Recommended Approaches for Modeling Utility Electric Grids with Multi-Day Energy Storage

For use in resource planning studies

About Form Energy

Form Energy, Inc. ("Form") is a U.S. energy storage technology and manufacturing company that is commercializing a rechargeable, iron-air battery capable of continuously discharging electricity for 100 hours at a system cost less than 1/10th the cost of lithium-ion battery technology. Form's multi-day battery will enable a clean electric grid that is reliable and cost-effective year-round, even in the face of multi-day weather events. With over 400 employees, Form has offices in Somerville, MA; the San Francisco Bay Area; and the Greater Pittsburgh area.

Form has raised over $820M of venture capital to date and aims to deploy GWs of energy storage by 2030. Form's team is actively pursuing partners for projects to come online in 2025 and 2026. Form's first full-scale battery manufacturing facility, sited in Weirton, West Virginia, will come online in 2024 ramping to an expected annual capacity of up to 500 MW / 50 GWh. With a target operational date in 2024, Form's first commercial project will be deployed in Minnesota with our utility partner Great River Energy, and this demonstration will be followed by a series of additional projects in 2025, including two deployments with Xcel Energy.

Recommended Approaches Overview

This document highlights modeling techniques that are critical for accurately capturing the dynamics of multi-day energy storage technologies (MDS) as they operate in utility electric systems, particularly as they move toward higher penetrations of renewable energy. These recommendations suggest that capacity optimization modeling should:

- Use a chronology that includes all 8,760 hours of the year;
- Include scenarios that capture periods of real grid stress, such as multi-day lulls in renewable energy generation or periods of high commodity prices;
- Develop weather-correlated load and renewable generation profiles; and
- Model multiple weather years covering a diversity of weather conditions, including periods of extreme weather.

Further, this document describes Form's recommended technical specifications for modeling multi-day energy storage technologies in utility capacity planning, production cost, and valuation exercises. These recommendations extend to all classes of storage that can cycle over multiple days, including, but not limited to, iron-air batteries and hydrogen storage.

Technological specifications

Various long-duration storage technologies are still in early stages of development. These early generation technologies are subject to substantial cost uncertainty, presenting a challenge for resource planners seeking to quantify the need for and value of energy storage technologies with different durations. We recommend using one of two separate approaches, reflecting that some organizations prefer to model broad resources classes in a technology-neutral manner (Option 1), and other organizations prefer to model technology-specific parameters (Option 2).

Option 1: Model a >24 hour duration storage archetype as "multi-day energy storage"

For organizations that prefer to model broad long-duration and multi-day energy storage resource classes, Form recommends that resource planning studies instead group all technology types with a dispatch duration at rated capacity of greater than 24 hours as part of a "multi-day storage" (MDS) asset class and include this asset class as a resource in applicable analyses.[1]

The Long Duration Energy Storage Council, in collaboration with McKinsey & Company, authored a report on the role of LDES technologies in electric power systems.[2] As part of this report, the LDES Council surveyed member companies for cost and performance data relating to their technologies. Data were grouped into two archetypes: those that are 8-24 hours in duration and those with >24 hours of duration.[3] Cost data from this benchmarking effort for these LDES and MDS resource archetypes are shown in Figure 1 below. Form participated in this benchmarking effort and provided data for our 100-hour iron-air battery.

