California. It will be the largest LDES project to be built in California and is expected to continuously discharge to the grid for up to 100 hours.[21]

In New York, energy storage is a key component of the state's clean energy goals, which include 70% renewable energy on the grid by 2030 and 100% emissions-free electricity by 2040. To address their anticipated energy storage needs, an energy storage procurement program in New York was signed into law in 2018 by former Governor Andrew Cuomo.[22] The legislation established the Energy Storage Roadmap ("Roadmap") to support the growth of the energy storage market in the state and includes policies and financing to meet the state's clean energy goals and combat climate change. New York had a goal of 1,500 MW of energy storage by 2025, which was subsequently doubled in 2022 to 6 GW by 2030. To support these procurement goals, the New York State Public Service Commission (NY-PSC) ordered a $310 million "bridge fund" to jumpstart the energy storage market.[23]

In December 2022, the New York State Energy Research and Development Authority (NYSERDA) and the New York State Department of Public Service (NYDPS) submitted the Roadmap to the NY-PSC.[24] The Roadmap included recommendations regarding specific levels of LDES deployment that would be needed for the state to achieve its goal of 100% carbon free electricity by 2040. The roadmap was based upon modeling exercises conducted by the firm E3 that included simulations of storage at varying levels of duration (i.e., 4, 6, 8, and 10 hours). These simulations concluded the state would need more than 4 GW of LDES by 2035 and 6.8 GW by 2050 to achieve and sustain the state's decarbonization goal. Notably, the Roadmap suggests giving NYSERDA flexibility to determine specific duration requirements for bulk solicitations. Recognizing this need, the NY-PSC issued an order in June 2024 that directs NYSERDA, which competitively procures bulk energy storage dispatch rights through Requests for Proposals (RFPs), to include in each bulk procurement a target of 20% of LDES resources.[25]

In Virginia, multiple clean energy and storage-related provisions are beginning to encourage a strong marketplace for LDES development. The 2020 Virginia Clean Economy Act (VCEA) established a decarbonization goal (zero carbon emissions by 2050); a goal for state utilities to generate electricity from 100% renewable energy sources by 2045; and an energy storage procurement target of 3.1 GW by 2035,

---

[20] "Long Duration Energy Storage Program." California Energy Commission.
[21] "CEC Awards $30 Million to 100-Hour, Long-Duration Energy Storage Project." California Energy Commission. December 13, 2023.
[22] Assembly Bill A6571, State of New York.
[23] Governor Cuomo Announces Dramatic Increase in energy Efficiency and Energy Storage Targets to Combat Climate Change.
[24] "New York State Energy Storage Roadmap and Department of Public Service/ New York State Energy Research and Development Authority Staff Recommendations (Roadmap)."
[25] NYSERDA Energy Storage Program.

subject to approval by the Virginia State Corporation Commission.[26] Despite these aggressive goals, current regulatory and market environments do not account for the benefits of deploying LDES to the grid, and Virginia's procurement target does not specify the type of storage required or minimum durations. Thus, the market reality in the state is that developers are not compensated for the full value of LDES projects, making them a less favorable target for study and deployment.[27]

Virginia has authorized state-sanctioned, utility-led pilot programs to evaluate LDES technologies. In September 2023, the Virginia State Corporation Commission approved an application submitted by Dominion Energy—the largest utility in the state—to develop a pilot program which will seek to test two novel non-lithium technologies designed for LDES applications. The two co-located technologies that will be tested in this pilot are Form Energy's 5 MW/500 MWh iron-air battery that is expected to store energy for up to 100 hours, and Eos Energy's 4 MW/16 MWh zinc-hybrid battery that is expected to store energy for up to 16 hours. The $70 million pilot will be located at Dominion Energy's Darbytown Power Station in Henrico County, Virginia, and is expected to come into operation by late 2026. In addition to these pilot projects, Dominion is also testing a 1.5 MW metal-hydrogen battery from EnerVenue, which has the capability of discharging energy for up to 10 hours at a time, at the Multi-Purpose Center at Virginia State University.[28]

In Minnesota, utilities must procure a significant amount of renewable capacity to meet the 2040 carbon-free electricity standard, estimated to require approximately 8 GW of wind and 7.6 GW of solar additions by 2040.[29] At this time, no procurement policy for energy storage or other LDES-specific policy has been established. Recognizing the need for further analysis of LDES, the Minnesota Department of Commerce commissioned the "Energy Storage Capacity Study" report in 2024.[30] The report identified the potential to leverage LDES to make the transition to carbon-free generation more affordable and reliable and encouraged further investigation into different storage technologies and durations with fast ramping and grid stabilization capabilities.[31]

There are two LDES projects that are currently underway in Minnesota. First, Form Energy, Inc., has partnered with Xcel Energy to deploy 10 MW / 1,000 MWh iron-air battery systems at two of the utility's retiring coal plant sites (one in Minnesota and one in Colorado). The storage technology will allow Xcel Energy to integrate more low-cost, renewable energy into its system and maintain resource adequacy by

---

[26] The Virginia Clean Economy Act. 2020.
[27] "Investing in long duration energy storage could take Virginia's energy transition to new peaks." Center for Climate and Energy Solutions. June 27, 2024.
[28] "Solar, Onshore Wind & Energy Storage Proposals.", Dominion Energy.
[29] "Energy Storage System Capacity Study Report." Prepared for the State of Minnesota. Siemens PTI. February 28, 2024.
[30] Minnesota Session Laws 2023, Chapter 60 (HF2310), Article 12, Sec. 74.
[31] "Energy Storage System Capacity Study Report." Prepared for the State of Minnesota. Siemens PTI. February 28, 2024.

providing more flexibility to cover periods of limited renewable generation output .[32] Second, Form Energy has partnered with Great River Energy, a not-for-profit wholesale electric power cooperative, through which a 1.5 MW multi-day energy storage project will be developed in Cambridge, Minnesota, and is expected to be operational by late 2025. Following its completion, Great River Energy will conduct a multiyear study to evaluate the system's performance and its potential for broader deployment.[33]

Other Relevant LDES Pilots

Along with LDES demonstration projects that have been driven through state regulatory initiatives, there are several pilot programs currently taking place that have emerged or resulted from federal funding sources, primarily through the DOE. The DOE has made an explicit commitment to support LDES through multiple projects related to the Energy Storage Grand Challenge R&D track that aims to reduce the cost of LDES by 90% within this decade. Funded by the Bipartisan Infrastructure Law, the DOE's LDES portfolio received $505 million to help advance LDES systems toward widespread commercial deployment. This portfolio provides an opportunity for nascent LDES technologies to overcome the technical and institutional barriers that exist for full-scale deployment with a focus on a range of different technology types for a diverse set of regions.[34]

The Office of Clean Energy Demonstrations (OCED) at the US DOE funds demonstration projects to accelerate the adoption of clean energy technologies, including LDES.[35]

Through the OCED programs, funding opportunities for emerging LDES technologies have been made available as follows:

- **Long-Duration Energy Storage Demonstrations Program:** A $350 million Funding Opportunity Announcement (FOA) issued in November 2022 to fund projects that can deliver electricity for 10–24 hours or longer.[36] These projects will help effectively demonstrate the commercial viability of innovative LDES technologies and facilitate wider commercial adoption.
- **Long-Duration Energy Storage Pilot Program:** A $100 million FOA issued in September 2024 to fund pilot-scale energy storage demonstration projects. These projects will advance a diverse set of LDES technologies towards

[32] "Form Energy Partners with Xcel Energy on Two Multi-day Energy Storage Projects." Form Energy. January 26, 2023.
[33] "Great River Energy, Form Energy break ground on first-of-its-kind multi-day energy storage project." Great River Energy. August 15, 2024.
[34] Department of Energy. Long-duration Energy Storage. https://www.energy.gov/oced/long-duration-energy-storage.
[35] Department of Energy. Office of Clean Energy Demonstrations, https://www.energy.gov/oced/long-duration-energy-storage.
[36] Funding Notice: Long-Duration Energy Storage Demonstrations | Department of Energy.

commercial viability and utility-scale demonstrations. Awards for this program are expected to be announced in Spring 2025.

The DOE's LDES Demonstrations Program focuses on displaying the commercial viability of more advanced LDES technologies through larger-scale demonstration projects, while the LDES Pilot Program aims to advance earlier-stage LDES technologies towards commercial viability by funding smaller, pilot-scale projects to test their feasibility and performance at a utility-scale level. The following nine projects have received funding under the LDES Demonstrations Program:[37]

- **Children's Hospital Resilient Grid with Energy Storage (CHARGES):** This project plans to install a 3.3 MW behind-the-meter, non-lithium-ion battery energy storage system that would provide power for at least 10 hours to Valley Children's Hospital, a pediatric hospital that serves Justice40 communities around Madera, California. *(Recipient: Charge Bliss)*
- **Columbia Energy Storage Project:** With an award of up to $30.7 million, through the Columbia Energy Storage project, Alliant Energy plans to demonstrate a compressed carbon dioxide (CO2) LDES system at the soon-to-be retired coal-fired Columbia Energy Center power station in Pacific, Wisconsin. Designed to discharge 18 MW of power for at least 10 hours, this facility would be the first of its kind in the US. *(Recipient: Wisconsin Power and Light, doing business as Alliant Energy)*
- **Communities Accessing Resilient Energy Storage (CARES):** With an award of $10 million and through what is entitled the CARES project, ReJoule plans to build modular energy storage systems made from repurposed batteries for installation at three sites across the Midwest, Southwest, and Western regions of the United States, improving energy resilience at two affordable housing complexes and a Red Lake Nation workforce development campus. *(Recipient: ReJoule)*
- **Front-of-the-meter Utilization of Zinc Bromide Energy Storage (FUZES):** With an award of up to $49 million, NextEra Energy Resources Development, LLC proposes development of zinc-bromide battery energy storage systems for a front-of-the-meter application at existing renewable energy sites in Morrow County, OR; Manitowoc County, WI; and LaMoure County, ND. Each of these energy storage systems aim to provide 5–10 MW of power for at least 10 hours. *(Recipient: NextEra Energy Resources Development)*
- **Multiday Iron air Demonstration (MIND):** With an award of up to $70 million, Xcel Energy, in collaboration with Form Energy, will deploy two 10 MW 100-hour LDES systems at retiring coal plants in Minnesota and Colorado. This project aims to accelerate the commercialization and market development of

[37] "Long-Duration Energy Storage Demonstrations Projects Selected and Awarded Projects." Office of Clean Energy Demonstrations.

multiday storage through strategic collaboration, technology, and scale. *(Recipient: Xcel Energy)*

- **Pumped Thermal Energy Storage in Alaska Railbelt (POLAR):** With an award of up to $50 million, Westinghouse Electric Company, LLC together with technology provider Echogen Power Systems will develop and deploy a Pumped Thermal Energy Storage (PTES) system with a 1200 MWh capacity, capable of a minimum continuous output of 50 MW for 24 hours at Alaska's Healy Power Plant. *(Recipient: Westinghouse Electric Company)*

- **Rural Energy Viability for Integrated Vital Energy (REVIVE):** With an award of up to $29.7 million, Dairyland Power Cooperative (DPC) plans to develop and build three battery energy storage systems using vanadium flow batteries (VFBs). Each system would be installed at DPC-owned distribution centers and provide at least 700 kW of power for at least 10 hours for rural communities in Illinois, Iowa, and Wisconsin. *(Recipient: Dairyland Power Cooperative)*

- **Second Life Smart Systems (SMART):** With an award of up to $10 million, Smartville, Inc. plans to demonstrate the viability of repurposed lithium-ion electric EV batteries in LDES systems across a range of use cases, environments, and sizes—from smaller scale (50kW x 10 hour) to larger scale (200kW x 10 hour). Smartville aims to install small-scale systems at two Historically Black Colleges and Universities (HBCUs) for education and training purposes; two large-scale systems for grid resilience, load balancing, and peak shaving in Los Angeles County; one large-scale system to support a town renovation project and promote green technologies; and two large-scale systems to support EV charging. *(Recipient: Smartville, Inc.)*

- **Stored Rechargeable Energy:** With an award of $6.5 million, Urban Electric Power aims to demonstrate the viability of its zinc manganese dioxide (ZnMnO2) batteries in large scale and long-duration energy storage systems in several communities in New York. This project will provide load management and power resilience to the selected sites. Between the two proposed sites, it will provide up to 600kW of power for up to 12 hours per discharge, yielding a total stored energy capacity of 7.2MWh. *(Recipient: Urban Electric)*

Military Demonstrations

LDES systems are particularly well suited for military and microgrid applications due to the expectation that they will be capable of providing power when renewables or distributed energy resources are either not available or not fully functioning. This capability can be a critically important resource to help military bases withstand extreme weather and cyberattacks. Projects funded through a partnership between the Department of Defense (DOD) and the DOE are presently enabling the testing of LDES technologies to evaluate energy resilience and decarbonization applications in controlled settings.

A previous technical report identified examples of projects that can help military bases withstand extreme weather and cyberattacks.[38] These examples include:

- **Stewart Air National Guard Base (Newburgh, N.Y.):** The DOD awarded a $2.83 million contract to Redflow to install a prototype LDES system at Stewart Air National Guard Base in New York. The system will repower the base's solar-powered microgrid, allowing it to provide energy during peak demand and improving the base's resilience.
- **Fort Carson Army Post (Colorado):** The US Army awarded a $17.5 million contract to Lockheed Martin to install a flow battery system at Fort Carson. The system will use engineered electrolytes made from common materials to improve durability and flexibility.
- **US Army Corps of Engineers:** The US Army Corps of Engineers is also testing LDES-powered microgrids. These tests are taking place at the Contingency Basing Integration Training Evaluation Center (CBITEC) at Fort Leonard Wood, Missouri. Called an energy warehouse, the tests will demonstrate how LDES systems, and specifically iron flow battery technology, can reduce the military's consumption of diesel as well as improve energy resilience at contingency bases. The energy warehouse was delivered by ESS Tech, a manufacturer of commercial and utility-scale LDES systems, and it replaces an ESS prototype that was installed in 2016.[39]

LDES Projects & R&D Efforts Led by the National Labs

In addition to the LDES projects listed above, OCED is funding six projects in two topic areas for development by DOE National Laboratories to demonstrate innovative LDES systems and resiliency advantages at the lab facilities. Projects selected for negotiation include:[40]

- **Topic Area 1:** Greater than 100kW and can discharge for 10+ hours
    - Argonne National Lab and Idaho National Lab will work with CMBlu, a solid-flow battery manufacturer, to enable economically viable electric vehicle fast charging in underserved communities and enhancing microgrids in cold climates by providing load management and reliability.
    - Sandia National Lab will demonstrate an innovative 18-hour storage technology using particle-based thermal energy storage with sand as the medium and an existing thermoelectric generation system.

[38] "Long-Duration Energy Storage: Resiliency for Military Installations." National Renewable Energy Laboratory. October 2023.
[39] Hitchens, Kathy. "U.S. Army Corps of Engineers to Test Long-Duration Energy Storage Microgrid." Microgrid Knowledge. January 18, 2024.
[40] Department of Energy Office of Clean Energy Demonstrations.

    - National Renewable Energy Lab will demonstrate thermal energy storage highlighting the versatility of this technology as energy storage and validating grid integration and controls.

- **Topic Area 2:** Greater than 500kW and can discharge for 24+ hours
    - Sandia National Laboratories will partner with E-Zinc, a large-scale zinc battery manufacturer, to demonstrate providing critical facilities an alternative to diesel backup generators during power safety shutoffs from the local utility.
    - Pacific Northwest National Lab will work with Invinity Energy Systems, a vanadium flow battery manufacturer, to demonstrate the flow battery performance with a 24-hour discharge duration technology. The system aims to meet critical loads during outages.
    - National Renewable Energy Lab will demonstrate a clean hydrogen-battery hybrid system with 24+ and 72+ hour duration, key durations to de-risk for use at military installations, utilities, airports, and universities.

The national laboratories, funded by the DOE, along with leading universities that have received federal funding from the DOE, are also leading R&D efforts to develop and test LDES technologies. One major project to note, led by the national laboratories and funded by the DOE, is the LDES National Consortium, which was launched in January 2024.[41] The LDES National Consortium provides a forum through which interested persons across the LDES ecosystem can convene to identify barriers, determine potential synergies, and collaboratively develop and implement strategies necessary to achieve LDES technology commercialization within the next decade.

A Leadership Team powered by the knowledge, expertise, and relationships possessed by six US National Laboratories (Sandia National Laboratories, Argonne National Laboratory, Idaho National Laboratory, the National Renewable Energy Laboratory, Pacific Northwest National Laboratory, and Oak Ridge National Laboratory) will guide a broad network of industry and community participants (i.e., "Teaming Partners") to collaboratively develop a set of actionable recommendations to address identified challenges facing LDES technologies. The output will be a comprehensive plan for LDES commercialization that can be offered to diverse regions, markets, communities, and end-use customers.

Section Summary:

In general, battery energy storage resources have primarily been developing in states that have adopted favorable policy frameworks for energy storage, including the development of incentives for utility procurements, adoption of favorable regulations, or the sanctioning of demonstration projects. Addressing current policy

[41] The Long Duration Energy Storage National Consortium.

gaps will help each state to better understand the role of LDES to contribute to grid reliability and be fairly compensated for its grid services.

While there are no formal recommendations identified through the development of this section, policymakers and regulators should consider the following policy actions to help advance the study and deployment of LDES:

- Consider policies that can be developed to enable the known best use-case scenarios for LDES.
- Require the evaluation of LDES in long-term system planning, particularly within the framework of established decarbonization goals.
- Revise existing energy storage procurement practices and targets to require specific amounts of LDES to be deployed.
- Support the early deployment of LDES through incentives to developers and/or ensuring cost recovery for utility pilot programs.
- Develop supportive market designs that begin to capture the full value of LDES, allowing it to play a greater role in meeting resource adequacy requirements and providing resilience and other ancillary services.

4. Costs and Specifications

Energy storage technologies present unique modeling challenges, as they require utility planners to include variables that may not apply to other energy technologies such as charging time, cycle limits, round-trip efficiency, and the impact to system load. To accurately assess the benefits of storage technologies and identify cost-effective opportunities to deploy them, planners need detailed information about how those technologies will perform and what they cost. This section will discuss the challenges that confront utility planners in obtaining data on LDES technologies and some options for addressing those challenges.

Challenges to Finding Data

Energy storage technologies are not homogenous; there are dozens of technologies, each with unique performance characteristics and capabilities. To accurately assess the wide range of energy storage technologies, planners need to individually collect that data for each of the storage technologies they want to study. Collecting that data presents a challenge. Like any emerging industry, the energy storage industry is a highly competitive space with many providers and many technology options. In this environment, cost and performance data are proprietary and closely guarded, making it difficult for utilities, regulators, and the public to access that data and independently study the value of LDES technologies.

Additionally, most LDES technologies have not yet been deployed at scale, so there may be little or no operational data to support the claims of those technologies. Even if a technology provider shares technical data about their product, there may be no way to independently verify those claims. This is not to imply that there are bad actors in this space or that performance claims should be disregarded; however, the use of unverified inputs and assumptions in the modeling process is a risk that may raise concerns around feasibility and accuracy for utility planners, and for regulated utilities, a risk to bearing unwarranted costs for their customers. Ongoing transparent communication between utilities, technology developers, and others involved in the resource planning process about these risks and how they can be managed may be helpful in the planning process.

