DOCKETED	
Docket Number:	20-MISC-01
Project Title:	2020 Miscellaneous Proceedings.
TN #:	244122
Document Title:	Presentation - UC San Diego - Long Duration Energy Storage Public Workshop #3
Description:	UC San Diego's slides for the workshop titled "Proposed Final Scenarios to Assess the Role of Long Duration Storage"
Filer:	Jeffrey Sunquist
Organization:	UC San Diego
Submitter Role:	Public Agency
Submission Date:	7/19/2022 4:22:19 PM
Docketed Date:	7/19/2022

Long duration storage modeling in California and Western North America

Preliminary results

Prof. Patricia Hidalgo-Gonzalez
phidalgogonzalez@eng.ucsd.edu
http://ream.ucsd.edu

Friday, Feb 4th, 2022

UC San Diego
JACOBS SCHOOL OF ENGINEERING

Agenda

Methodology: SWITCH WECC model

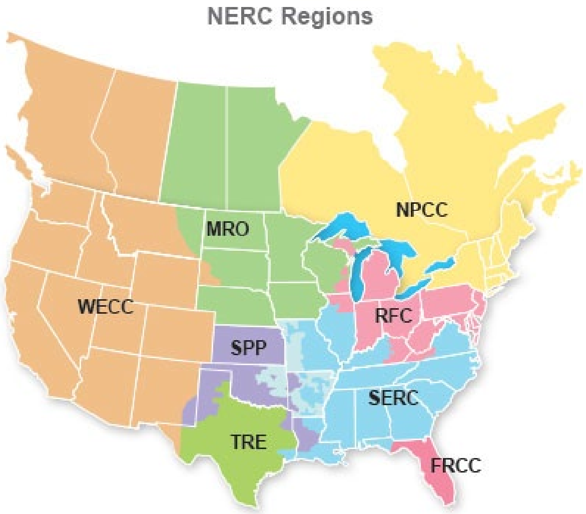
Preliminary results

- Sánchez-Pérez, P. et al., “Effect of modeled time horizon on long-duration storage”
- Staadecker, M. et al., “The value of long-duration energy storage”

Planned studies and research questions

Questions (10 min)

Methodology: SWITCH WECC model[1]



- Capacity expansion deterministic linear program
- Minimizes total cost of the power system:
  - Generation investment and operation
  - Transmission investment and operation
- Geographic:
  - Western Electricity Coordinating Council
  - 50 load areas
- Temporal:
  - Investment periods: 2026-2035 (“2030”); 2036-2045 (“2040”); 2046-2055 (“2050”);
  - Time resolution: sampling every 4 hours, for a subset of days or every day in a year
  - Dispatch simulated simultaneously with investment decisions

[1] https://github.com/REAM-lab/switch/

Architecture of the SWITCH WECC model[1]

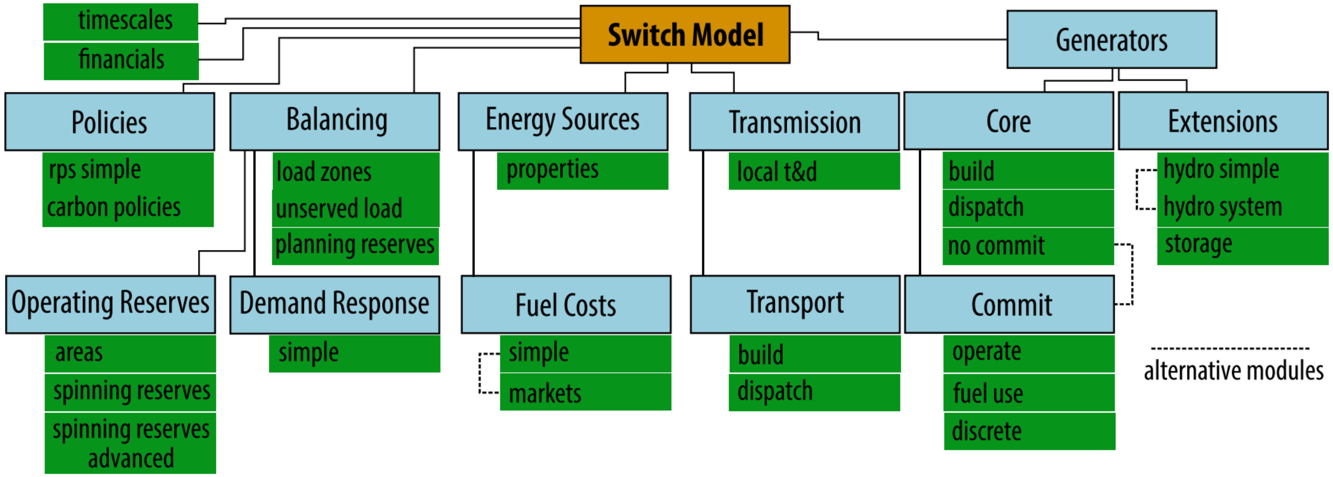


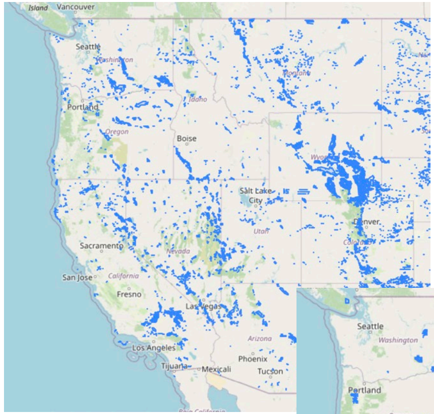
Image source: J. Johnson et al., Switch 2.0: A modern platform for planning high-renewable power systems, 2019

[1] https://github.com/REAM-lab/switch/

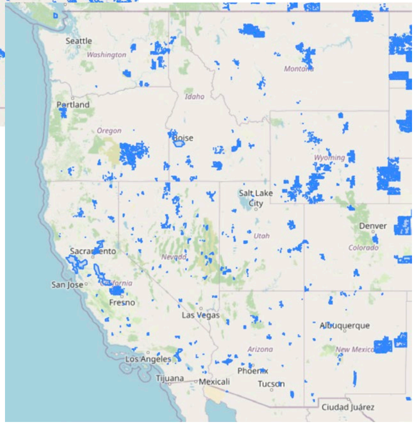
SWITCH WECC model input data and outputs

