Photo by Werner Slocum, NREL 65320

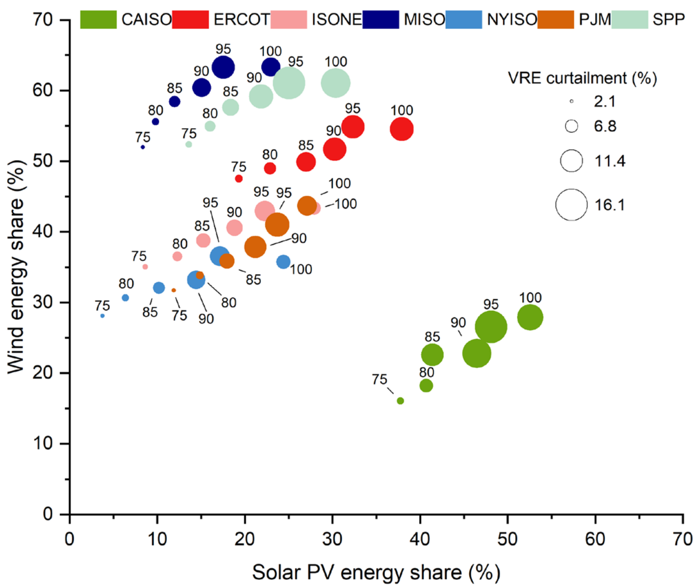
Least-Cost Storage Mix for Low-Carbon Operations

Detailed Analysis Provides New Insights into High-Renewable Storage Portfolios with Regional Variation

As communities plan for high- or ultrahigh-renewable power systems, they face diverse options for energy storage. Each energy storage technology has a unique cost structure, round-trip efficiency, and lifetime, and each community has a unique load, generation mix, and weather pattern. Determining the optimal storage portfolio across these conditions could save planners significant costs when building out high-renewable power systems. This document summarizes results from the article "Optimal energy storage portfolio for high and ultrahigh carbon-free and renewable power systems."

Study Background

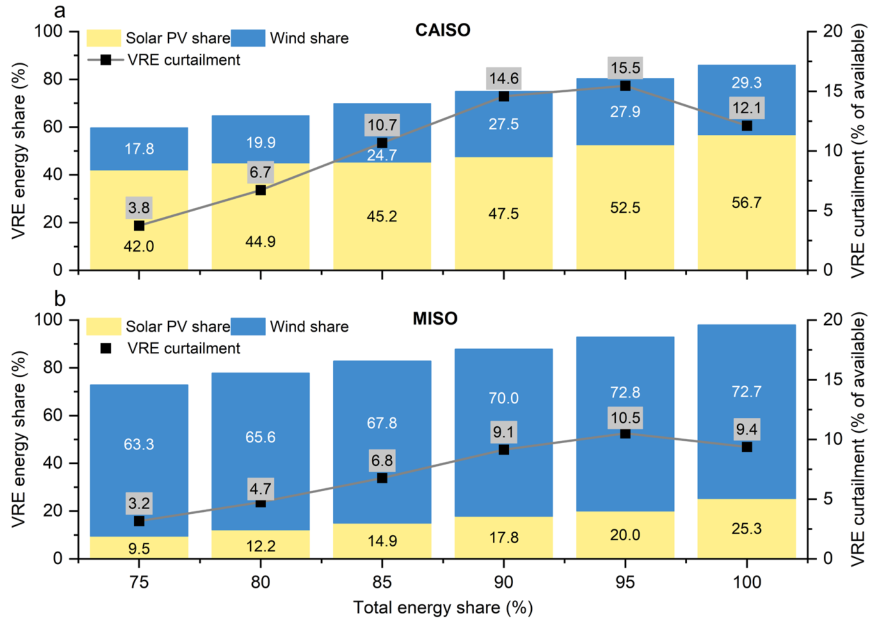
We used an optimization framework with high spatial and temporal resolution to simultaneously assess variable renewable energy (VRE) deployment and optimal storage portfolios for all seven independent system operators (ISOs) in the United States. We considered storage technologies across three timescales: short-duration discharge (less than 10 hours), long-duration discharge (between 10–100 hours), and seasonal discharge (more than 100 hours). We optimized these storage technologies to support renewable growth under different target scenarios, from 75%–100%. Within this framework, we found that optimal storage portfolios varied considerably across the United States, a fact that became more pronounced as systems approached 100% renewable generation.