Finally, many sources that provide cost information on LDES technologies express those costs in terms of the levelized cost of storage (LCOS), which is a measurement of the cost to store and deliver each unit of energy from a storage device over its lifetime (usually expressed in dollars per kilowatt-hour or $/kWh). Calculating LCOS requires knowledge of a technology's costs, round-trip efficiency, and cycle life, as well as assumptions about how the technology will be used. LCOS is useful in comparing different energy storage technologies on a similar basis, protecting proprietary cost and performance data and tracking the cost declines of a technology over time. However, because it obscures the specific cost and technological specifications that a planning model requires, LCOS is of limited use to a utility planner.

Through the Pacific Northwest National Laboratory, the DOE maintains the energy storage cost and performance database, which provides detailed, public cost and performance data for commercially available energy storage technologies. These data can be collected and shared because each of the technologies included has many providers, allowing them to be averaged in a way that obscures the proprietary data of any single provider. But for emerging technologies that may have only one or two providers, that anonymity cannot be provided. **Figure 4.1** provides an example of the information available in the database:

Figure 4.1. Levelized cost of storage for various energy storage technologies[42]

The following additional public sources provide high-level information on the cost and performance parameters of LDES and MDES technologies:

- Long Duration Energy Storage Council/McKinsey & Co., "Net-zero power: Long-duration energy storage for a renewable grid" (2021)

[42] Energy Storage Cost and Performance Database | PNNL.

- California Energy Commission, "Evaluating the Value of Long-Duration Energy Storage in California" (2024)

Other Potential Data Sources

While obtaining technical information about emerging LDES technologies can be difficult, there are strategies that utilities may use to overcome the challenge. Each of these strategies has potential strengths and weaknesses, so it may be helpful for utilities and regulators to come into an agreement about how such data will be acquired, used, and shared in the planning process. Ultimately, utilities conducting IRP modeling should prioritize using public data sources for cost and technology information. If adequate public data is not available, utilities should utilize data that can be shared with Staff and intervening parties through nondisclosure agreements to ensure the opportunity for thorough evaluation while protecting proprietary information.

Requests for Information

As utility planners have navigated an era of rapid technological development, many have begun using requests for information (RFI) to remain current with emerging technologies and inform their planning efforts. At the beginning of the planning process, the utility issues a public call for technology providers to submit cost and performance information about their technology to the utility so that it can be included in the planning process. Information provided in these submissions is usually protected through a nondisclosure agreement or similar mechanism to prevent the release of the provider's proprietary data.

RFIs reduce the amount of time the utility needs to spend gathering information, as technology providers have a strong incentive to provide their information to educate utilities about their product and have it studied as a potential option. However, RFIs also create transparency challenges since the information gathered cannot be shared with regulators or the public. While the Commission may have access to this type of information when reviewing contracts resulting from a competitive solicitation process, these proposals are specific to an individual or group of projects, not a broad view of an entire technology type. It is unlikely that information gained through an RFI process for the purposes of modeling LDES and MDES technologies would then be directly used by that utility in a solicitation process where the Commission would have this visibility. Instead, a separate solicitation process would be conducted to identify the specific projects to meet the identified need. Therefore, to the extent this data was utilized in the decision-making process, it would not be visible to the Commission or other parties in the case. It will also be important for utilities to demonstrate good-faith usage of the information they receive from RFIs in their modeling to maintain trust with LDES providers so that they will continue to respond to RFIs in future planning cycles. Responding to an RFI can be a time-consuming process, and technology providers who do not believe that planners are seriously considering their information may stop responding to RFIs. There is also a risk that, even if the utility is using the information in good faith, its analysis may not

result in the selection, and ultimately development, of LDES technologies. This can also dampen the responsiveness of developers to future RFIs.

Data subscription service

Some commercial information providers release detailed studies about LDES technologies that include detailed cost and performance information. Bloomberg New Energy Finance, for example, publishes a report of LDES technology costs and performance characteristics every year. Some energy consulting firms, like Guidehouse, have also developed proprietary storage modeling tools that include detailed information about LDES technologies.

Purchasing these reports or consulting services can be a quick way to gather information on multiple technologies, but it is unclear how extensive they are. Bloomberg's report, for example, includes 20 technologies but does not identify them in the publicly available description of the report. These services also raise transparency concerns, as their expensive and proprietary nature means that utilities may be the only party in a planning process that can afford to purchase them but would not be able to share that information with others.

Section Recommendation:

4-1: Utilities should use public data to source cost and technology information for the modeling of energy storage in IRPs. If adequate public data is not available, utilities should utilize data that can be shared with Staff and intervening parties through nondisclosure agreements to allow the review of sensitive information.

5. Modeling LDES

This section will discuss several aspects relating to modeling LDES technologies. To evaluate both the economic and technical potential as well as the limitations of LDES technologies, grid planners must ensure that the data used, and assumptions made in the model, accurately represent the performance of LDES to enable informed investment decisions. This section will first discuss best practices in model development, including the sourcing of input data and associated challenges. Best practices for model execution will then be considered, including parameters necessary to accurately represent LDES and advanced tools and techniques which can be employed to accomplish these analyses.

Data Collection and Model Inputs

LDES modeling requires high-quality data inputs that accurately represent the storage technology and current grid as compared to future grid scenarios. This section identifies essential data needed for modeling LDES and highlights challenges in data collection. These data needs support the adoption of the following best practices for utilities when developing LDES models:

- **Standardization:** Develop standardized protocols for data collection, formatting, and reporting to ensure consistency across regions and technologies.[43]
- **High Resolution:** Use high-resolution data for both spatial and temporal dimensions to capture detailed geographic and operational characteristics.[44]
- **Transparency:** Use public data sources to promote open access and ensure transparency in reporting methodologies to build trust among involved participants.[45]
- **Collaboration:** Foster partnerships between utilities, researchers, and policymakers to create shared databases and reduce data silos.[46]
- **Validation:** Cross-validate data with field measurements and pilot project outcomes to ensure their accuracy and applicability to real-world conditions.[47]

---

[43] Mantegna, G., et al. (2024). Establishing Best Practices for Modeling Long Duration Energy Storage. https://doi.org/10.48550/arXiv.2404.17474.
[44] Guerra, O. J., et al. (2024). Towards Robust and Scalable Dispatch Modeling of Long-Duration Energy Storage. https://doi.org/10.1016/j.rser.2024.114940.
[45] Shrager (2023). Storage Innovations 2030: Accelerating the Future of Long Duration Energy Storage. U.S. Department of Energy.
[46] Thatte, A. A., et al. (2024). "The Role of Extended Horizon Methodology in Renewable-Dense Grids With Inter-Day Long-Duration Energy Storage," *2024 IEEE Power & Energy Society General Meeting (PESGM)*, Seattle, WA, USA, 2024, pp. 1-5, https://doi.org/10.1109/PESGM51994.2024.10689014.
[47] Denholm, P., Cole, W., & Blair, N. (2023). "Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage." NREL.

Available Databases:

Several databases and useful sources to leverage when evaluating and modeling LDES technologies have been collected and summarized in **Appendix B.1**. Note, this is not an exhaustive list of databases but serves as a starting point to begin gathering the relevant data needed to perform the analysis. In addition to these data sources, utilities should maintain awareness of industry work that may lead to additional sources of this information, such as the LDES Consortium currently being convened by the DOE.[48]

Demand and Energy Forecasts:

Understanding energy demand is the foundation of any resource planning process. Historical load data provides insights into patterns of electricity usage, including peak periods, seasonal variations, and daily fluctuations. For instance, integrating historical data with decarbonization scenarios can help model the flexibility requirements that LDES could fulfill under different future applications.[49] Additionally, future load forecasts are critical for assessing how demand might evolve due to factors like population growth, electrification of transportation, and industrial decarbonization.[50] It is important for load data to align with the spatial and temporal resolution of the model. High-resolution data enables precise modeling of LDES operations, while long-term forecasts help in planning investments. However, challenges arise in harmonizing data collected from different sources, particularly in regions with diverse demand profiles. Developing standardized methods for load data collection and aggregation is vital to achieve consistent modeling outcomes.[51]

Renewable Generation Data:

The variability of renewable generation is a key driver for LDES deployment. High-resolution data on solar irradiance and wind speeds are often used to create generation profiles for modeling. These profiles can be combined with historical weather data to simulate how renewable energy production fluctuates over time.[52] Due to their impact on the operations of other dispatchable resources and storage, the integration of detailed renewable generation profiles into models is critical. This integration also allows for detailed exploration of different LDES applications, such as smoothing intermittent generation, shifting energy between surplus and deficit periods, and enabling long-term storage solutions. However, data gaps remain,

---

[48] LDES National Consortium – Sandia National Laboratories.
[49] Augustine, C., & Blair, N. (2021). Storage Futures Study: Storage Technology Modeling Input Data Report. https://doi.org/10.2172/1785959.
[50] "Long Duration Energy Storage for a Renewable Grid", DOE, 2022.
[51] Mantegna, G., et al. (2024). Establishing Best Practices for Modeling Long Duration Energy Storage. [2404.17474] Establishing best practices for modeling long duration energy storage in deeply decarbonized energy systems.
[52] Denholm, P., Cole, W., & Blair, N. (2023). "Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage." NREL.

particularly in regions with less renewable development.[53] Expanding access to high-fidelity renewable data and improving data sharing across jurisdictions can support more accurate and scalable models.[54]

Cost Data:

Cost is a key consideration in resource planning and LDES deployment. Cost data includes capital expenditure (CAPEX), operational expenditure (OPEX), and lifecycle costs. These metrics are used to calculate the LCOS, which enables comparisons between different technologies and configurations.[55] For example, even if emerging LDES technologies such as flow batteries or compressed-air energy storage show promise from an operations and performance standpoint, they must demonstrate competitive LCOS values to justify investment.[56] Accurate cost modeling requires granular data, including costs associated with manufacturing, installation, maintenance, and end-of-life disposal. Transparency in cost data is crucial for entities to make informed decisions.[57] However, newer technologies often lack comprehensive lifecycle cost assessments and real operations data and may not yet be included in industry databases for storage technologies, creating uncertainties in economic modeling as detailed in Section 4. Establishing open databases and standardizing cost-reporting practices can address these gaps, while providing necessary visibility into the process for regulators and other parties to validate inputs.[58]

Technical Performance Data:

The technical performance of LDES systems determines their feasibility and effectiveness in delivering anticipated grid benefits. Key metrics include round-trip efficiency and its impact on forecasted load, energy density, charge/discharge rates, cycle life, and degradation rates. These parameters directly influence the LDES system's ability to meet demand and provide grid benefits under various operational scenarios.[59] Technical performance data must reflect real-world conditions, including environmental impacts, scaling challenges, and integration with existing grid infrastructure.[60] For instance, round-trip efficiency and degradation rates vary with

---

[53] Jafari, M., Korpas, M., & Botterud, A. (2019). Power System Decarbonization: Impacts of Energy Storage Duration and Interannual Renewables Variability. Renewable Energy, Volume 156, 2020, Pages 1171-1185, https://doi.org/10.1016/j.renene.2020.04.144.
[54] "Long Duration Energy Storage for a Renewable Grid", DOE, 2022.
[55] NREL. (2021). Storage Futures Study. National Renewable Energy Laboratory.
[56] Denholm, P., Cole, W., & Blair, N. (2023). "Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage." NREL.
[57] Mantegna, G., et al. (2024). Establishing Best Practices for Modeling Long Duration Energy Storage. https://doi.org/10.48550/arXiv.2404.17474.
[58] Shrager (2023). Storage Innovations 2030: Accelerating the Future of Long Duration Energy Storage. U.S. Department of Energy.
[59] Guerra, O. J., et al. (2024). Towards Robust and Scalable Dispatch Modeling of Long-Duration Energy Storage. https://doi.org/10.1016/j.rser.2024.114940.
[60] Shrager (2023). Storage Innovations 2030: Accelerating the Future of Long Duration Energy Storage. U.S. Department of Energy.

usage patterns, necessitating robust datasets to capture this correlation. Incorporating real-time performance data from pilot projects and field deployments can enhance the accuracy of models and support continuous improvement, particularly where other real-world operations data may not yet be available.[61]

Challenges in Data Collection:

Despite advancements in data collection and analytics, several challenges remain. Harmonizing disparate datasets, aligning temporal and spatial resolutions, and ensuring data quality are recurring issues. For example, load data and renewable generation data often originate from different sources with varying formats and resolutions, complicating integration.[62] Additionally, data availability is uneven across regions and technologies. Emerging markets and novel storage solutions often suffer from a lack of historical data, limiting their inclusion in models.[63] Privacy concerns and proprietary restrictions further constrain access to valuable datasets.[64] While this report attempts to identify potential solutions, addressing these challenges requires a combination of policy interventions, technological advancements, and collaborative efforts among involved persons. While there are ongoing national efforts, described in Sections 3 and 4 above, to reduce these data collection barriers for LDES, these barriers remain a challenge for comprehensive and precise modeling of all LDES technologies in capacity expansion planning.

Grid Planning Modeling with LDES

Along with ensuring accurate input data and forecasts have been used, modeling LDES technologies to make informed investment and grid planning decisions also requires deploying state-of-the-art simulation and modeling techniques. Sioshansi et al. (2022) provide an in-depth review of state-of-the-art modeling techniques, associated challenges, and future improvements for modeling energy storage technologies.[65] Typically, grid planning processes require significant modeling efforts using advanced optimization models such as long-term capacity expansion planning, production cost, and resource adequacy models. However, many of these traditional models are not currently operated in a way that captures, or are not otherwise capable of capturing, the full value of LDES. Several modeling tools exist to

---

[61] Thatte, A. A., et al. (2024). "The Role of Extended Horizon Methodology in Renewable-Dense Grids With Inter-Day Long-Duration Energy Storage," *2024 IEEE Power & Energy Society General Meeting (PESGM)*, Seattle, WA, USA, 2024, pp. 1-5, https://doi.org/10.1109/PESGM51994.2024.10689014.

[62] Jafari, M., Korpas, M., & Botterud, A. (2019). Power System Decarbonization: Impacts of Energy Storage Duration and Interannual Renewables Variability, Renewable Energy, Volume 156, 2020, Pages 1171-1185, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2020.04.144.

[63] Denholm, P., Cole, W., & Blair, N. (2023). "Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage." NREL.

[64] Mantegna, G., et al. (2024). Establishing Best Practices for Modeling Long Duration Energy Storage. https://doi.org/10.48550/arXiv.2404.17474.

[65] Ramteen Sioshansi et al., "Energy-Storage Modeling: State-of-the-Art and Future Research Directions," *IEEE Transactions on Power Systems* 37, no. 2 (2022): 860-875, https://doi.org/10.1109/TPWRS.2021.3104768.

assess the economic potential of LDES that can supplement traditional resource planning models. While LDES technologies are nascent in nature and methods to evaluate a broad range of LDES technologies are still being developed, this section will discuss potential methods and best practices for modeling LDES.

Available Grid Planning Tools

Various grid planning tools which are currently available have been identified and grouped by planning function. This information is included in **Appendix B.2**. These tools are either open-source or commercial tools which facilitate the modeling of LDES technologies. While there are many tools currently available, evaluating LDES technologies is considered a nascent area actively being researched. As such, this report recommends utilities investigate the use of advanced tools and techniques, such as those identified, as necessary to accurately model the operations of LDES technologies, their participation in markets, and their support of the reliability, with a focus on practical application to existing planning processes.

Accurate Representation of Technologies:

Modeling LDES requires careful attention to the assumptions made when simulating the operational characteristics.[66] Therefore, grid planners should evaluate the following characteristics to accurately represent the LDES technologies and work to adopt these best practices:

- **Technology-Specific Models:** Develop detailed candidate resources of different storage technologies (e.g., batteries, pumped hydro, thermal storage) that represent their unique characteristics in planning models.
- **Efficiency and Degradation:** Account for efficiency losses and degradation over time. This includes health monitoring and optimally managing the system for extended operation through the asset's lifetime.
- **Operational Constraints:** Incorporate constraints such as minimum and maximum state of charge (SOC), ramp rates, response times, market participation, reserves contributions, and look-ahead periods that allow the model to optimize operations. These constraints vary by technology, and operational constraints (e.g. proper look-ahead periods, SOC balancing, use of imperfect foresight for SOC management) should align with the duration of the LDES technologies being evaluated.
- **Capital & Operational Costs and Asset Lifetimes:** Ensure the most up-to-date estimates for capital and operating costs are used. The model should reflect accurate projected lifetimes of technologies to account for long-term

[66] Rui Shan, Jeremiah Reagan, Sergio Castellanos, Sarah Kurtz, Noah Kittner, "Evaluating emerging long-duration energy storage technologies", Renewable and Sustainable Energy Reviews, Volume 159, 2022, 112240, ISSN 1364-0321, https://www.sciencedirect.com/science/article/pii/S1364032122001630.

economic impacts and LCOS calculations. Section 4 addresses sources for these data in more detail.

- **Capacity Credits:** Accurately account for the storage resource's contribution toward meeting capacity needs under the relevant independent system operator's (ISO) capacity construct. Typically, this is done using metrics such as effective load carrying capability (ELCC).[67] The ELCC is dependent on the duration and market participation of the LDES resource and can also be influenced by the mix of generating resources throughout the ISO market.[68]
- **High-Fidelity Temporal Scope:** Sub-hourly resolution is essential to fully capture the value of LDES by modeling LDES's fast response times and interactions with variable renewable generation. Tools like Sienna, A-LEAF, and Prescient enable utilities to simulate these transient phenomena and optimize operational decisions without the need for sub-hourly resolution in traditional capacity expansion models. When sub-hourly modeling is not practically feasible, for example, due to computational limits, hourly resolution provides the next best option to capture daily cycles in energy demand.
- **Representative Periods:** Representative periods are widely used to balance computational efficiency with modeling accuracy within capacity expansion planning models. Sandia's QuESt Planning and similar tools incorporate these techniques, making it suitable for utilities and states to efficiently identify optimal LDES investments. Representative periods reduce the computational demand of capacity expansion modeling at the cost of resolution into the system, and their use must therefore be weighed against this loss of resolution.
- **Multi-Temporal Frameworks:** Grid planning often requires modeling a combination of shorter-term operational and long-term planning horizons. Tools like A-LEAF, QuESt Planning, and GridPath facilitate multi-temporal analyses, enabling planners to align near-term operational strategies with long-term decarbonization objectives.
- **Spatial Resolution:** The spatial resolution used in modeling is increasingly important because it can be used to account for the variation in renewable potential and performance across the areas considered. Increasing spatial granularity also allows for climate impacts and extreme weather to be assessed with high-fidelity. Increased spatial resolution is also necessary for modeling to consider LDES's role in supporting the transmission and distribution system, as discussed further in Section 7.
- **Transmission Modeling:** Modeling the transmission system is needed when sizing and siting LDES on the grid. Grid planning techniques, such as transportation models and DC power flow, are typically used to model the

[67] PJM Interconnection, "December 2022 Effective Load Carrying Capability (ELCC) Report, 2023, https://www.pjm.com/-/media/planning/res-adeq/elcc/elcc-report-december-2022.ashx
[68] As the penetration of resources change with time the capacity credits of various resource types will change with time as well.

transmission system's thermal limits and real power flow constraints. However, such analysis is typically done in separate processes, or even by separate organizations, rather than in resource planning, which guides utility investment decisions. Co-optimizing generation, storage, and transmission systems is an effective method to identify least cost and robust solutions. Transparent coordination of planning and data-sharing between utilities, transmission owners, and ISOs and regional transmission organizations (RTO) are necessary to ensure effective transmission planning across several regions.