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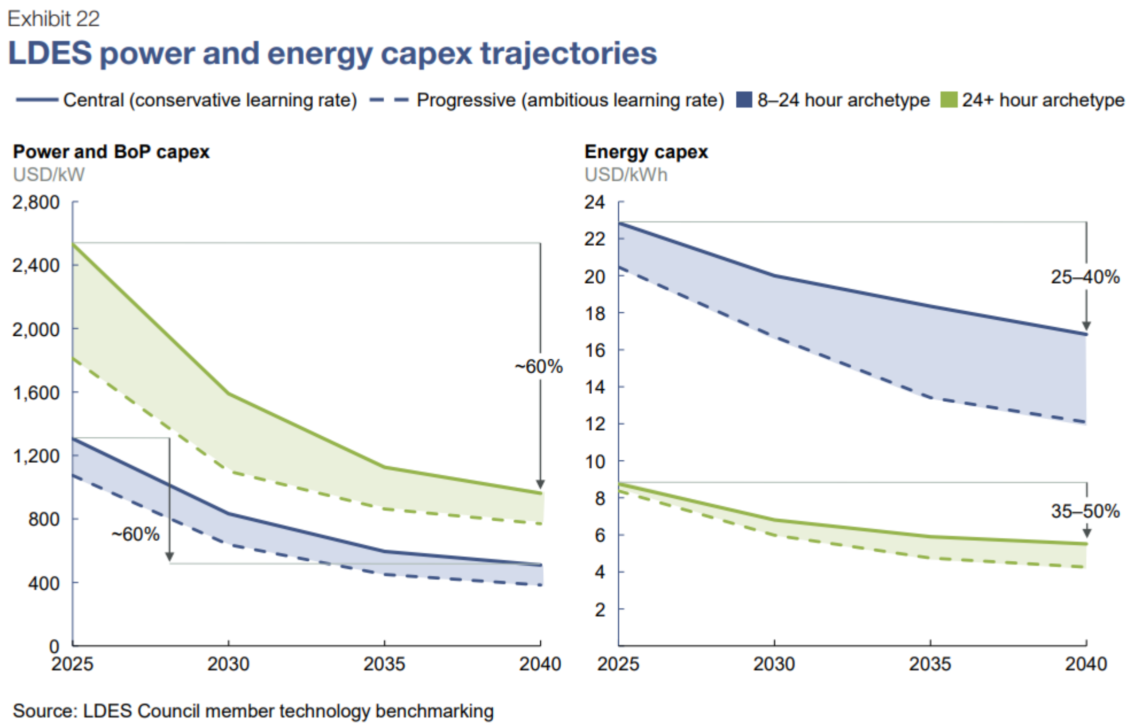
[1] Grouping individual technologies into "asset classes" by duration may help to limit the problem size and speed model simulation times.
[2] LDES Council. November 2021. *Net-zero power: Long duration energy storage for a renewable grid.*
[3] Some jurisdictions (e.g. the commonwealth of Massachusetts) have defined LDES as having a minimum 10-hr duration. Form recommends that policy makers define "long-duration energy storage" as resources that can discharge at rated capacity for at least 8 or 10 hours, and up to 24-hours, in contrast to the "multi-day storage" class defined above.

Figure 1. LDES Council's cost data representing a 24+ hour duration asset class



Each technology type that falls into the MDS archetype will have different costs for power and for energy; thus Form recommends that data for the MDS archetype, shown above in Figure 1, are used to represent the multi-day storage asset class as a whole in resource planning studies rather than attempting to adjust these costs to represent individual technology types based on duration. For example, it would not be reasonable to linearly scale the energy component of the capex costs for the MDS storage archetype to estimate the costs of a 100-hour battery.

Option 2: Technology-specific parameters for iron-air batteries of 100-hour duration

Form is commercializing a rechargeable iron-air battery capable of continuously discharging electricity for 100 hours at system costs competitive with legacy power plants. Made from iron, one of the most abundant materials on Earth, this front-of-the-meter battery will enable a cost-effective, 100% renewable grid.

The active components of Form's iron-air battery are some of the safest, cheapest, and most abundant materials on the planet — low-cost iron, water, and air. The basic principle of operation is reversible rusting: while discharging, the battery breathes in oxygen from the air and converts iron metal to rust; while charging, the application of an electrical current converts the rust back to iron and the battery breathes out oxygen. Each individual battery module is about the size of a side-by-side washer/dryer set. These battery modules are grouped together with auxiliary systems in weatherized, factory-assembled enclosures. Hundreds of these modules make up modular, megawatt-scale power blocks.