INPUTS

- Existing generators in the WECC (3,000+, 2020 EIA Form 860)
- 7,000+ potential new generators
- Aggregated existing transmission capacity
- Hourly loads by zone
- Hourly capacity factors for wind and solar supply
- Fuel and overnight yearly costs projections (NREL ATB 2020)



Wind candidates



Solar candidates

OUTPUTS

- Optimal investment of new generators by decade until 2050
- Optimal hourly dispatch for each generator
- Optimal transmission capacity expansion by decade until 2050
- Hourly CO_2 emissions by generator
- Investment and operational costs

Preliminary results

P. A. Sánchez-Pérez, M. Staadecker, J. Szinai, S. Kurtz, and P. Hidalgo-Gonzalez, "Effect of modeled time horizon on quantifying the need for long-duration storage"

Motivation

- The U.S. future requirement of energy in storage or its duration for a growing electrical demand with high levels of reliability for a zero emissions grid is still unclear[1,2]
- Some recent works[3-6] found that long-duration energy storage (LDES) can fulfill a variety of grid services to balance the grid with durations ranging from 10 - 650 hours.
- Due to computational complexity, studies simplify the temporal resolution by modeling representative days or season of the year of interest.

[1]J. D. Hunt, E. Byers, Y. Wada, S. Parkinson, D. E. H. J. Gernaat,S. Langan, D. P. van Vuuren and K. Riahi, "Global Resource Potential of Seasonal Pumped Hydropower Storage for Energy and Water Storage" Nature Communications, 2020,11, 947.

[2]O. J. Guerra, J. Zhang, J. Eichman, P. Denholm, J. Kurtzand B.-M. Hodge, "The Value of Seasonal Energy Storage Technologies for the Integration of Wind and Solar Power" Energy & Environmental Science, 2020,13,1909–1922.

[3]O. J. Guerra, "Beyond Short-Duration Energy Storage" Nature Energy, 2021,6, 460–461.

[4]P. Albertus, J. S. Manser and S. Litzelman, "Long-Duration Electricity Storage Applications" Joule, 2020,4,21–32

[5]J. A. Dowling, K. Z. Rinaldi, T. H. Ruggles, S. J. Davis,M. Yuan, F. Tong, N. S. Lewis and K. Caldeira, "Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems" Joule, 2020.

[6]N. A. Sepulveda, J. D. Jenkins, A. Edington, D. S. Mallapragada and R. K. Lester, The Design Space for Long-Duration Energy Storage in Decarbonized Power Systems"" Nature Energy, 2021,6, 506–516.

Sánchez-Pérez, P. et al. "Effect of modeled time horizon on quantifying the need for long-duration storage"

Research gap

- Most U.S. capacity expansion models use a subset of days during a year to optimize.
- This does not allow the energy community to understand the value of long-duration storage technologies to the grid.

Problem formulation

- 6 hours sampled/day x 365 days/year in 2050
- We model a range of consecutive days for the storage balancing horizon (SBH):

  - 7 days up to 365 days
- Three LDES cost scenarios for 2050: $113/kW with $130/kWh (baseline), $13/kWh, and 1.3/kWh.
- Zero emissions WECC-wide in 2050

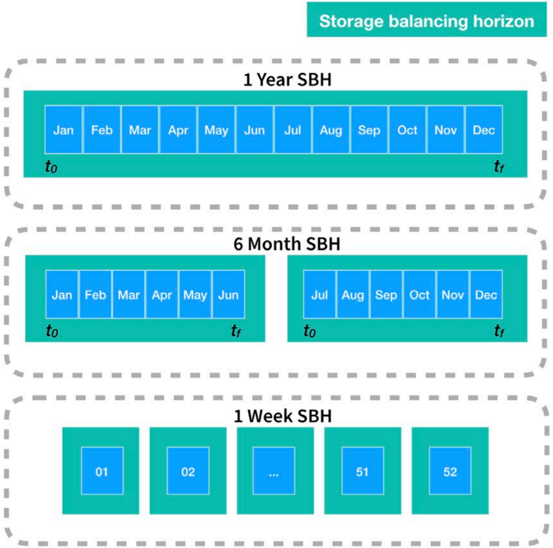
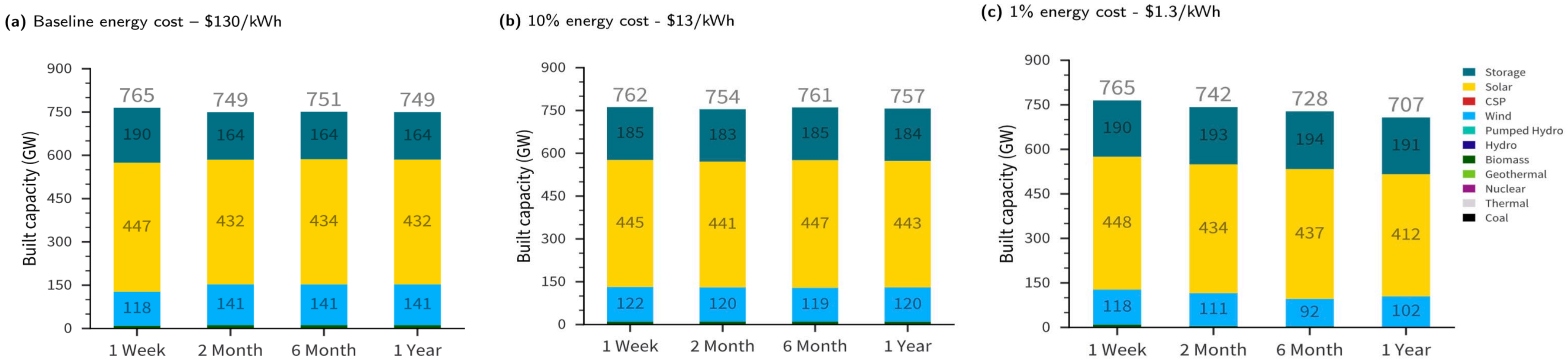


Fig. 1 Diagram showing the storage balancing horizon (SBH) concept for three different lengths: 1 Year, 6 Month and 1 Week.