Long-term Grid Planning:

Long-term grid planning, such as an IRP, is an essential process to ensure that long-term resource needs are identified and optimally planned for. Capacity expansion planning models are the primary tools deployed to assist with identifying data-driven and optimal investment decisions when forming a resource plan. Significant research is still required to improve today's long-term grid planning tools to adequately represent the potential future of the grid and nascent technologies like LDES. The following part of this section identifies and considers advanced techniques to evaluate LDES such as stochastic optimization, the value of co-optimization between planning processes, and the need to represent advanced market dynamics.

Co-Optimization & Investment Optimization:

For LDES to be evaluated as a potential distribution or transmission solution, it must first be integrated into these respective planning processes. Integration of LDES, and energy storage more generally, into distribution and transmission processes leads to efficiencies in system planning and has the potential to reduce overall costs. Krishnan et al. (2015) provide a comprehensive review of modeling approaches for co-optimizing transmission, resources, and storage.[69] Spyrou et al. (2017) demonstrate that co-optimizing generation and transmission system investments results in least cost solutions when compared to sequential optimization techniques.[70] The Electric Power Research Institute (EPRI) and collaborators provide an extensive overview of methods to perform co-optimized, or coordinated, expansion planning.[71] An alignment of utility distribution, resource, and transmission planning was identified as a central recommendation that resulted from the Commission led MI Power Grid Advanced Planning Processes workgroup.[72] This was

[69] Krishnan, V., Ho, J., Hobbs, B.F. et al. Co-optimization of electricity transmission and generation resources for planning and policy analysis: review of concepts and modeling approaches. Energy Syst 7, 297–332 (2016). https://doi.org/10.1007/s12667-015-0158-4.
[70] Evangelia Spyrou, Jonathan L. Ho, Benjamin F. Hobbs, Randell M. Johnson, and James D. McCalley, "What are the Benefits of Co-Optimizing Transmission and Generation Investment? Eastern Interconnection Case Study," IEEE Transactions on Power Systems 32, no. 6 (2017): 4265-4277, https://doi.org/10.1109/TPWRS.2017.2660249.
[71] Electric Power Research Institute, "Program on Technology Innovation: Coordinated Expansion Planning: Status and Research Challenges", 2019, https://www.epri.com/research/products/000000003002016661.
[72] MI Power Grid Phase II - Integration of Resource/Distribution/Transmission Planning.

envisioned as an iterative process where results and information from one plan would feed into the others to help inform planning decisions.[73]

Reliability-Based Capacity Expansion Planning

Traditional capacity expansion planning often focuses on cost minimization, which may overlook critical aspects of grid reliability, especially in systems with high renewable penetration. To address this gap, planners are adopting reliability-based capacity expansion frameworks that integrate metrics such as Loss of Load Expectation (LOLE), Expected Energy Not Served (EENS), and Expected Unserved Energy (EUE). Bera et al. (2023) introduced a reliability-based capacity expansion planning framework that incorporates LDES to facilitate decarbonization while maintaining grid reliability.[74] By simulating renewable generation variability and storage system operations, their methodology ensures the grid can meet demand even under adverse conditions. Metrics, such as LOLE, EENS, and EUE, provide quantitative benchmarks for evaluating system adequacy, guiding decisions on resource deployment.

Stochastic Optimization & Handling Uncertainties

Stochastic modeling uses probabilistic analyses to test the impact of uncertainties in renewable generation, electricity demand, and market prices, which are critical for large-scale grid planning. Stochastic modeling is often used as a form of risk assessment to test the robustness of the modeled system by varying a parameter stochastically using a probabilistic curve of likely outcomes for that parameter and measuring the system's response.

- **Uncertainty in Renewable Energy and Demand:** Stochastic approaches enable planners to understand the impact of variability in renewable outputs and demand on the planned system.[75] Sandia's Prescient tool uses stochastic programming to simulate uncertainties, generating optimized unit commitment schedules for power systems. Tools like this are well suited for utilities to understand and plan for increasing penetration of renewables, and the corresponding variability in their generation, which is vital to plan and operate LDES technologies.
- **Stochastic Optimization:** Stochastic optimization is a common method deployed to make optimal decisions under uncertainty. Several methods exist including stochastic dynamic programming, robust optimization, chance-

[73] MI Power Grid Phase II - Integration of Resource/Distribution/Transmission Planning Final Report.
[74] Bera, A., Newlun, C. J., Olis, W., Benson, A., Nguyen, T., & Mitra, J. (2023). Reliability-based Capacity Expansion Planning for Decarbonization with the Aid of Energy Storage. 2023 IEEE PES Innovative Smart Grid Technologies Europe (ISGT EUROPE), 1-5. https://www.doi.org/10.1109/ISGTEUROPE56780.2023.
[75] Yan, C., et al. (2021). " Two-stage robust energy storage planning with probabilistic guarantees: A data-driven approach", Applied Energy, Volume 313, 2022, 118623, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2022.118623.

constrained optimization, and Monte Carlo simulations.[76] Stochastic optimization has been used across a variety of planning processes to assess risk, including transmission planning for the Western Interconnection.[77] The use of stochastic optimization can aid in identifying how LDES performance can provide grid benefits during times of unexpected risk.

- **Probabilistic Risk, Resilience, & Reliability Analysis:** Deploying probabilistic analysis and methodologies is essential for evaluating the resilience and reliability of the system and the expected performance of LDES in the presence of uncertainties inherent in the power system. Such analysis requires probabilistic modeling of component failures, variable generation (such as wind and solar production), load conditions, and extreme weather events.[78, 79] Additionally, advanced techniques, such as Monte Carlo Simulations and Markov Chain Models, are often deployed in reliability and resource adequacy models to simulate thousands of grid conditions and calculate necessary reliability metrics.[80] Modeling LDES within these frameworks remains a challenge, but leveraging these advanced models is necessary to size and site LDES such that it will realize its full potential operational benefits, including improving resilience and reliability. Open-source tools such as the Probabilistic Grid Reliability Analysis with Energy Storage Systems and the Probabilistic Resource Adequacy Suite are viable options to perform advanced reliability analysis of the evolving grid.[81, 82] Commercial tools, such as SERVM, provide similar advanced modeling techniques and are widely used by utilities and RTOs/ISOs.[83]

Market Participation and Revenue Optimization Strategies

In the context of market participation, storage assets must be adept at navigating market dynamics to maximize their revenue potential. Nguyen et al. (2017) demonstrates this by presenting strategies for optimizing revenue through active

---

[76] L. A. Roald, D. Pozo, A. Papavasiliou, D. K. Molzahn, J. Kazempour and A. Conejo, "Power systems optimization under uncertainty: A review of methods and applications," Electric Power Systems Research, vol. 214, no. A, 2023. https://doi.org/10.1016/j.epsr.2022.108725.
[77] J.L. Ho et al. "Planning Transmission for Uncertainty: Applications and Lessons for the Western Interconnection" 2016 Final Report for WECC: https://sangwoopark-njit.github.io/Planning-for-Uncertainty-Final-Report.pdf.
[78] A. Bera, T. Nguyen, B. Chalamala and J. Mitra, "Sizing Energy Storage to Aid Wind Power Generation: Inertial Support and Variability Mitigation," 2022 IEEE Power & Energy Society General Meeting (PESGM), Denver, CO, USA, 2022, pp. 1-5.
[79] Bera, A., Nguyen, N., Chalamala, B., Mitra, J.: Quantification of storage required for preserving frequency security in wind-integrated systems. IET Renew. Power Gener. 17, 2366–2378 (2023).
[80] C. Singh, P. Jirutitijaroen, J. Mitra, Electric Power Grid Reliability Evaluation: Models and Methods, 2019, Wiley-IEEE Press, https://ieeexplore.ieee.org/servlet/opac?bknumber=8614382
[81] Probabilistic Grid Reliability Analysis with Energy Storage Systems (ProGRESS).
[82] PRAS: Probabilistic Resource Adequacy Suite.
[83] SERVM.

participation in both the energy and frequency regulation markets of MISO.[84] The research highlights the importance of understanding market signals and pricing mechanisms to optimize the operational schedules of energy storage systems (ESS) for maximum profitability and the need to translate that into a model valuation analysis. Further expanding on this, Nguyen et al. (2019b) explore the concept of value stacking, or optimizing an ESS's operations to maximize the value it provides from multiple services, including resilience, T&D deferral, and energy arbitrage. This study reveals how diversifying the revenue streams of energy storage can substantially enhance its economic viability, suggesting that energy storage can offer multiple grid services simultaneously, thus maximizing its market participation and profitability.[85] The ability to accurately model value stacking of an energy storage resource was identified in Section 2 as a best practice general to all energy storage. This need is especially important for LDES technologies, which have even more diverse use cases and less market penetration.

Challenges of Modeling LDES

Although advancements in LDES modeling have taken place, including LDES in grid planning and operational models introduces a diverse set of challenges that grid planners and decision-makers face when planning for future investments[86, 87]. The remainder of this section will discuss various challenges that arise when modeling LDES, highlighting the need for continued LDES modeling advancement. These challenges are identified to demonstrate the complexity of the problems grid planners face and to bring forward future directions that can be taken to overcome these challenges. Briefly, these challenges include:

- **Data Gaps:** There still exist significant gaps in data relied on to model LDES, as discussed in the previous section. High-resolution, site-specific data remains a significant barrier for smaller utilities, state agencies, and researchers. Without accurate data related to the load profiles, renewable generation, and economic data, the operational characteristics and economic potential can be modeled incorrectly. Consequently, this leads

[84] Nguyen, T. A., Byrne, R. H., Concepcion, R. J., & Gyuk, I. (2017). Maximizing revenue from electrical energy storage in MISO energy & frequency regulation markets. 2017 IEEE Power & Energy Society General Meeting, 1-5. https://doi.org/%2010.1109/PESGM.2017.8274348.
[85]Nguyen, T. A., Copp, D. A., & Byrne, R. H. (2019). Stacking revenue from energy storage providing resilience, T&D deferral, and arbitrage. 2019 IEEE Power & Energy Society General Meeting, 1-5. https://doi.org/10.1109/PESGM40551.2019.8973986.
[86] Ramteen Sioshansi et al., "Energy-Storage Modeling: State-of-the-Art and Future Research Directions," *IEEE Transactions on Power Systems* 37, no. 2 (2022): 860-875, https://doi.org/10.1109/TPWRS.2021.3104768.
[87] Levin, Todd, Bistline, John, Sioshansi, Ramteen, Cole, Wesley J., Kwon, Jonghwan, Burger, Scott P., Crabtree, George W., Jenkins, Jesse D., O'Neil, Rebecca, Korpås, Magnus, Wogrin, Sonja, Hobbs, Benjamin F., Rosner, Robert, Srinivasan, Venkat, and Botterud, Audun. Energy storage solutions to decarbonize electricity through enhanced capacity expansion modelling. United States: Nat Energy 8, 1199-1208, (2023). https://doi.org/10.1038/s41560-023-01340-6.

to the misrepresentation of LDES technologies and prevents informed decision-making.

- **Computational Complexity:** Significant computational complexity is necessary to incorporate advanced modeling techniques, such as high-fidelity spatio-temporal representation of the system, which are needed to capture dynamic SOC calculations, market dynamics, and operational constraints. Deploying complex models to evaluate LDES technologies requires state-of-the-art solvers, modeling platforms, and hardware to effectively build, solve, and process the results of the optimization models. With increased complexity comes increased computational cost. Such examples include incorporating appropriate look-ahead periods to fully assess LDES and optimizing large sets of operational data at the hourly and/or sub-hourly levels.
- **Uncertainty Management:** Industry adoption of stochastic methods remains constrained by the complexity and difficulty of performing this analysis and interpreting the results. Stochastic modeling requires assumptions of probability and statistical methods that may not be accepted amongst all groups. Furthermore, capturing technology-specific uncertainties, such as capital costs assumptions, operational characteristics of LDES, and the maturity of technologies to be invested at large-scale (i.e. assumptions in capacity expansion planning models to reflect current market readiness of LDES), introduces several additional dimensions of uncertainties that grid planners face today and will continue to face in the coming decades.
- **Incorporating Extreme Events, Policies, & Market Standards:** Extreme weather events can significantly impact the system's reliability and resilience, requiring the proper sizing, siting, and operating LDES technologies to address these challenges. Identifying, characterizing, and simulating these extreme weather events are difficult due to data availability and variable nature of extreme conditions. Grid planning models must adapt to the evolving policies that exist at the state and federal levels, and they must account for new standards and incentives that could be provided for LDES technologies. This requires constant re-evaluation and improvement of assumptions made when modeling LDES. Lastly, ensuring that market standards are modeled correctly poses a challenge as the markets are evolving and the role of LDES within the markets is still in its infancy.
- **Public Engagement:** LDES technologies are emerging, and the public and other parties are still being educated on the intricacies that are involved with modeling and deploying LDES. Therefore, careful consideration must be taken to effectively communicate the benefits and trade-offs of the LDES technologies to a broad group of interested parties.

Section Recommendations:

This section highlights modeling best practices that are key to conducting a robust analysis of LDES and its ability to support the evolving electric grid. Staff recommends utilities adopt the best practices and methods for modeling LDES as discussed in this section. Specifically:

5-1: To ensure that LDES technologies are adequately represented in utility modeling, the following best practices related to the sourcing and application of data should be adopted to the extent feasible:

- Use high-resolution data in the spatial and temporal dimensions to capture detailed geographic and operational characteristics.

- Use public data sources to promote an open and transparent planning process.

- Use actual operational data from deployments and pilots to validate sources when available.

5-2: Utilities should investigate the use of advanced tools and techniques, such as those identified in this section, and work to incorporate the LDES modeling best practices herein as necessary to accurately model the operations of LDES and MDES technologies, their participation in markets, and their support of the reliability and resilience of the system. A focus should be on practical application to current planning practices, including application to, or supplementation of, current modeling software and tools.

6. LDES as a Replacement Resource

When detailing the scope of this report in its February 8, 2024 Order, the Commission included the following two deliverables:

- An analysis of the aggregated capacity of existing fossil resources in each regulated utility service territory within Michigan that utilities should analyze for replacement with storage resources in their next IRP after issuance of the report.

- To the extent practicable, indications of what capacity may be better suited to be replaced with long-duration or multi-day storage or guidelines for how utilities should perform this assessment.

The following section is focused on these two deliverables, first by providing background and guidance to legislators, utilities, and other interested persons on how to perform an assessment of the potential for existing fossil resources to be replaced by LDES/MDES technologies. The next part of this section will then qualify and provide Staff's sample capacity replacement analysis and identify any additional parameters that must be considered to complete this analysis.

Generation Replacement Analysis

Identifying Important Resource Characteristics

While the sample analysis in this section considers only a generator's output, to fully assess the potential to replace an existing generating resource, both existing and candidate replacement resources need to be fully characterized. A full evaluation of candidate replacement resources requires detailed capacity expansion and production cost modeling, necessitating accurate sources of cost and technology data as discussed in greater detail in Section 4 and advanced practices in modeling as discussed in Section 5. The following is an example of the kinds of data necessary to fully characterize a fossil-fueled generating resource: capacity factor, ramp rate, heat rate, random outage rate or outage schedule, fixed and variable operations and maintenance costs, a forecast of capital and major maintenance expenses, fuel used, and emissions rates and any established emission limits. Energy storage technologies have their own unique set of parameters required to be fully defined, including duration of full discharge, rate of charge, cycle time and rest period, RTE, energy density, and LCOS.

Beyond including information that fully characterizes the existing and candidate resources intended for study, a complete analysis requires a comprehensive model of the study area, including simulating the operations of the generation in both the study area and wider regional market to meet load forecasts of demand, energy, capacity and other market prices, weather forecasts, and numerous other parameters. Additional considerations that would be necessary to supplement the

sample analysis performed in this report will be detailed in the next part of this section.

Additional Parameters of Analysis

Beyond ensuring that any replacement generation can provide capacity and energy output in a similar magnitude, frequency, and duration of the retiring resource, there are also numerous other factors which must be considered. Analysis must be done to ensure the replacement resource is the most economic option, is able to provide similar levels of other services as the resource it's replacing and can be done without compromising system reliability. While the analysis contained in this section is a good starting point to identify candidate resources to consider for replacement, as discussed further, a much more rigorous analysis that considers additional factors must be performed before determining the optimal replacement of existing generation.

The following identifies some additional factors to a replacement analysis that must be considered and provides a summary of the process planners may conduct to analyze them, including identifying suitable analytical tools and software to conduct the analysis:

- **Utility economics of replacement:** Analysis of a potential replacement scenario necessitates a thorough understanding of the economic costs and benefits of both the existing generating resource(s) and candidate replacement resources. To fully understand how existing and new resources may operate, it is also necessary to simulate the broader region, including market operations and some representative links for power flow between areas. This type of complex analysis often necessitates capacity expansion and production cost modeling, which is discussed further in Section 5 with further resources in the appendices.

- **T&D system impacts/constraints:** While some transmission limitations are represented in capacity expansion modeling, understanding the impacts of the replacement of existing generation on the transmission system requires detailed power flow simulations. In Michigan, this requires that utilities work with the local transmission owners and respective ISO to perform these analyses.[88] Understanding impacts to the transmission system is particularly important when considering the replacement of existing generation, which may provide system support or other services, the loss of which may need to be mitigated prior to a successful retirement. [89] Other services, such as providing black-start support to meet NERC requirements may also limit the retirement of an existing generator without the loss of such service first being mitigated. Analysis of a potential replacement should also consider impacts to

[88] MISO Planning Modeling Manual v4.2, 2023.
[89] MISO BPM 020 - Transmission Planning.

the distribution system, and utility planners should coordinate with their Company's respective distribution planning organization and consult any distribution planning documents filed under the established distribution planning process. See **Appendix B.2** for additional details on potential system reliability modeling software.

- **Environmental considerations:** Retirement of existing fossil-fueled generating resources has a direct impact on the quantity and makeup of local pollution levels. It is also essential to understand any new emissions that will result from the operation of a potential replacement generation source. The potential risk for existing or new generation to violate existing or new environmental regulations should also be considered, as well as the potential cost for any compliance or remediation actions.