In Table 1 below, we present a range of cost and performance characteristics that are achievable by 2030 at the gigawatt manufacturing scale.[4] These cost and performance targets are achievable through Form's investments in optimizing the full iron-air battery production supply chain, from iron processing to cell chemistry and design to final enclosure assembly. Like all new clean energy technologies, the costs for Form's first projects will be higher than what is stated below. The cost and performance metrics reflected in Table 1 are achievable over the next decade through Form's investments in research and development, manufacturing automation and scale, and performance improvements of our iron-air technology. These cost and performance parameters do not require fundamental technological breakthroughs and are fully within Form's control.

Table 1. Iron-air cost and performance at gigawatt manufacturing scale (~2030)

Discharge duration at full rated capacity	100 hours
All-in installed capital cost ($/kWh)*	$15 - $20
Fixed O&M ($/kW-year, Yr 1 dollars)	$15 - $20
Round trip efficiency**	40 - 45%
Charge efficiency	69% - 73%
Discharge efficiency	58% - 62%
Annual discharge throughput limit	1,500-2,000 equivalent hours at full power
System lifetime	30 - 40 yrs
Module lifetime	15 - 20 yrs
Repowering (NPV, $/kWh)***	$4/kWh
Power Degradation	0%/yr
Energy Capacity Degradation	2%/yr
Energy Efficiency Degradation	0.5%/yr

** Landed costs of the AC modular power block at ~100 MW scale, inclusive of EPC, developer costs, and grid interconnection costs*
*** AC-AC round trip efficiency, full charge and full discharge at rated power, inclusive of losses from power conversion and auxiliary loads.*
**** NPV: NPV of repowering cost ($15/kWh) in year 15-20, assumes 8% WACC.*

[4] Assumptions included are for planning purposes only and do not constitute a firm quote.

For modeling beyond 2030, Form anticipates further declines in capital costs for iron-air, with learning rates in line with other similar technologies. While future Form products may feature shorter or longer durations, the specifications shown above are specific to Form's 100-hour iron-air battery.

Form Deployment Capacity 2026-2030

Form's first full-scale manufacturing facility, sited in Weirton, WV, will come online in 2024 to begin manufacturing for broad commercialization. Once fully ramped, the facility is targeting an annual manufacturing capacity of 500 MW / 50 GWh. Following Form's commercial demonstration projects in 2024 and 2025, Form plans to deploy projects 10-50+ MW in size with commercial operation dates starting in 2026.

Approaches to accurately model multi-day energy storage

Recommendation: Capacity optimization modeling should use a chronology that includes all 8,760 hours of the year, rather than a "typical day" or "typical week" methodology. Modeling 8,760 hours captures the dynamics of long-duration and multi-day storage state-of-charge, as well as realistic variation in demand and renewables production.

Historically, capacity optimization models used for resource planning analyses have relied on a simulation chronology that takes a sample of representative days or relies on a "typical week" or an "on- and off-peak day." Models build resources to meet demand during these sampled periods, and combine representative days together to simulate dispatch over the entire year. Such sampling methods fail to capture the variability in renewable generation and storage dispatch across longer time scales, and thus fail to accurately value resources that can provide flexibility across these time scales, such as long-duration and multi-day storage technologies.

Form recommends that optimized resource portfolios be constructed using a modeled chronology of 8,760 hours in the year in order to accurately capture the ability of MDS to shift energy over multi-day, multi-week, and seasonal horizons. We recognize that this is computationally intensive and that certain trade-offs might need to be made within a model to accomplish this goal, such as aggregating individual generating units into a block according to fuel type, or modeling resource builds in a single year as opposed to over a period of ten years or more. This may require a multi-step modeling process, in which the capacity optimization step is performed over all 8,760 hours in a specific future year, and resulting resource builds are locked down in that year before optimizing the builds in the remaining years.