Results: installed capacity



- Total installed capacity slightly decreases as the balancing horizon increases (most noticeable in c)
- The solar to wind deployment ratio stays constant at ~3

Results: duration

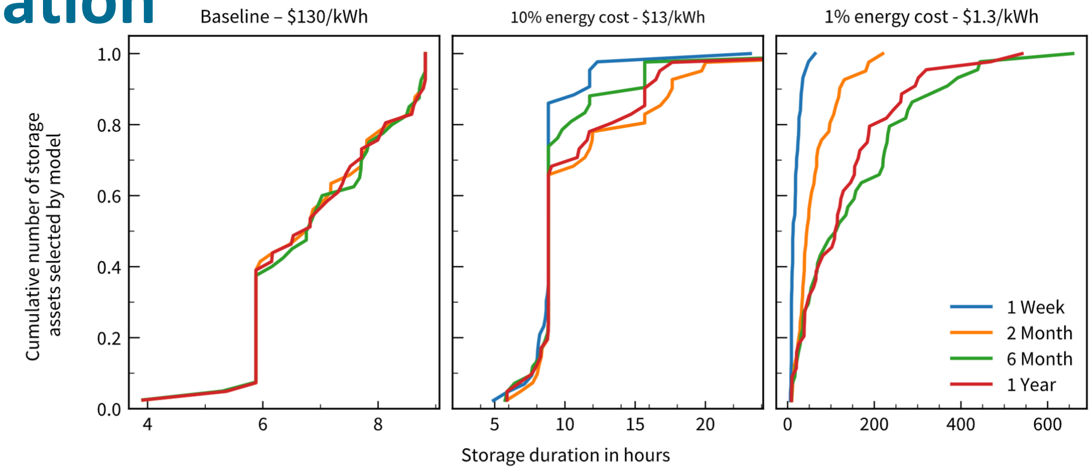


Fig. 4 Cumulative number of storage assets selected by model for the optimal energy storage duration (energy to power ratio) of the candidate storage for the 50 load zones in the SWITCH-WECC model. Each line color represents a different storage balancing horizon (SBH) where the blue line represents the 1-week, orange 2-month, green 6-month and red 1-year.

- Baseline: 50% of the storage assets have 7 or less hours of duration and balancing horizon does not change duration
- 10% cost scenario: 50th percentile at least 8+h, up to 24 hours
- 1% cost scenario: Up to 600 hours of duration

Results: state of charge and curtailment

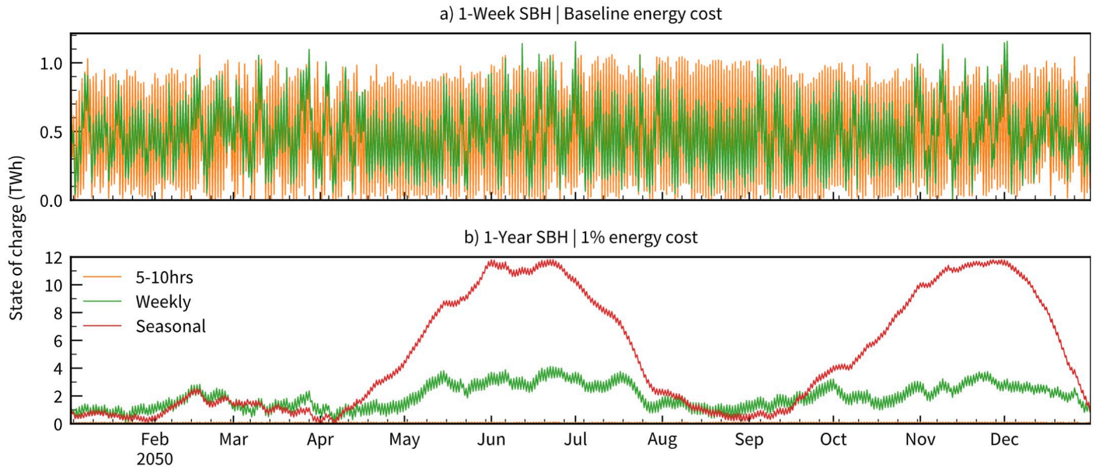


Fig. 6 Aggregated state of charge for all energy storage technologies installed throughout the WECC region. a) For the 1-week SBH using \$130/kWh and b) for the 1-year SBH with \$1.3/kWh. Duration of energy storage is classified according to its optimal range of duration. For weekly the range is between 10-100 hours and seasonal 100+ hours (energy to power ratio).

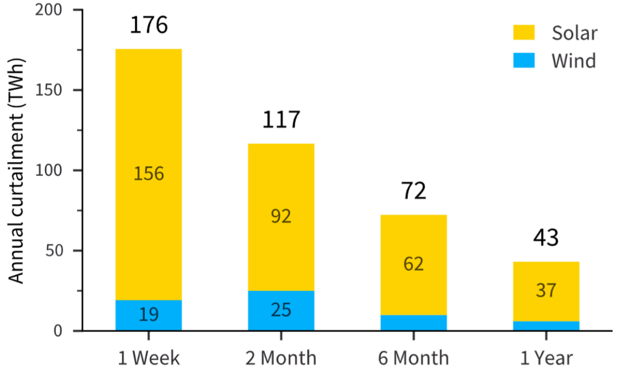


Fig. 5 Total solar and wind curtailment for each of the storage balancing horizon scenarios. Curtailment is defined as the difference of the available dispatch capacity at each time point and dispatch decision.

