Optimal Energy Storage Portfolio for High and Ultrahigh Carbon-Free and Renewable Power Systems

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Supplementary file

1. Overview of the electric grid planning framework

An overview of the Storage Deployment Optimization Model (SDOM) is presented in Figure 1. SDOM is implemented as a mixed-integer linear programming (MILP) model in the General Algebraic Modeling System (GAMS); see https://www.gams.com/.

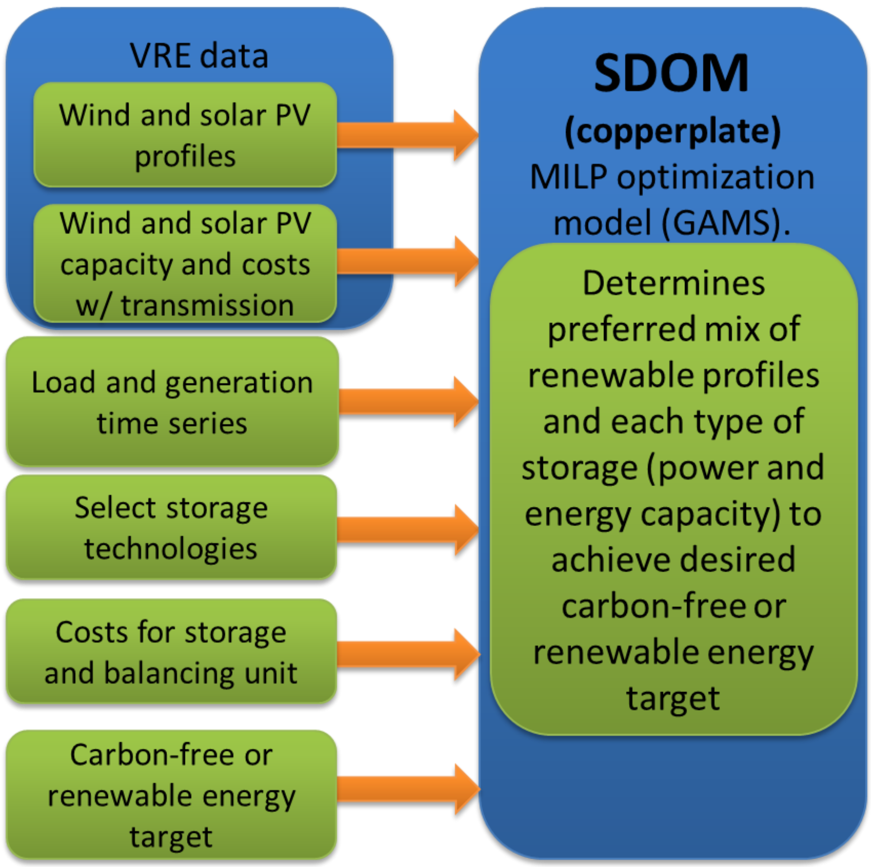

Figure 1. Overview of the Storage Development Optimization Model (SDOM). VRE: variable renewable energy, e.g., wind and solar photovoltaic (PV) power sources.

2. Summary of techno-economic assumptions

A summary of the techno-economic assumptions for variable renewable energy (VRE), balancing units, and storage technologies is presented in Table 1.

Table 1. Techno-economic assumptions for VRE, energy storage, and balancing technologies. All dollars are in 2020 dollars.

VRE techno-economic assumption (2050 projections)[1]	VRE technology
	Solar PV (utility scale)
Capex-Reference (US$ kW^{-1})	708.5
Capex-Minimum (US$ kW^{-1})	533.2
Capex-Maximum (US$ kW^{-1})	861.6
FO&M-Reference (US$ $kW\text{-}yr^{-1}$)	8.3
FO&M-Minimum (US$ $kW\text{-}yr^{-1}$)	6.2
FO&M-Maximum (US$ $kW\text{-}yr^{-1}$)	10.1
	Land-based wind (Class 1, Class 2, Class 3, Class 4, Class 5, Class 6, Class 7, Class 8, Class 9, Class 10)
Capex-Reference (US$ kW^{-1})	1057.7, 1002.0, 1002.3, 1009.7, 1051.8, 1145.1, 1269.4, 1465.8, 1766.4, 1784.8
Capex-Minimum (US$ kW^{-1})	698.2, 657.3, 656.5, 659.2, 676.5, 705.6, 757.3, 929.9, 1048.4, 860.4
Capex-Maximum (US$ kW^{-1})	1294.9, 1218.4, 1213.4, 1217.9, 1264.8, 1355.2, 1519.8, 1752.4, 2109.4, 2118.4
FO&M-Reference (US$ $kW\text{-}yr^{-1}$)	34.1 (same for each class)
FO&M-Minimum (US$ $kW\text{-}yr^{-1}$)	24.8 (same for each class)
FO&M-Maximum (US$ $kW\text{-}yr^{-1}$)	42.3 (same for each class)

Storage techno-economic assumption (2050 projections)	Storage technology			
	Short-duration (SD)	Long-duration 1 (LD1)	Long-duration 2 (LD2)	Seasonal (SS)
Power capex (US$ kW^{-1})	97.8[2]	842.6[2–4]	1063.3[2,3]	1414.8[3]
Energy capex (US$ kWh^{-1})	115.7[2]	34.7[2–4]	53.1[2,3]	1.1[3]
Round-trip efficiency (%)	86.0[2]	63.0[2–4]	78.2[2,3]	44.0[3]
FO&M (US$ $kW\text{-}yr^{-1}$)	10.3[2]	4.1[2]	8.2[2]	47.4[2]
VO&M (US$ kWh^{-1})	3.1[2]	4.1[2]	1.0[2]	0[2]
Ratio of cost for charging power capacity to total power-related cost	-	0.325[5]	-	0.49[3]
Lifetime (years)	13[2]	30[2]	55[2]	18[2]

Techno-economic assumption for balancing units (2050 projections)[1]	Gas combined cycle (GAS CC)
Capex (US\$ kW^{-1})	940.6
FO&M (US\$ $kW\text{-}yr^{-1}$)	13.3
VO&M (US\$ kWh^{-1})	2.2
Heat rate (MMBtu MWh^{-1})	6.4
Fuel cost (US\$ $MMBtu^{-1}$)	4.11

Technology costs and performance parameters for SD, LD1, LD2, and SS were estimated based on Li-Ion battery, CAES, PHS, and hydrogen storage, respectively.

3. Independent system operator load and conventional generation data

The independent system operator (ISO) load and conventional generation time series are presented in Figs. 2–8. The corresponding references are provided in the caption of each figure.

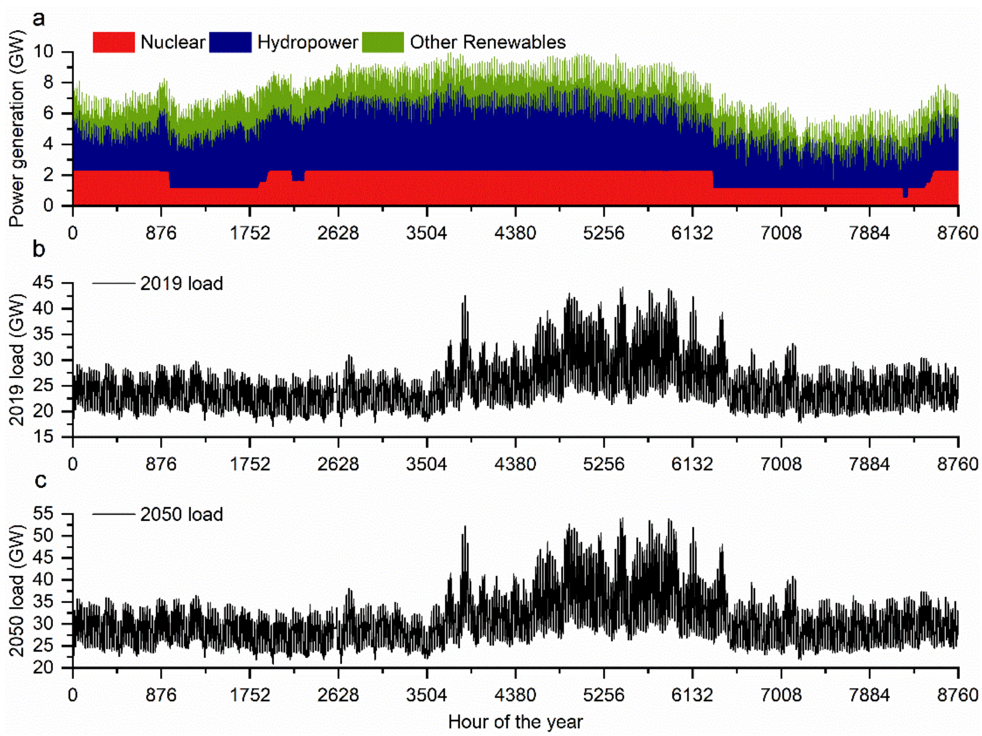

Figure 2. California Independent System Operator (CAISO) load and conventional generation profiles. **a**, 2019 conventional power generation. **b**, 2019 load data. **c**, projected 2050 load data. Ref. http://oasismap.caiso.com/mrioasis/logon.do.

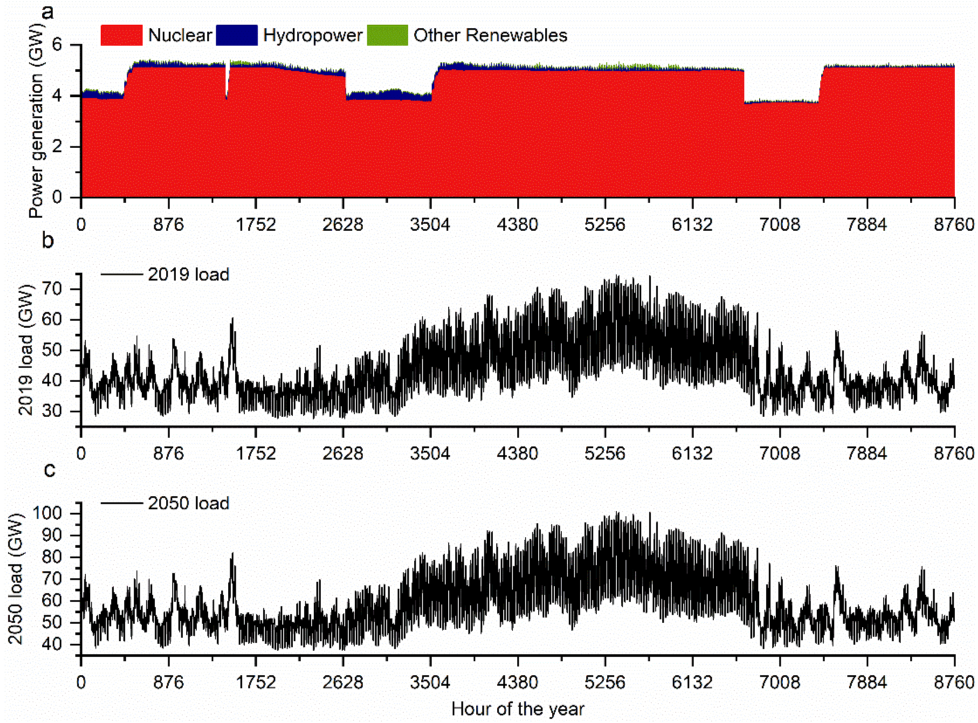

Figure 3. Electric Reliability Council of Texas (ERCOT) load and generation profiles. **a**, 2019 conventional power generation. **b**, 2019 load data. **C**, projected 2050 load data. Ref. http://www.ercot.com/gridinfo.

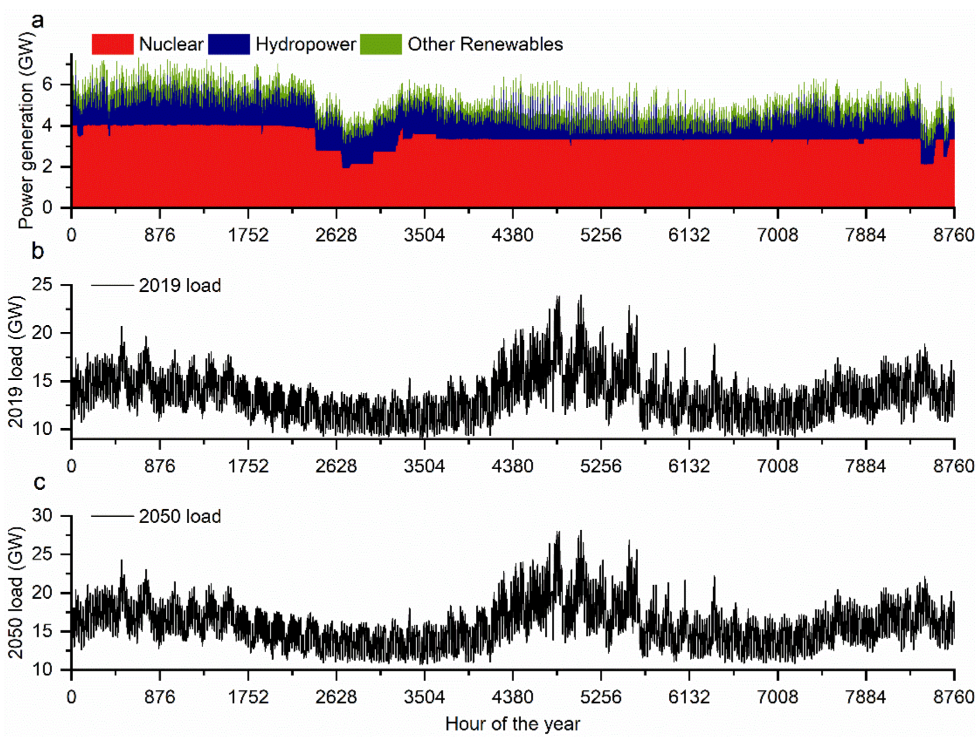

Figure 4. Independent System Operator–New England (ISONE) load and conventional generation profiles. **a**, 2019 conventional power generation. **b**, 2019 load data. **c**, projected 2050 load data. Ref. https://www.iso-ne.com/markets-operations/iso-express.