While many models today can perform 8,760-hour capacity expansion modeling, not all can. In that case, Form recommends an approach that allows for the use of representative days for most grid assets while still representing the full 8,760 hours of the year (or longer) for tracking long-duration storage state-of-charge.[5] This approach meets the minimum requirement of representing the state-of-charge of long-duration storage over a long enough time period to accurately capture its value in shifting energy on a weekly and seasonal basis.[6] However, this approach can still be misleading if an insufficient number of representative days are used, and we encourage sensitivity testing to investigate this choice. The higher the levels of renewables on the system modeled, the larger the number of representative days needed to sufficiently capture the weather patterns that can cause reliability problems.

Recommendation: Include scenarios that capture periods of real grid stress, such as multi-day lulls in renewable energy generation or periods of high commodity prices.

Given the incorporation of time sampling methodologies in most industry-standard modeling tools, as described above, many energy system modeling approaches do not capture multi-day lulls in renewable energy generation and do not consider the implications of such events on resource builds, energy prices, grid reliability, etc. Daily - and often weekly - sampling techniques fail to include 24+ hour periods of correlated wind and solar outages. The magnitude of such solar and wind lulls is expected to increase as regional electricity supply shifts toward renewable energy technologies. Therefore, it is critical that resource planning models rely on renewable generation profiles that include lull periods, such as the National Renewable Energy Laboratory (NREL) System Advisor Model (SAM) data,[7] and evaluate how MDS can mitigate the threats to system reliability posed by such multi-day renewable energy lulls.

NREL's SAM data has specific features that distinguish it from other data sets:

- It includes weather data from a publicly validated source such as National Oceanic and Atmospheric Administration (NOAA) or the European Center for Medium-range Weather Forecasts (ECMWF);
- The model outputs have been corrected for known errors and biases, i.e. solar irradiance; and
- The operation of renewable generators are modeled accurately to reflect real-world characteristics.

However, SAM does have only a limited number of weather years with coincident wind and solar data (2007 – 2014). We recommend that system modelers include as many unique weather years as possible in policy-related studies, recognizing that computation time and expense increases as more weather years are modeled.

[5] Leander Kotzur, Peter Markewitz, Martin Robinius, Detlef Stolten, "Time series aggregation for energy system design: Modeling seasonal storage", Applied Energy, Volume 213, 2018, Pages 123-135, https://doi.org/10.1016/j.apenergy.2018.01.023. (https://www.sciencedirect.com/science/article/pii/S0306261918300242)

[6] For further explanation of this approach, see: https://genxproject.github.io/GenX/dev/long_duration_storage/#Long-Duration-Storage . See also: regulatory filings by consulting firm E3 provide an overview of this approach, beginning on slide 29; available at https://efiling.energy.ca.gov/GetDocument.aspx?tn=242516

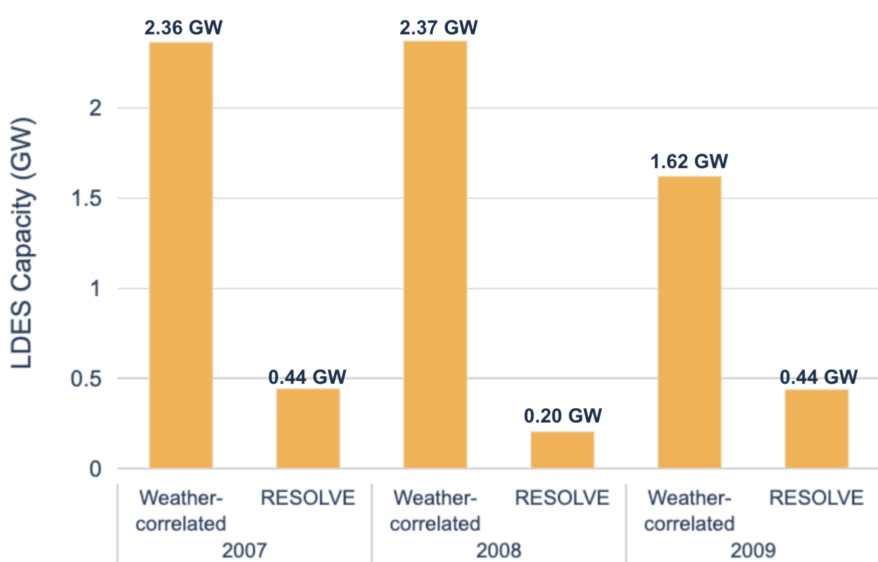
[7] Available at: https://sam.nrel.gov/download.html

Recommendation: Weather-correlated load profiles and renewable generation profiles should be used as input assumptions to capacity optimization modeling.