- From 1 TWh (baseline, 1 week) to 12 TWh of energy stored (1% of the cost, 1 year)
- Curtailment goes from 176 TWh to 43 TWh for \$1.3/kWh cost scenarios

Conclusions

- Accurately modeling consecutive 365 days for storage arbitrage affects the deployment and operation of LDES

- **For 365 days of balancing, storage energy capacity ranges from:**

  1.5 TWh to 12 TWh

Durations deployed by cost scenario:

up to 8 hours (baseline cost scenario \$130/kWh in 2050)

up to 24 hours (\$13/kWh cost scenario in 2050)

up to 620 hours (\$1.3/kWh cost scenario in 2050)

- **\$1.3/kWh cost scenario in 2050 :**

  1 week for storage balancing: up to 10 hours of duration

  2 months for storage balancing: up to ~200 hours of duration

  1 year for storage balancing: up to 620 hours of duration

Preliminary results

M. Staadecker, P. A. Sánchez-Pérez , J. Szinai, S. Kurtz, and P. Hidalgo-Gonzalez, "The value of long-duration energy storage and its interaction with a zero-emissions western North-America electricity grid" (submitted)

Motivation

- The U.S. future requirement of energy in storage or its duration for a growing demand in a reliable zero emissions grid is still unclear[1,2]
- Some report 100% renewable energy grids with[3] and without storage[4],
- others rely on "clean firm power"[5] or even biomass to achieve negative emissions[6],
- others consider intraday storage[7], and in some cases seasonal[8].

[1] J. D. Hunt, E. Byers, Y. Wada, S. Parkinson, D. E. H. J. Gernaat,S. Langan, D. P. van Vuuren and K. Riahi, "Global Resource Potential of Seasonal Pumped Hydropower Storage for Energy and Water Storage" Nature Communications, 2020,11, 947.

[2] O. J. Guerra, J. Zhang, J. Eichman, P. Denholm, J. Kurtzand B.-M. Hodge, "The Value of Seasonal Energy Storage Technologies for the Integration of Wind and Solar Power" Energy & Environmental Science, 2020,13,1909–1922.

[3] C. Clack et al., "Evaluation of 100% wind, water, and solar power" Proceedings of the National Academy of Sciences Jun 2017, 114 (26) 6722-6727; DOI: 10.1073/pnas.1610381114

[4] Mark Z. Jacobson, Mark A. Delucchi, Mary A. Cameron, Bethany A. Frew "Stabilizing grid with 100% renewables 2050" Proceedings of the National Academy of Sciences Dec 2015, 112 (49) 15060 15065; DOI: 10.1073/pnas.1510028112

[5] Nestor A. Sepulveda, Jesse D. Jenkins, Fernando J. de Sisternes, Richard K. Lester, "The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation" Joule, Volume 2, Issue 11, 2018, Pages 2403-2420, ISSN 2542-4351

[6] Sanchez, D., Nelson, J., Johnston, J. *et al.* Biomass enables the transition to a carbon-negative power system across western North America. *Nature Clim Change* **5,** 230–234 (2015).

[7] Fernando J. de Sisternes, Jesse D. Jenkins, Audun Botterud, The value of energy storage in decarbonizing the electricity sector, Applied Energy, Volume 175, 2016, Pages 368-379, ISSN 0306-2619

[8] O. J. Guerra, J. Zhang, J. Eichman, P. Denholm, J. Kurtz, B. Hodge, "The value of seasonal energy storage technologies for the integration of wind and solar power" Energy & Environmental Science, 2020, Pages 1909-1922

Staadecker, M. et al. “The Value of Long-Duration Energy Storage and Its Interaction with the Western North America Electricity Grid” (submitted)

Research gap

- Some studies[9,10] explore the role of LDES but they have not modeled physical constraints of the grid, nor their results stem from a least cost perspective
- The conditions that would affect the need for long-duration storage have not been studied
- To the best of our knowledge, there are no studies that analyze the benefits in electricity pricing of federal or state mandates for LDES deployment.

Contributions

- Quantification of the benefits in electricity pricing of federal/state mandates for LDES deployment.
- How does the deployment of LDES change depending on:
    1. the ratio of solar/wind deployed
    2. if transmission expansion is restricted?
    3. The costs of long-duration storage (NREL ATB 2020, DOE storage shot, and ultra low)
    4. Hydropower availability

[9] J. A. Dowling, K. Z. Rinaldi, T. H. Ruggles, S. J. Davis,M. Yuan, F. Tong, N. S. Lewis and K. Caldeira, “Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems” Joule, 2020.

[10] N. A. Sepulveda, J. D. Jenkins, A. Edington, D. S. Mallapragada and R. K. Lester, “The Design Space for Long-Duration Energy Storage in Decarbonized Power Systems” Nature Energy, 2021,6, 506–516.

Staadecker, M. et al. “The Value of Long-Duration Energy Storage and Its Interaction with the Western North America Electricity Grid” (submitted)

Contributions

- Quantification of the benefits in electricity pricing of federal/state mandates for LDES deployment.
- How does the deployment of LDES change depending on:
  1. the ratio of solar/wind deployed
  2. if transmission expansion is restricted?
  3. The costs of long-duration storage (NREL ATB 2020, DOE storage shot, and ultra low)
  4. Hydropower availability