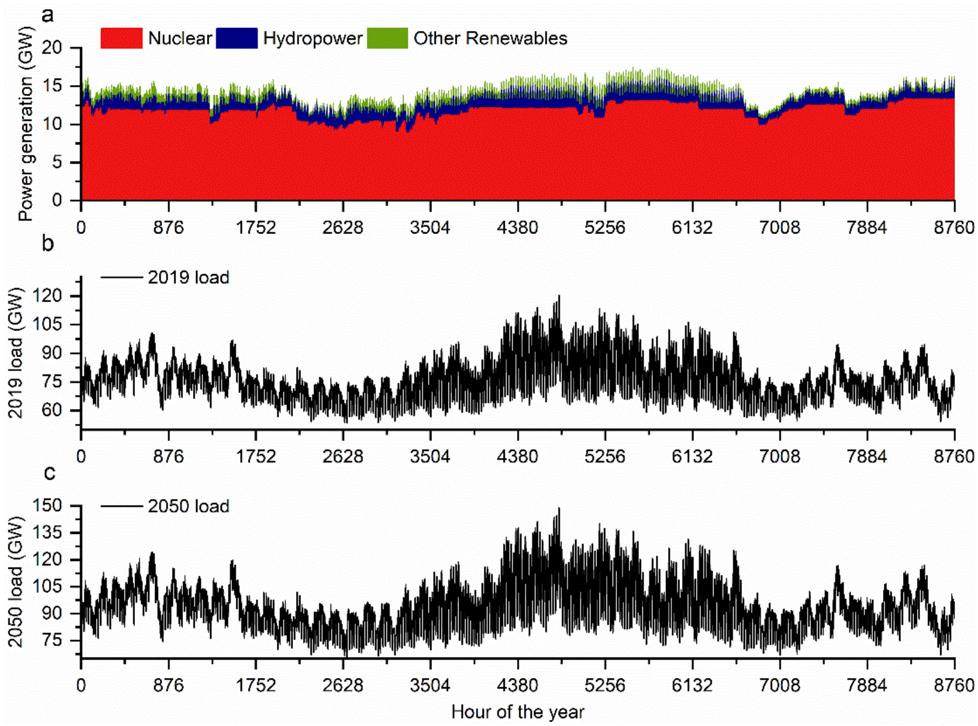

Figure 5. Midcontinent Independent System Operator (MISO) load and generation profiles. **a**, 2019 conventional power generation. **b**, 2019 load data. **c**, projected 2050 load data. Ref. https://docs.misoenergy.org/marketreports/YYYYMMDD_rf_al.xls.

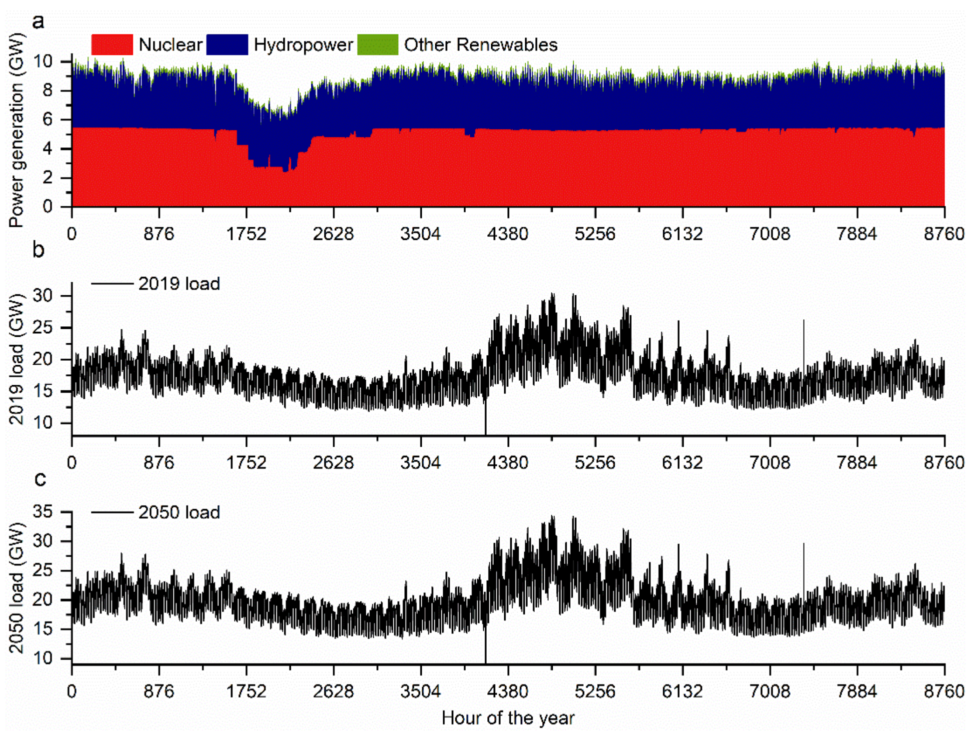

Figure 6. New York Independent System Operator (NYISO) load and generation profiles. **a**, 2019 conventional power generation. **b**, 2019 load data. **c**, projected 2050 load data. Ref. load data:

http://mis.nyiso.com/public/P-58Blist.htm, generation data: http://mis.nyiso.com/public/P-63list.htm.

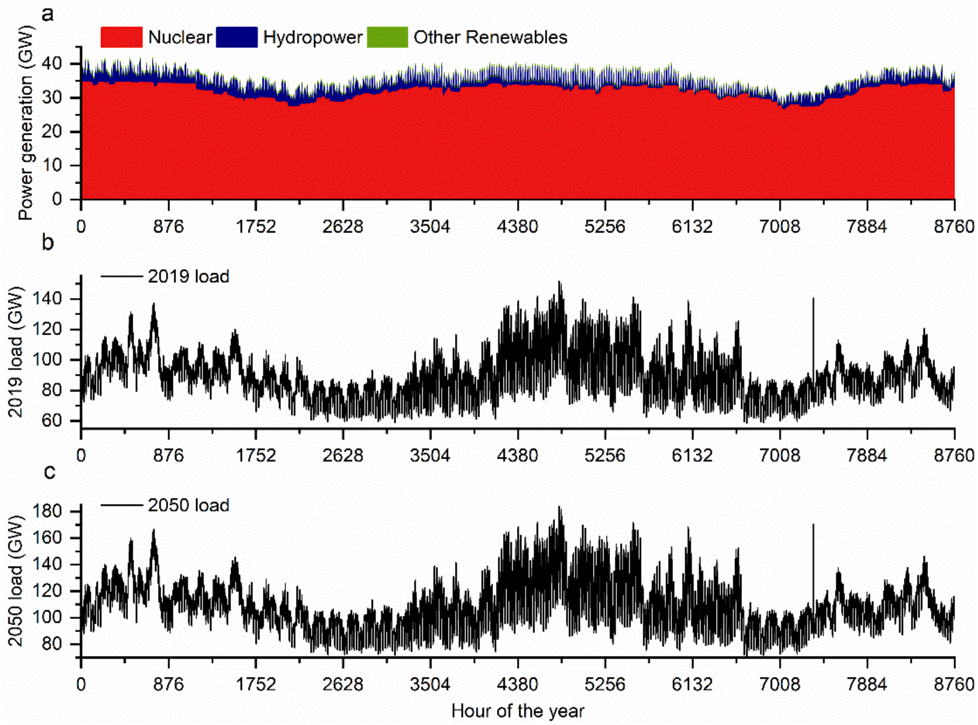

Figure 7. Pennsylvania-Jersey-Maryland Power Pool (PJM) load and generation profiles. **a**, 2019 conventional power generation. **b**, 2019 load data. **c**, projected 2050 load data. Ref. https://dataminer2.pjm.com/list.

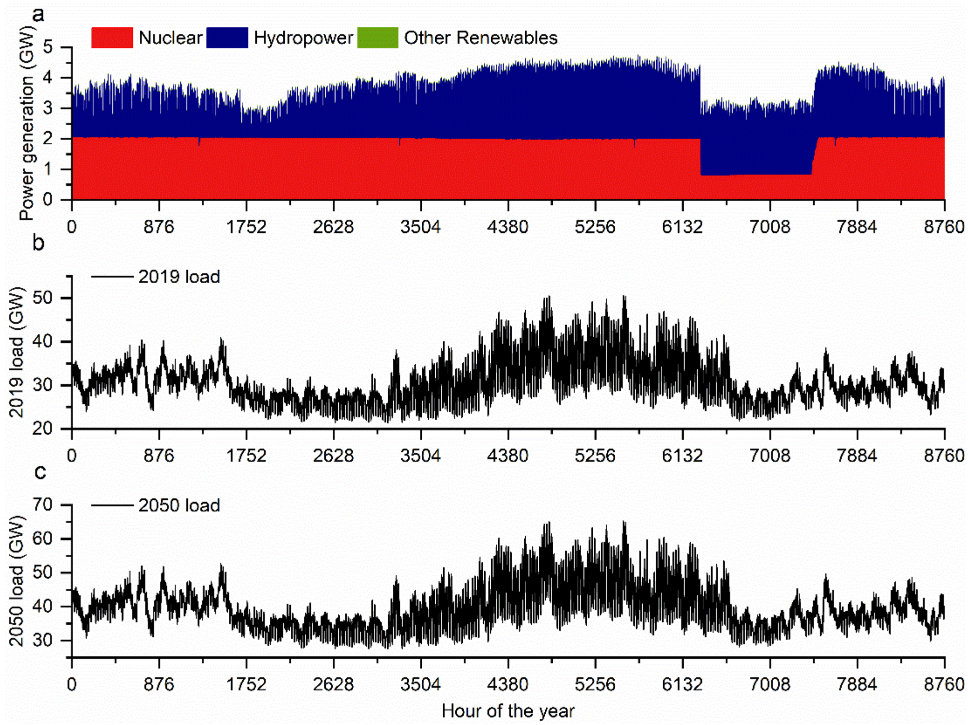

Figure 8. Southwest Power Pool (SPP) load and generation profiles. **a**, 2019 conventional power generation. **b**, 2019 load data. **c**, projected 2050 load data. Ref. https://marketplace.spp.org/pages/generation-mix-historical.

4. Average capacity factor and maximum generation capacity for variable renewable energy units and for each independent system operator

The distributions of the yearly capacity factor and maximum power generation capacity for potential VRE units and for each ISO are summarized in Figs. 9–15.

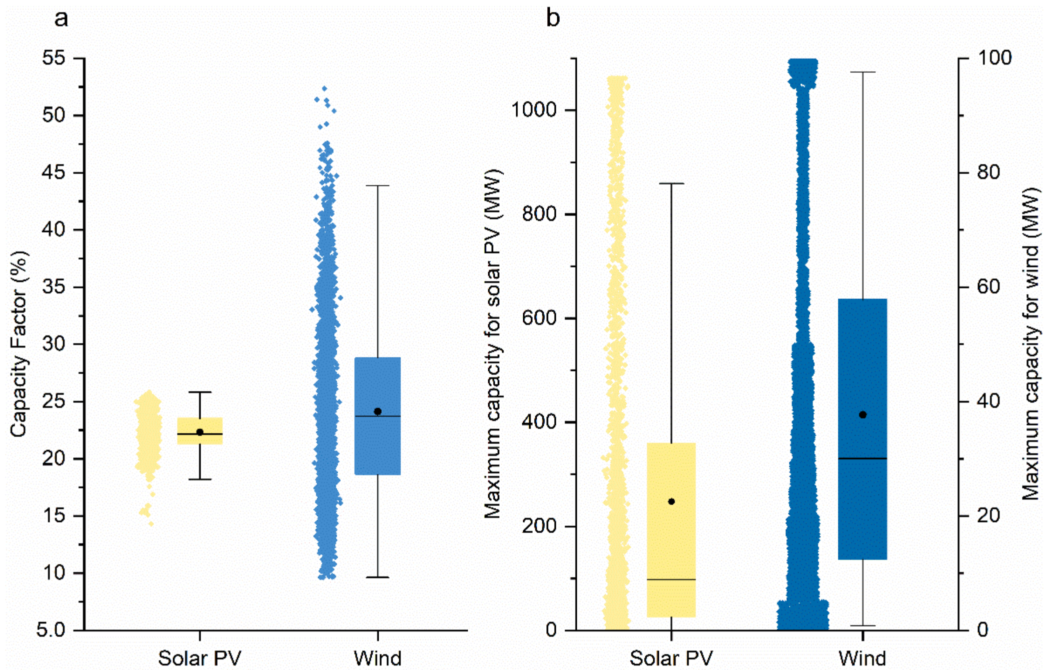

Figure 9. Capacity factor (**a**) and maximum generation capacity (**b**) for VRE units in CAISO. Box and whisker plots were based on the interquartile range (IQR), which is defined as the difference between the 75th (Q3) and 25th (Q1) percentiles, i.e., IQR = Q3 − Q1. The lower and upper whiskers correspond to Q1 − 1.5*IQR and Q3 + 1.5*IQR, respectively. All the data points were used by SDOM (potential outliers were not excluded).

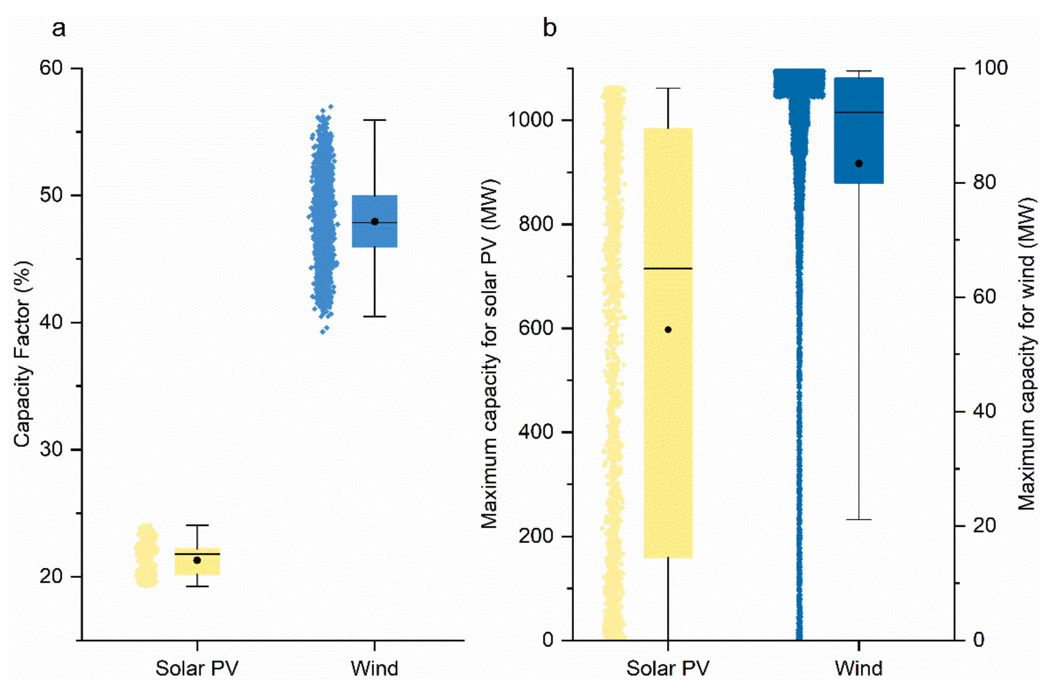

Figure 10. Capacity factor (**a**) and maximum generation capacity (**b**) for VRE units in ERCOT.

