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<td><strong>Docket Number:</strong> 20-MISC-01</td>
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<td><strong>Document Title:</strong> Presentation - UC San Diego - Long Duration Energy Storage Public Workshop #3</td>
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<tr>
<td><strong>Description:</strong> UC San Diego's slides for the workshop titled &quot;Proposed Final Scenarios to Assess the Role of Long Duration Storage&quot;</td>
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<td><strong>Filer:</strong> Jeffrey Sunquist</td>
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<td><strong>Organization:</strong> UC San Diego</td>
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Long duration storage modeling in California and Western North America

Preliminary results
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 model¹

- 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 model¹

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)

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 CO2 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 unclear1,2
• Some recent works3-6 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.

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

• 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

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.
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).

- 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

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.
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


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 unclear¹,²

• Some report 100% renewable energy grids with³ and without storage⁴,

• others rely on “clean firm power”⁵ or even biomass to achieve negative emissions⁶,

• others consider intraday storage⁷, and in some cases seasonal⁸.


³Clack 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

⁴Mark 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


⁷Fernando 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


Research gap
• Some studies\textsuperscript{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


Contributions
• Quantification of the benefits in electricity pricing of federal/state mandates for LDES deployment.
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  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>
<thead>
<tr>
<th>Energy Storage Cost</th>
<th>WECC-wide energy storage capacity (TWh)</th>
<th>WECC mean storage duration (h)</th>
<th>Largest storage duration (h)</th>
<th>Wind Capacity (GW)</th>
<th>New Transmission Capacity (million MW-km)</th>
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<tbody>
<tr>
<td>102 $/kWh</td>
<td>1.5 (-22%)</td>
<td>7.0</td>
<td>8.9</td>
<td>113 (+14%)</td>
<td>27 (+31%)</td>
</tr>
<tr>
<td>22 $/kWh (Baseline)</td>
<td>1.9</td>
<td>8.2</td>
<td>18</td>
<td>99</td>
<td>21</td>
</tr>
<tr>
<td>10 $/kWh</td>
<td>2.4 (+21%)</td>
<td>9.9</td>
<td>29</td>
<td>98 (-1%)</td>
<td>17 (-18%)</td>
</tr>
<tr>
<td>5 $/kWh</td>
<td>6.6 (+239%)</td>
<td>28</td>
<td>378 (16 days)</td>
<td>94 (-5%)</td>
<td>13 (-40%)</td>
</tr>
<tr>
<td>1 $/kWh</td>
<td>22 (+1042%)</td>
<td>96 (4 days)</td>
<td>620 (26 days)</td>
<td>82 (-17%)</td>
<td>4.9 (-76%)</td>
</tr>
<tr>
<td>0.5 $/kWh</td>
<td>36 (+1747%)</td>
<td>151 (6.3 days)</td>
<td>825 (34 days)</td>
<td>69 (-30%)</td>
<td>5.3 (-75%)</td>
</tr>
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</table>

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

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- 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

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- 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?