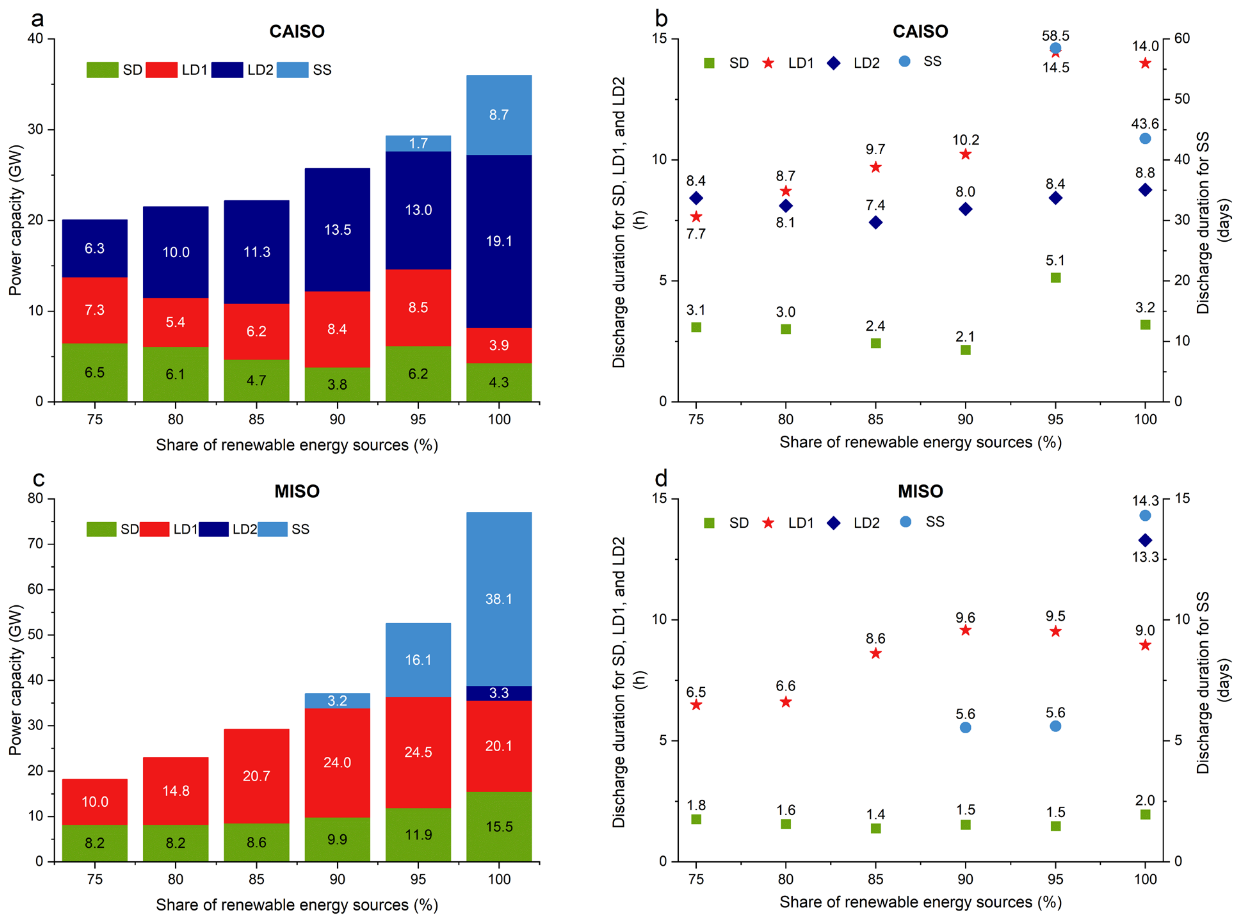
A comparison of curtailment for wind and solar PV as they provide a greater proportion of power generation for each of the U.S. independent system operators. Numbers near the bubbles represent the renewable energy mix target (75%–100%).

Wind and Solar PV Growth and Curtailment

- Achieving a 100% renewable energy mix in the CAISO modeled scenarios required 96.5 GW of PV and 36.2 GW of wind generation capacity. In contrast, achieving a 100% renewable energy mix in MISO would require deploying 146.8 GW of PV and 170 GW of wind generation capacity.
- For renewable energy targets less than 95%, VRE curtailment increases with the share of carbon-free or renewable energy sources, regardless of the ISO; however, optimal VRE curtailment decreases significantly when moving from the 95% to the 100% energy target.



The California Independent System Operator (CAISO) has a solar-heavy footprint, while the Midcontinent Independent System Operator (MISO) is wind-heavy. Differences in each system's renewable power sources lead to differences when selecting their least-cost energy storage portfolio.



Short-duration (SD) storage has high energy-related costs but the lowest power-related costs. Long-duration technology 1 (LD1) is intended to capture technologies with somewhat lower power and energy costs but with lower round-trip efficiencies. Long-duration technology 2 (LD2) captures technologies with somewhat higher capacities and energy costs but also higher efficiencies. Seasonal storage (SS) technology has higher power-related costs, very low energy-related costs, and low round-trip efficiencies. Additionally, the charge and discharge power for LD1 and SS can be independently optimized.