- **Local health impacts:** The operation of a generating resource can be a significant driver of local health outcomes. Studies have shown a correlation between proximity to fossil fuel power plants and higher incidences of hospitalizations for asthma and other respiratory diseases.[90] Similar studies have correlated proximity to fossil fuel power plants with higher incidences of adverse birth outcomes and increased rates of heart disease.[91, 92] Tools have been developed, such as the EPA's Co-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA) which allows for analysis of local air quality and health outcomes that result from varying rates of pollutants.[93] COBRA has been used in Michigan IRP filings to evaluate the impacts from operating existing coal-fired power plants.[94]

- **Local economic impacts:** While not necessarily considered part of the main function of a system planner, the siting of a generating resource results in

[90] Liu Xiaopeng, Lessner Lawrence, Carpenter David O., Association between Residential Proximity to Fuel-Fired Power Plants and Hospitalization Rate for Respiratory Diseases, Environmental Health Perspectives, Volume 120, 2012, Pages 807-810, Association between Residential Proximity to Fuel-Fired Power Plants and Hospitalization Rate for Respiratory Diseases | Environmental Health Perspectives | Vol. 120, No. 6.
[91] Ha Sandie, Hu Hui, Roth Jeffery, et. al, Associations Between Residential Proximity to Power Plants and Adverse Birth Outcomes, American Journal of Epidemiology, Volume 182, 2015, Pages 215-224, Associations Between Residential Proximity to Power Plants and Adverse Birth Outcomes | American Journal of Epidemiology | Oxford Academic.
[92] Shrestha Rajat, Saha Devashree, "Fossil Fuel-producing Communities Face a 'Cumulative Burden' of Pollution, Poor Health and Job Loss in the US," World Resources Institute, published December 11, 2023, US Energy Communities Often Face Multiple Health and Socioeconomic Burdens | World Resources Institute.
[93] COBRA Web Edition | CO-Benefits Risk Assessment (COBRA) Health Impacts Screening and Mapping Tool | US EPA.
[94] Direct Testimony of Kelsey Bilsback, Case No. U-21090.

significant impacts to the local community, including economic impacts. This can be an important consideration for planners to keep in mind, as the potential loss or gain of a significant economic driver can greatly impact public perception, and therefore support or resistance, to siting a generating resource. Software such as IMPLAN provides a tool for planners to measure direct and indirect impacts of an economic decision and has been used by utilities in Michigan to support long-term resource decisions.[95, 96]

Fossil Generation Replacement Optimization Using Analytical Software

Numerous tools and software have and are currently being developed to evaluate and model different generating resources, including energy storage, some of which have been listed and categorized in **Appendix B**. The following section provides an example of how these tools can be leveraged to provide additional information when considering a potential generation replacement scenario, by using the tool QuEST to perform an example analysis. QuEST is an open-source, python-based tool which was developed by Sandia National Laboratory as a comprehensive tool for analyzing energy storage.[97] One of the applications that QuEST had previously been designed to perform is a power plant replacement analysis. Specifically, the QuEST Equity program used real-world operating data from the EPA's power plants and neighboring communities' databases to provide a potential replacement analysis focused on equitable replacement solutions using a combination of renewables and energy storage. While this program is not currently a publicly available part of the QuEST application, a combination of tools to perform techno-economic analyses, as provided in **Appendix B**, tools to evaluate emissions and public health impacts like the EPA's COBRA tool, and tools to identify environmental justice (EJ) communities like the MIEJscreen tool developed by EGLE, can be used to perform a similar analysis. The following part of this section will focus on an example replacement analysis conducted on a recently retired coal plant in Michigan.

Example Replacement Analysis for Dan E. Karn Unit 1

To illustrate how the QuEST Equity program can be used to perform a power plant replacement analysis, a sample analysis was performed, with the results provided in **Appendix C** and summarized here. The analysis was performed considering the replacement of Dan E. Karn Unit 1 (Karn Unit 1).

Dan E. Karn is a power plant facility owned and operated by Consumers Energy and located in Bay County, Michigan, which has historically had four generating units: units 1 and 2, which are coal-fired units that retired in 2023, and units 3 and 4, which are natural gas-fired units and are currently operating. Karn Unit 1 was a 265 MW

[95] IMPLAN | Economic Impact Analysis Software.
[96] Exhibit A-44, MPSC Case No. U-21585.
[97] QuESt 2.0 – Open-source platform for Energy Storage Analytics – DOE Office of Electricity Energy Storage Program.

coal-fired generation unit, with a capacity factor of 18.1% in 2022 (its last year of full operation). **Table 6.1** provides the input parameters used to determine the replacement portfolio of a combination of photovoltaic (PV) solar and energy storage (ES), in this case lithium-ion batteries, necessary to replace 50%, 80%, and 100% of Karn Unit 1's hourly energy output in 2022.

Table 6.1.

QuEST Equity Analysis Parameters

Discount Rate	3.0%
Cost per Ton of CO2	$93.0
Cost per MW PV System	$2,000,000.0
Fixed Cost of PV System	$0.0
Cost per MW ES	$1,643,000.0
Cost per MWh ES	$410,700.0
Fixed Cost of the ES	$0.0
Round-trip efficiency	83.0%

The results of this analysis are tabulated below in **Table 6.2**. The first table represents the necessary size and cost of the replacement PV and ES resources under the three replacement scenarios:

Table 6.2.

QuEST Equity Analysis Investment Results

Replacement Fraction of Karn Unit 1's Energy Output	50.0%	80.0%	100.0%
PV Power	975 MW	1,910 MW	4,228 MW
ESS Power	295 MW	670 MW	1,478 MW
ESS Energy	1,640 MWh	3,660 MWh	16,488 MWh
PV Cost	$1.95B	$3.82B	$8.46B
ESS Cost	$1.16B	$2.60B	$9.20B
Total Cost	**$3.11B**	**$6.42B**	**$17.66B**

When reviewing the necessary investment in replacement resources under each scenario, there are some clear trends to observe. The most significant is the

magnitude of additional solar and storage capacity needed to replace increasing amounts of Karn Unit 1, with an 80% replacement requiring a more than doubling of solar and storage capacity from the 50% scenario, and a 100% replacement requiring another doubling of the capacity needed in the 80% replacement scenario. In terms of investment costs, the increase is even more stark, with the cost of the 100% replacement scenario more than 5 times as much as the 50% replacement scenario. These results indicate a common issue when considering resource replacement. Due to how they operate, it is increasingly costly to replace larger portions of an existing fossil-fuel generator's output with solar and energy storage. This means that replacing the final 20% of a generator's output may require more investment than replacing the initial 80%, as is indicated in the results from the analysis of Karn Unit 1. This issue informed the reasonable thresholds for matching output to be used in the example replacement analysis that is presented in the final part of this section.

Tables 6.3 and 6.4 present results on the health impacts and the equity results of the analysis:

Table 6.3.

QuEST Equity Health Impact Results

Replacement Fraction of Karn 1 Output	50.0%	80.0%	100.0%
Health Benefits Low	$34.6M	$55.4M	$69.2M
Health Benefits High	$55.7M	$89.1M	$111.4M
CO2 Offset	926,451 Tons	1,482,321 Tons	1,852,901 Tons
Climate Benefits	$86.2M	$137.9M	$172.3M
sNPV[98] (Health) Low	$514.9M	$823.9M	$1.03B
sNPV (Health) High	$828.9M	$1.33B	$1.66B
sNPV (Climate)	$1.28B	$2.05B	$2.56B
sNPV (Total) Low	$1.80B	$2.87B	$3.59B
sNPV (Total) High	$2.11B	$3.38B	$4.22B

[98] sNPV is the social Net Present Value of a decision, which considers the present value of a decision from the viewpoint of society.

Table 6.4.

QuEST Equity Results

Replacement Fraction of Karn 1's Energy Output	50.0%	80.0%	100.0%
DAC Population	33.3%	33.3%	33.3%
Low-Income Population	23.1%	23.1%	23.1%
DAC Benefits	30.6%	30.6%	30.6%
DAC sNPV Low	$157.7M	$252.3M	$315.4M
DAC sNPV High	$253.9M	$406.2M	$507.7M
Low-Income Benefits	23.2%	23.2%	23.2%
Low-Income sNPV Low	$119.5M	$191.3M	$239.1M
Low-Income sNPV High	$192.4M	$307.9M	$384.9M

Health and equity results are based off assumed health benefits that result from COBRA modeling that are integrated into the QuEST Equity program. Climate benefits were estimated using an assumed social cost of carbon of $93 per ton. Impacts to disadvantaged communities (DAC) and low-income customers were estimated using census-tract data for the local areas surrounding Karn Unit 1. Consideration of health and equity impacts as part of a potential resource replacement is discussed more in Section 8.

Replacement Analysis Methodology

The following is a sample analysis that considers the potential replacement of existing fossil-fueled generation in Michigan with LDES or MDES. This analysis uses generator dispatch data from 2023 (or the previous year's data if the plant had a major plant outage or other factors that resulted in an abnormal annual performance) to consider whether an LDES or MDES technology could approximately match the output of this resource. Generator dispatch data was sourced directly from a survey sent to electric providers, or otherwise from the publicly available Clean Air Markets program data through the EPA.[99]

Three parameters were used to characterize each generator's output: unit age, number of starts, and longest continuous dispatch. Metrics were then established for these parameters to identify existing fossil generators that, based on their dispatch, could potentially be replaced by LDES and MDES. It is important to note that this analysis should be viewed as the starting point to a generator replacement analysis; the purpose is to provide a broad list of candidate resources to recommend for

[99] Clean Air Markets Program Data (CAMPD) | US EPA.

further study. As such, the metrics were set conservatively, to not preclude resources prematurely. This analysis is also a snapshot view of Michigan's fossil-fueled generation fleet in a single year. Therefore, it is subject to potential misrepresentations of usual plant operations and will require updates and refinements in the future as its information becomes outdated, and more data are added to the data set. Further study, including rigorous capacity expansion modeling using best practices identified in Section 5, consideration of grid impacts discussed in Section 7, and consideration of environmental and community impacts as detailed in Section 8, is necessary to properly identify the appropriate solution to replacing an existing resource.

For unit age, units which have operated for over 25 years were filtered out. This threshold was chosen as a reasonable proxy as it would generally be after the asset's initial development costs are fully depreciated, while also approaching the expected useful life of many newer fossil-fuel plant technologies. Additionally, plants of an older vintage are less likely to have emissions control technology, further limiting their viability under potential future emissions restrictions.

For unit starts, units with over 300 starts were filtered out, as this would require near daily cycling. Due to the time required for a full battery cycle and any necessary rest time, this frequency of cycling would be difficult to achieve economically with an LDES or MDES technology, and analysis of a shorter duration energy storage technology would be more appropriate for replacement.

For a unit's longest continuous dispatch, units which operated for over 200 hours continuously were filtered out, as this would be approximately twice the current dispatch duration design of MDES technologies. A threshold that exceeds the current duration limits of MDES technologies was appropriate, as requiring the replacement storage resource to completely match a resource's longest dispatch would likely result in significant and costly overbuild, as indicated in the QuEST analysis presented previously. Requiring each replacement energy storage resource to fully match the output of the generator that it is replacing assumes that these generators' longest dispatches occur simultaneously, with no other replacement energy storage facility or other resources on the system available to meet this demand. Additionally, outside of these peak demand events, energy storage resources will likely operate more efficiently than the existing fossil-fuel fleet, providing additional value and allowing for a more efficient management of the grid. For similar reasons, a limit of 48 hours of continuous dispatch was set as the limit for LDES technologies to be suitable as a potential replacement option.

Based on the results of the analysis, aggregated capacity of fossil-fueled generation suitable for further study has been identified. The results are grouped and presented in different ways to provide a more detailed look at the impact this aggregated capacity has for each utility, the Lower and Upper Peninsulas, and the entire state.

Sample Analysis

Starting from the highest viewpoint and getting more granular, this analysis identified a total of 2,581 MW of existing fossil-fueled generator capacity in the state which are suitable candidates for further study of a potential replacement with LDES/MDES. Breaking out this candidate capacity by peninsula, this equates to 2539 MW and 42 MW in the Lower and Upper Peninsula, respectively. See the tables below for further breakdown of candidate units by utility service territory and necessary duration of a potential storage replacement (LDES or MDES).

Table 6.5 identifies and groups the aggregated candidate capacity into those located in the Lower and Upper Peninsulas. Of note, the UP has significantly less candidate capacity to study for replacement due to several factors, including demographics and customer load. Electric providers in the UP also have smaller energy storage procurement obligations under Section 101 of 2023 PA 235, making developing individual energy storage projects, particularly novel LDES or MDES technologies, more difficult. Difficulties in resource planning for utilities in the UP, particularly in relation to meeting procurement targets like the Renewable Portfolio Standard, have been identified by the Commission in other reports. Recognition of these challenges have led to recommendations to coordinate resource planning efforts among UP electric providers, to reduce individual burdens and help streamline the planning process. This report makes a similar recommendation for the study, evaluation, and potential replacement of the candidate fossil fueled resources identified in **Table 6.5**. Electric providers in the UP should coordinate efforts, where possible, to evaluate these resources, and provide the results in each of their individual IRPs. Results should detail any coordination in the analysis, the results of MISO's study of the injection of 60 MW of energy storage into the UP's system, and any potential future coordination in the procurement of resources needed to comply with Section 101 of 2023 Act 235, with other electric providers in the UP.

Table 6.5.

Candidate Replacement Capacity by Peninsula

Peninsula	LDES (MW)	MDES (MW)	Total (MW)
LP	1589.5	949.2	**2538.7**
UP	41.9	0	**41.9**
Total	1631.4	949.2	2580.6

Table 6.6 identifies and groups the aggregated candidate capacity by electric provider and identifies the appropriate replacement energy storage duration requirements.

Table 6.6.

Candidate Replacement Capacity by LSE

LSE	Area Served	LDES (MW)	MDES (MW)	Total (MW)
DTE Electric	LP (LRZ 7)	647	341.2	**988.2**
Consumers Energy	LP (LRZ 7)	600	608	**1208**
Cloverland	UP (LRZ 2)	19.3	0	**19.3**
Wolverine	LP (LRZ 7)	45	50	**95**
Upper Peninsula Power Company	UP (LRZ 2)	22.6	0	**22.6**
CMS Energy	LP (LRZ 7)	247.5	0	**247.5**
Total		1581.4	999.2	**2580.6**

While this analysis has been qualified as only an initial framework to adequately consider and vet the replacement of an existing electric generator, it can serve as a reference point for future resource planning in the state. 2023 PA 235 establishes a statewide target of 2,500 MW of energy storage capacity. However, simply adding 2,500 MW of energy storage capacity to the system, without consideration of its potential to replace existing generation, does not result in the most efficient and economic resource mix for the state. The potential for this new capacity to replace existing resources must also be examined. This analysis demonstrates the significant potential for the existing fleet to become more efficient, as new energy storage resources come online with the potential to replace the capacity of the existing fleet while operating more economically with less adverse community impacts. These results should be kept in mind by the Commission, Commission Staff, and other Parties when evaluating future IRP filings. While this analysis is only a starting point, it cannot be ignored by a utility if it is truly submitting the most reasonable and prudent plan as required by MCL 460.6t.

Therefore, it is recommended that each utility, which has candidate resource capacity identified in the above study, conduct a full analysis of its existing fleet and consider LDES and MDES, along with other potential replacement solutions, using the best practices for such an evaluation identified in Sections 5 through 8 of this report. For rate-regulated utilities, this analysis should be presented in its next IRP, where a utility considers the optimal mix of resources to serve its customers over the long term. Providing this analysis in the next round of IRPs also aligns with the filing

of utility's energy storage procurement plans to satisfy PA 235, allowing for the most efficient planning of qualifying storage facilities to meet a utility's compliance.

Section Recommendations:

There are two recommendations for follow-up actions by LSEs, which resulted from this section:

6-1: Electric providers in the UP should consider coordinating storage planning efforts, where possible, to evaluate candidate resources identified in this analysis and provide any results in their respective IRPs.

6-2: Each electric provider with candidate resource capacity identified in the example study included in Section 6 of this report should conduct a full analysis of its existing fleet, considering the replacement of existing generation with LDES, MDES, or other solutions, in at least the capacity amount identified in this report and using the best practices identified in Sections 4 through 8 of this report.

7. Grid Impacts and Considerations

In addition to the capacity and societal benefits explored in other sections of this paper, LDES technologies can have impacts and benefits that extend throughout the electric grid and beyond, reaching into the communities that host such projects. This section will briefly describe other implications of LDES that are not included in capacity expansion planning but that will affect other planning and investment decisions, including transmission system impacts, interaction with shorter-duration technologies, and resilience objectives.

Transmission System Impacts

Public Act 341 of 2016 re-established integrated resource plan (IRP) requirements for Michigan utilities. Capacity expansion planning is a central component of an IRP process; it is the tool by which a utility identifies potential resource mixes to meet future needs. Other tools, such as production cost models and power flow models, are then used to test different portfolios across multiple potential futures to build the portfolio that delivers the most value across the widest range of potential futures. While the resources that will serve Michigan customers will ultimately be selected by capacity auctions in the MISO and PJM territories, integrated resource planning allows Michigan utilities and regulators to shape that process.

Transmission planning follows a similar structure, in which individual utility plans inform broader regional outcomes. The Federal Energy Regulatory Commission (FERC), which has authority over transmission planning, issued Order 1000 in 2011 to require utilities to prepare collaborative regional transmission plans.[100] In Michigan, MISO and PJM are the entities that coordinate regional transmission planning, though they do so in slightly different ways. In MISO, utilities develop transmission plans and then submit them to MISO, which conducts its own analysis of those plans and can amend or remove utility projects as it assembles a regional transmission plan.[101] PJM employs a shared authority approach in its service territory, in which PJM leads the planning for large projects that could benefit multiple utility service territories while individual utilities lead the planning for smaller projects in their individual territories.[102]

Transmission planning processes have two primary objectives: expanding the transmission system to meet forecasted demand and reinforcing the transmission system to improve reliability. FERC also requires transmission planners to consider projects that would improve the overall efficiency of the grid or facilitate the realization of state energy policies.

[100] Order No. 1000 - Transmission Planning and Cost Allocation | Federal Energy Regulatory Commission.
[101] MISO Transmission Expansion Planning website: MTEP.
[102] PJM - Regional Transmission Expansion Plan (RTEP).

Energy storage can contribute to all these planning objectives, but it is primarily relevant within the context of reliability planning. To improve system reliability, transmission planners utilize contingency planning, in which they develop potential scenarios involving the failure of grid infrastructure. These scenarios, which are called *n*-1 (in which a single piece of grid infrastructure, such as a transmission line or generation unit, fails), *n*-1-1 (in which two pieces of infrastructure fail in sequence), *n*-2 (in which two pieces of infrastructure simultaneously fail), and so forth. The objective of these contingency studies is to identify those in which the grid would not be able to recover, allowing the failure to spread throughout the system, and then identify the necessary reinforcements to prevent such a failure.

As Michigan deploys LDES technologies, they will contribute to transmission system reliability both indirectly and directly. Indirectly, the growth of energy storage adds flexibility to the transmission system that can reduce the number of problematic contingencies that utilities need to address. Contingency events are much less likely to spread when nearby storage projects can step into respond to supply interruptions. The California Independent System Operator (CAISO), for example, has identified several contingencies in recent transmission plans that were adequately addressed by local energy storage projects.[103]

On a direct basis, planners may identify contingency events that can be resolved by targeted energy storage investments, such as supporting system voltage to ensure power flows or managing power flows to ensure that transmission lines are not overloaded. Through various orders and decisions in recent years, FERC has supported the consideration of energy storage and other non-transmission alternatives in transmission planning. In 2019, MISO developed a process for analyzing energy storage as a transmission alternative and selected storage as the best option for resolving a contingency identified in Wisconsin. Although FERC formally approved MISO's approach for analyzing storage alternatives in 2020, MISO has not studied one since.