System load and renewable generation can often be anticorrelated, meaning that system load is high in hours in which renewable output is low, and is often driven by weather conditions over a given time period. These periods are a driver of system need for firm capacity, making weather-driven input assumptions for load and renewable generation particularly important in energy system analysis of high renewable grids.

Weather affects profiles for both load and renewable generation. Form, in conjunction with consulting firm Energy and Environmental Economics (E3), demonstrated the importance of utilizing weather-correlated profiles in an analysis that examines the future of long duration and multi-day storage technologies in CAISO. Form's modeling shows up to a tenfold increase in adoption of long-duration energy storage (LDES) technologies, defined in this study as having a duration of >12 hours when weather-correlated profiles are used. When weather-correlated inputs from the 2008 weather year were used, for example, 2.37 GW of long-duration storage resources were selected by the optimization model, compared to the 0.2 GW of LDES selected when renewable generation profiles from the 2008 weather year are not correlated with the modeled load profile.[8] Figure 2 below details the difference in amount of LDES the model selects using either weather-correlated profiles or non-correlated profiles (labeled in Figure 2 as "RESOLVE").

Figure 2. Impact of weather-correlated inputs on LDES adoption in CAISO (2045)



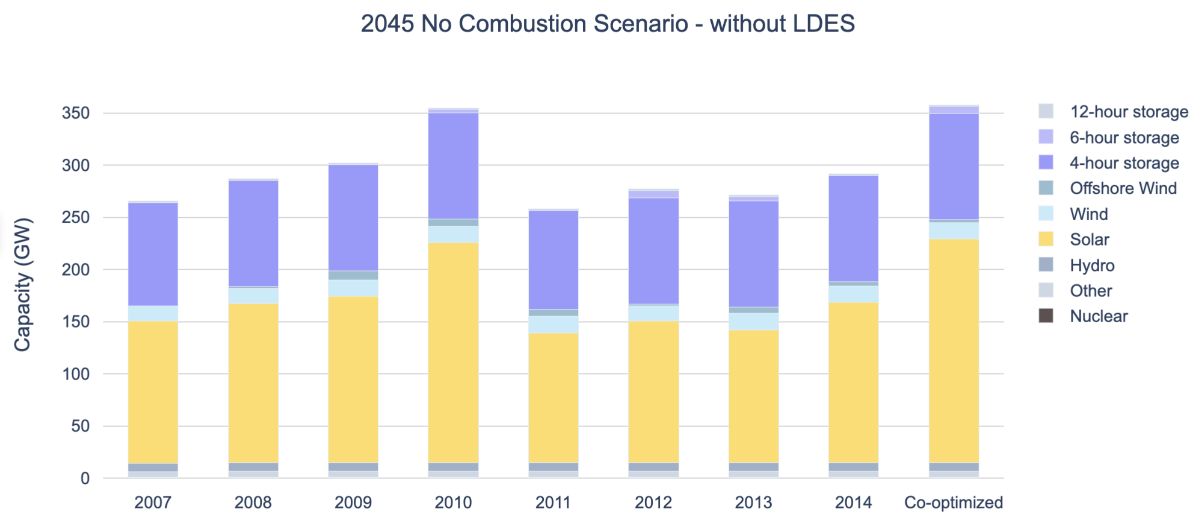
[8] CEC EPC-19-056, "Assessing the Value of Long Duration Energy Storage." Project overview available at: https://www.energy.ca.gov/sites/default/files/2020-12/E3%20Presentation.pptx.