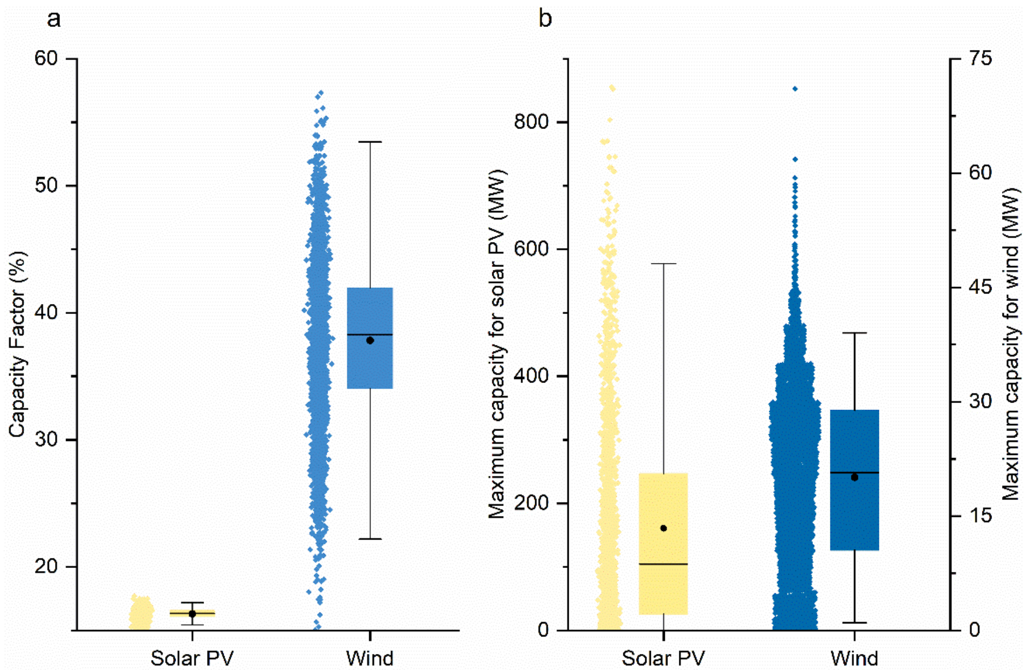

Figure 11. Capacity factor (**a**) and maximum generation capacity (**b**) for VRE units in ISONE.

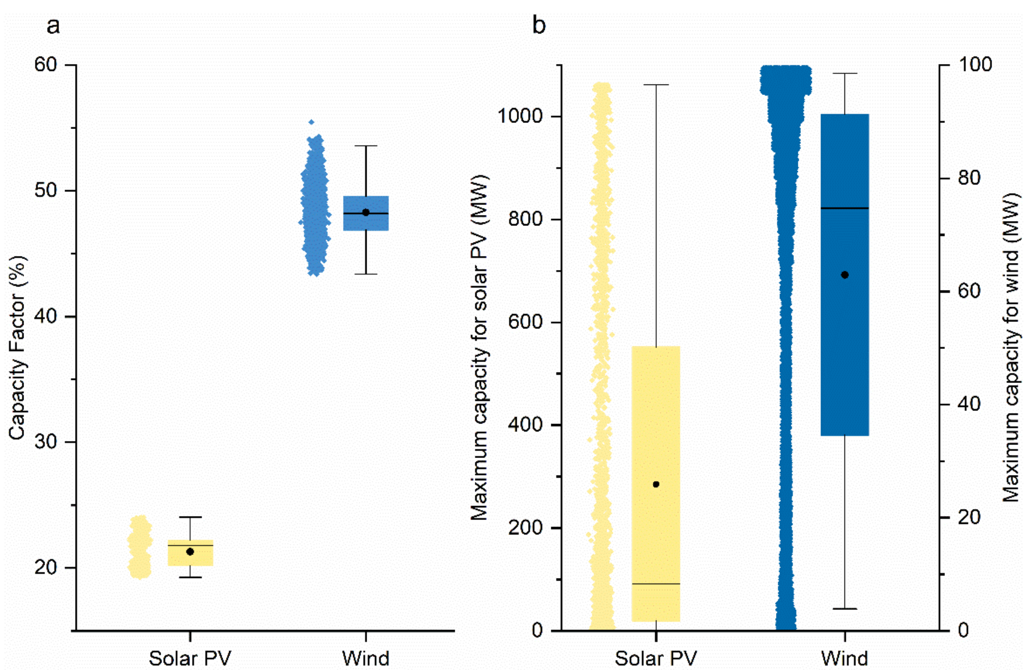

Figure 12. Capacity factor (**a**) and maximum generation capacity (**b**) for VRE units in MISO.

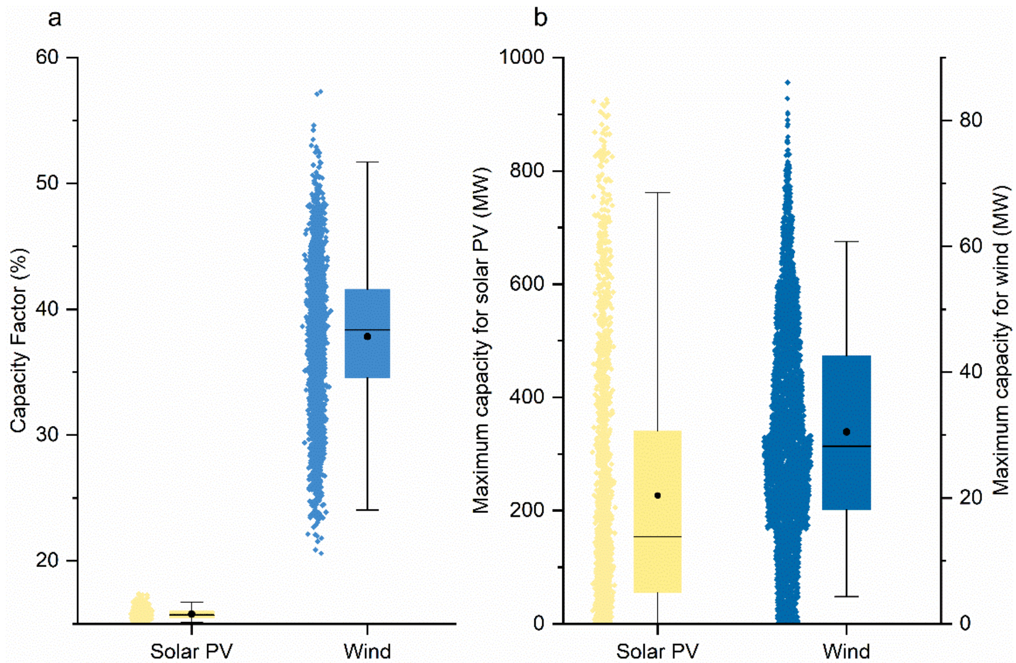

Figure 13. Capacity factor (**a**) and maximum generation capacity (**b**) for VRE units in NYISO.

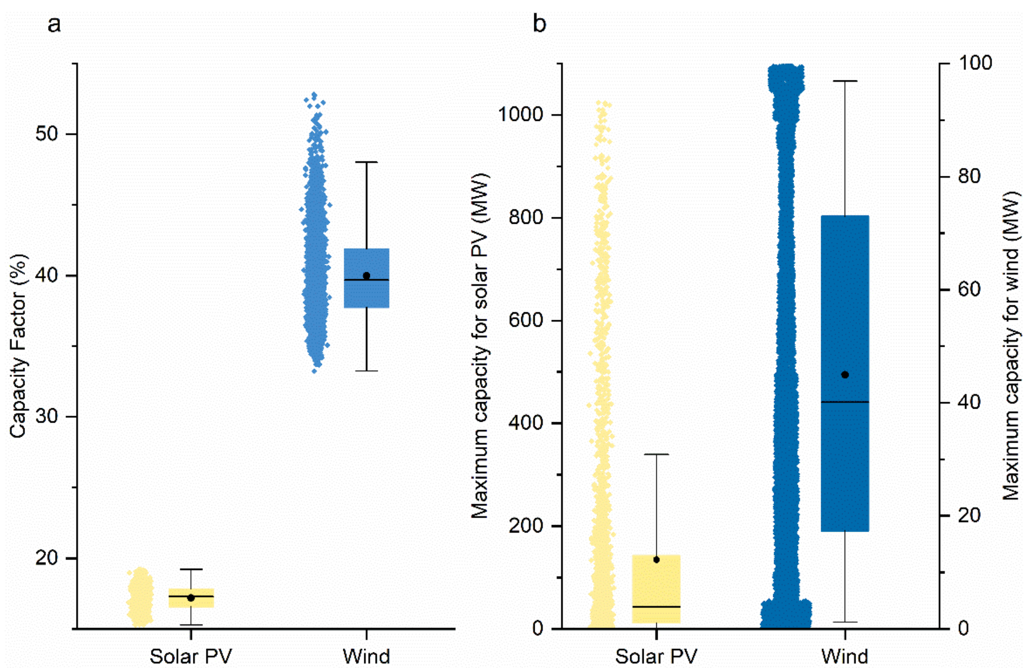

Figure 14. Capacity factor (**a**) and maximum generation capacity (**b**) for VRE units in PJM.

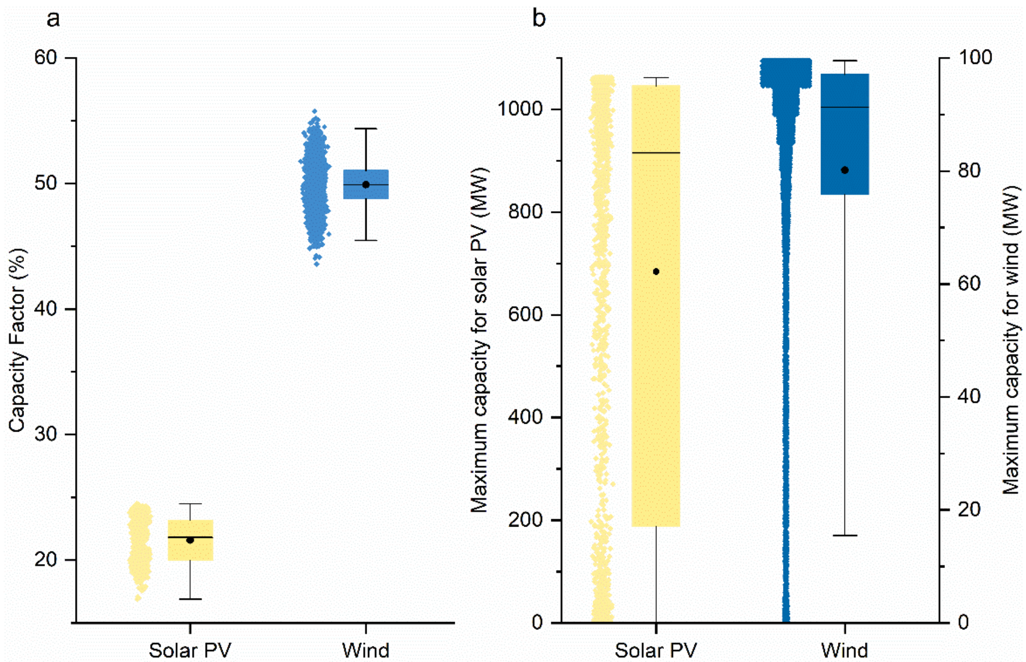

Figure 15. Capacity factor (**a**) and maximum generation capacity (**b**) for VRE units in SPP.

5. Optimal variable renewable energy mix and curtailment

The optimal VRE energy mix and curtailment for CAISO, ERCOT, ISONE, MISO, NYISO, PJM, and SPP are summarized in Figs. 16–21.

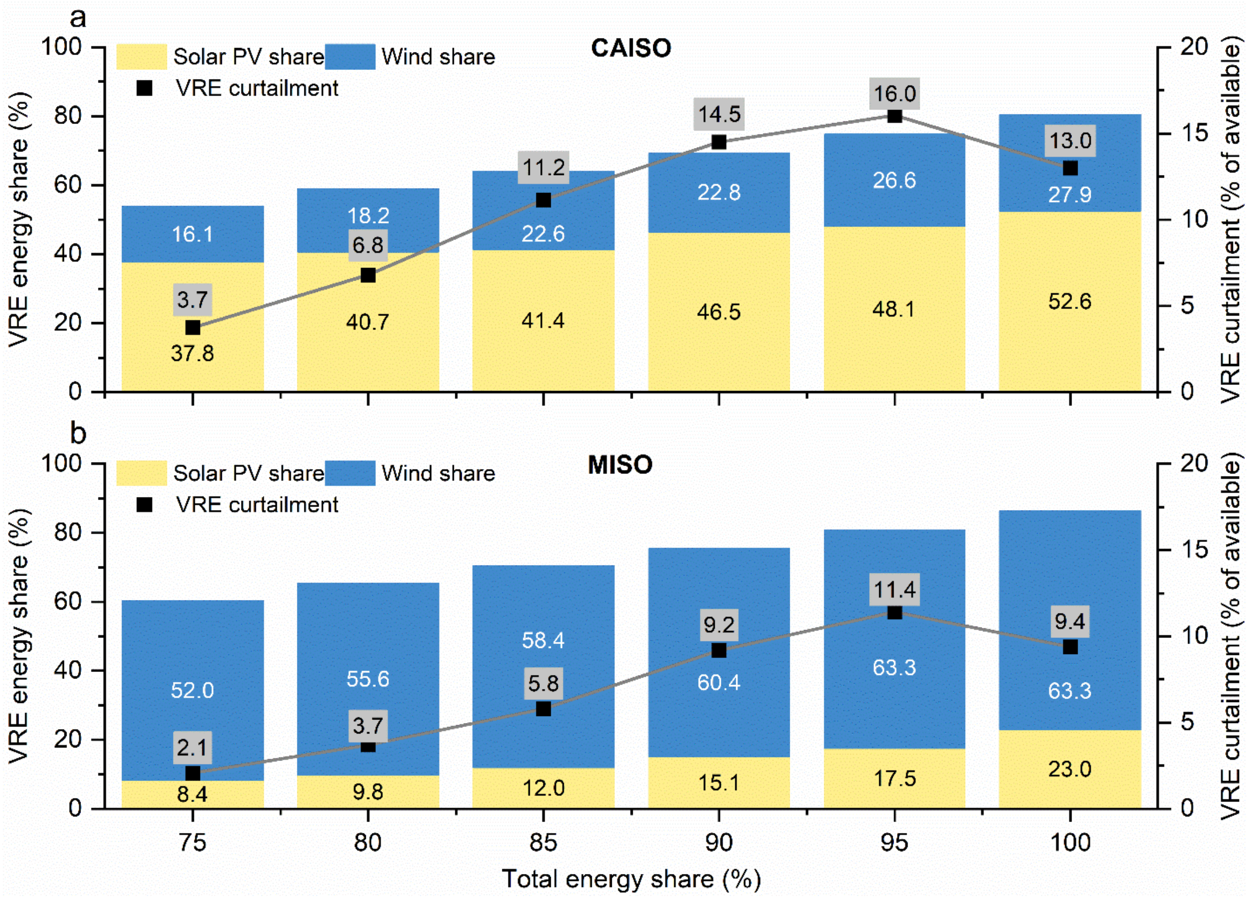

Figure 16. Optimal VRE mix and curtailment for carbon-free energy mix targets in CAISO (top) and MISO (bottom) in 2050. **a**, optimal VRE mix and curtailment for CAISO carbon-free energy mix targets. **b**, optimal VRE mix and curtailment for MISO carbon-free energy mix targets.

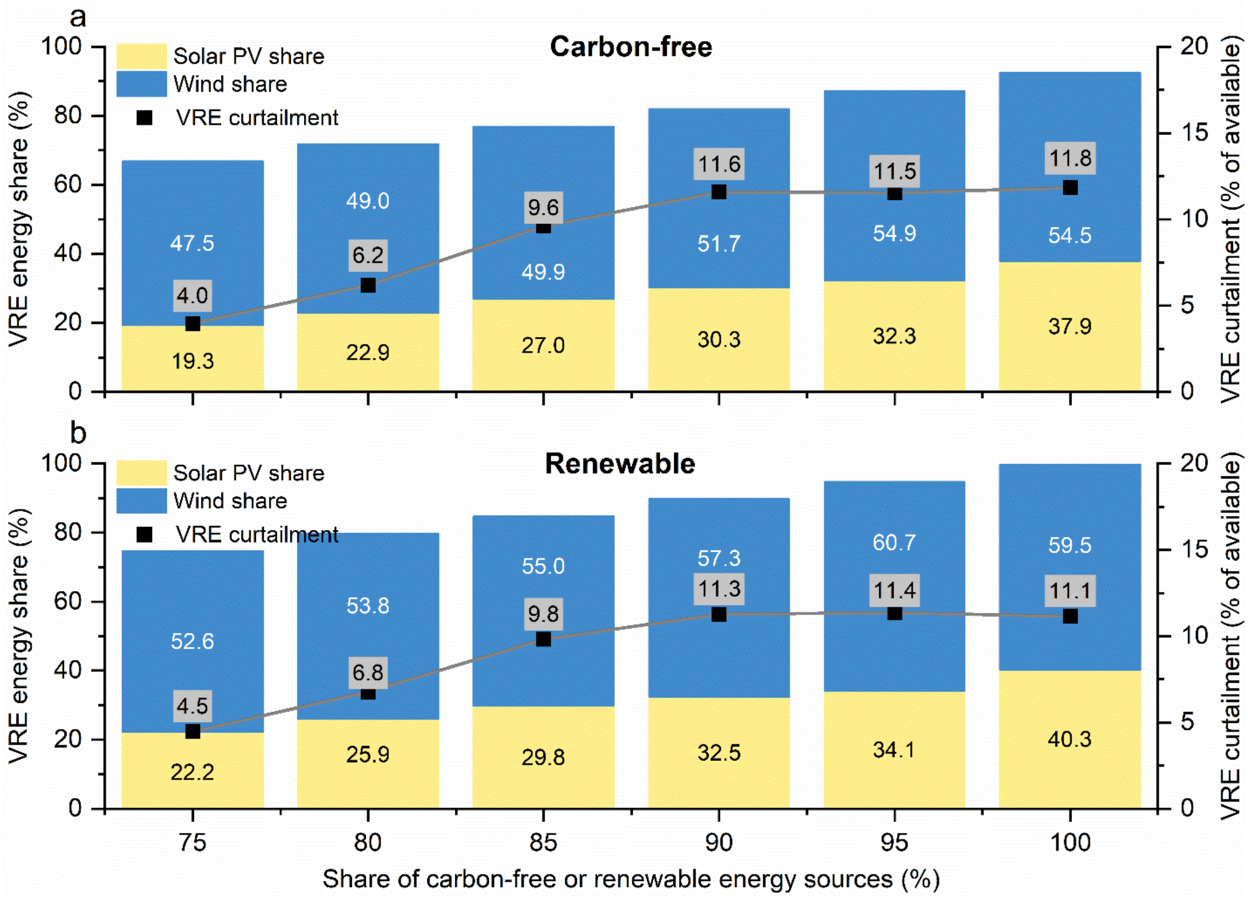

Figure 17. Optimal VRE energy mix and curtailment for ERCOT in 2050. **a**, carbon-free energy share targets. **b,** renewable energy share targets.

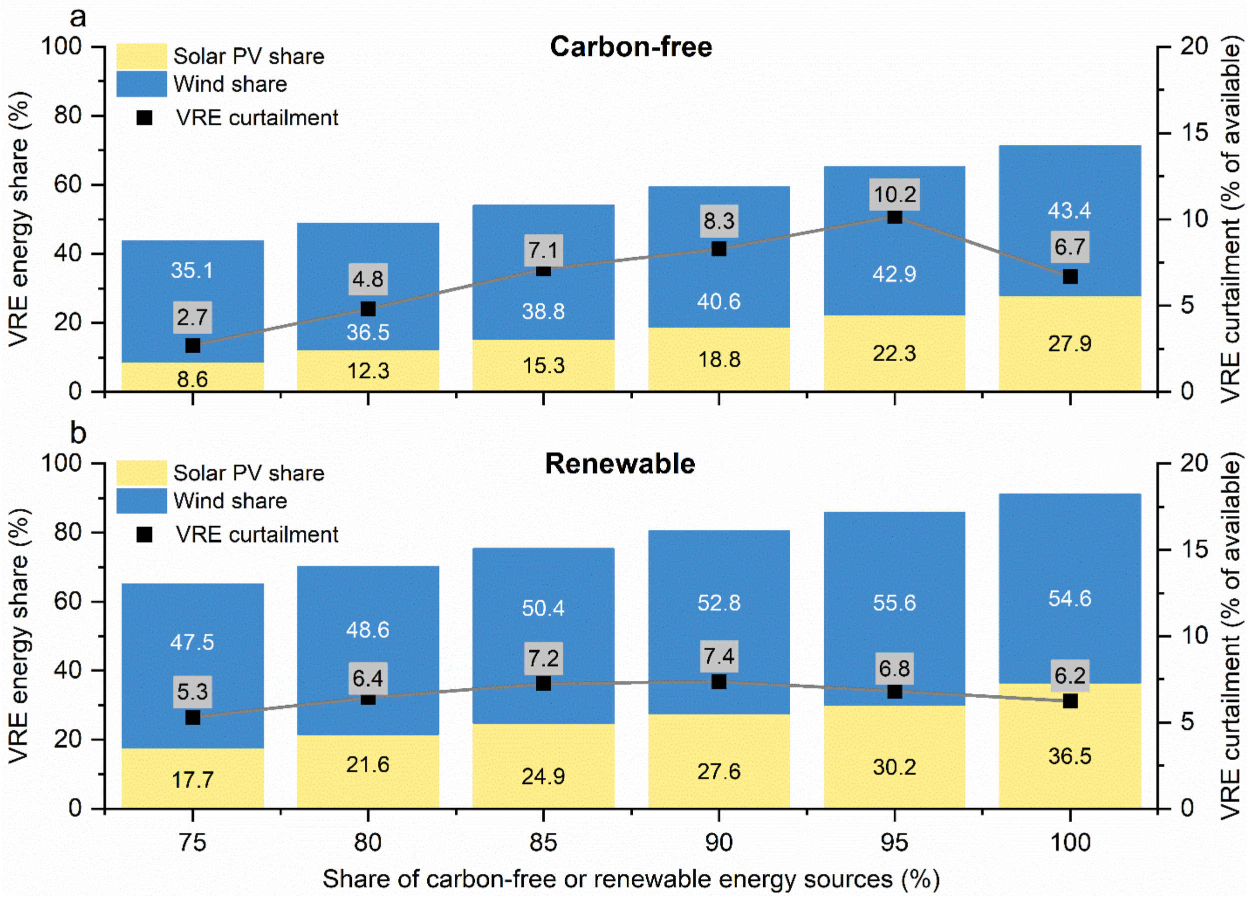

Figure 18. Optimal VRE energy mix and curtailment for ISONE in 2050. **a,** carbon-free energy share targets. **b,** renewable energy share targets.

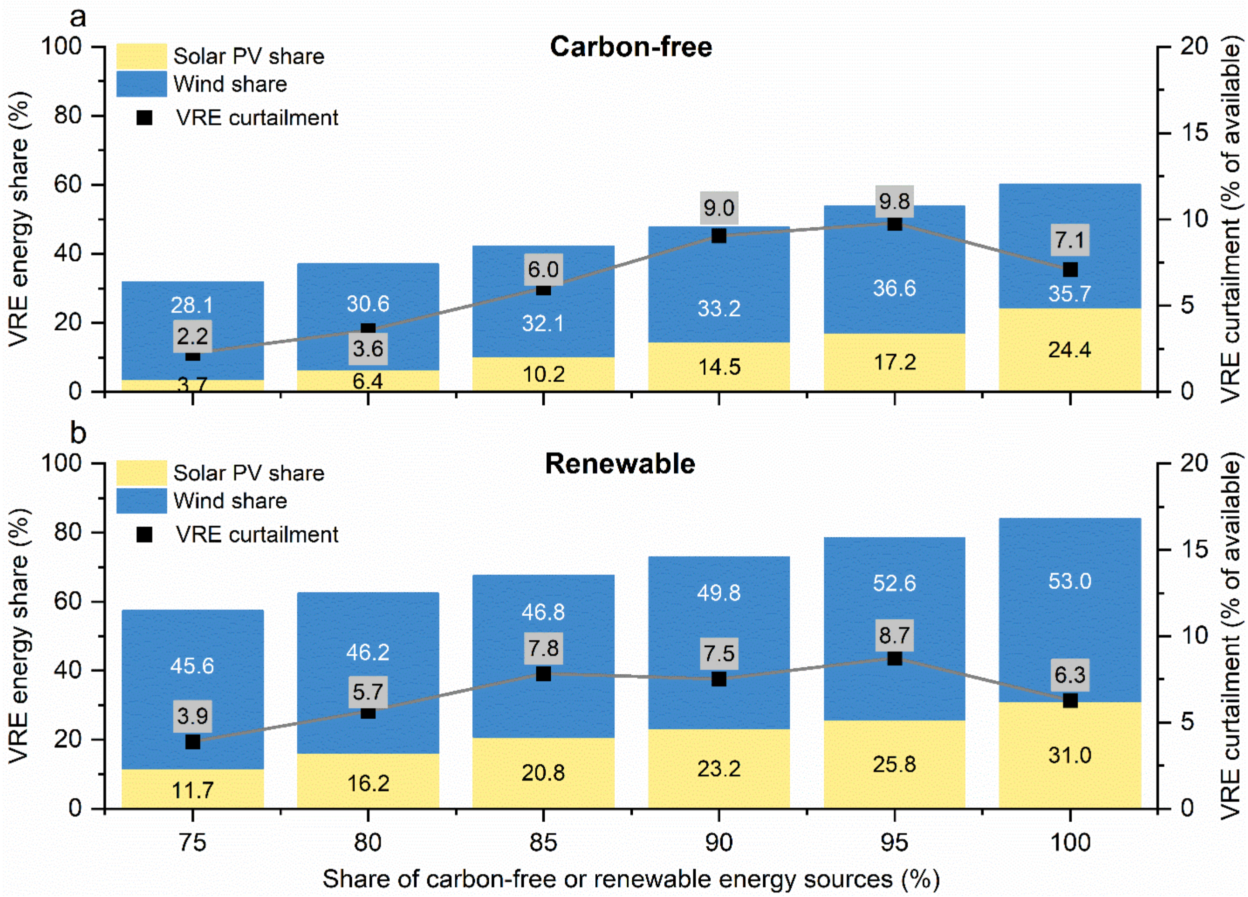

Figure 19. Optimal VRE energy mix and curtailment for NYISO in 2050. **a,** carbon-free energy share targets. **b,** renewable energy share targets.

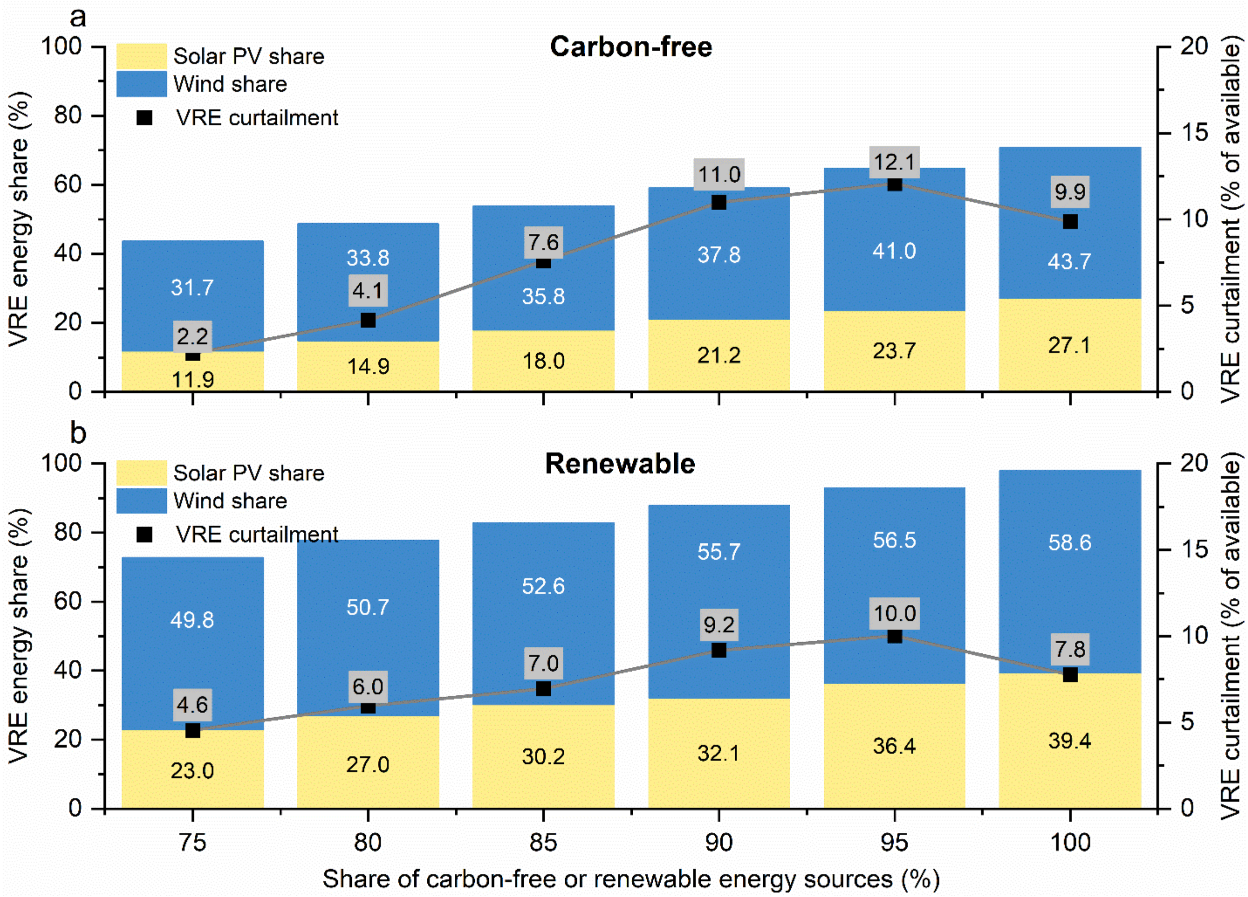

Figure 20. Optimal VRE energy mix and curtailment for PJM in 2050. **a,** carbon-free energy share targets. **b,** renewable energy share targets.

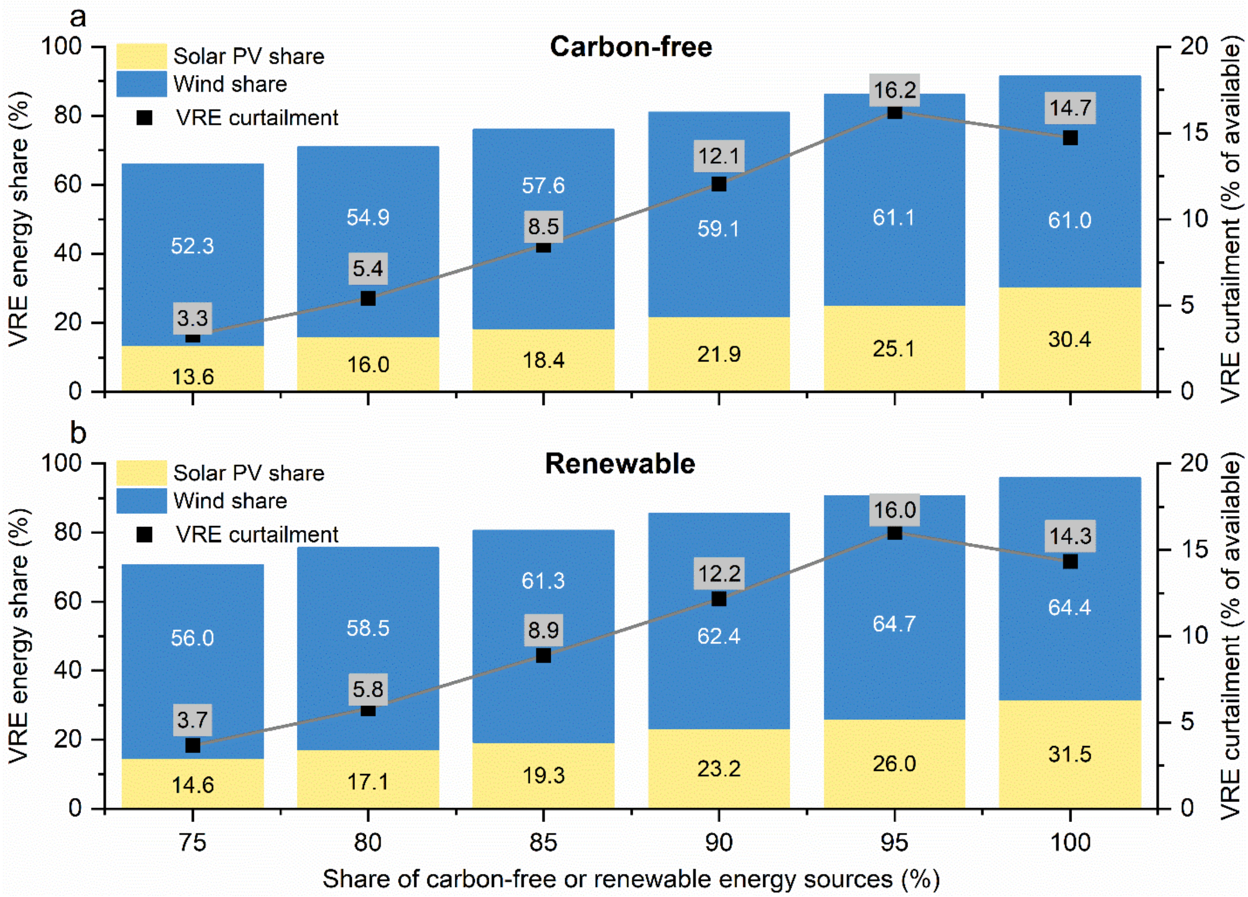

Figure 21. Optimal VRE energy mix and curtailment for SPP in 2050. **a,** carbon-free energy share targets. **b,** renewable energy share targets.

6. Optimal storage portfolio, charging/discharging power capacity ratios, normalized metrics for storage deployment, and energy and CO_2 emission costs

The optimal energy storage portfolio for each carbon-free or renewable energy mix target and for CAISO, ERCOT, ISONE, MISO, NYISO, PJM, and SPP are summarized in Figs. 22–27. The charging/discharging power capacity ratios for LD1 and seasonal storage are summarized in Fig. 28. The normalized metrics for storage deployment are presented in Fig. 29. Energy and CO_2 emission costs are summarized in Fig. 30.

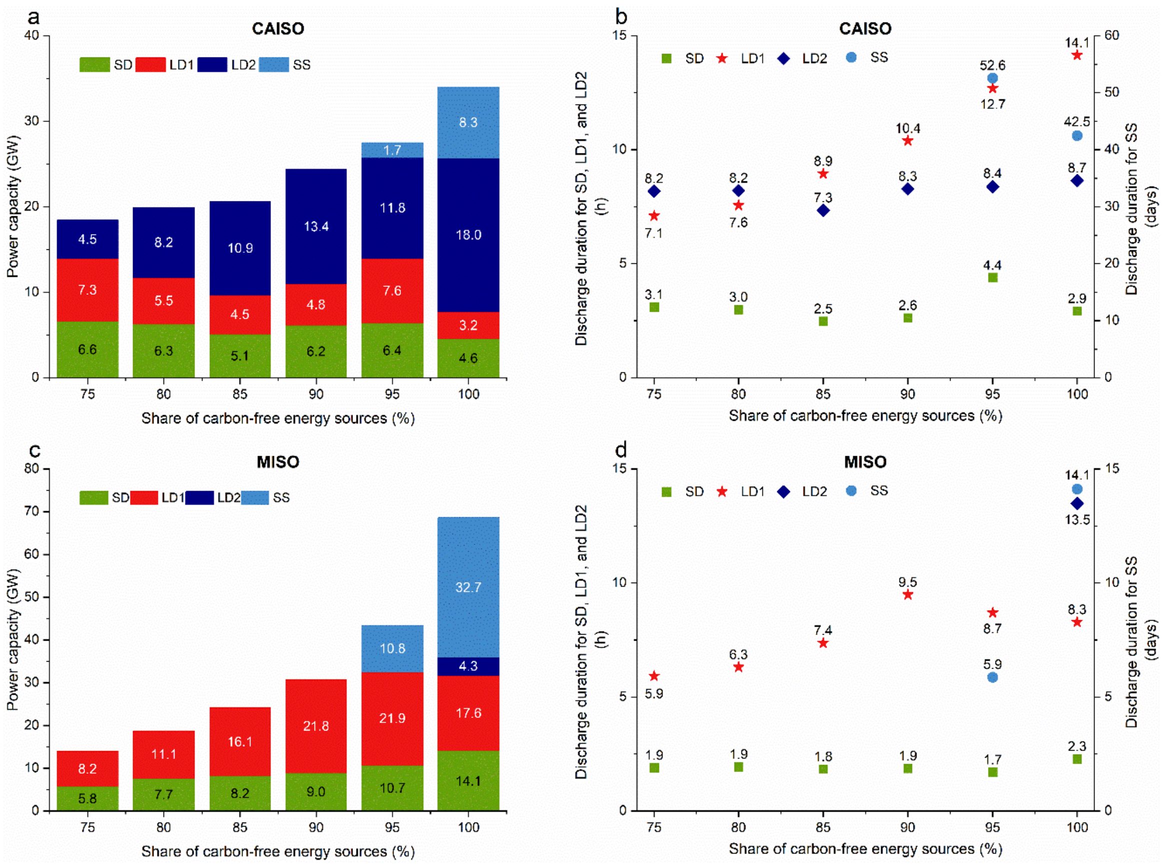

Figure 22. Optimal storage portfolio for carbon-free energy mix targets in CAISO (top) and MISO (bottom) in 2050. **a**, storage power capacity for CAISO carbon-free energy share targets. **b**, storage discharge duration for CAISO carbon-free energy share targets. **c**, storage power capacity for MISO carbon-free energy share targets. **d**, storage discharge duration for MISO carbon-free energy share targets. The average power capacity is reported for storage technologies that can decouple charge/discharge power capacity (LD1 and seasonal storage; see Methods). The definition of storage discharge duration is presented in Methods.

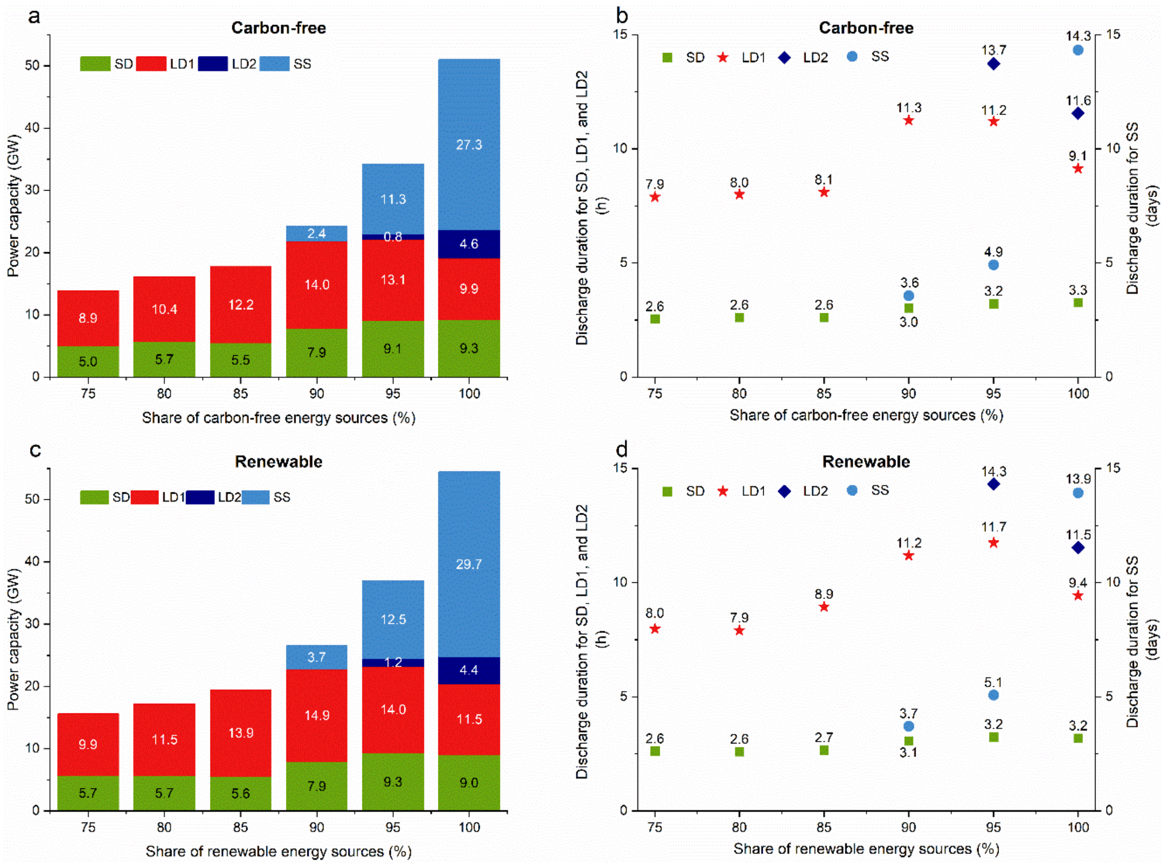

Figure 23. Optimal storage portfolio for ERCOT in 2050. **a,** storage power capacity for carbon-free energy share targets. **b,** storage discharge duration for carbon-free energy share targets. **c,** storage power capacity for renewable energy share targets. **d,** storage discharge duration for renewable energy share targets. The average power capacity is reported for storage technologies that can decouple charge/discharge power capacity, i.e., LD1 and seasonal storage.

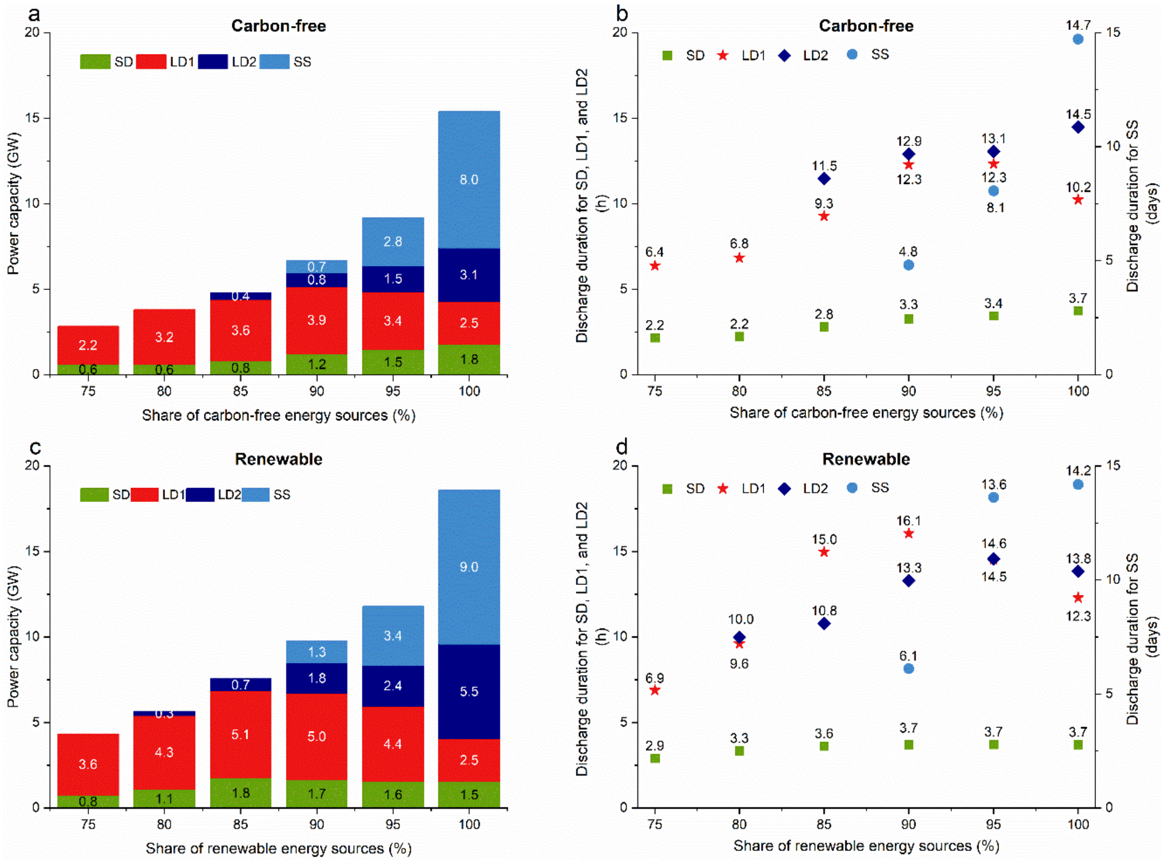

Figure 24. Optimal storage portfolio for ISONE in 2050. **a,** storage power capacity for carbon-free energy share targets. **b,** storage discharge duration for carbon-free energy share targets. **c,** storage power capacity for renewable energy share targets. **d**, storage discharge duration for renewable energy share targets. The average power capacity is reported for storage technologies that can decouple charge/discharge power capacity, i.e., LD1 and seasonal storage.

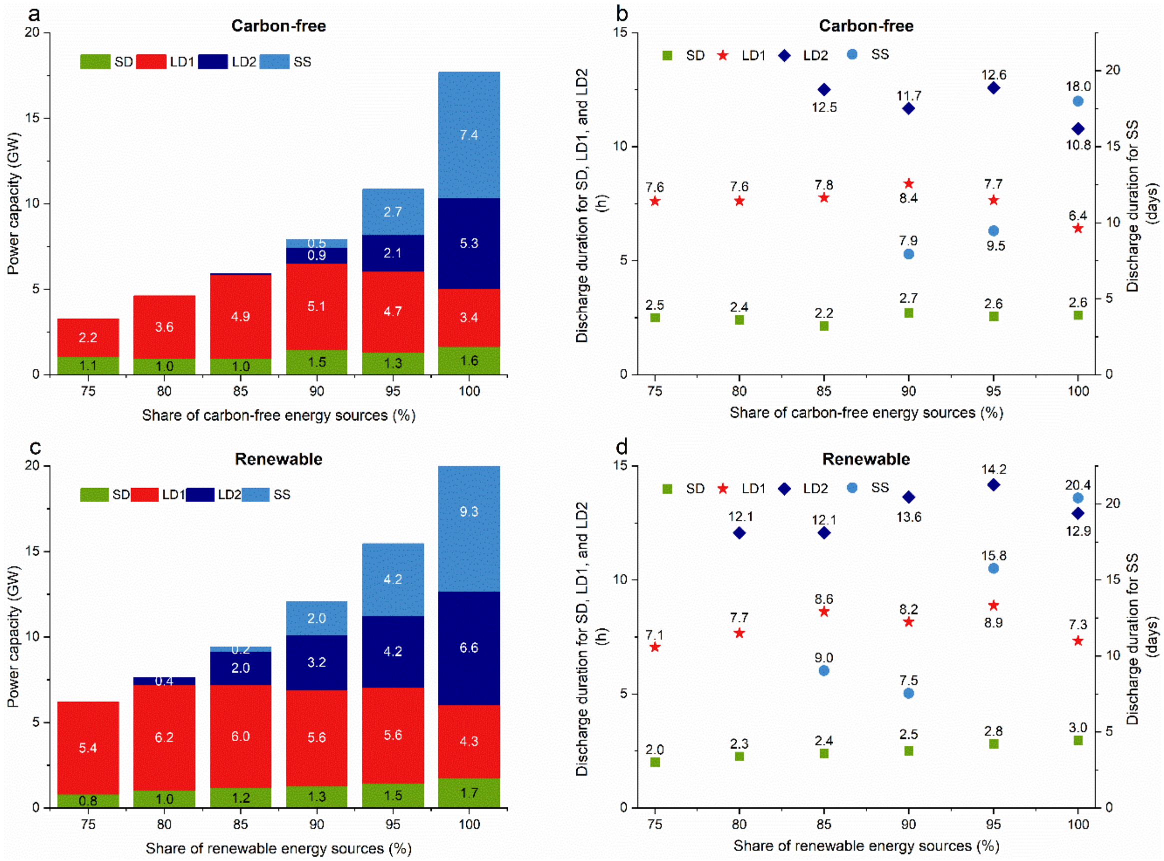

Figure 25. Optimal storage portfolio for NYISO in 2050. **a**, storage power capacity for carbon-free energy share targets. **b,** storage discharge duration for carbon-free energy share targets. **c,** storage power capacity for renewable energy share targets. **d,** storage discharge duration for renewable energy share targets. The average power capacity is reported for storage technologies that can decouple charge/discharge power capacity, i.e., LD1 and seasonal storage.

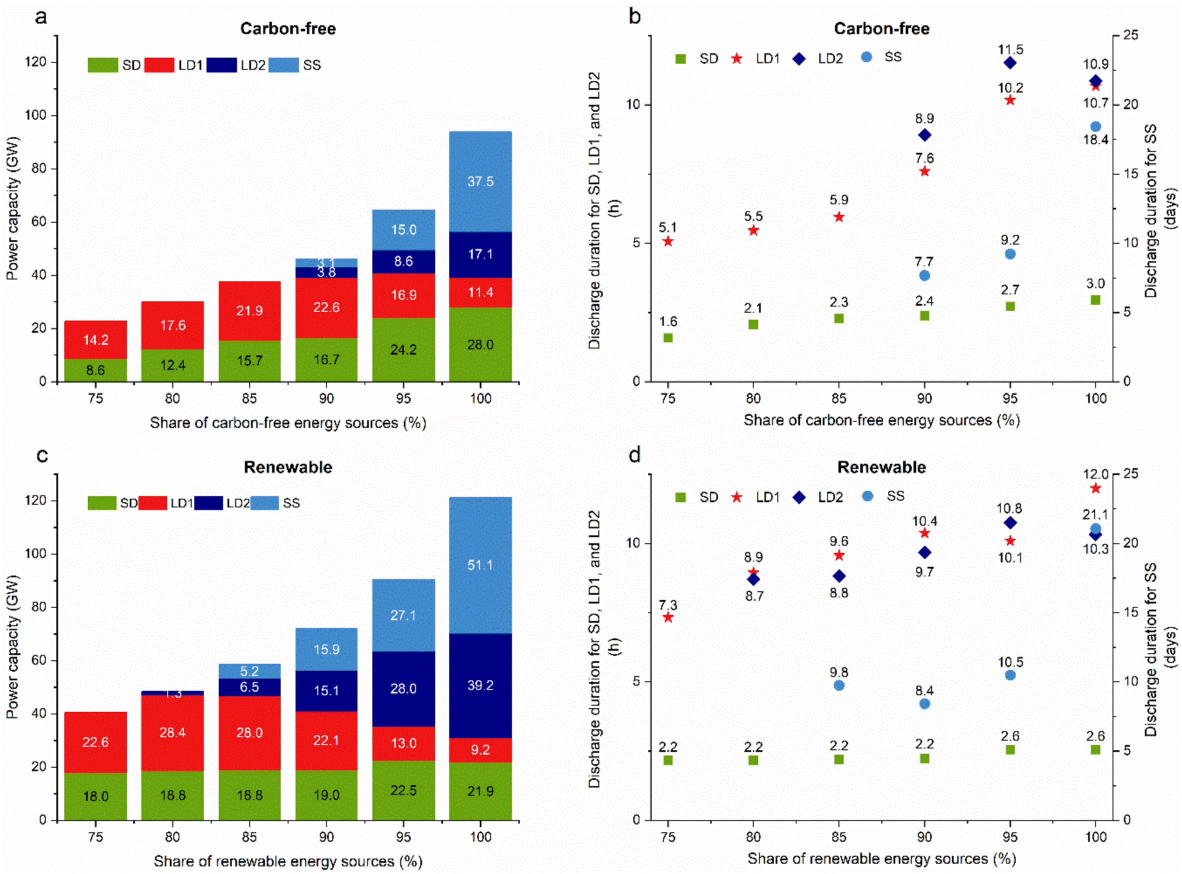

Figure 26. Optimal storage portfolio for PJM in 2050. **a,** storage power capacity for carbon-free energy share targets. **b,** storage discharge duration for carbon-free energy share targets. **c,** storage power capacity for renewable energy share targets. **d,** storage discharge duration for renewable energy share targets. The average power capacity is reported for storage technologies that can decouple charge/discharge power capacity, i.e., LD1 and seasonal storage.

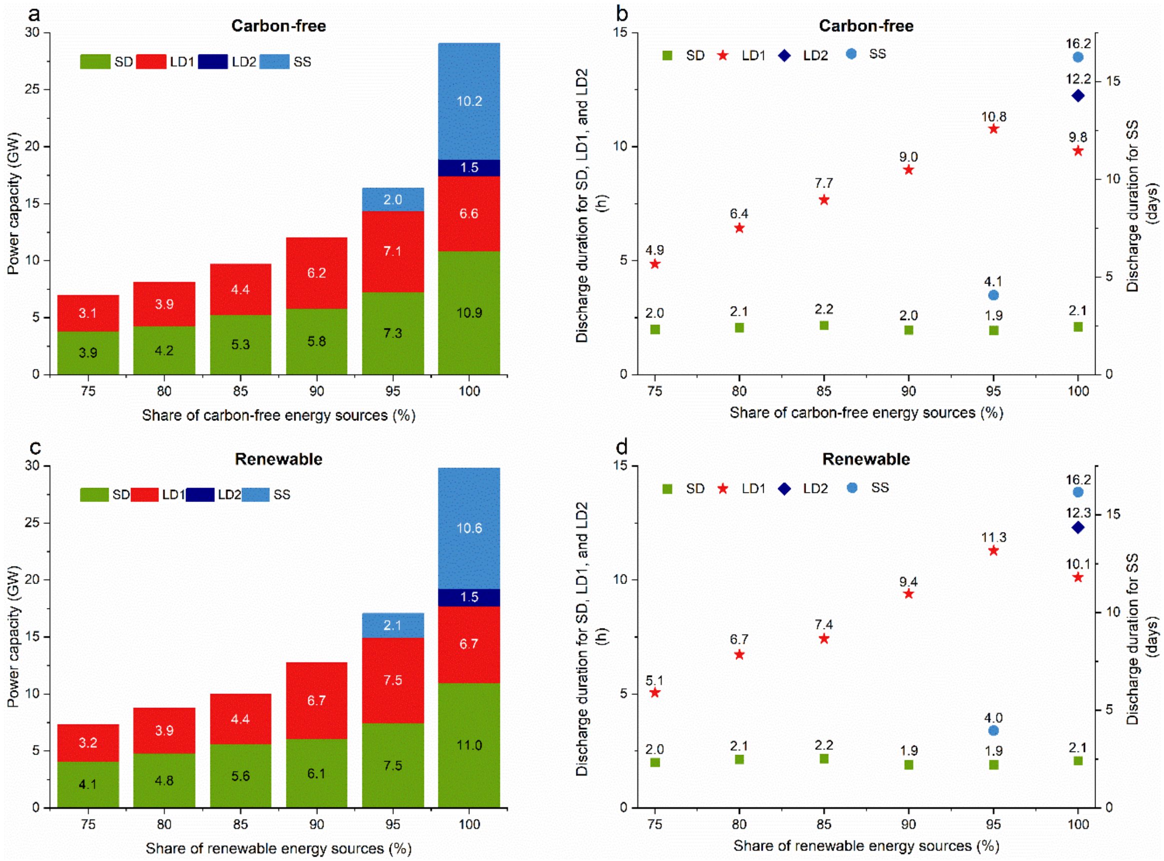

Figure 27. Optimal storage portfolio for SPP in 2050. **a,** storage power capacity for carbon-free energy share targets. **b,** storage discharge duration for carbon-free energy share targets. **c,** storage power capacity for renewable energy share targets. **d,** storage discharge duration for renewable energy share targets. The average power capacity is reported for storage technologies that can decouple charge/discharge power capacity, i.e., LD1 and seasonal storage.

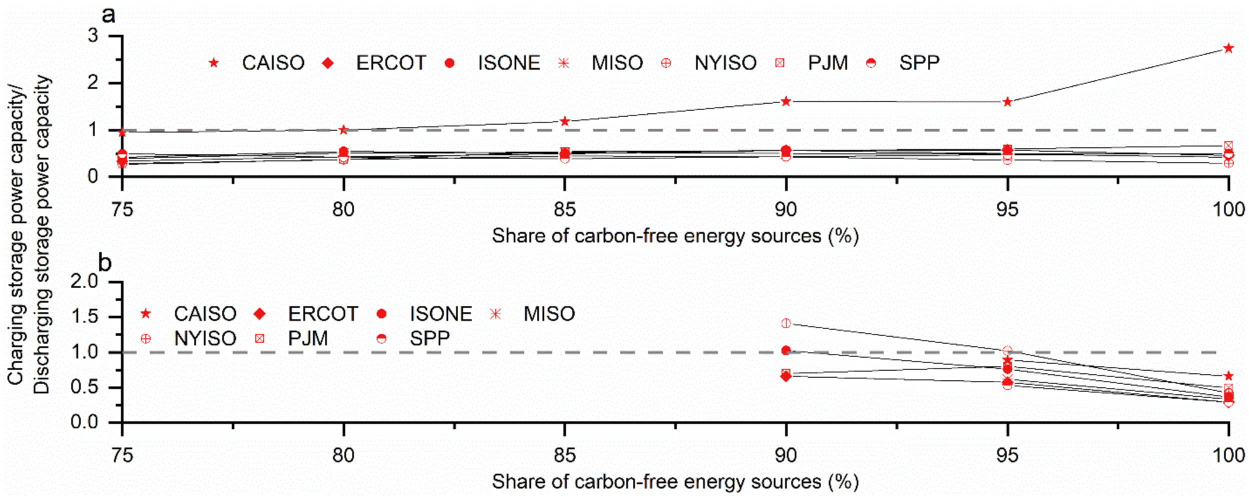

Figure 28. Optimal charging/discharging power capacity ratio for storage technology. **a**. optimal charging/discharging power capacity ratio for LD1 and carbon-free energy mix targets. **b**. optimal charging/discharging power capacity ratio for seasonal storage and carbon-free energy mix targets.

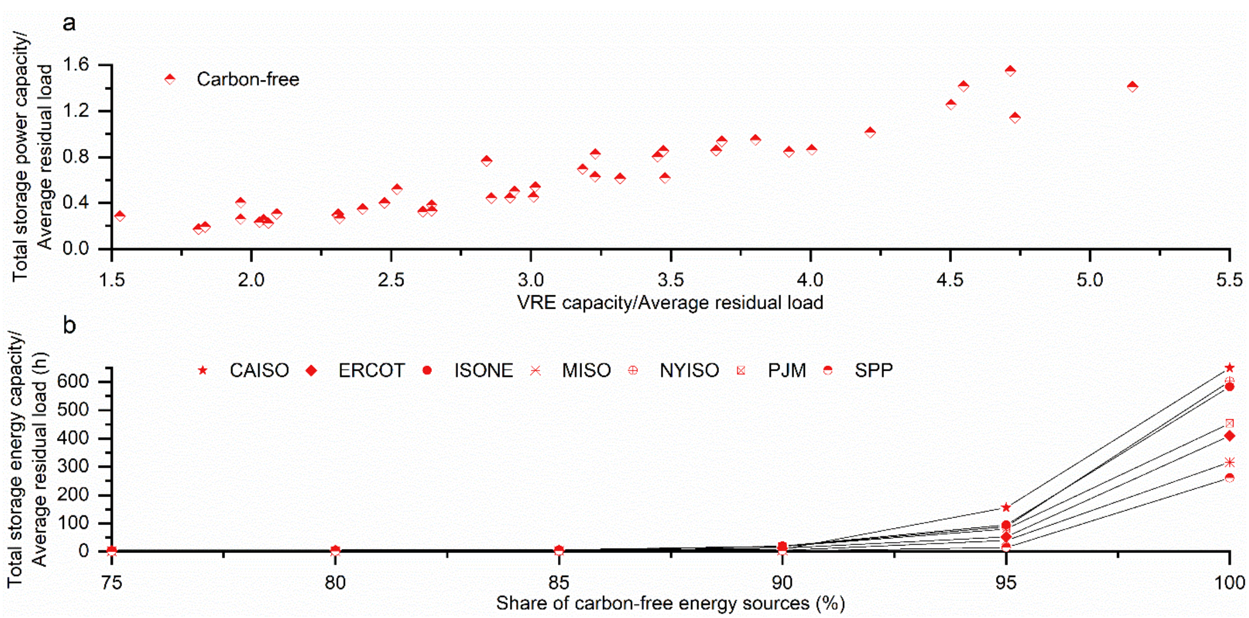

Figure 29. Total storage power and energy capacity for carbon-free scenarios as a function of VRE deployment in 2050. **a**, normalized total storage power capacity as a function of the normalized VRE capacity across all the ISOs. **b**, normalized total energy storage capacity as a function of the carbon-free energy share.

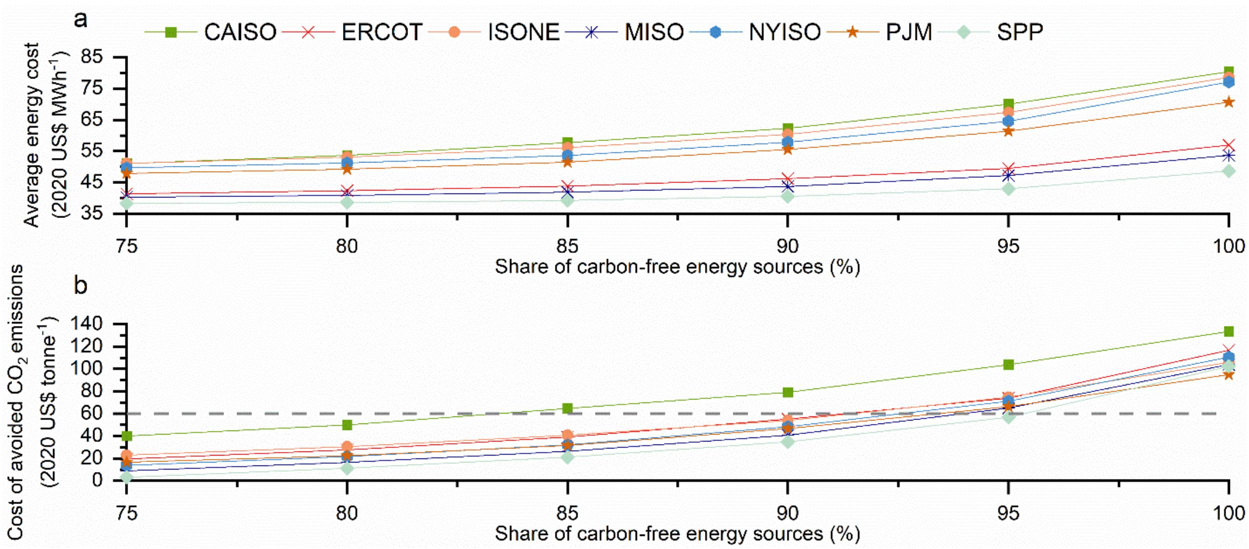

Figure 30. Energy cost and cost of avoided CO_2 emissions. **a**, energy cost for carbon-free energy mix targets. **b**, cost of avoided CO_2 emissions for carbon-free energy mix targets.

7. Storage operation

The normalized SOC for storage devices in CAISO and MISO 100% carbon-free power systems are summarized in Figure 31.

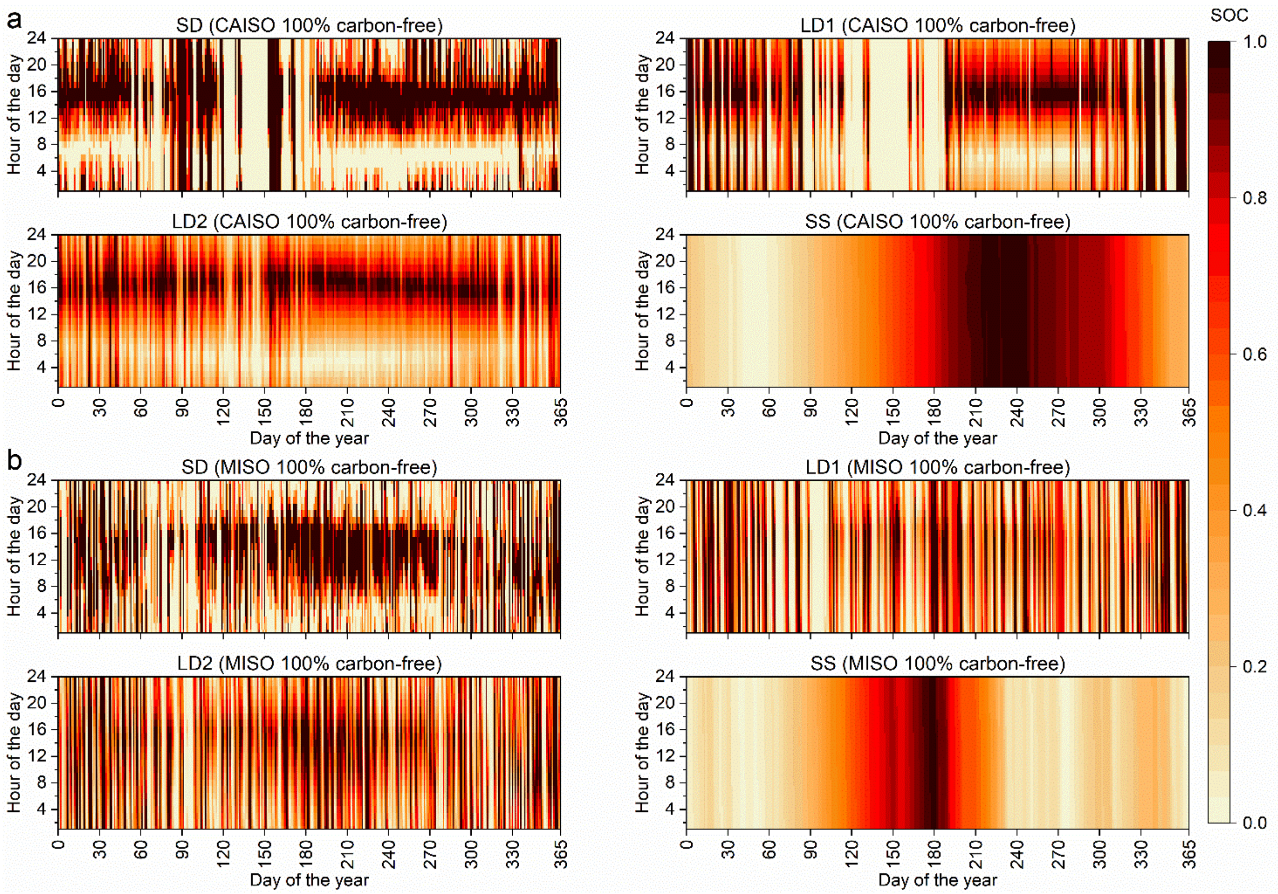

Figure 31. Normalized SOC for storage devices in CAISO and MISO. **a,** normalized SOC for storage devices for CAISO 100% carbon-free energy mix. **b,** normalized SOC for storage devices for MISO 100% carbon-free energy mix. The definition of normalized SOC is presented in Methods. SOC=1 (dark red) implies that the storage device is full. SOC=0 (Light red) implies that the storage device is empty.

8. Sensitivity for 100% carbon-free and 100% renewable energy mix targets in CAISO and MISO

To quantify the effects of the techno-economic assumptions on the optimal VRE energy mix and storage portfolio, we implemented a simple sensitivity analysis based on the projected costs for VRE and energy storage technologies. Additionally, we evaluated the effects of the decoupling charging and discharging power capacity for LD2 technology. We focused on the 100% carbon-free and 100% renewable energy mix targets in CAISO and MISO. The cost sensitivity includes capital expenditure, FO&M, and VO&M, whereas the sensitivity for LD2 was based on a cost ratio (ratio of the total power-related cost to the cost for charging power capacity) of 0.5. The following scenarios were considered: (i) low (minimum) costs for both VRE and energy storage technologies (scenario 2L), (ii) low costs for VRE and high (maximum) costs for energy storage technologies (scenario LH), (iii) high costs for VRE and low costs for storage technologies (scenario HL), (iv) high costs for both VRE and storage technologies (scenario 2H), and (v) decoupling charging and discharging power capacity for LD2 (scenario DecLD2). Projected minimum and maximum costs for VRE by 2050 are provided in Table 1. Additionally, we used +50% and -50% (from the reference values) for the maximum and minimum cost values of the storage technologies, respectively. As a reference, the projected 2050 standard deviation of power- and energy-related costs for Li-ion, CAES, PHS, and hydrogen ranges from 36%–70%, depending on the storage technology (https://www.sciencedirect.com/science/article/pii/S254243511830583X). Note that even though this is not a robust sensitivity analysis, the evaluation of these scenarios could provide valuable insights into how future technology costs and developments could impact the deployment of VRE and energy storage technologies. The results from the sensitivity analysis are summarized in Figs. 32–35. Note that although the VRE energy mix and the storage portfolio are sensitive to the cost assumptions and to decoupling the charging and discharging power capacity for LD2, achieving a 100% carbon-free or renewable energy mix always requires a combination of power curtailment, short-duration, long-duration, and seasonal storage.

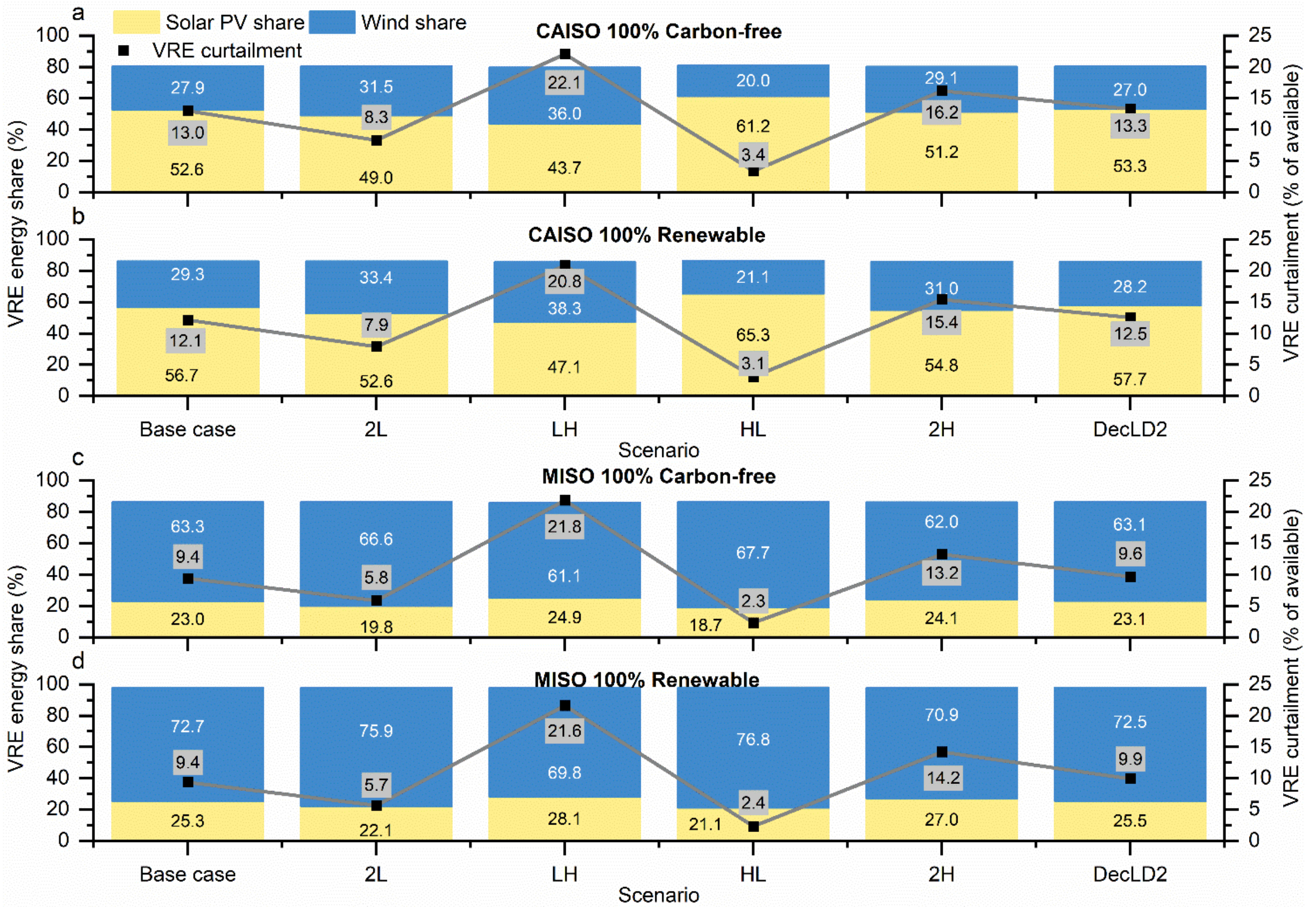

Figure 32. Optimal VRE energy mix and curtailment from the sensitivity scenarios for CAISO (top panel) and MISO (bottom panel) in 2050. **a**, optimal VRE energy mix and curtailment for CAISO 100% carbon-free energy mix target. **b**, optimal VRE energy mix and curtailment for CAISO 100% renewable energy mix target. **c**, optimal VRE energy mix and curtailment for MISO 100% carbon-free energy mix target. **d**, optimal VRE energy mix and curtailment for MISO 100% renewable energy mix target. 2L = low costs for both VRE and energy storage technologies. LH = low costs for VRE and high costs for energy storage technologies. HL = high costs for VRE and low costs for energy storage technologies. 2H = high costs for both VRE and energy storage technologies. DecLD2 = decoupling of charging and discharging power capacity for LD2.

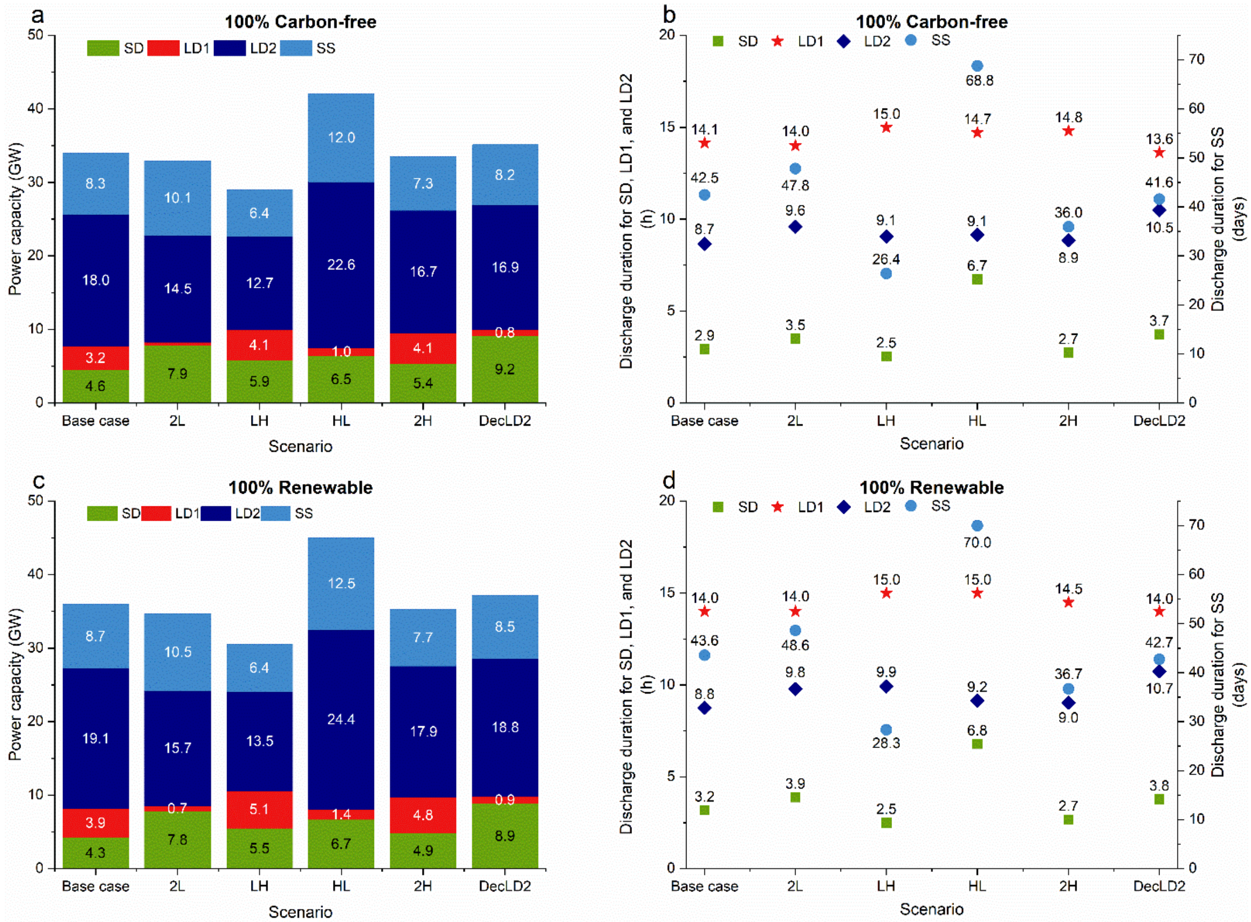

Figure 33. Optimal storage portfolio from the sensitivity analysis for CAISO in 2050. **a**, storage power capacity for 100% carbon-free energy share target. **b**, storage discharge duration for 100% carbon-free energy share target. **c**, storage power capacity for 100% renewable energy share target. **d**, storage discharge duration for 100% renewable energy share target. The average power capacity is reported for storage technologies that can decouple charge/discharge power capacity, i.e., LD1, seasonal storage, and LD2 for scenario DecLD2; see Methods. The definition of storage discharge duration is presented in Methods.

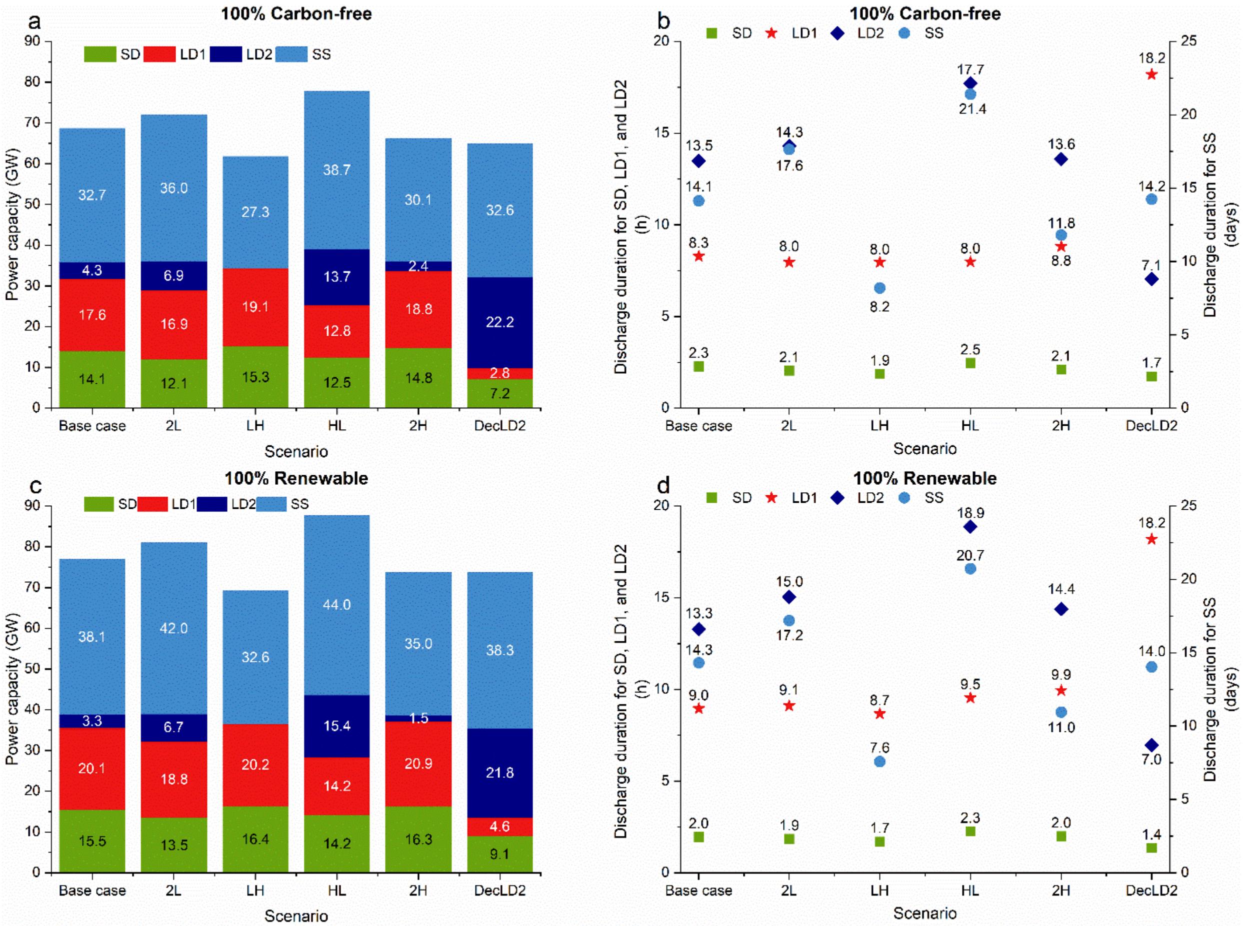

Figure 34. Optimal storage portfolio from the sensitivity analysis for MISO in 2050. **a**, storage power capacity for 100% carbon-free energy share target. **b**, storage discharge duration for 100% carbon-free energy share target. **c**, storage power capacity for 100% renewable energy share target. **d**, storage discharge duration for 100% renewable energy share target. The average power capacity is reported for storage technologies that can decouple charge/discharge power capacity, i.e., LD1, seasonal storage, and LD2 for scenario DecLD2; see Methods.

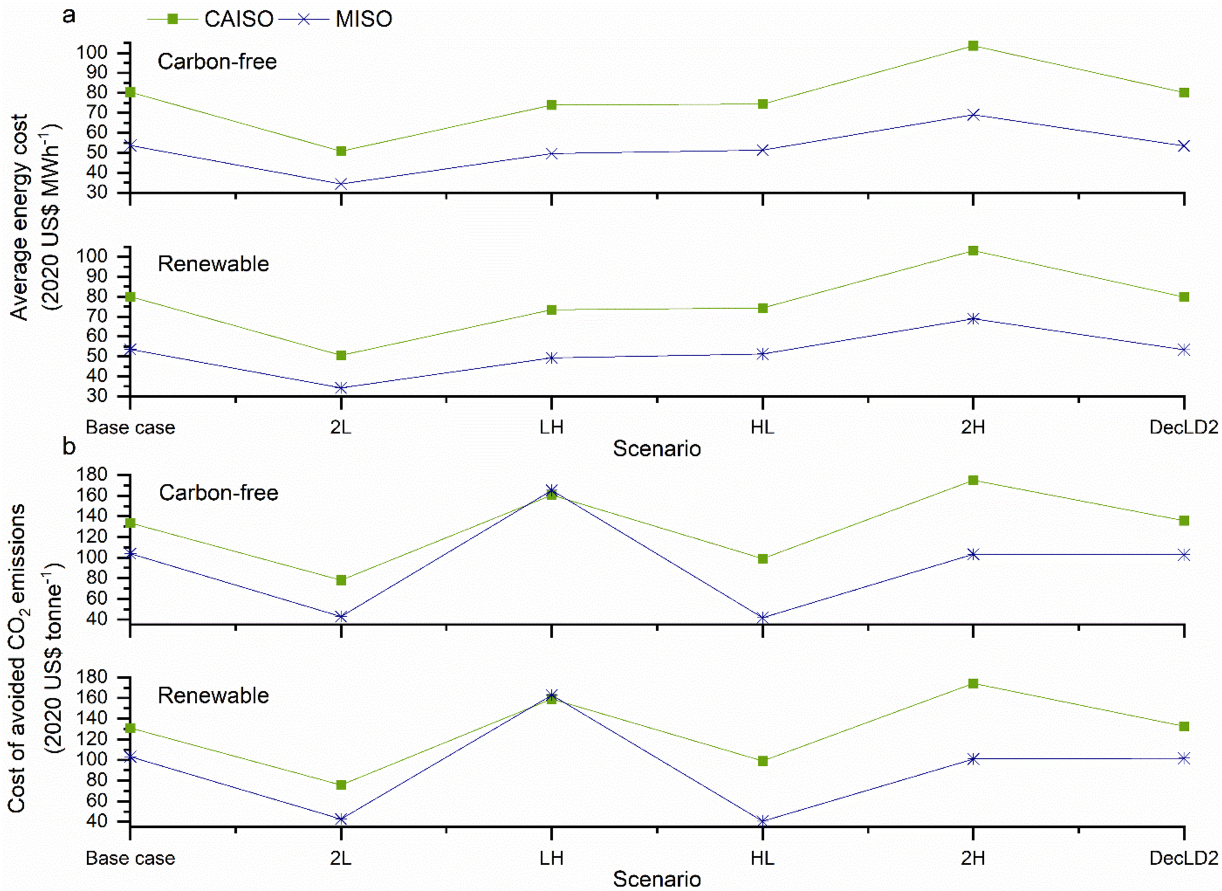

Figure 35. Energy cost and cost of avoided CO_2 emissions for the sensitivity scenarios for CAISO and MISO in 2050. **a**, average energy cost for 100% carbon-free and renewable energy share targets. **b**, cost of avoided CO_2 emissions for 100% carbon-free and renewable energy share targets.

9. Net load ramp duration curve

The net load ramp duration curves for 100% renewable energy target in CAISO and MISO are summarized in Figure 36.

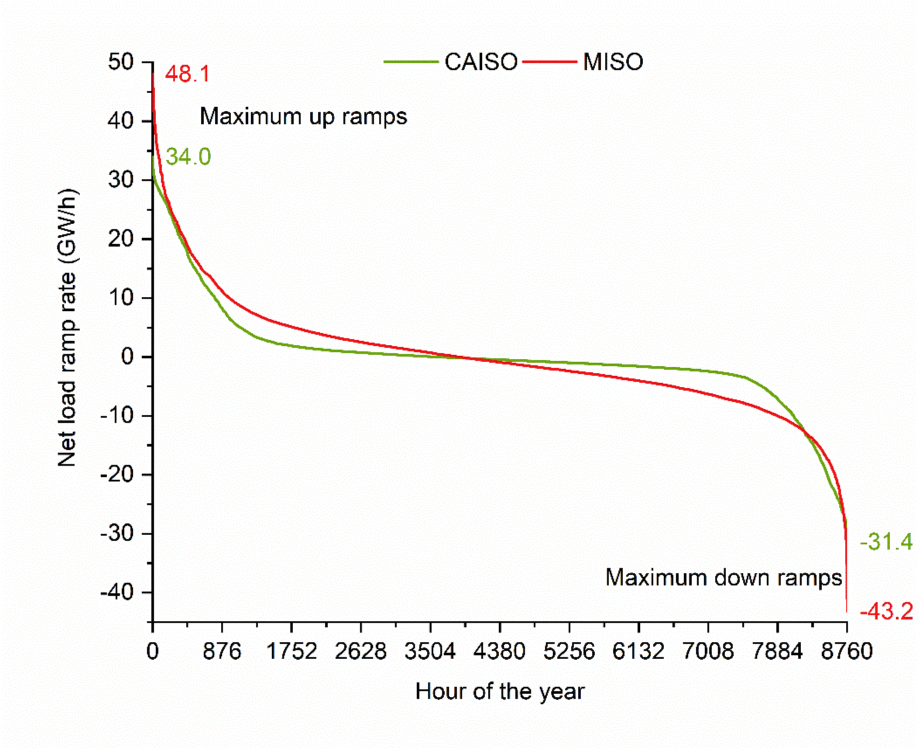

Figure 36. 1-hour net load ramp duration curves for 100% renewable energy share targets in CAISO and MISO.

10. References

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