Ultimately, Michigan investments in LDES resources will have a symbiotic relationship with the transmission system. In some instances, transmission planners may identify needs for storage resources to support the transmission system, and in other instances, storage resources deployed for their market benefits may also provide system flexibility that reduces or eliminates the need for transmission infrastructure.

Identifying these benefits and ensuring their consideration in the transmission planning process will require advocacy in the MISO and PJM planning processes. FERC's rules for transmission planning are written in a way that only requires transmission planners to consider storage and other non-transmission alternatives, or 'non-wires alternatives' (NWAs), when some party directly asks them to; there is no requirement for planners to consider those alternatives on their own. Therefore,

[103] CAISO's Board Approved 2023-2024 Transmission Plan: iso-board-approved-2023-2024-transmission-plan.pdf.

ensuring that the potential benefits of storage investments in Michigan are captured in regional transmission planning processes will require that a party participating in those processes request that those benefits be studied. As this section has identified, such a consideration of storage and other NWAs is essential to maximize the benefits to the transmission system.

Interaction with shorter-duration technologies

LDES technologies will play a complementary role to lithium-ion batteries and other shorter-duration storage technologies. LDES technologies, with their ability to move large quantities of energy over longer periods of time, will play a crucial role in maintaining system reliability and resource adequacy as the utilities work to meet the statutory Clean Energy Standard and more variable generation resources come online. This ability to discharge energy over a long period provides a critical use case for LDES technologies that is not economical or technically feasible to achieve with shorter-duration energy storage. However, lithium-ion batteries and similar technologies will continue to play an important role in grid reliability for three reasons: cyclability, round-trip efficiency, and energy density.

Because shorter-duration technologies can only hold a few hours' worth of energy, they can also fully recharge in a few hours. LDES and MDES technologies can hold much more energy, which means they also need much longer to recharge. For grid services that need to be provided daily, such as ancillary services or meeting daily demand peaks, shorter-duration technologies will have an advantage over LDES and MDES technologies.

All energy storage technologies lose energy in the conversion process and on serving additional needs (such as cooling and ventilation). Round-trip efficiency (RTE) is a measure of how much energy a storage technology can discharge relative to how much energy it took to charge and operate it, considering those losses. **Table 7.1** summarizes the RTEs of various energy storage technologies:

Table 7.1.

Round-trip efficiencies of various energy storage technologies[104, 105, 106, 107]

Technology	Discharge Duration	Round-Trip Efficiency
Compressed air energy storage	24-100+ hours	55%
Hydrogen	24-100+ hours	31%
Iron air battery	100 hours	40%
Iron flow battery	8-24 hours	70%
Lithium-ion	4 hours	83%
Pumped storage hydropower	24-100+ hours	80%
Sodium-ion	6-8 hours	80%
Vanadium flow battery	8-24 hours	65%

As **Table 7.1** indicates, LDES and MDES technologies tend to have lower RTE than lithium-ion batteries. RTE is just one of many factors that go into selecting a technology; these data are not meant to communicate a comparative disadvantage for LDES and MDES technologies, which can provide services that lithium-ion cannot.

The final advantage that will preserve a role for shorter-duration technologies is their energy density, which is a measurement of how much energy a technology can store relative to its size. Lithium-ion batteries have the highest energy density of any proven form of energy storage, which is why their primary uses remain consumer electronics and transportation. LDES and MDES technologies generally have much lower energy density than lithium-ion, which means that they will require a larger physical footprint. Where space is limited, such as projects located in densely urban

[104] PNNL; Maisch; Form Energy; DOE.
[105] ESS,Inc. 2021. "Energy Warehouse." https://essinc.com/wp-content/uploads/2021/06/ESSDatasheet_EnergyWarehouse_3-19-21.pdf.
[106] Form Energy. 2022. "Breakthrough Low-cost, Multi-Day Energy Storage." https://archive.legmt.gov/content/Committees/Interim/2021-2022/Energy-and-Telecommunications/2022MayMeeting/FormEnergy.pdf.
[107] U.S. Department of Energy. 2023. Technology Strategy Assessment: Findings from Storage Innovations 2030 Bi-Directional Hydrogen Storage." https://www.energy.gov/sites/default/files/2023-07/Technology%20Strategy%20Assessment%20-%20Bidirectional%20Hydrogen%20Storage_0.pdf.

areas or on a customer's premises, the energy density of shorter-duration technologies will be an important consideration.

Resilience Impacts

Climate change is straining the electric grid, driving temperature extremes that increase customer demand while fueling storms that can damage grid infrastructure. Recognizing this growing threat, FERC's recently adopted transmission planning rule requires utility transmission planners to consider major events like storms in their planning process.[108] These risks are well-known in Michigan, which experienced 157 power outages caused by storms from 2000 to 2023—the second-highest rate in the country behind Texas.[109] The Commission has addressed the importance of resilience repeatedly. The final report delivered as part of the Michigan Statewide Energy Assessment defines resilience as "the robustness and recovery characteristics of utility infrastructure and operations, which avoid or minimize interruptions of service during an extraordinary and hazardous event."[110] Additionally, in the August 20, 2020 Order in Case No. U-20147, the Commission addressed resilience in two parts. First, resilience is "the ability to restore power following a catastrophic event," and second, resilience is "planning to mitigate more localized, high-impact outages caused by equipment issues, access limitation, or system configurations that inhibit timely restoration or back-up capabilities."[111]

LDES resources can be powerful tools in making the grid resilient against these major events, but since resilience objectives are not included in traditional IRP processes, achieving those outcomes will require new planning practices. To understand the difference between grid *reliability* and grid *resilience*, it is helpful to understand the Institute of Electrical and Electronics Engineers (IEEE) Standard 1366.[112] This standard includes several metrics that provide a common foundation for defining and measuring grid reliability across the country. Commonly used terms to define reliability come from this standard, including SAIFI (System Average Interruption Frequency Index), which measures the number of times the average customer experiences an outage during a given period, and SAIDI (System Average Interruption Duration Index), which measures the total amount of time the average customer was without service during a given period.

Because IEEE 1366 clearly defines reliability and provides metrics for measuring it, this standard provides outcomes for planning models to achieve. A utility planner knows how to plan for a reliable system because there are agreed upon terms for measuring a system's reliability, and a regulator can clearly compare the costs and

---

[108] Explainer on the Transmission Planning and Cost Allocation Final Rule | Federal Energy Regulatory Commission.
[109] Surging Weather-related Power Outages | Climate Central.
[110] 2019-09-11_SEA_Final_Report_with_Appendices.pdf.
[111] 8/20/20 Order in Case No. U-20147, pp. 48-49.
[112] 1366-2012 - IEEE Guide for Electric Power Distribution Reliability Indices | IEEE Standard | IEEE Xplore.

benefits of different reliability investments. Reliability standards also inform market design, as resources are paid for their contributions toward meeting those standards.

But IEEE 1366 provides an exception for major event days, which are those days in which a utility's outage numbers are at least two standard deviations above their average outage numbers. The standard essentially treats major event days as *force majeure* events that are beyond a utility's control and are exempted from reliability reporting. There are no standards or metrics to measure how a utility's system responds to these major events, so there are no clear outcomes for a planning model to achieve. Absent those underlying standards and metrics to serve as a reference, investments in resilience tend to be much more subjective, which makes them more difficult for utilities to identify and for regulators to review. Because there are no underlying resilience requirements, markets are not specifically designed to compensate resources that provide that service.

Figure 7.2 illustrates the relationship between reliability and resilience, with IEEE 1366 drawing the line between them:

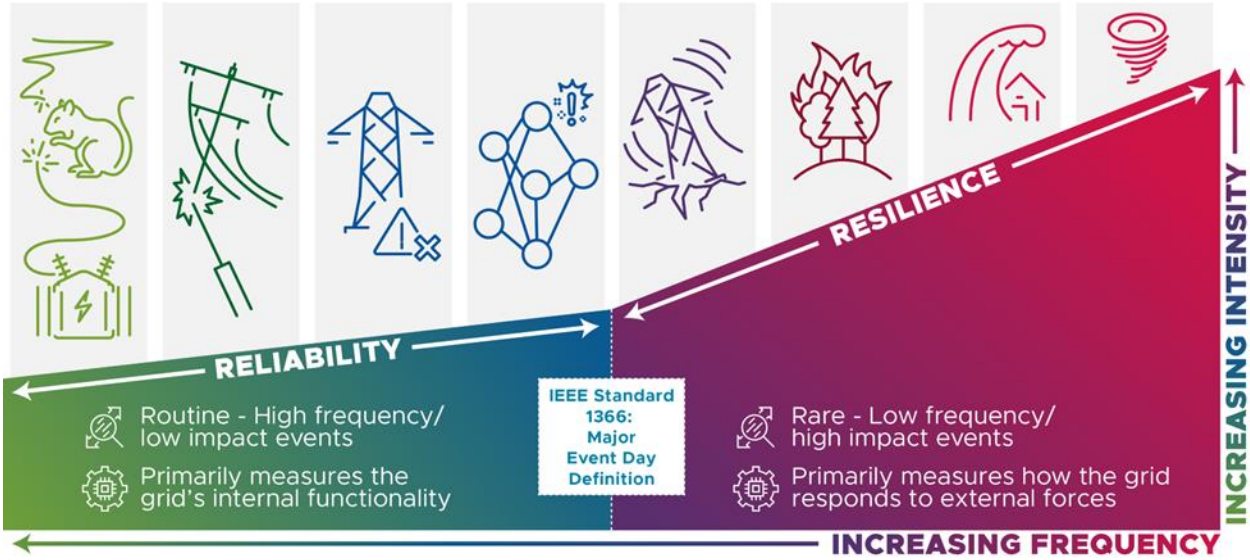


Figure 7.2. Reliability and Resilience Under IEEE 1366 (PNNL).

As **Figure 7.2** illustrates, reliability deals with how the grid functions under normal circumstances and how it manages the high-frequency, low-impact events that happen daily. Resilience, on the other hand, deals with how the grid functions when it is interrupted by external forces; low-frequency and high-impact events like major storms or cyberattacks. However, it is important to keep in mind that these are regulatory constructs; a customer experiencing an outage does not really care about whether a utility and a regulator would call it a reliability event or a resilience event. As major events increase in frequency and impact, customers are increasingly demanding investments in the resilience space.

Developing a resilience plan requires a more granular and detailed planning that will accomplish three things:

- **Define the resilience need.** Since there are no agreed-upon definitions or metrics to inform resilience planning, the process must begin by defining its desired outcomes. What major events does the utility face? What would the impacts of those events be? What services would need to be provided? How long will service restoration take? By asking these questions, utilities and involved persons can define the need in narrow terms—how, where, and how long power will be needed to provide a specific outcome that a planning model can achieve.

- **Incorporate revenue opportunities.** As discussed above, the absence of grid resilience requirements means that no market revenue streams are designed to directly compensate for resilience, which in turn means that assets deployed to address resiliency will need to do other things to be cost-effective. Because energy storage technologies can provide a wide range of monetizable reliability services in addition to non-monetizable resilience services, LDES technologies are well-suited to reduce the net cost of resilience investments. Incorporating potential revenue streams into a resilience analysis can better inform the sizing and operation of LDES resources.

- **Identify optimal site.** Deciding where to place an asset that will provide both system-wide reliability benefits and local resilience benefits will likely involve tradeoffs. Market prices or interconnection opportunities may not align with where the resilience services are needed; determining the optimal site for the asset will require planners to optimize across multiple objectives while ensuring that the system is sited and configured to meet the primary objective of local resilience.

Section Recommendations:

MISO released its reliability imperative report in 2024, which highlighted the need for evaluating emerging technologies, such as LDES, and their potential role in providing reliability services.[86] However, it calls out that these technologies need to become more mature to be a feasible option at grid-scale. Additionally, MISO's 2021 Renewable Integration Impact Assessment (RIIA) highlighted the risks that emerge in the presence of increased renewables on the system and provided an in-depth resource adequacy study of the Eastern Interconnection.[87] A key insight provided was that storage will be essential for grid reliability when optimally paired with renewable and transmission assets.

There are two recommendations that result from this section, 7-1 is all participants in ISO planning processes, and 7-2 is for the Commission:

7-1: Utilities, regulators, and other interested persons who participate in RTO/ISO study activities should proactively request that the RTO/ISO study storage

alternatives as transmission planning solutions during the transmission planning process to ensure they are adequately considered.

7-2: The Commission should encourage RTOs/ISOs to develop specific metrics and objectives for resilience planning to incorporate these metrics/objectives into existing transmission planning processes. The Commission should direct Staff to develop specific metrics and objectives related to resilience as part of the distribution planning process to encourage consideration of resilience alongside traditional reliability metrics when analyzing regulated utility investments.

8. Environment and Community Impacts

Resource Siting Impacts

The ultimate location where an electrical generating unit is installed and operates is influenced by multiple factors. For instance, some factors can limit potential locations for siting a resource due to cost or operational needs. Certain factors, such as the technology type and size of the generating facility, will determine its potential to impact the community in which it is located. These same factors also influence the locations that are suitable for a particular generating resource. For example, a large solar generating facility requires significant amounts of continuous tracts of land and high-voltage transmission which makes rural farmland a preferred location. Meanwhile, a large natural gas combined cycle facility requires a smaller physical footprint but also requires dedicated fuel supply and access to the high-voltage transmission network. The process to evaluate, select, and develop resources is complicated, involving different groups, organizations, and people that participate throughout the approval process and are impacted in different ways by the siting decision that is ultimately made. Therefore, it is essential for utilities to fully consider and balance the technical, infrastructure, community, and other related benefits and impacts of siting a generating resource in a specific location.

In Michigan, there are several ways in which electric providers determine the need for additional electric generating capacity and/or energy. This is primarily done through the Integrated Resource Planning (IRP) process under MCL 460.6t, as an IRP provides a holistic look at the utility, state, and region's electrical system under multiple potential future situations.[113] While the IRP process is a useful tool for determining the optimal mix of generating resources from the utility perspective, it has had shortcomings in considering the impact of decisions on individual communities or areas because the location of new resources is not necessarily known at the time the IRP is developed, reviewed, or even approved. Sections of MCL 460.6t require the filing utility to consider and present information on the affordability of its plans, and the Commission-approved IRP filing requirements require the utility to provide details around public outreach sessions the utility is encouraged to host prior to filing.[114, 115] PA 231 of 2023 added requirements to file environmental justice impact analyses for plans, which include fossil-fuel plant retirements.[116] While these updates now require the utility to consider the impact of its resource decisions on the affected local communities, it can be difficult to fully consider the impacts of resource decisions in a long-term and far-reaching process such as an IRP, requiring deliberate efforts from all parties to ensure there is a complete analysis that considers impacts to all affected communities and people.

[113] PA 3 of 1939, amended by PA 341 of 2016, adopted as MCL 460.6t.
[114] MCL 460.6t(5)(k).
[115] 10/27/22 Order in Case No. U-18461, Attachment A, p. 4.
[116] MCL 460.6t(4)(p).

Resource siting impacts have thus far been detailed at a high-level without consideration for different technologies and the safety concerns associated with them. Concerns with the siting of energy storage have largely been focused on lithium-ion battery storage, particularly the safety risks associated with fire caused by thermal runaway.[117] To address these concerns, the National Fire Protection Agency (NFPA) has produced a standard, NFPA 855, to establish best practices for lithium-ion batteries to reduce the risk of fires. LDES technologies, while generally not at risk of thermal runaway, have additional potential safety risks depending on the technology employed. Due to their limited deployment, safety standards have not been developed to address the operational risks of these technologies. Additional diligence is necessary to understand the safety risks and take the necessary mitigation measures when deploying these technologies. Additional concerns around sound, visual, and land impacts, which generally are not a major barrier to the development of lithium-ion batteries, may become more significant issues depending on the technology being developed.

The impacts of a resource operating in a community are widespread and, depending on the perspective, may be viewed as either positive, negative, or sometimes both simultaneously. Policies, regulations, and external pressure from both the public and the private sector will likely continue to accelerate the closure of existing fossil fueled generation plants. It is critical for an analysis of existing or new generation to consider the multifaceted impact from not just the utility's perspective, but also from the perspective of the community. Analysis tools, such as IMPLAN, have been used by utilities in Michigan to better analyze the impacts of the operation of a power plant on the local community.[118, 119] Additional tools, such as the EPA's Co-Benefits Risk Assessment Health Impacts screening model (COBRA) have also been used in Michigan IRP filings to better understand the impact of fossil-fueled plant operations on local air quality.[120, 121] While there is no one tool or set of tools which can be recommended that perfectly considers all factors, this report identifies a plethora of additional modeling tools and techniques which can be used to better quantify and consider impacts prior to implementation.

Michigan's energy transition addresses historical inequities in policies and practices by including Environmental Justice (EJ) considerations in the MI Healthy Climate plan. One of the key features of this plan is to provide at least 40% of state funding for climate-related and water infrastructure initiatives that benefit Michigan's disadvantaged communities, in line with federal Justice40 guidelines.[122] An EJ community is one where, due to demographic or other socio-economic factors and policies of systemic racism, are subject to disproportionate environmental burdens.

---

[117] Yixin Dai, Aidin Panahi, Thermal runaway process in lithium-ion batteries: A review, Next Energy, Volume 6, 2025, 100186, ISSN 2949-821X, https://doi.org/10.1016/j.nxener.2024.100186.
[118] IMPLAN | Economic Impact Analysis Software.
[119] Exhibit A-44, MPSC Case No. U-21585.
[120] COBRA Web Edition | CO-Benefits Risk Assessment (COBRA) Health Impacts Screening and Mapping Tool | US EPA.
[121] Direct Testimony of Kelsey Bilsback, MPSC Case No. U-21090.
[122] MI Healthy Climate Plan.

These communities, often low-income and/or predominantly Indigenous or people of color, are subject to greater concentrations of environmental burdens, such as high levels of air pollution, high traffic volume, and high potential exposure to hazardous waste, combined with other indicators of social disadvantage like low educational level and high poverty rates.[123] Often times, the most vulnerable communities experiencing the negative impacts of environmental burdens also have less representation in decision-making processes, which has been identified as a major barrier to achieving environmental justice.[124] The current IRP Filing Requirements encourage the filing utility to host public meetings, both in person and virtually, to inform and collaborate with its ratepayers on its resource plan, with proposed updates including additional parameters to focus on outreach to EJ communities.[125]

EJ Community Mapping

For the state to achieve the goals of the MI Healthy Climate plan, including those centered on energy equity, EJ communities must be meaningfully involved throughout the resource planning process. To understand how a decision or plan impacts EJ communities, these communities must first be identified. This has been done through EJ mapping tools, such as the Michigan-specific tool MiEJScreen or the U.S. EPA tool EPA EJ Screen. These tools provide insight into communities using socioeconomic data from the US Census Bureau American Community Survey (ACS) 5-year Estimates, which provides data every year, but require updated data to stay current. It also should be noted that these tools provide a view of census tracts that meet the thresholds for an EJ community, as defined by the tool, and that these results are a snapshot in time based on the tool's current dataset. Staff recommends that when determining an appropriate tool to use in environmental justice community identification, data granularity, and frequency of data updates should be considered because EJ communities will change and shift with time.