Optimal Storage Portfolios

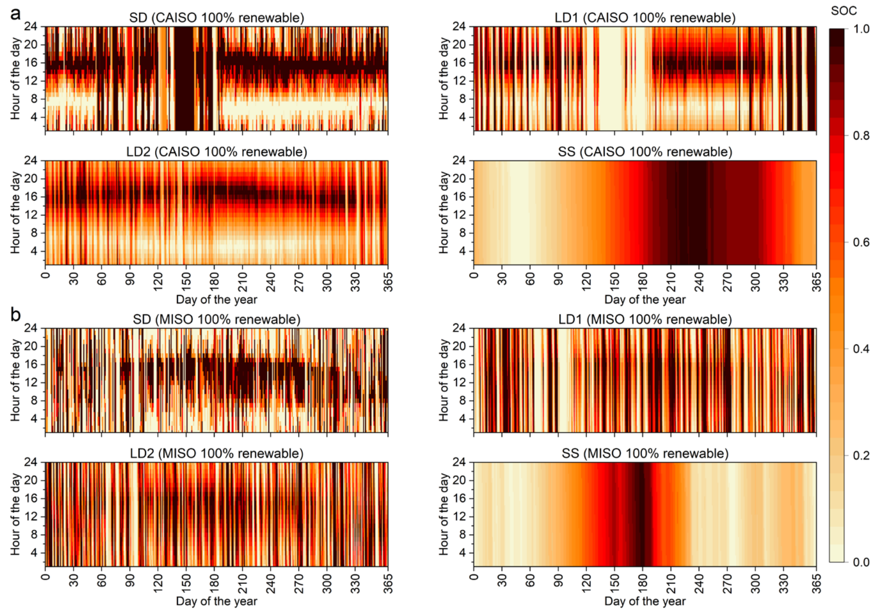
- The optimal proportion of seasonal storage power capacity is less for CAISO than for the other ISOs.
- Carbon-free and renewable energy targets up to 80% are achieved with curtailment and a combination of short- and long-duration energy storage.
- Seasonal storage is not deployed before a renewable mix of approximately 85%–90%.
- The difference between PV-driven systems, like CAISO, and wind-driven systems, like MISO, is amplified by diurnal and seasonal coincidence with load and the inherently higher spatial variability of wind, particularly in the diurnal time frame.

Storage Operation Across Different Timescales

- In CAISO, short-duration, LD1, and LD2 generally discharge storage between 16:00–20:00 and charge storage between 08:00–16:00. This accommodates CAISO's solar profiles.
- The seasonal storage state-of-charge profile exhibits strong seasonal behavior, charging in the spring and summer and discharging in the fall and winter.
- These findings are similar for MISO, except that LD1 and LD2 exhibit more multiday energy shifting than daily arbitrage.

Storage Cycling and Storage-to-Storage Operation

- Considering all scenarios, short-duration energy storage provides predominantly diurnal energy shifting with 1.4–5.1 hours of discharge capacity, and high cycling with 129–250 equivalent annual discharge cycles.
- Cycling behavior is driven by round-trip efficiency—technologies with a higher efficiency tend to have a higher number of equivalent cycles.