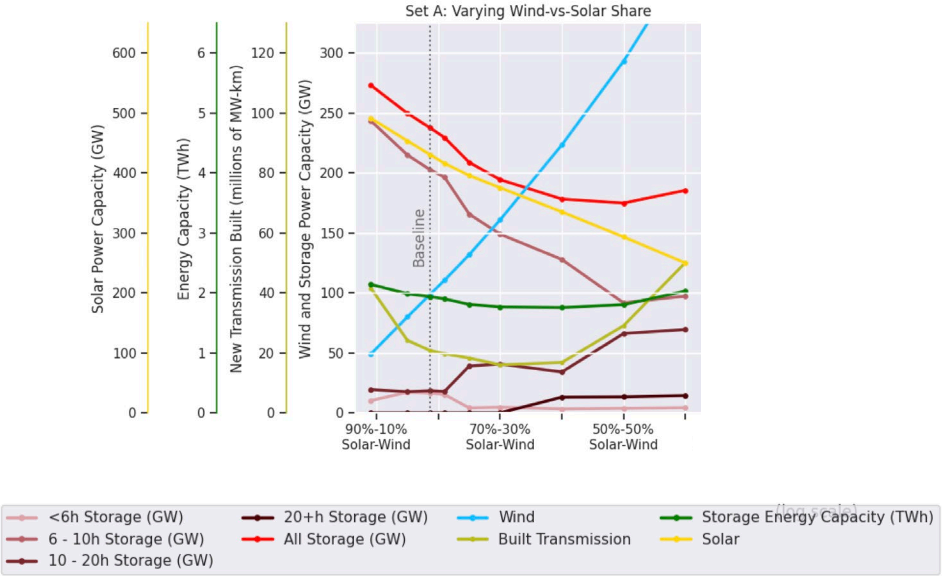
Problem formulation

- 6 hours sampled/day x 365 days/year in 2050
- Zero emissions WECC-wide in 2050

Results: Wind or solar dominant grids

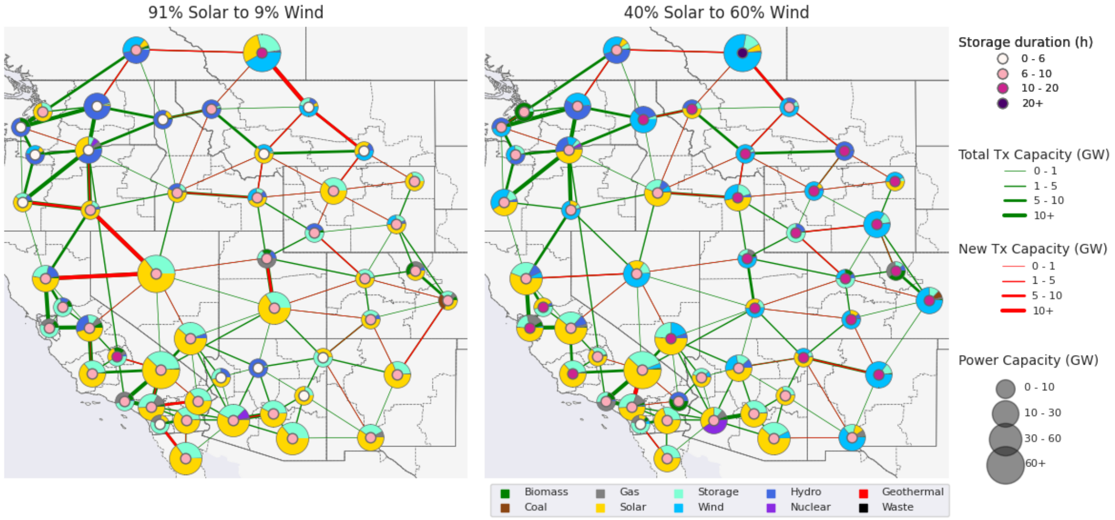
- **6-to-10-hour** storage (pink) proportional to the **solar** capacity (diurnal cycles)

- **10-to-20-hour** storage (dark pink) is most useful in supporting **wind** dominant grids



Results: Wind or solar dominant grids

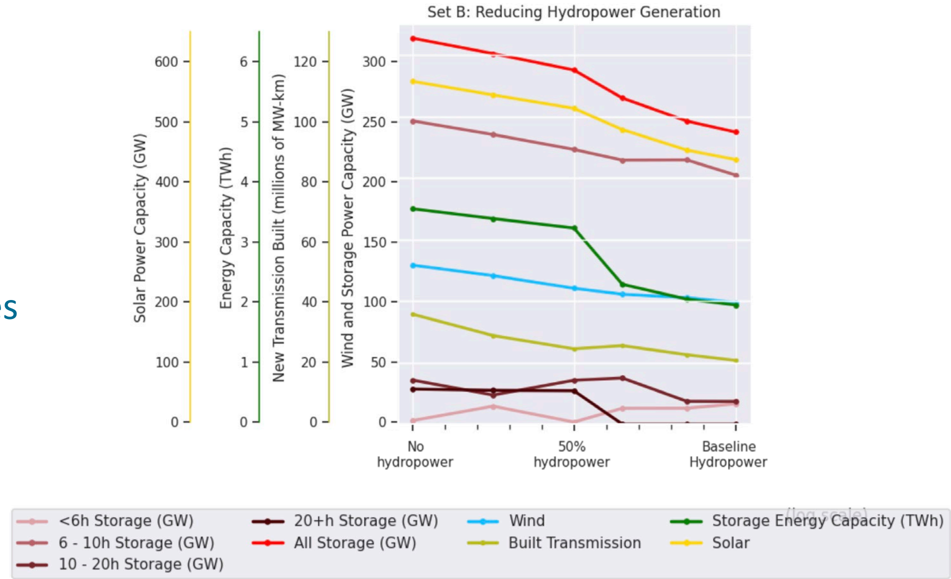
- Nearly all **solar-dominant** load zones have a light pink dot representing **6-to-10-hour storage**
- Nearly all **wind-dominant** load zones have a dark pink dot representing **10-to-20-hour**



Results: Hydropower availability

- Less than 15% of the WECC's yearly energy generation comes from hydropower

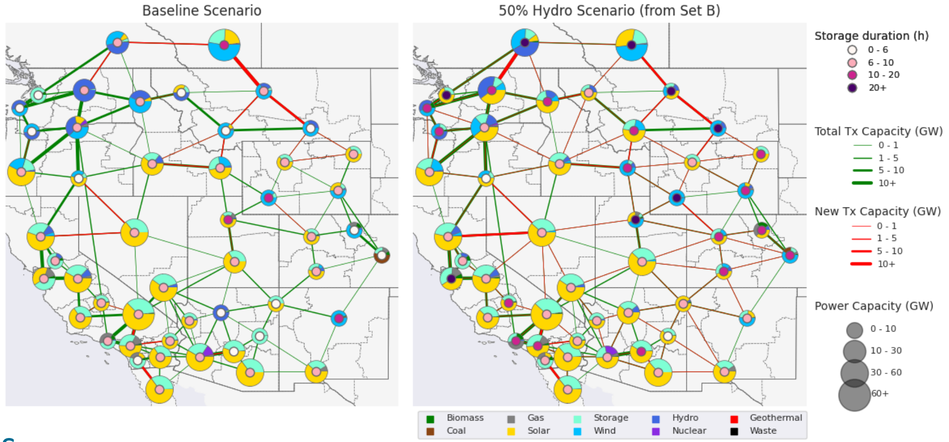
- 50% reduction in hydropower:
  - 65% increase in energy storage capacity (green)
  - 21% increase in storage power capacity (red)
  - shift in average storage duration from 6.3 to 23 hours in the six load zones where hydropower dominates