To assist in the consideration of the potential replacement of existing fossil-fueled generating resources with energy storage, which is the focus of Section 6 of this report, the following example EJ maps were generated. The maps below were formed using the Department of Environment, Great Lakes, and Energy's MiEJScreen, which is an interactive screening tool that identifies a variety of stressors and demographics within communities that may impact environmental conditions or the public health of residents.[126] Within the mapping tool is a layer for a MiEJ Score Percentile, which is determined by weighted environmental conditions and population characteristics for each census tract in the state of Michigan. While there

[123] U-M study reveals hot spots of environmental injustice across Michigan | University of Michigan News.
[124] Nicola Ulibarri, Omar Pérez Figueroa, Anastasia Grant, Barriers and opportunities to incorporating environmental justice in the National Environmental Policy act, Environmental Impact Assessment Review, Volume 97, 2022, 106880, ISSN 0195-9255, https://doi.org/10.1016/j.eiar.2022.106880.
[125] Michigan IRP Filing Requirements, 10/27/22 Order, MPSC Case No. U-18461.
[126] MIEJScreen.

is no set MiEJ Score that classifies a community as overburdened or an environmental justice community, the tool allows for users to determine which score or range of scores are most appropriate for their analysis.

In this analysis, any facilities located in census tracts with a MiEJ composite score percentile of 70 or above were flagged for further EJ-related review and shown in **Table 8.1**. A cumulative score of 70 was chosen to provide a wider view of the potential siting of fossil fueled plants in EJ communities, as opposed to more conservative metrics which may artificially limit its scope. In concert with other considerations discussed in the previous sections, and in furtherance of the directive in MPC 460.6t, the impact of the potential retirement of these units on the EJ communities in which they are located should be prioritized as electric providers consider the potential replacement of the existing fossil-fueled generating fleet.

Table 8.1.

List of Michigan generating facilities in communities with a cumulative MiEJ Score above 70

Facility Name	**MiEJ Score**
Delray	99
River Rouge	99
Dearborn Industrial Generation	96
Monroe (MI)	89
Battle Creek Mill	88
Lansing BWL REO Town Plant	87
Jackson Generating Station	83
Wyandotte	82
E.B. Eddy Paper Inc	80
The Andersons Albion Ethanol LLC	77
Lorin Industries	75
Holland Energy Park	72
Water Street Station	71
Beaumont Hospital Dearborn Campus	71
Kalamazoo River Generating Station	71

Figure 8.2 is a choropleth map of Michigan, with each pin representing the location of a power plant facility with at least one fossil-fueled generation source.

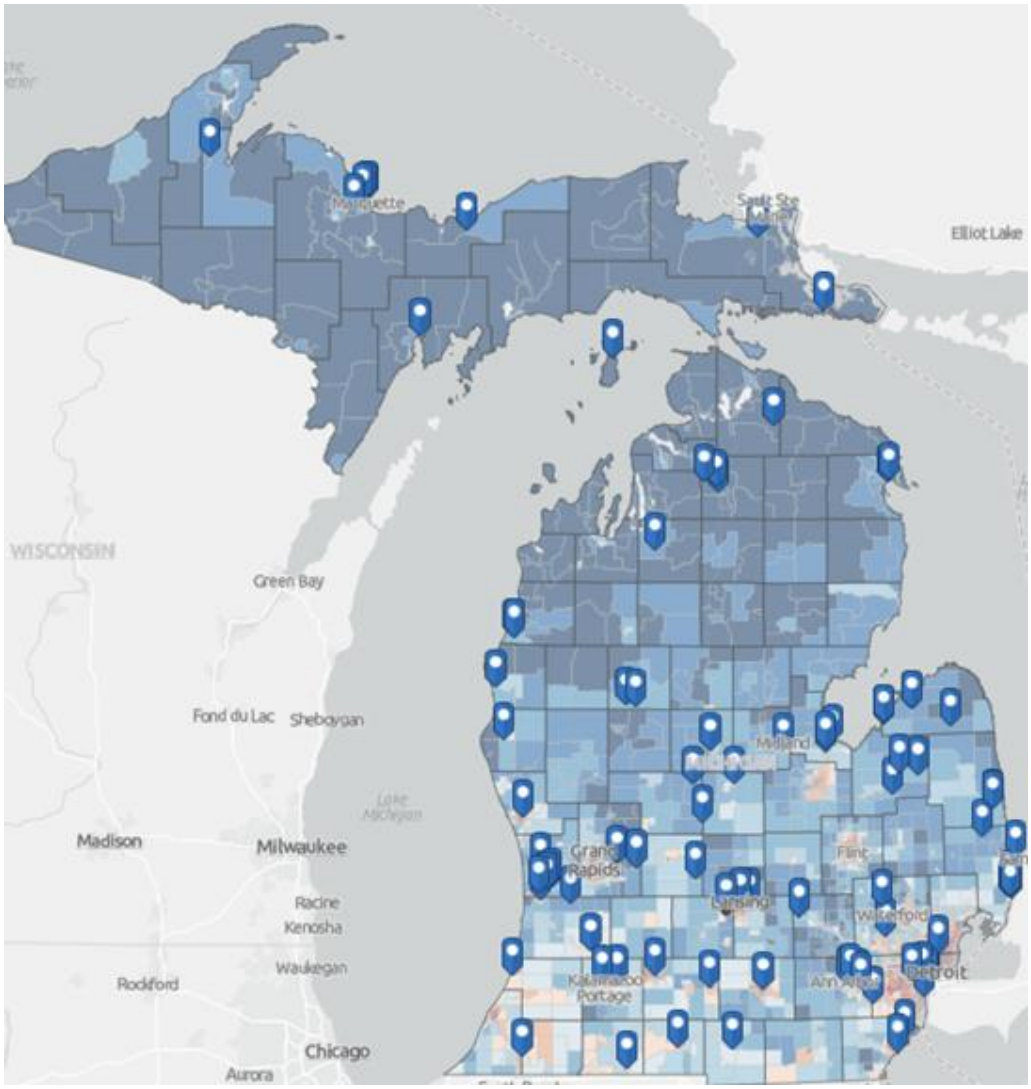


Figure 8.2. Map of fossil-fueled generating facilities in Michigan.

Figure 8.3 is a choropleth map of the state, with only fossil-fueled facilities located in census tracts with MiEJ Scores above 70 included.

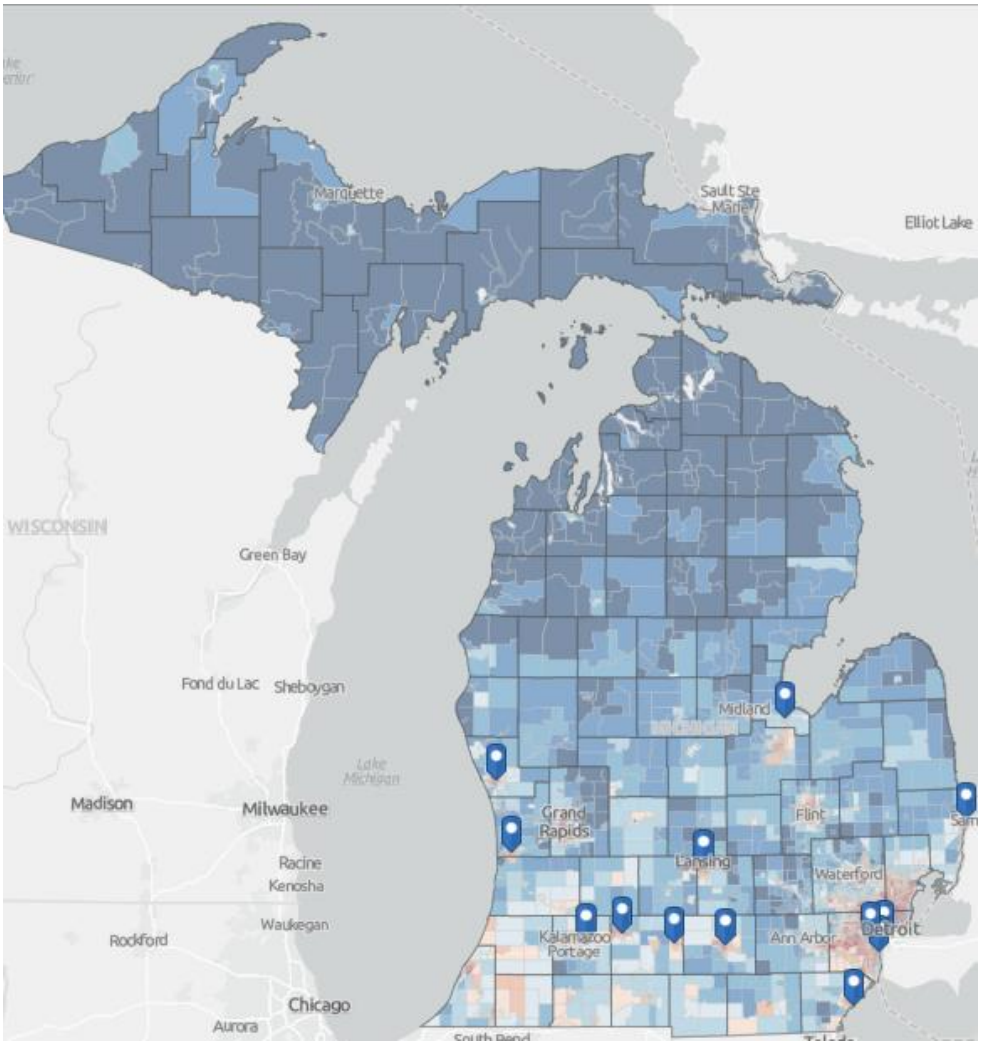


Figure 8.3. Map of fossil-fueled generating facilities in EJ communities.

Figure 8.4 is a detailed view of the Metro Detroit area, to provide a better view of the distribution of fossil-fueled facilities in this area.

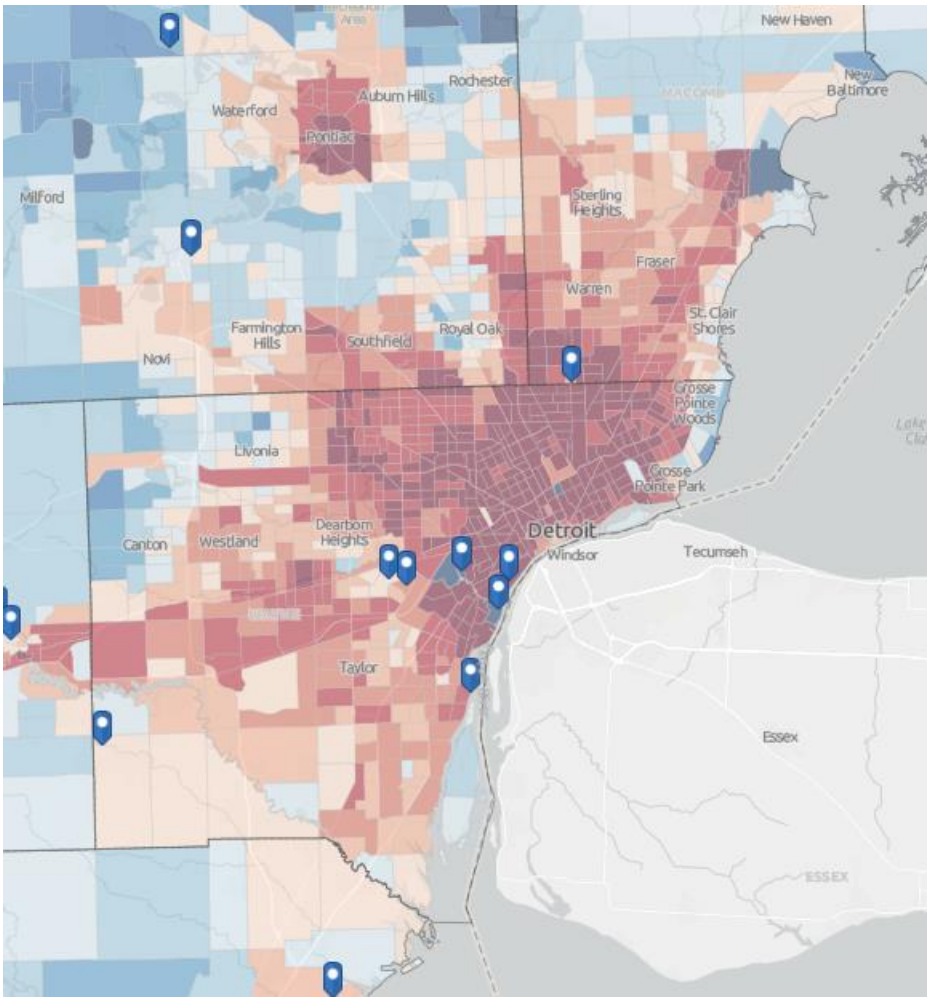


Figure 8.4. Detailed view of fossil-fueled generating facilities in Metro Detroit.

Figure 8.5 is the same view of the Metro Detroit area with only facilities located in census tracts with MiEJ Scores above 70 included.

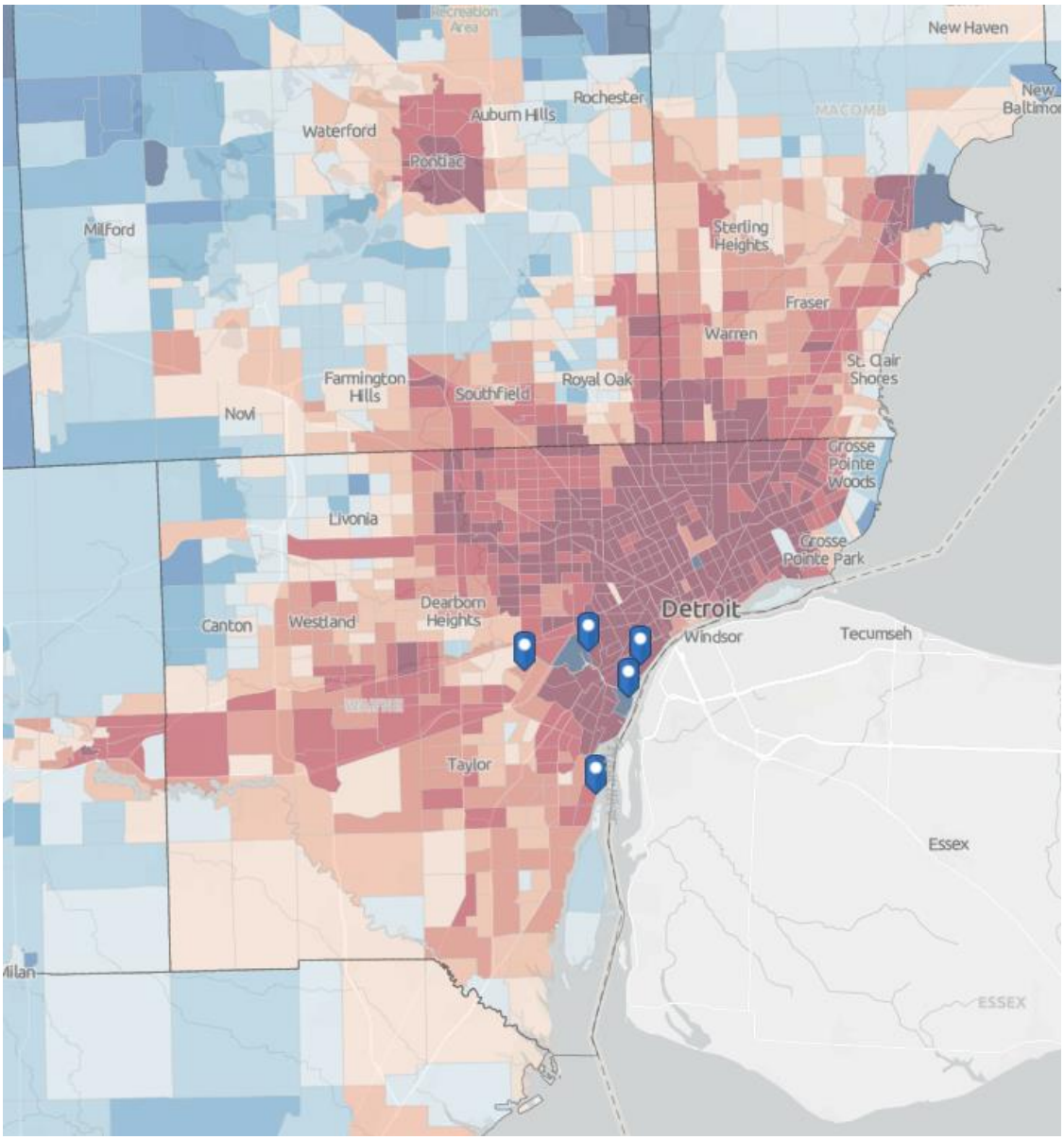


Figure 8.5. Detailed view of fossil-fueled generating facilities in EJ communities in Metro Detroit.

Section Recommendations:

8-1: As part of future IRP filings and consistent with the requirements in MCL 460.6t, utilities should develop and include maps, using tools such as MiEJScreen or the EPA EJ Screen, that identify the location of proposed and existing power plants in EJ communities and further detail how EJ communities were considered when making decisions about existing resource retirements and future resource investment. This information should be used to inform an analysis of the impact of the proposed course of action on EJ communities and support this plan as the most reasonable and prudent in comparison to alternatives.

Conclusion

The utility industry is undergoing a fundamental transition in how energy is sourced and then delivered to its customers while maintaining system reliability. This transition has caused traditional planning processes and paradigms to be challenged as planners are tasked with managing an increasingly complex grid to meet new regulatory and policy goals such as wide scale decarbonization. Energy storage, and LDES/MDES technologies in particular, offer a unique set of services to the system, being dispatchable without generating emissions from using fossil fuels. It is well accepted that dispatchable technologies such as energy storage are needed to provide grid balancing when intermittent generation is not sufficient to meet this demand. It is also anticipated that shorter duration energy storage, such as lithium-ion batteries which are currently the most commonly deployed energy storage technology, will not be able to be economically discharged long enough to bridge gaps in renewable generation, requiring new technologies to provide for this service if decarbonization and renewable energy goals are to be achieved.

While this transition is currently underway, the industry is still struggling to consider and integrate new technologies and solutions into planning processes to meet customer demand and align with regulations and policy goals. LDES technologies have significant opportunities to provide a part of this solution. However, barriers exist to characterize these technologies and model them accurately in existing processes for their consideration alongside other potential resources. This report provided an analysis which considered the potential for LDES to replace existing fossil-fueled generation that should serve as a starting point for further consideration of the replacement of fossil-fueled generation in future long-term resource planning. It is clear from the findings of this report that while significant opportunities exist for LDES technologies to provide services to the system in the future, work must be done for these technologies to be considered and to maximize the value they can provide to the system.

As a result of its work developing this report, Staff has identified the following recommendations as useful to advance the future consideration of long-duration and multi day energy storage:

Recommendations:

Section 2-1: Utilities should continue to improve the evaluation and modeling of all energy storage in long-term resource planning, including adopting best practices such as hourly/sub-hourly optimizations, advanced market dynamics (imperfect foresight, advanced cycling, impact to ancillary market prices), and consideration of multiple value streams.