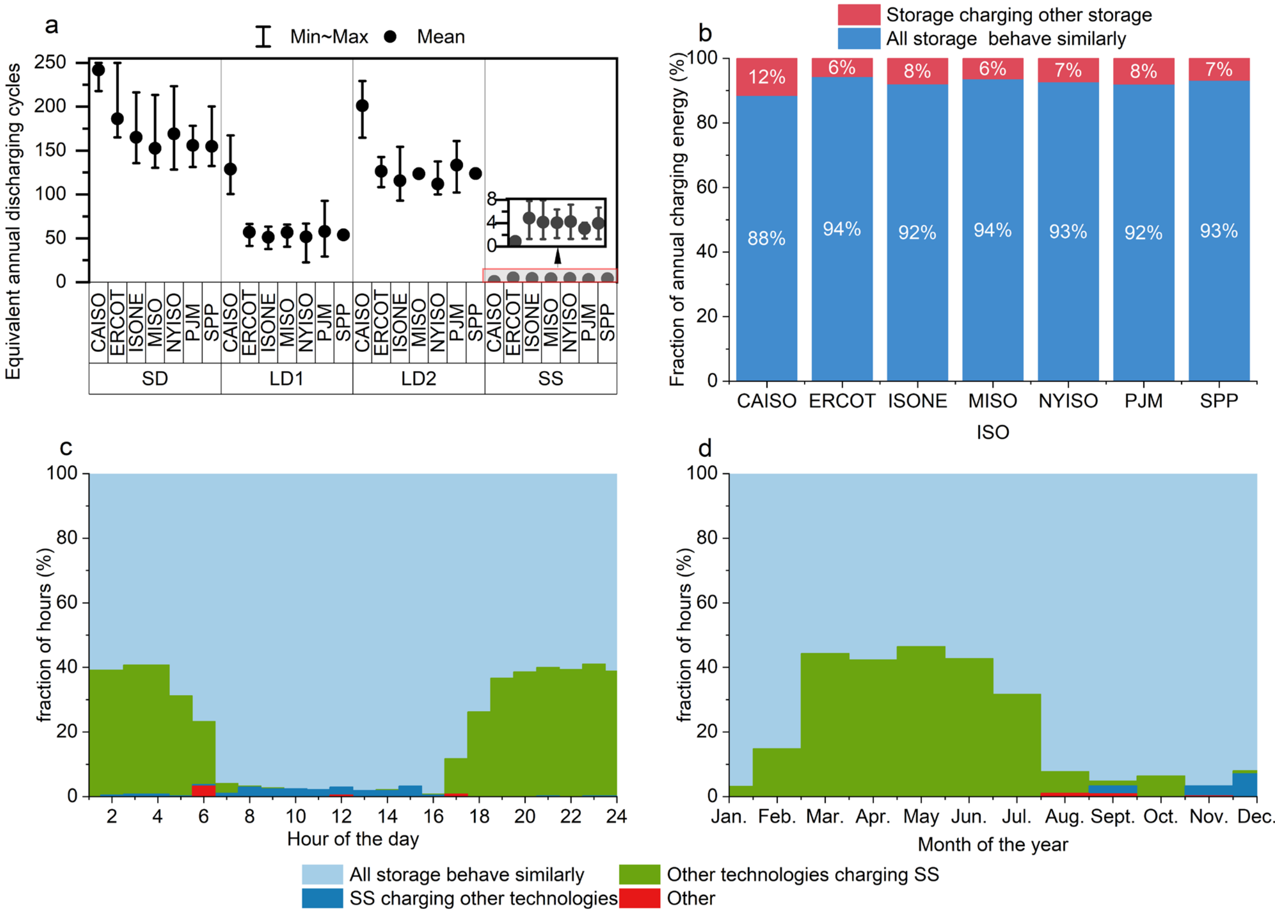


Normalized state of charge (SOC) has different charging dynamics for SD, LD1 and LD2, and SS in CAISO and MISO. (a) Normalized SOC for devices in CAISO with 100% renewable energy mix. (b) Normalized SOC for devices in MISO with 100% renewable energy mix. SOC = 1 (dark red) implies that the storage device is full. SOC = 0 (light red) implies that the storage device is empty.

- Seasonal storage is not installed in every system or deployed for every energy target, but when installed, it comprises between 2%–54% of the storage portfolio power capacity and is particularly important for achieving 100% energy targets.
- As the renewable energy target approaches 100%, it becomes cost-effective to use short- and long-duration storage devices to charge seasonal storage devices.

Economics of VRE and Storage Deployment

- In the Southwest Power Pool—the ISO with the lowest average energy costs—a high renewable energy mix can be achieved at electricity costs ranging from $38.1 MW/h–$48.2 MW/h, depending on the energy mix target.
- In contrast, energy costs for CAISO vary from $51.6 MW/h–$80.0 MW/h for a high renewable energy mix, depending on the target.
- Excluding CAISO, a 90% carbon-free or renewable energy mix can be achieved at a cost of $63.5/tonne or less in all other ISOs. In general, the cost of avoided carbon emissions is higher in CAISO (a PV-driven system) than in the other ISOs.



At and near 100% renewable energy, it becomes more economical for one storage type to charge another. a) Discharge cycles for all storage types and ISOs, and across all renewable energy mixes from 75% to 100%. b) Percentage of storage used to charge other storage at 100% renewable energy. c) Hourly breakdown of CAISO at 100% renewable energy. d) Monthly breakdown of CAISO at 100% renewable energy.

Key Findings

- Carbon-free and renewable energy mix targets up to 80% are achieved with economic curtailment and a combination of short- and long-duration energy storage.
- There is a point between 80% and 95% when seasonal storage becomes cost-competitive, depending on the specific power system.
- Storage-to-storage operation—one storage device charging another storage device—and the decoupling of charging and discharging storage power capacity are cost-effective options for the integration of high and ultrahigh shares of carbon-free or renewable power sources.
- An 85% carbon-free or renewable energy mix can be achieved with an avoided carbon emissions cost of $66.0/ tonne or less, regardless of the power system.

Read the full article: "Optimal energy storage portfolio for high and ultrahigh carbon-free and renewable power systems."

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