Results: Hydropower availability

- Less than 15% of the WECC's yearly energy generation comes from hydropower

- 50% reduction in hydropower:
  - 65% increase in energy storage capacity
  - 21% increase in storage power capacity
  - shift in average storage duration from 6.3 to 23 hours in the six load zones where hydropower dominates



Results: Transmission

- Baseline: 1.9 TWh of energy capacity

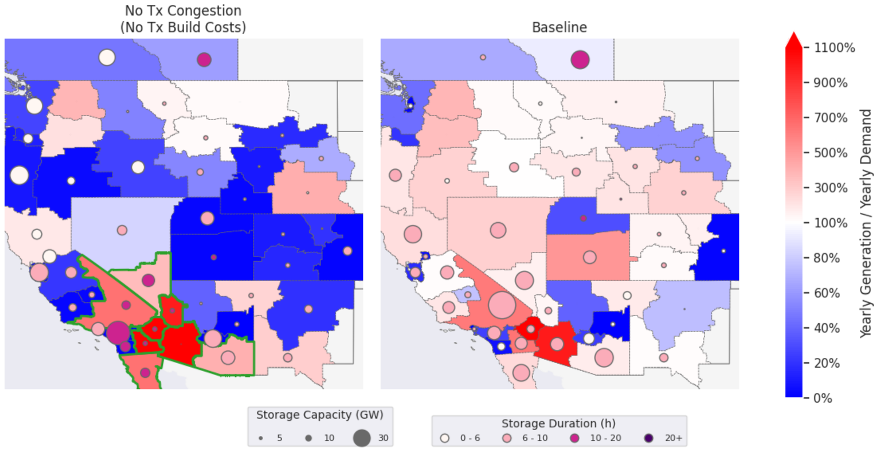
versus

- No transmission deployment: 2.5 TWh (+32%)

versus

- No transmission congestion: 1.8 TWh

Results: Transmission



- Baseline: 1.9 TWh of energy capacity

versus

- No transmission deployment: 2.5 TWh (+32%)

versus

- No transmission congestion: 1.8 TWh

- **No transmission congestion:**
  - Generation shifts from the wind-dominant regions towards the solar-dominated southwest
  - 28/50 load zones generate locally less than half their yearly demand

Results: Varying LDES energy capacity costs by 2050

- Energy capacity ranges from 1.5 TWh to 36 TWh
- Largest duration ranges from 9h to 825h
- Transmission deployment decreases by 75% for the cheapest LDES case

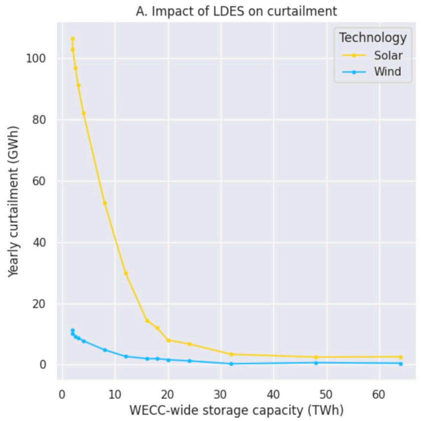
Table 2: Storage, wind, and transmission characteristics under varying energy storage costs

Energy Storage Cost	WECC-wide energy storage capacity (TWh)	WECC mean storage duration (h)	Largest storage duration (h)	Wind Capacity (GW)	New Transmission Capacity (million MW-km)
102 $/kWh	1.5 (-22%)	7.0	8.9	113 (+14%)	27 (+31%)
22 $/kWh (Baseline)	1.9	8.2	18	99	21
10 $/kWh	2.4 (+21%)	9.9	29	98 (-1%)	17 (-18%)
5 $/kWh	6.6 (+239%)	28	378 (16 days)	94 (-5%)	13 (-40%)
1 $/kWh	22 (+1042%)	96 (4 days)	620 (26 days)	82 (-17%)	4.9 (-76%)
0.5 $/kWh	36 (+1747%)	151 (6.3 days)	825 (34 days)	69 (-30%)	5.3 (-75%)

Percentages in parentheses represent the change compared to the baseline.

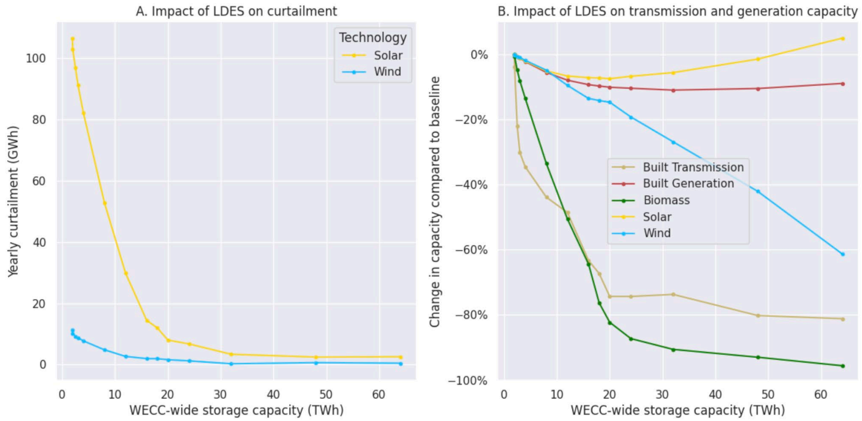
Results: LDES energy capacity mandates

- Energy storage is increased from 2 to 64 TWh
- A: Solar and wind curtailment drop
- A: Sharp curtailment drop from 118 GWh to 9.6 GWh (- 92%) as 20 TWh of storage are added