Section 4-1: Utilities should use public data to source cost and technology information to for the modeling of energy storage in IRPs. If adequate public data is not available, utilities should utilize data that can be shared with Staff and

intervening parties through non-disclosure agreements to allow for review of sensitive information.

Section 5-1: To ensure that LDES technologies are adequately represented in utility modeling, the following best practices related to the sourcing and application of data should be adopted to the extent feasible:

- Use high-resolution data in the spatial and temporal dimensions to capture detailed geographic and operational characteristics.
- Use public data sources to promote an open and transparent planning process.
- Use actual operational data from deployments and pilots to validate sources when available.

Section 5-2: Utilities should investigate the use of advanced tools and techniques, such as those identified, as necessary to accurately model the operations of LDES technologies, their participation in markets, and their support of the reliability and resilience of the system. A focus should be on practical application to current planning practices, including application to, or supplementation of, current modeling software and tools.

Section 6-1: Electric providers in the UP should consider coordinating storage planning efforts, where possible, to evaluate candidate resources identified in this analysis, and provide any results in their respective IRPs.

Section 6-2: Each electric provider with candidate resource capacity identified in the example study included in Section 6 of this report should conduct a full analysis of its existing fleet, considering the replacement of existing generation with LDES, MDES, or other solutions, in at least the capacity amount identified in this report and using the best practices identified in Sections 4 through 8 of this report. **Section 7-1:** Utilities, regulators, and other interested persons that participate in RTO/ISO study activities should proactively request that the RTO/ISO study storage alternatives as transmission planning solutions during the transmission planning process to ensure they are adequately considered.

Section 7-2: The Commission should encourage RTOs/ISO to develop specific metrics and objectives for resilience planning to incorporate these metrics/processes into existing transmission planning processes. The Commission should direct Staff to develop specific metrics and objectives related to resilience as part of the distribution planning process to encourage consideration of resilience alongside traditional reliability metrics when analyzing regulated utility investment.

Section 8-1: As part of future IRP filings and consistent with the requirements in MCL 460.6t, utilities should develop and include maps, using tools such as MiEJScreen or the EPA EJ Screen, that identify the location of proposed and existing power plants in EJ communities and further detail how EJ communities were considered when making decisions about existing resource retirements and future resource investment. This information should be used to inform an analysis of the

impact of the proposed course of action on EJ communities and support this plan as the most reasonable and prudent in comparison to alternatives.

Appendices

Appendix A: List of Tables & Figures

Section 4

Figure 4.1. Levelized cost of storage for various energy storage technologies.

Section 6

Table 6.1. QuEST Equity Analysis Parameters.

Table 6.2. QuEST Equity Analysis Investment Results.

Table 6.3. QuEST Equity Health Impact Results.

Table 6.4. QuEST Equity Results.

Table 6.5. Candidate Replacement Capacity by Peninsula.

Table 6.6. Candidate Replacement Capacity by LSE.

Section 7

Table 7.1. Round-trip efficiencies of various energy storage technologies.

Figure 7.2. Reliability and Resilience Under IEEE 1366 (PNNL).

Section 8

Table 8.1. List of Michigan generating facilities with a cumulative MiEJ Score above 70.

Figure 8.2. Map of fossil-fueled generating facilities in Michigan.

Figure 8.3. Map of fossil-fueled generating facilities in EJ communities.

Figure 8.4. Detailed view of fossil-fueled generating facilities in Metro Detroit.

Figure 8.5. Detailed view of fossil-fueled generating facilities in EJ communities in Metro Detroit.

Appendix B: Advanced Modeling Tools & Software

The following tables were collected and summarized during the development of this report. **Appendix B.1** focuses on available datasets for sourcing input data needed for modeling LDES. **Appendix B.2** lists different tools and software which can be used to accomplish different utility planning functions. This information was collected to serve as a reference for utilities and others in the industry when developing advanced models to represent LDES.

Appendix B.1: Sources of data for LDES modeling

Category	Database	Description
Historical Load Data	U.S. Energy Information Administration (EIA)	Provides comprehensive electricity data, including historical load statistics and forecasts.
	NREL Data Catalog	Offers datasets related to energy consumption and demand profiles.
	EPRI's Load Shape Library	Repository of end-use and building load profiles categorized by climate zone, building type, end-use load, and geography.
	OpenEI	Commercial and residential hourly load profiles for locations in the United States.
	FERC Form 714	Comprehensive annual information of balancing authority load and generation.
	ISO New England (ISO-NE)	Provides hourly real-time system demand reports.
	California ISO (CAISO)	Historical hourly load data and revised datasets.
	Midcontinent ISO (MISO)	Hourly actual load data by Local Resource Zone.
	PJM Interconnection	Integrated hourly load data calculated from raw telemetry.
	NYISO	Detailed load data, including historical and real-time information.
	ERCOT	Hourly load data archives for eight weather zones in Texas.
	Southwest Power Pool (SPP)	Historical load and market data for its operational region.
Renewable Generation & Climate Data	IEA Renewables Dataset	Historical data and forecasts for renewable electricity capacity and generation.

Category	Database	Description
	NREL's Renewable Energy Data Tools	Provides access to various datasets and tools related to renewable energy generation.
	Sandia's PVLib	Open-source library for modeling photovoltaic (PV) systems, supporting solar resource assessment and system performance analysis.
	PNNL's Earth and Energy Systems Research Portal	Portal that provides datasets about extreme weather, demand, climate, and policy.
	Climate Risk and Resilience Portal (ClimRR)	Provides future climate data used for planning and adaptation of infrastructure.
	Sandia's Wind Turbine Loads Database	Simulated load data for the NREL 5 MW wind turbine under various conditions.
Capital & Operational Cost Data	NREL Annual Technology Baseline (ATB)	Provides cost and performance data for energy technologies, including storage.
	EIA Cost and Performance Characteristics	Cost data for new energy generation and storage technologies.
	PNNL Energy Storage Cost and Performance Database	Detailed cost and performance metrics for energy storage technologies.
	BloombergNEF 2023 Battery Price Survey	Reports lithium-ion battery costs and market trends.
	Sandia 2020 Energy Storage Pricing Survey	Standardized pricing data for energy storage technologies across various ratings.
Technological Performance	NREL Energy Storage Data and Tools	Datasets and tools related to energy storage performance metrics.
	Open Energy Data Initiative (OEDI)	Datasets on energy storage performance and related technologies.
	Battery Archive	Repository of battery cycling data, including performance metrics for various chemistries and configurations.

Appendix B.2: Grid planning tools for LDES modeling

† *Denotes open-source tool* ‡ *denotes commercial tool.*

Category	Tool	Description	Developer
Capacity Expansion Planning Models	QuESt Planning†	A Python-based long-term power system capacity expansion planning model that finds cost-optimal energy storage, generation, and transmission investments and evaluates a broad range of energy storage technologies.	Sandia National Laboratories
	Regional Energy Deployment System (REEDS) †	Open-source capacity planning model that simulates the evolution of the bulk power system out to 2050.	National Renewable Energy Laboratory
	Argonne Low-Carbon Electricity Analysis Framework (A-LEAF) †	An integrated national-scale power system simulation framework that includes capacity expansion, unit commitment, and economic dispatch.	Argonne National Laboratory
	GridPath†	Versatile grid analytics platform that includes ability expansion, production cost, and resource adequacy models.	Sylvan Energy Analytics
	Open TEPES†	Decision support system for defining integrated generation, storage, and transmission expansion plans.	Instituto de Investigación Tecnológica (IIT) of the Universidad Pontificia Comillas.
	Switch †	Open-source power system planning model designed study future power systems including renewables and storage.	University of Hawaii at Manoa
	E3 RESOLVE‡	Resource planning model that finds optimal long-term electric generation and transmission investments.	Energy + Environmental Economics (E3)
	EnCompass‡	Software for making informed power supply decisions from short-term scheduling and trading to	YES Energy

Category	Tool	Description	Developer
		long-term capital investment.	
	Electric Generation Expansion Analysis System (EGEAS) ‡	Production cost and generation expansion software designed for utility planners and integrated resource planning.	Electric Power Research institute (EPRI)
	Formware‡	Optimizes investments and operations of any portfolio of technologies to better understand and capture the value of multi-day energy storage.	Form Energy
Production Cost Models	Prescient & EGRET†	Python-based software package designed to simulate power system operations and stochastic behavior of renewables.	Sandia National Laboratories
	Sienna†	Open-source framework that builds, solves, and analyzes scheduling problems and dynamic solutions of quasi-static infrastructure systems.	National Renewable Energy Laboratory
	PLEXOS‡	Commercial tool that offers decision support for energy markets including ES investments, operations, and revenue maximization.	Energy Exemplar
Resource Adequacy & Reliability	Probabilistic Grid Reliability Analysis with Energy Storage Systems (PROGRESS) †	Python-based open-source tool for assessing the resource adequacy of the evolving electric power grid integrated with energy storage systems (ESS).	Sandia National Laboratories
	Probabilistic Resource Adequacy Suite (PRAS) †	Open-source, research-oriented collection of tools for analyzing the resource adequacy of bulk power systems.	NREL
	GridPathRA Toolkit †	Open-source toolkit to support advanced resource adequacy analysis.	Moment Energy Insights
	SERVM‡	Commercial capacity expansion and reliability planning model.	Astrape Consulting

Category	Tool	Description	Developer
Market Evaluation & Techno-Economic Analysis	QuESt 2.0 †	Open-source Python software platform for improved ES analytics. Includes market valuation, BTM, microgrid, and equity tools with integrated Workspace.	Sandia National Laboratories
	Energy Storage Evaluation Tool (ESET) †	Suite of applications to model, improve, and evaluate ESS.	Pacific Northwest National Laboratory
	ReOpt †	Web-based tool that performs techno-economic analysis of DER and microgrids.	National Renewable Energy Laboratory
	Aurora ‡	Optimizes dispatch and commitment of power plants, storage, hydro, and renewables within markets.	Energy Exemplar
	GridView ‡	User-friendly market simulation and asset performance evaluation tool.	Energy Exemplar
	Homer ‡	Commercial tool to optimize microgrids, grid-connected ESS, and utility-scale hybrid systems.	UL Solutions

Appendix C: QuEST Equity Karn Unit 1 Sample Analysis

Energy Storage Equity Report

Autogenerated using QuESt Equity

October 29, 2024

This report shows the results from optimizations performed by QuESt Equity.

Scenario Summary

Powerplant Name: Dan E Karn
Fuel Type: COAL
Facility Nameplate Capacity: 1946.3 **MW**
Unit ID(s): 1
Unit Nameplate Capacity: 265 **MW**
Capacity Factor: 0.18078
Powerplant State: MI
Powerplant County: Bay
Dispatch Year: 2022

The powerplant replacement analysis parameters are summarized in Table 1.

Table 1: Analysis Parameters

Discount Rate	3.0	%
Cost per Ton of CO2	93.0	$
Cost per MW PV system	2000000.0	$
Fixed Cost of PV system	0.0	$
Cost per MW ES	1643000.0	$
Cost per MWh ES	410700.0	$
Fixed Cost of the ES	0.0	$
Round-trip efficiency	83.0	%

Flexible Dispatch

Flexible dispatch assumes that any power produced by the ESS + PV directly offsets power that would have been produced by the powerplant in any given hour. Fractional replacement then offsets the total powerplant dispatch based on this assumption over the course of a full year.

Assumptions

The following assumptions were used:

- The time periods are hourly.
- The analysis period is one calendar year.
- The ESS system can only charge from PV, not from the grid.
- The ESS+PV power reduces the output of the powerplant at any given time.
- Powerplant minimum dispatch is assumed to be 0 MW.

- Excess ESS+PV power is not considered in this analysis.

Optimization Formulation (Flexible Dispatch)

We solve the following mathematical optimization problem to minimize the capital cost of energy storage and photovoltaic (PV) systems, and the notation is described in Table 2 below.

$$\min_{\mathbf{x}\in\mathbb{R}^{3n+4}} C_{\text{BESS}}^{\text{MWh}} E_{\text{BESS}} + C_{\text{BESS}}^{\text{MW}} P_{\text{BESS}} + C_{\text{PV}}^{\text{MW}} P_{\text{PV}} + \Pi||g||_1 \tag{1}$$

subject to the following constraints

$$P_{PV}\mathbf{p}_{pv} + \mathbf{p}^- + \mathbf{p}^+ \geq \mathbf{p}_{\text{plant}}\mathbf{g} \;\; \forall i \in P_{\text{plant}} \tag{2}$$
$$\mathbf{D}\varsigma = \mathbf{p}^- + \eta\mathbf{p}^+ \tag{3}$$
$$[\mathbf{0}] \leq \varsigma \leq E_{\text{BESS}}[\mathbf{1}] \tag{4}$$
$$\mathbf{p}^+ - \mathbf{p}^- \leq P_{\text{BESS}}[\mathbf{1}] \tag{5}$$
$$\varsigma_{[0]} = \varsigma_{[n]} = E_{\text{BESS}} \tag{6}$$
$$\mathbf{p}_{\text{plant}}^\top \mathbf{g} \geq \rho||\mathbf{p}_{\text{plant}}||_1 \;\; \forall i \in P_{\text{plant}} \tag{7}$$

where

$$\mathbf{D} = \frac{1}{\Delta t}\begin{bmatrix} -1 & 1 & 0 & . & . & 0 \\ 0 & -1 & 1 & 0 & . & . \\ & & . & . & & \\ & & & . & . & \\ 0 & & & 0 & -1 & 1 \end{bmatrix}_{n\times(n+1)} \tag{8}$$

Table 2: Notation

Parameter	Description	Units
$\mathbf{p}_{pv}$	Vector of PV power at each time step normalized to 1 per unit.	MW
$\mathbf{p}^+$	Vector of ESS charge power at each time step	MW
$\mathbf{p}^-$	Vector of ESS discharge power at each time step	MW
ς	Vector of ESS state of energy at each time step	MWh
$\mathbf{g}$	Vector of fractional replacement values	[0,1]
P_{plant}	The set of indices, of size n', where the powerplant is producing power	#
P_{PV}	PV power rating	MW
P_{BESS}	ESS power rating	MW
E_{BESS}	ESS energy capacity	MWh
η	Round-trip efficiency	%
$C_{\text{PV}}^{\text{MW}}$	Cost per MW of the PV system	%
$C_{\text{BESS}}^{\text{MW}}$	Cost per MW of the ESS system	%
$C_{\text{BESS}}^{\text{MWh}}$	Cost per MWh of the ESS system	%
Π	Regularization weight for fractional replacement values	none

This optimization is formulated in Python using Pyomo and solved using the numerical solver selected in QuESt Valuation.

Summary of results

The following summarizes the results of the analysis to replace 50% of the energy of the Dan E Karn powerplant with a combination of energy storage and PV:
- The replacement system would need 975 MW of PV, and a 295 MW / 1,640 MWh energy storage system.
- The PV would cost approximately $1.95B and the ESS would cost approximately $1.16B, making the total capital cost estimate $3.11B.
- This system would provide between $69.2M and $111.4M in health benefits to people living in the U.S. per year.
- The system would prevent 926,451 tons of carbon emissions each year. Assuming a Social Cost of Carbon (SCC) of $93 per ton, this would provide roughly $86.2M in climate benefits per year.
- Assuming a 20 year time horizon, with a 3.0% discount rate, this system would provide a social Net Present Value (sNPV) of $671.9M for the health benefits and $1.28B for the climate benefits adding up to a total sNPV of $1.95B.
- Where 33.3% of the U.S. population live in disadvantaged communities, 30.6% of the health benefits would be accrued to people living in disadvantaged communities. This means an estimated sNPV between $157.7M and $253.9M would go to disadvantaged communities.
- Where 23.1% of the U.S. population have incomes below 200% of the poverty line, 23.2% of the health benefits would be accrued to people with incomes below 200% of the poverty line. This means an estimated sNPV between $119.5M and $192.4M would go to people with low incomes.

The following summarizes the results of the analysis to replace 80% of the energy of the Dan E Karn powerplant with a combination of energy storage and PV:
- The replacement system would need 1,910 MW of PV, and a 670 MW / 3,660 MWh energy storage system.
- The PV would cost approximately $3.82B and the ESS would cost approximately $2.60B, making the total capital cost estimate $6.42B.
- This system would provide between $69.2M and $111.4M in health benefits to people living in the U.S. per year.
- The system would prevent 1,482,321 tons of carbon emissions each year. Assuming a Social Cost of Carbon (SCC) of $93 per ton, this would provide roughly $137.9M in climate benefits per year.
- Assuming a 20 year time horizon, with a 3.0% discount rate, this system would provide a social Net Present Value (sNPV) of $1.08B for the health benefits and $2.05B for the climate benefits adding up to a total sNPV of $3.13B.
- Where 33.3% of the U.S. population live in disadvantaged communities, 30.6% of the health benefits would be accrued to people living in disadvantaged communities. This means an estimated sNPV between $252.3M and $406.2M would go to disadvantaged communities.
- Where 23.1% of the U.S. population have incomes below 200% of the poverty line, 23.2% of the health benefits would be accrued to people with incomes below 200% of the poverty line. This means an estimated sNPV between $191.3M and $307.9M would go to people with low incomes.

The following summarizes the results of the analysis to replace 100% of the energy of the Dan E Karn powerplant with a combination of energy storage and PV:
- The replacement system would need 4,228 MW of PV, and a 1,478 MW / 16,488 MWh energy storage system.
- The PV would cost approximately $8.46B and the ESS would cost approximately $9.20B, making the total capital cost estimate $17.66B.
- This system would provide between $69.2M and $111.4M in health benefits to people living in the U.S. per year.
- The system would prevent 1,852,901 tons of carbon emissions each year. Assuming a Social Cost of Carbon (SCC) of $93 per ton, this would provide roughly $172.3M in climate benefits per year.
- Assuming a 20 year time horizon, with a 3.0% discount rate, this system would provide a social Net Present Value (sNPV) of $1.34B for the health benefits and $2.56B for the climate benefits adding up to a total sNPV of $3.91B.
- Where 33.3% of the U.S. population live in disadvantaged communities, 30.6% of the health benefits would be accrued to people living in disadvantaged communities. This means an estimated sNPV between $315.4M and $507.7M would go to disadvantaged communities.
- Where 23.1% of the U.S. population have incomes below 200% of the poverty line, 23.2% of the health benefits would be accrued to people with incomes below 200% of the poverty line. This means an estimated sNPV between $239.1M and $384.9M would go to people with low incomes.