Recommendation: Storage build and dispatch should be modeled over multiple weather years, and should capture periods of grid stress caused by extreme weather events

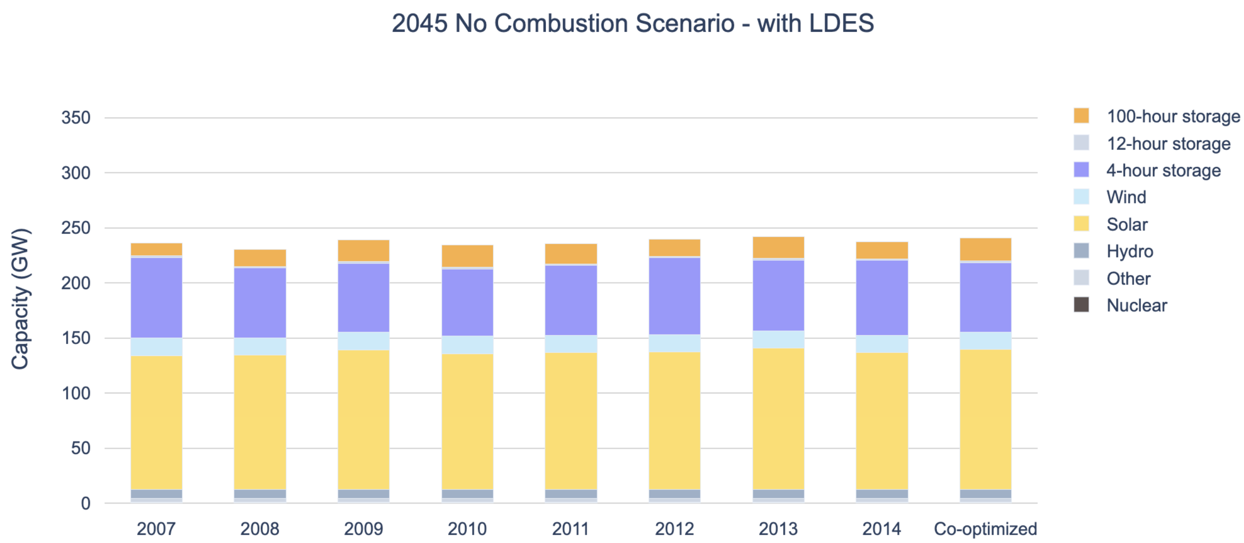
Industry-standard modeling often builds an optimal resource mix designed to meet the average annual peak load, with an established reserve margin, under typical weather conditions. However, weather can vary significantly from year to year, which has major impacts on the requirements of the energy system. Research has shown that modeling only one weather year or only typical conditions underestimates the benefits of flexibility resources like storage.[9] Form strongly recommends that the study models MDS resource builds and operations across multiple historical weather years. This modeling approach will produce results which are robust against interannual variability in weather patterns.

Results from the joint Form/E3 study of CAISO highlight the importance of modeling multiple weather years. Figure 3, below, displays capacity expansion results for individual weather years, as well as co-optimized resource needs across all 2007-2014 weather years.[10] The upper plot displays results for when LDES is excluded from the capacity expansion model while the lower plot displays results that include LDES. We observe that when LDES is excluded from the resource selection, there is significant variation in portfolios, with total nameplate capacity ranging from 260-350 GW. In contrast, when LDES is included resource variance is minimal, with total nameplate capacity ranging from 230-240 GW.

Figure 3. Variation in CAISO capacity expansion results across weather years



[9] Dowling et al., 2020. Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. Joule; 4: 1907-1928, https://doi. org/10.1016/j.joule.2020.07.007.
[10] CEC EPC-19-056, "Assessing the Value of Long Duration Energy Storage." Project overview available at: https://www.energy.ca.gov/sites/default/files/2020-12/E3%20Presentation.pptx.



Modeling a single, typical weather year also neglects the potential for extreme weather events that lead to grid stress. These events challenge both the reliability and resiliency of the regional electric grid, and they are increasing in frequency and severity as a result of climate change. Therefore, Form recommends that the study models MDS in extreme weather scenarios, such as a multi-day winter storm, evaluating the reliability and resiliency benefits that MDS can provide during these catastrophic events.

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