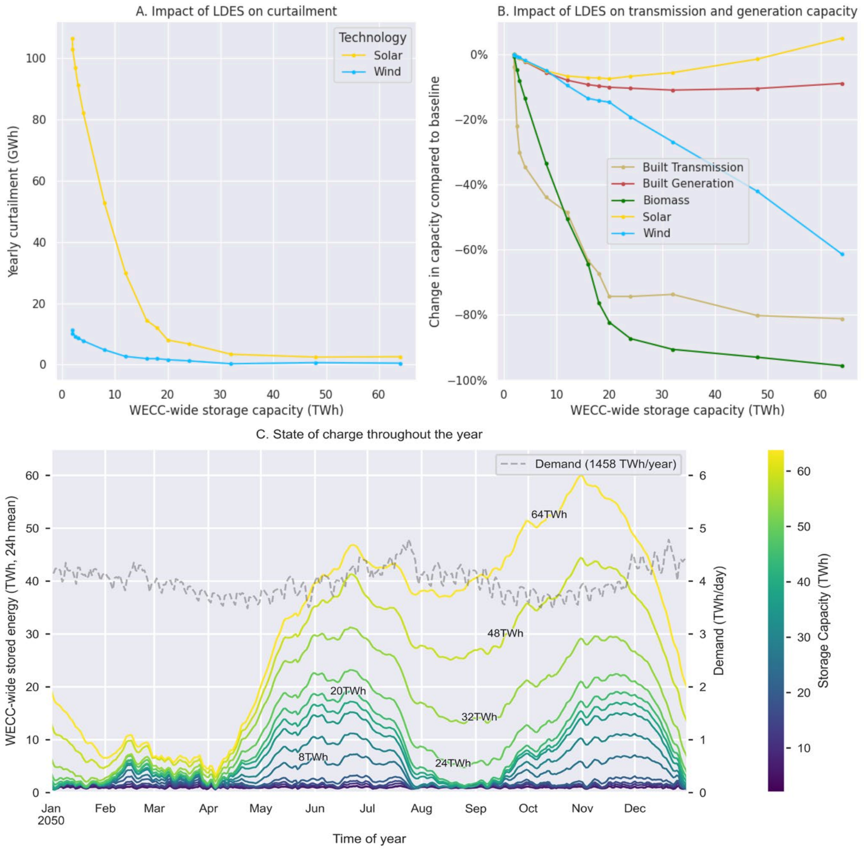
Results: LDES energy capacity mandates

- Energy storage is increased from 2 to 64 TWh
- A: Solar and wind curtailment drop
- A: Sharp curtailment drop from 118 GWh to 9.6 GWh (- 92%) as 20 TWh of storage are added
- B: Due to the curtailment drop, less generation capacity is needed (10.2% drop for 20 TWh)
- B: Beyond 20 TWh, panel B shows a shift towards solar and away from wind.
- B: Transmission deployment drops by ~75% when 20 TWh are added



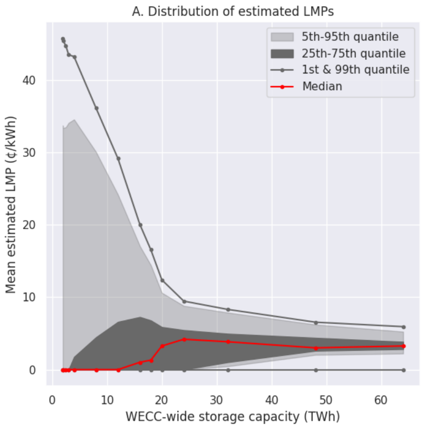
Results: LDES energy capacity mandates

- Energy storage is increased from 2 to 64 TWh
- A: Solar and wind curtailment drop
- A: Sharp curtailment drop from 118 GWh to 9.6 GWh (- 92%) as 20 TWh of storage are added
- B: Due to the curtailment drop, less generation capacity is needed (10.2% drop for 20 TWh)
- B: Beyond 20 TWh, panel B shows a shift towards solar and away from wind.
- B: Transmission deployment drops by ~75% when 20 TWh are added
- C: Seasonal use of LDES to serve winter and summer peaks



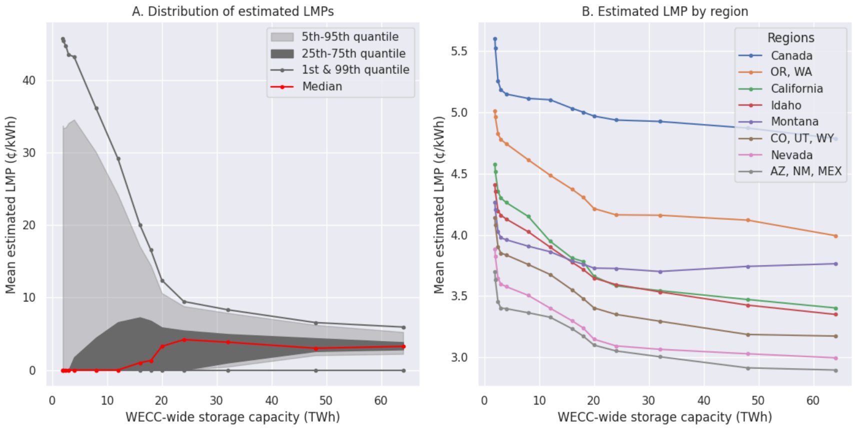
Results: LDES energy capacity mandates

- A: LMPs variability drastically reduced beyond 20 TWh of energy storage



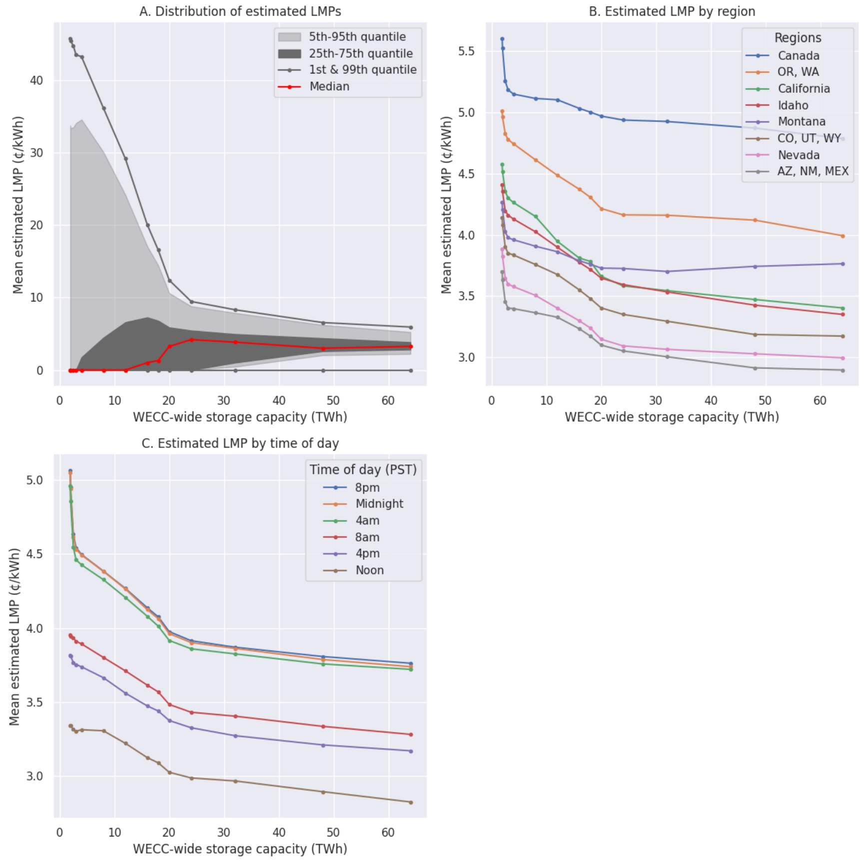
Results: LDES energy capacity mandates

- A: LMPs variability drastically reduced beyond 20 TWh of energy storage
- B: LMP variability across states



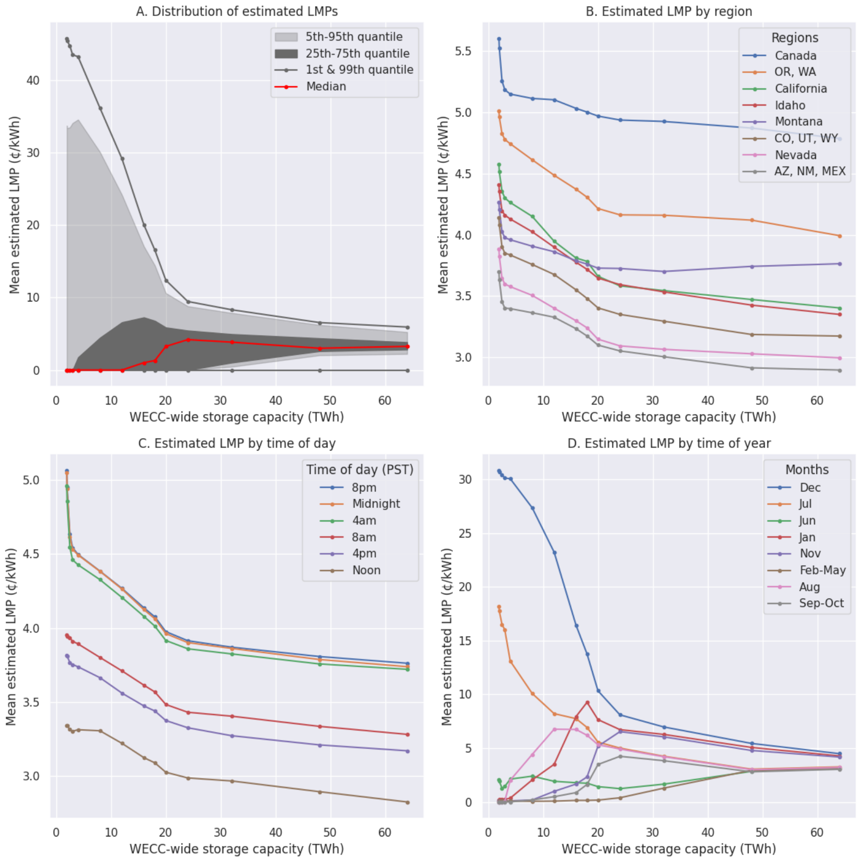
Results: LDES energy capacity mandates

- A: LMPs variability drastically reduced beyond 20 TWh of energy storage
- B: LMP variability across states
- C: 8am – 4pm lowest LMPs due to solar generation
- C: 20 TWh reduce LMPs the most
- C: sharpest drop between 1.94 TWh and 3 TWh: every additional 100 GWh of energy storage decrease night-time LMPs by 1.04%



Results: LDES energy capacity mandates

- A: LMPs variability drastically reduced beyond 20 TWh of energy storage
- B: LMP variability across states
- C: 8am – 4pm lowest LMPs due to solar generation
- C: 20 TWh reduce LMPs the most
- C: sharpest drop between 1.94 TWh and 3 TWh: every additional 100 GWh of energy storage decrease night-time LMPs by 1.04%
- D: LMPs are highest in July and December (highest demands) while near zero for in other months due to excess renewable energy



Upcoming studies

- **Infrastructure and economic opportunities of California coordinating with the WECC resources to achieve 100% RE by 2045**
  - How would the capacity mix deployment change (in CA and the WECC if they can coordinate)?
  - How would the duration of LDES deployment change?

- **Cost targets required by hydrogen to be deployed as LDES in the WECC**

- **Identification of cost targets: How does the deployment of a LDES tech change as the cost decreases?**
  - Comparative analysis using SWITCH WECC and RESOLVE

Questions?

Prof. Patricia Hidalgo-Gonzalez
phidalgogonzalez@eng.ucsd.edu
http://ream.ucsd.edu

Friday, Feb 4th, 2022

UC San Diego
JACOBS SCHOOL OF ENGINEERING