Table 3: Investment Results

Replacement Fraction	50.0 %	80.0 %	100.0 %

PV Power	975 MW	1,910 MW	4,228 MW
ESS Power	295 MW	670 MW	1,478 MW
ESS Energy	1,640 MWh	3,660 MWh	16,488 MWh
PV Cost	$1.95B	$3.82B	$8.46B
ESS Cost	$1.16B	$2.60B	$9.20B
Total Cost	$3.11B	$6.42B	$17.66B

Table 4: Impact Results

Replacement Fraction	50.0 %	80.0 %	100.0 %
Health Benefits Low	$34.6M	$55.4M	$69.2M
Health Benefits High	$55.7M	$89.1M	$111.4M
CO2 Offset	926,451 Tons	1,482,321 Tons	1,852,901 Tons
Climate Benefits	$86.2M	$137.9M	$172.3M
sNPV (Health) Low	$514.9M	$823.9M	$1.03B
sNPV (Health) High	$828.9M	$1.33B	$1.66B
sNPV (Climate)	$1.28B	$2.05B	$2.56B
sNPV (Total) Low	$1.80B	$2.87B	$3.59B
sNPV (Total) High	$2.11B	$3.38B	$4.22B

Table 5: Equity Results

Replacement Fraction	50.0 %	80.0 %	100.0 %
DAC Population	33.3 %	33.3 %	33.3 %
Low-Income Population	23.1 %	23.1 %	23.1 %
DAC Benefits	30.6 %	30.6 %	30.6 %
DAC sNPV Low	$157.7M	$252.3M	$315.4M
DAC sNPV High	$253.9M	$406.2M	$507.7M
Low-Income Benifits	23.2 %	23.2 %	23.2 %
Low-Income sNPV Low	$119.5M	$191.3M	$239.1M
Low-Income sNPV High	$192.4M	$307.9M	$384.9M

The analysis assumes the powerplant is flexibly dispatched. Below, Fig. R1 shows the powerplant's dispatch profile, sorted from low to high, before and after each fractional replacement scenario.

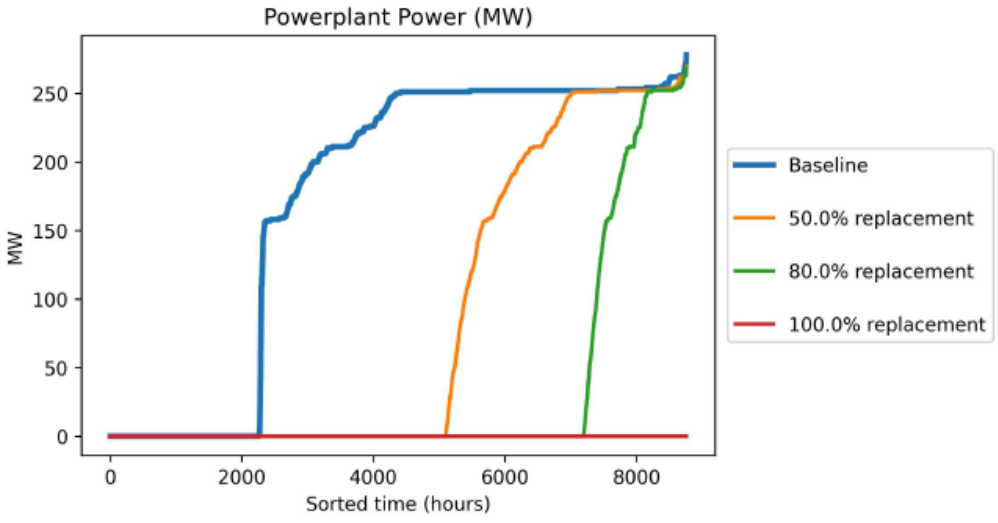
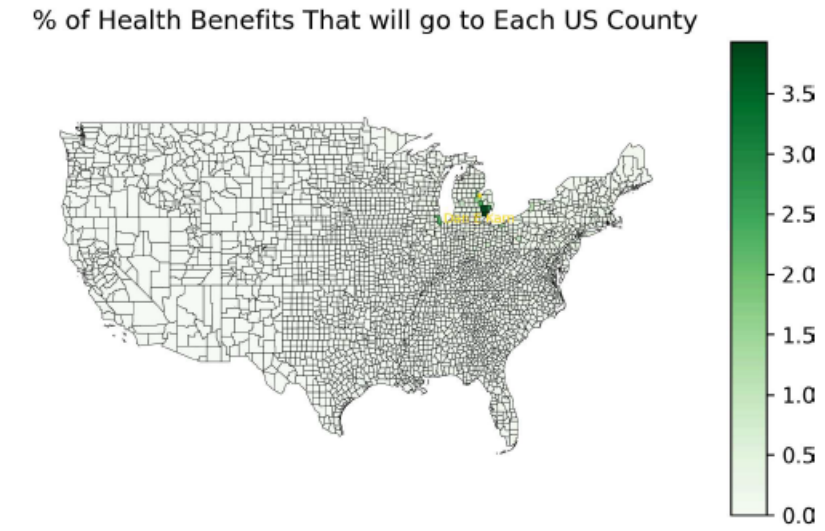


Fig. R1: Sorted Power Distribution Before (baseline) and After ES+PV Installation

Below is a map of the locations where the aggregate pollution reduction benefits are accrued. Benefits are calculated based on changes in pollutant concentrations and on county populations. Hence, the counties that benefit most are not necessarily those where the powerplant is located but are often the closest large population centers instead.



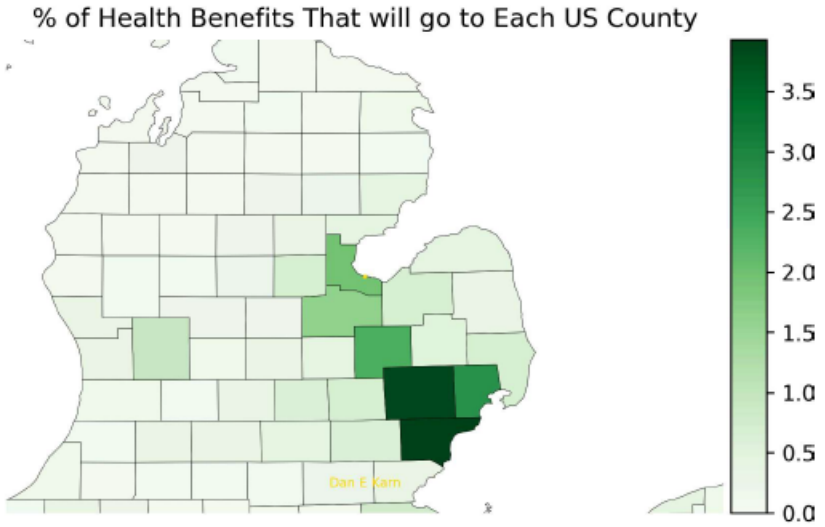


Fig. R2: County Level Benefits Map

The following chart shows the capital cost (x-axis) and social benefits per year. The social benefits are the sum of the climate benefits, calculated as the social cost of carbon times tons of carbon emissions avoided, and the health benefits which are the low to high range plotted as a vertical line. The sloped lines represent, from most to least steep, a 5-year, 10-year, 15-year, and 20-year social return on investment (sROI). These lines could also be seen as the points where the social net present value (sNPV) equals the capital cost after the specified period. The thinner lines reflected to the left

marked 10% through 90% represent potential public-cost-share fractions. This plot illustrates how much public investment in a powerplant replacement project would have a positive sROI. If a local, state, or federal government is considering providing cost-share on a project that would offset the production of a powerplant, they would identify the relevant replacement scenario, and then move left to the cost-share fraction where the social benefits are above the sROI line for a desired time horizon.

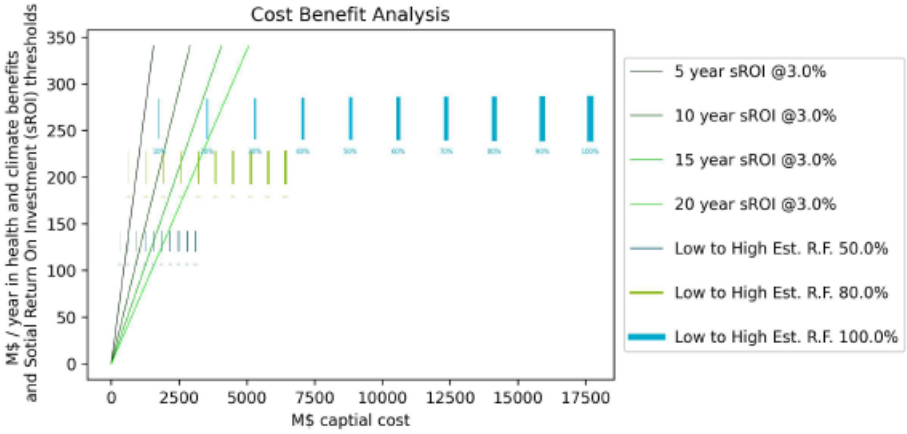


Fig. R3: Capital-Cost / Social Benefit Chart

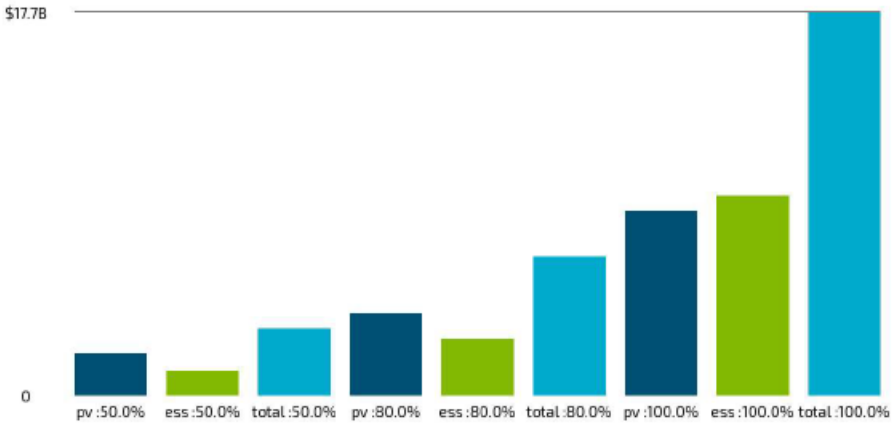


Fig. 1: Capital Cost

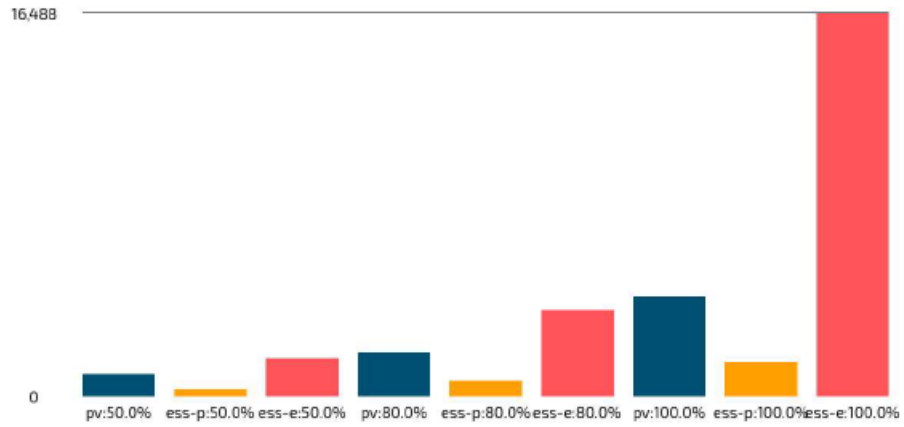


Fig. 2: Power and Energy

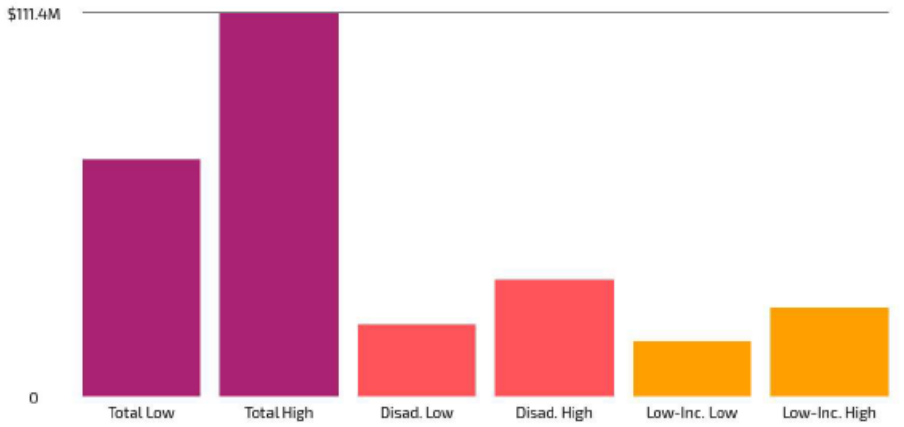


Fig. 3: Pollution Reduction Benefits

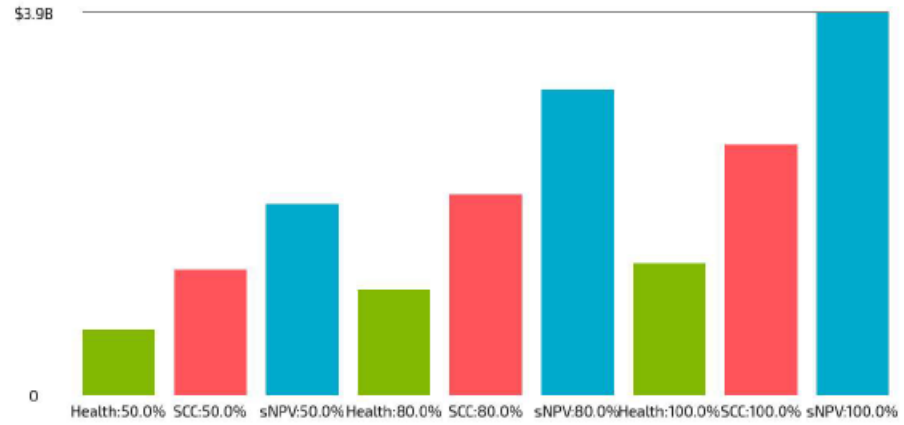


Fig. 4: Sotial Net Present Value (sNPV)

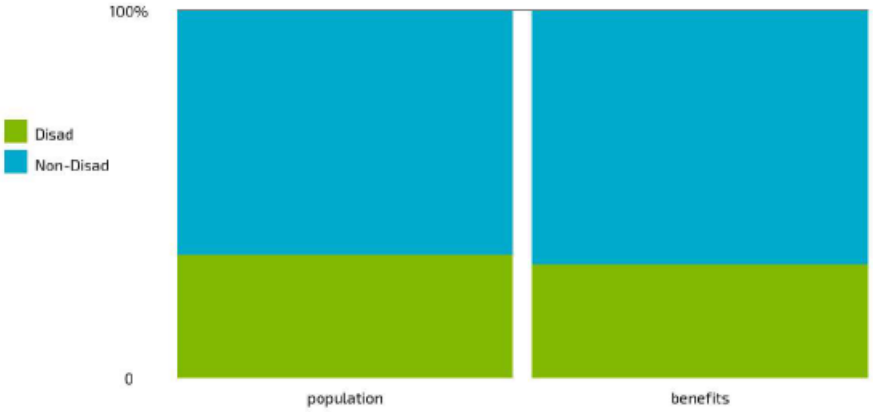


Fig. 5: Disadvantaged benefits fraction

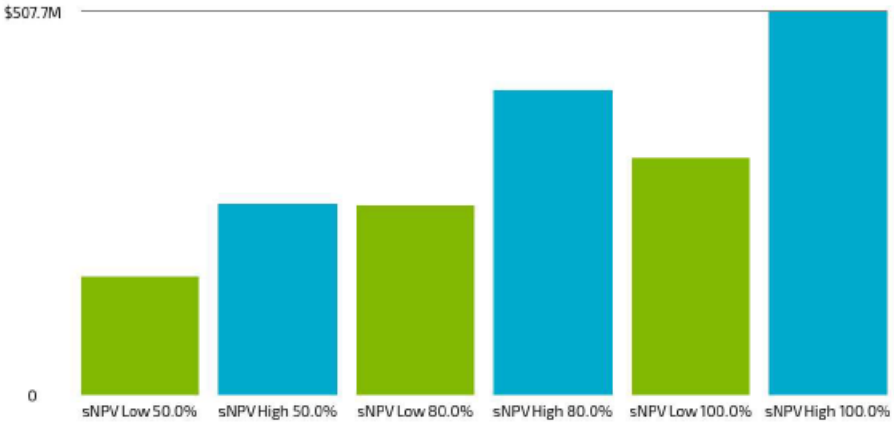


Fig. 6: Disadvantaged sNPV

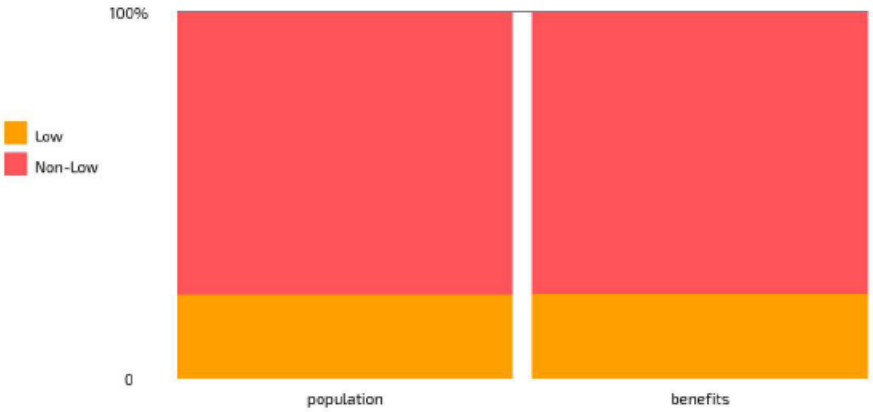


Fig. 7: Low-Income benefits fraction

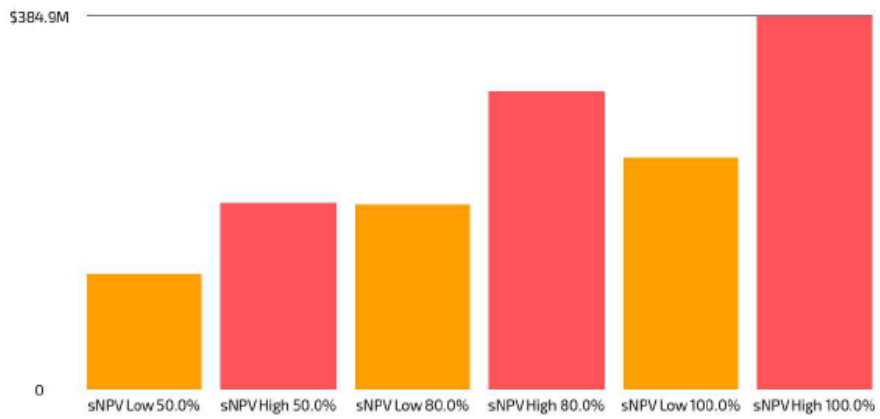


Fig. 8: Low-Income sNPV

References

DOE OE Energy Storage Program: www.sandia.gov/ess/
EPA Power Plants and Neighboring Communities:www.epa.gov/airmarkets/power-plants-and-neighboring-communities
EPA CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA): www.epa.gov/cobra
EPA Field Audit Checklist Tool (FACT): www.epa.gov/airmarkets/field-audit-checklist-tool-fact
NREL PVWatts Calculator: pvwatts.nrel.gov/
Climate and Economic Justice Screening Tool (From Justice40): screeningtool.geoplatform.gov

Acknowledgements

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY