Evolving Energy Storage Modeling Practices

EPRI's 43rd Annual Seminar on Resource Planning for Electric Power Systems

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Wednesday, Oct 30th, 2024

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Agenda

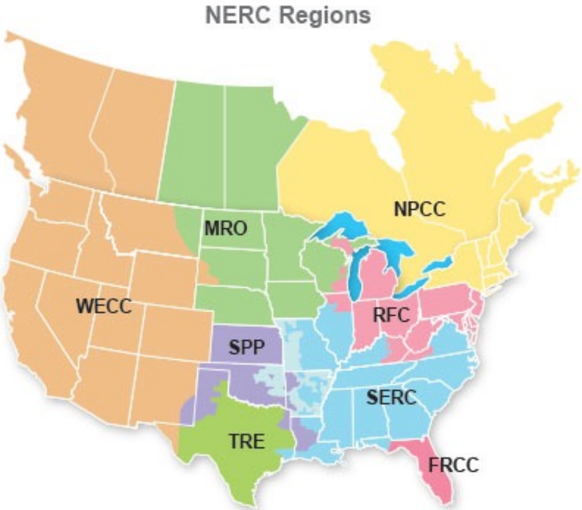
- Key features when accurately modeling storage in capacity expansion models
  1. Treatment of time
  2. Cost assumptions
  3. Grid conditions (hydro availability, solar, wind and transmission assumptions)

- Numerical issues and techniques to reduce run time

- Discussion:
  1. Storage energy mandates
  2. Market designs for long-duration storage
  3. Open-source capacity expansion to support electric utility tools/planning

Key features when accurately modeling storage in capacity expansion models

Methodology: SWITCH WECC model[1]



- Capacity expansion deterministic linear program

- Minimizes total cost of the power system:
  - Generation and transmission
  - Investment and operation
- Geographic:
  - Western Electricity Coordinating Council
  - 50 load areas
- Temporal:
  - Investment periods: 2030, 2040, 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]

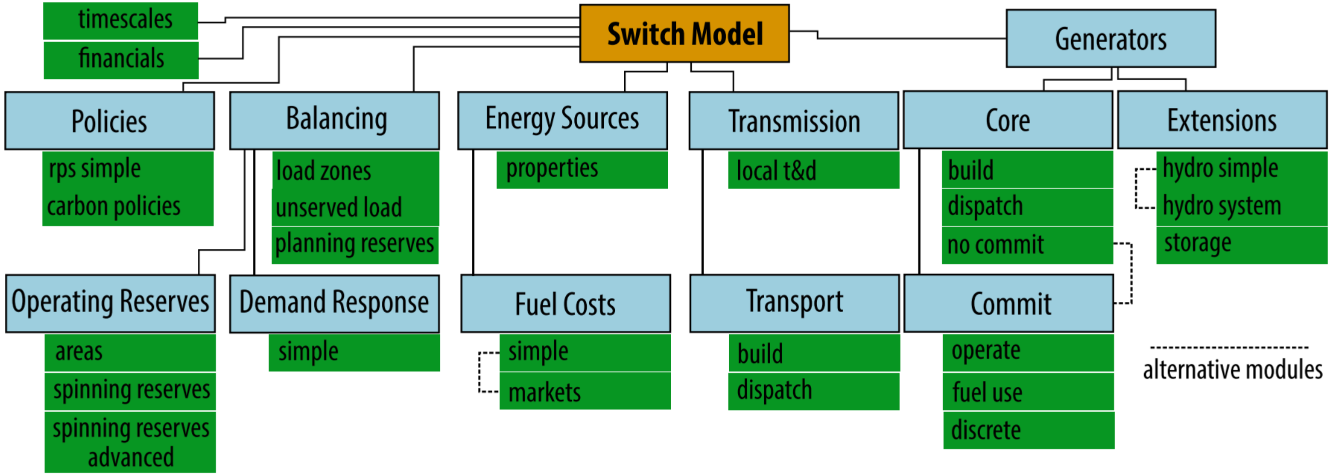


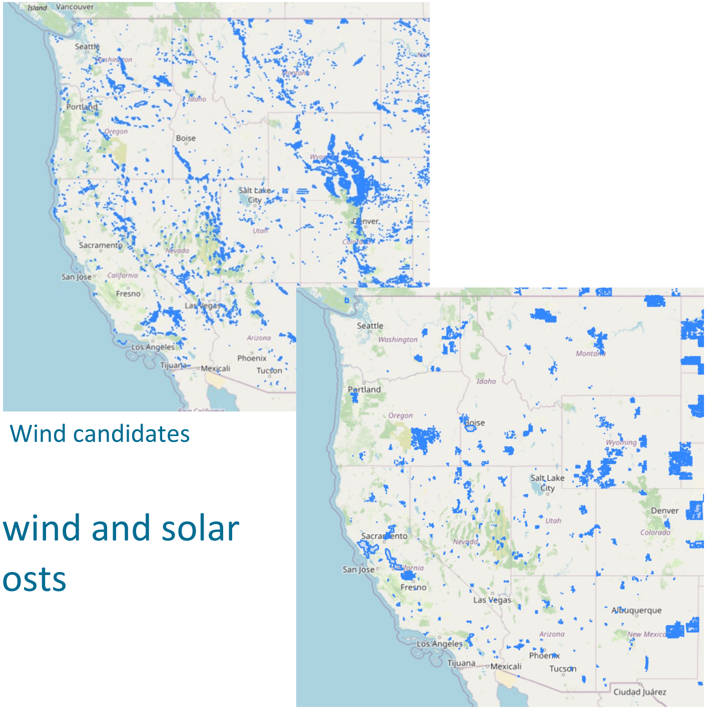
Image source: J. Johnson et al., Switch 2.0: A modern platform for planning high-renewable power systems, 2019

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

SWITCH WECC model input data and outputs

INPUTS

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



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 CO2 emissions by generator
- Investment and operational costs

Accurately representing storage: 1. Modeling of time

Relevance

- Computational complexity: Most U.S. capacity expansion models use a subset of days or seasons of interest
- 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)
- Three LDES cost scenarios for 2050: $113/kW with $130/kWh (baseline), $13/kWh, and 1.3/kWh.
- Zero emissions WECC-wide in 2050

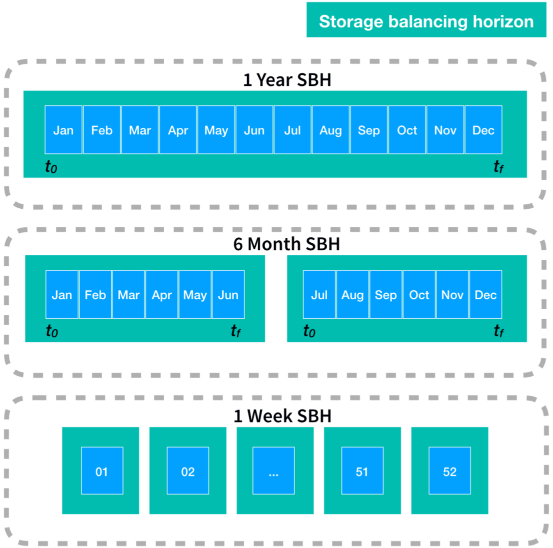


Fig. 1 Diagram showing the storage balancing horizon (SBH) concept for three different lengths: 1 Year, 6 Month and 1 Week.

Sánchez-Pérez, P. et al. "Effect of modeled time horizon on quantifying the need for long-duration storage" Applied Energy, 2022.

Accurately representing storage: 1. Modeling of time

Duration

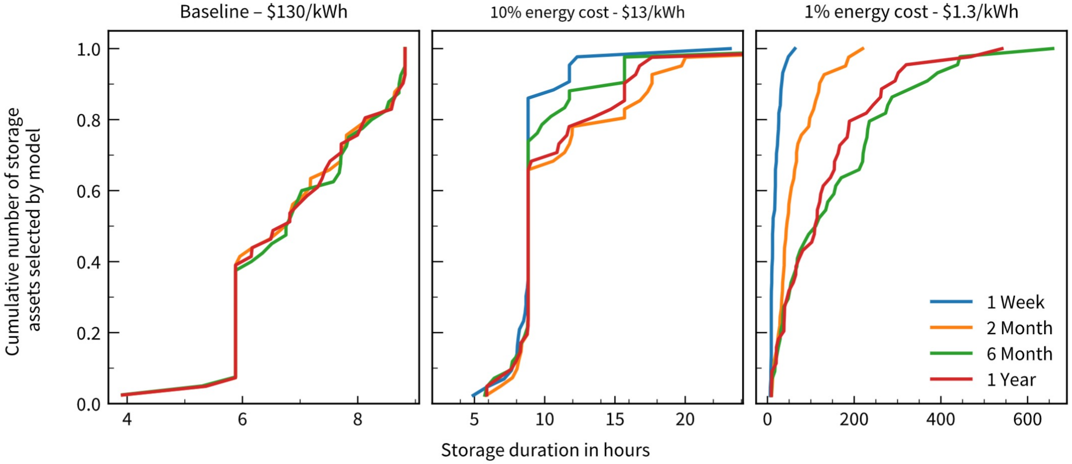


Fig. 4 Cumulative number of storage assets selected by model for the optimal energy storage duration (energy to power ratio) of the candidate storage for the 50 load zones in the SWITCH-WECC model. Each line color represents a different storage balancing horizon (SBH) where the blue line represents the 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
- 1% cost scenario: Up to 600 hours of duration

Accurately representing storage: 1. Modeling of time

State of charge and curtailment

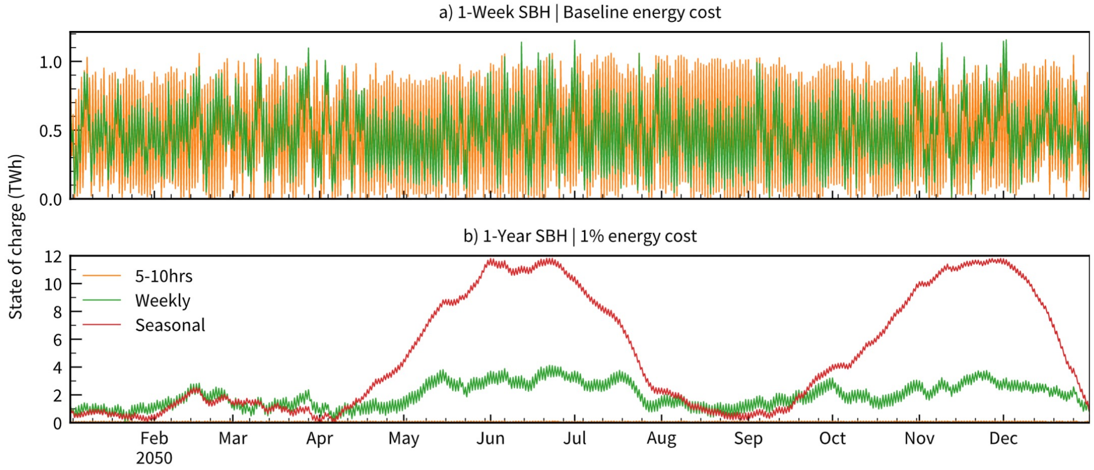


Fig. 6 Aggregated state of charge for all energy storage technologies installed throughout the WECC region. a) For the 1-week SBH using $130/kWh and b) for the 1-year SBH with $1.3/kWh. Duration of energy storage is classified according to its optimal range of duration. For weekly the range is between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

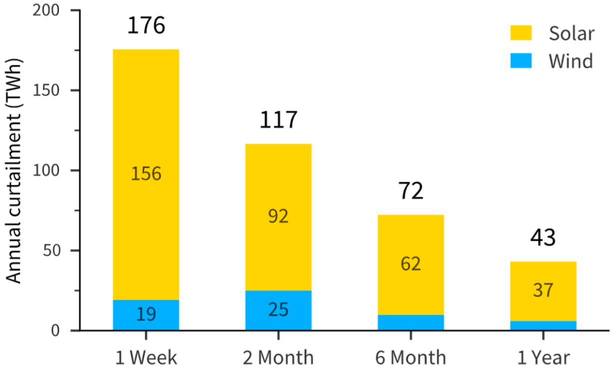


Fig. 5 Total solar and wind curtailment for each of the storage balancing horizon scenarios. Curtailment is defined as the difference of the available dispatch capacity at each time point and dispatch decision.

- 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

Accurately representing storage:
2. Cost assumptions

- 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%)

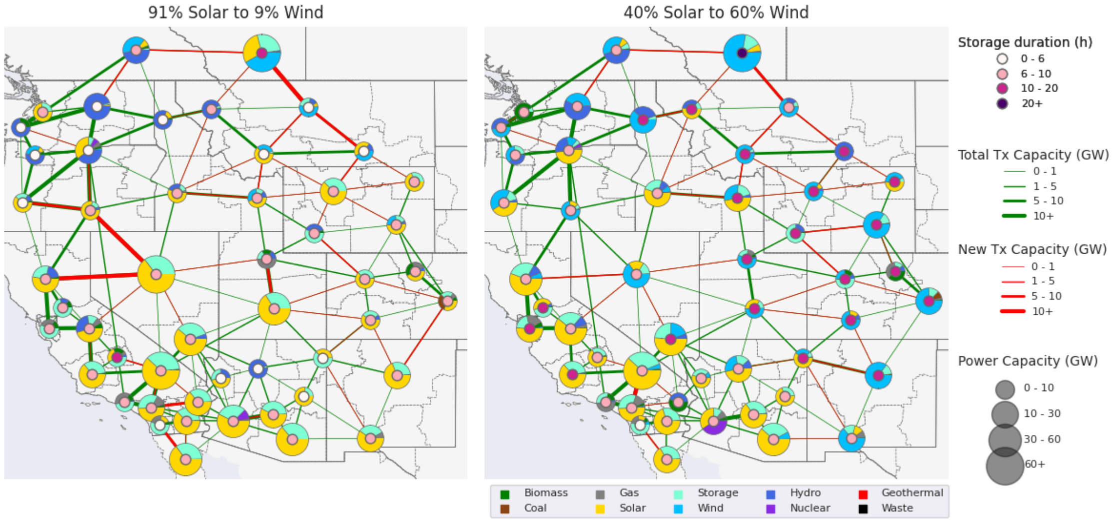
Percentages in parentheses represent the change compared to the baseline.

Staadecker, M. et al. “The value of long-duration energy storage under various grid conditions in a zero-emissions future” Nature Communications (2024).

Accurately representing storage: 3. Grid conditions

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**



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Accurately representing storage: 3. Grid conditions

Hydropower availability

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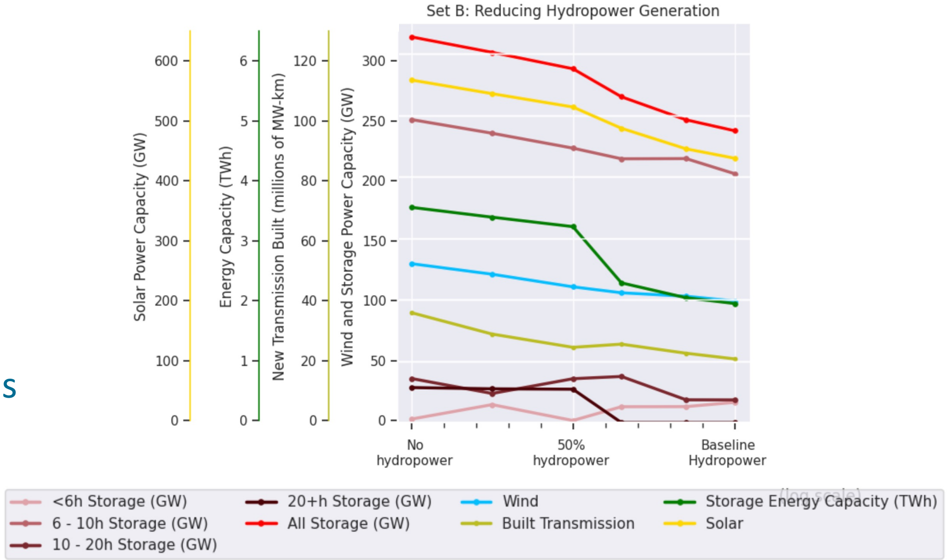
Accurately representing storage: 3. Grid conditions

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



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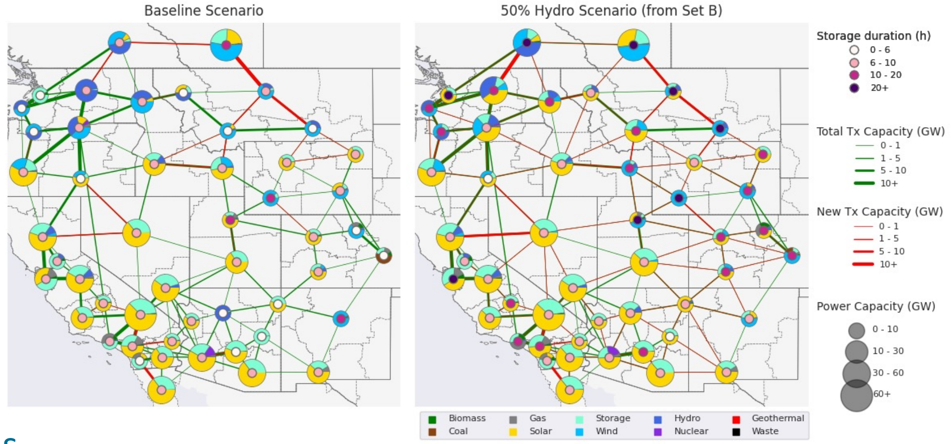
Baseline Scenario

50% Hydro Scenario (from Set B)

Staadecker, M. et al. "The value of long-duration energy storage under various grid conditions in a zero-emissions future" Nature Communications (2024).

Accurately representing storage: 3. Grid conditions

Transmission

- Baseline: 1.9 TWh of energy capacity

versus

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

versus

- No transmission congestion: 1.8 TWh

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Accurately representing storage: 3. Grid conditions

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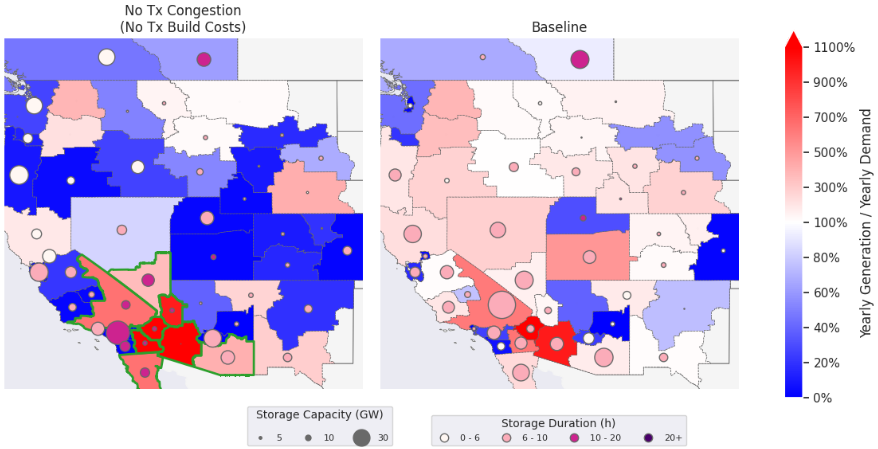


- **No transmission congestion:**
  - Generation shifts from the wind-dominant regions towards the solar-dominated southwest
  - 28/50 load zones generate locally less than half their yearly demand

Staadecker, M. et al. “The value of long-duration energy storage under various grid conditions in a zero-emissions future” Nature Communications (2024).

Numerical issues and tips to reduce run time

Numerical issues and tips to reduce run time

What are numerical issues and why do they occur?

- Numerical values with very small or very large magnitudes
- Very large/small values are stored less accurately (binary system for storage)
- Thus, incurring in greater error

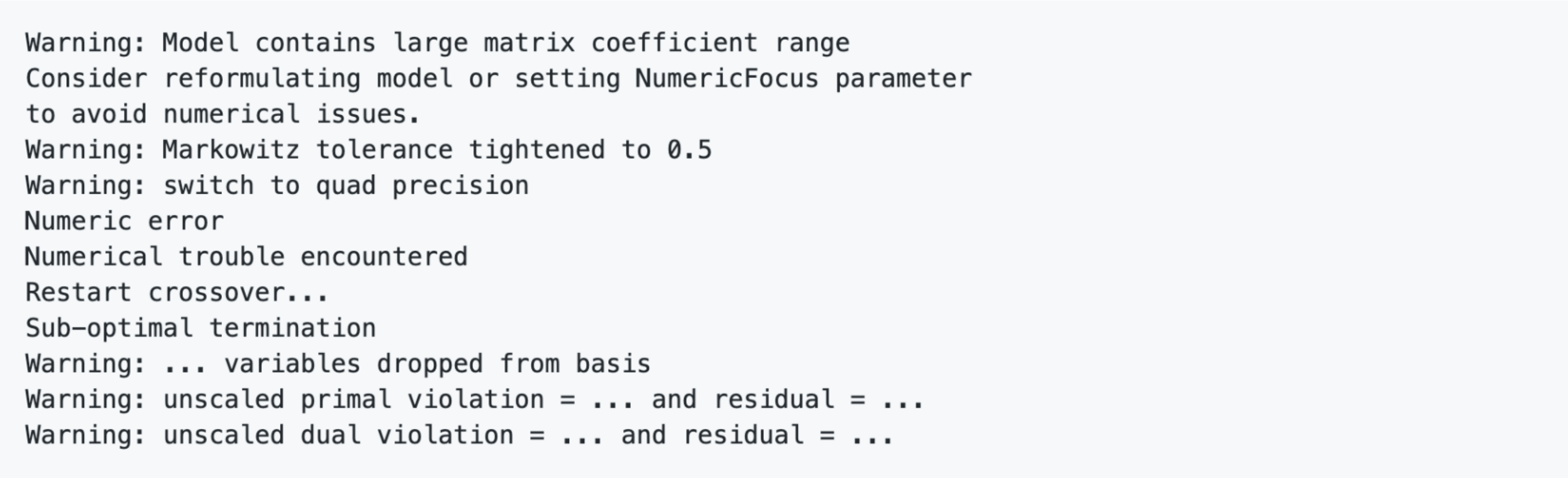
More details:

- Floating-point arithmetic (how arithmetic is done on computers)
- IEEE 754 standard (the standard used by almost all computers today)
- What Every Computer Scientist Should Know About Floating-Point Arithmetic

Staadecker, M., https://github.com/REAM-lab/switch/blob/wecc/docs/Numerical%20Issues.md

Numerical issues and tips to reduce run time

How to detect numerical issues?



```
Warning: Model contains large matrix coefficient range
Consider reformulating model or setting NumericFocus parameter
to avoid numerical issues.
Warning: Markowitz tolerance tightened to 0.5
Warning: switch to quad precision
Numeric error
Numerical trouble encountered
Restart crossover...
Sub-optimal termination
Warning: ... variables dropped from basis
Warning: unscaled primal violation = ... and residual = ...
Warning: unscaled dual violation = ... and residual = ...
```

Staadecker, M., https://github.com/REAM-lab/switch/blob/wecc/docs/Numerical%20Issues.md

Numerical issues and tips to reduce run time

How to detect numerical issues?

- These warnings indicate Gurobi (or any solver) is trying to work around the numerical issues.

- Examples:
  - If the barrier method fails due to numerical issues, Gurobi will switch to dual simplex method (Message: `Numerical trouble encountered`).
  - If Gurobi's dual simplex method encounters numerical issues, Gurobi might switch to quadruple precision (`Warning: switch to quad precision`).

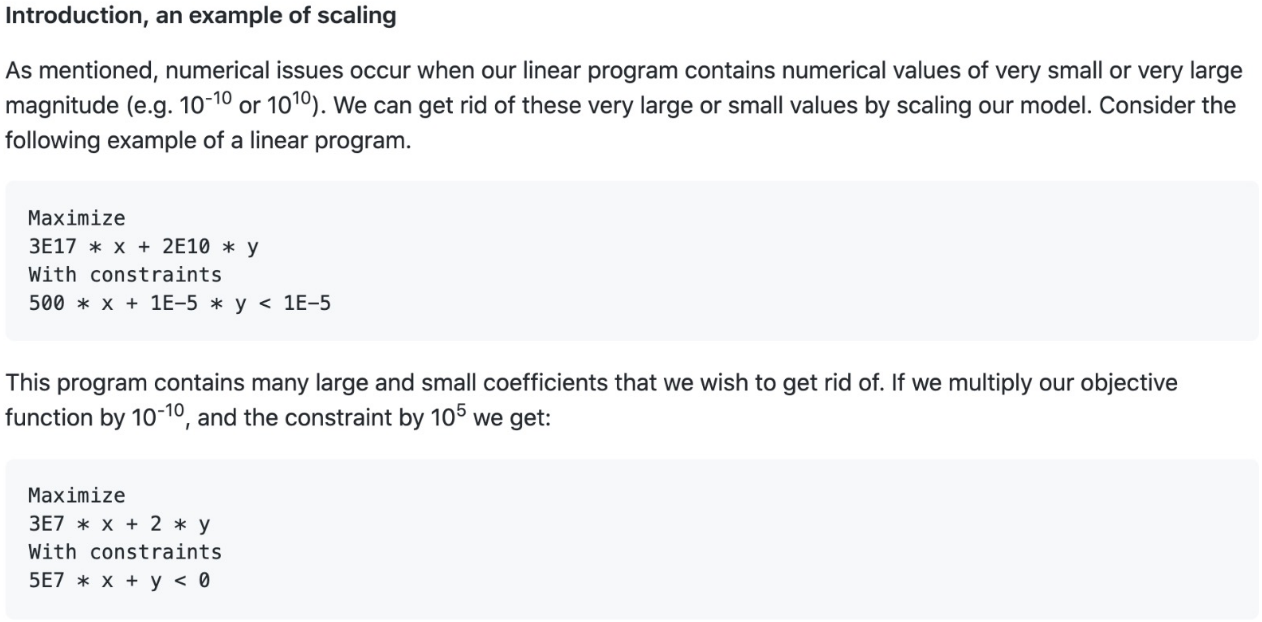
    This is 20 to 80 times slower.

- Internal mechanisms may not be sufficient or may be too slow
- Hence, we want to solve numerical issues in the modeling stage

Staadecker, M., https://github.com/REAM-lab/switch/blob/wecc/docs/Numerical%20Issues.md

Numerical issues and tips to reduce run time

Scaling models



Introduction, an example of scaling

As mentioned, numerical issues occur when our linear program contains numerical values of very small or very large magnitude (e.g. 10^{-10} or 10^{10}). We can get rid of these very large or small values by scaling our model. Consider the following example of a linear program.

```
Maximize
3E17 * x + 2E10 * y
With constraints
500 * x + 1E-5 * y < 1E-5
```

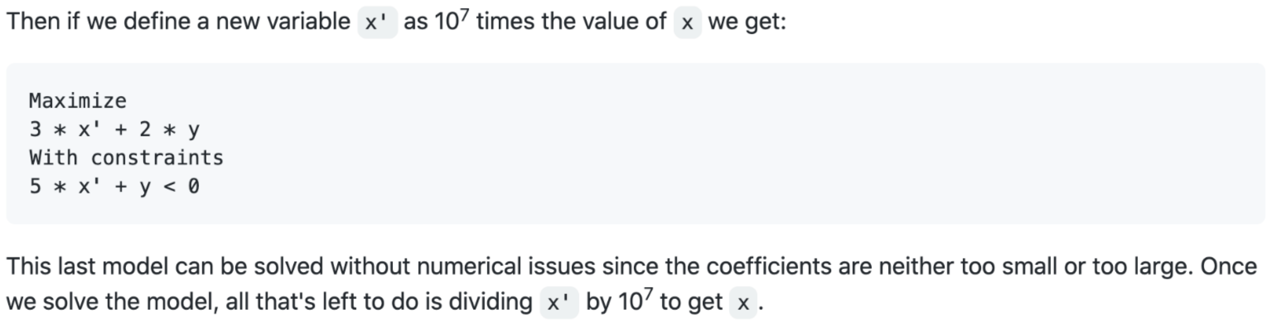
This program contains many large and small coefficients that we wish to get rid of. If we multiply our objective function by 10^{-10}, and the constraint by 10^{5} we get:

```
Maximize
3E7 * x + 2 * y
With constraints
5E7 * x + y < 0
```

Staadecker, M., https://github.com/REAM-lab/switch/blob/wecc/docs/Numerical%20Issues.md and Gurobi

Numerical issues and tips to reduce run time

Scaling models



Then if we define a new variable `x'` as 10^7 times the value of `x` we get:

```
Maximize
3 * x' + 2 * y
With constraints
5 * x' + y < 0
```

This last model can be solved without numerical issues since the coefficients are neither too small or too large. Once we solve the model, all that's left to do is dividing `x'` by 10^7 to get `x`.

Staadecker, M., https://github.com/REAM-lab/switch/blob/wecc/docs/Numerical%20Issues.md and Gurobi

Numerical issues and tips to reduce run time

Gurobi’s guidelines for ranges of values

What is considered too small or too large?

- Gurobi's documentation on ranges
- Gurobi's recommendation on scaling

Summary:

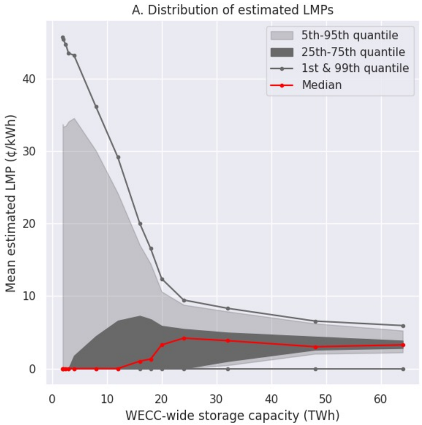
- Right-hand sides of inequalities and variable bounds be in the order of 10^4 or less.
- The objective function's optimal value should be between 1 and 10^5.
- The matrix coefficients should span a range of six orders of magnitude or less and ideally between 10^{-3} and 10^6.

Staadecker, M., https://github.com/REAM-lab/switch/blob/wecc/docs/Numerical%20Issues.md and Gurobi

Discussion

Discussion: LDES energy capacity mandates

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



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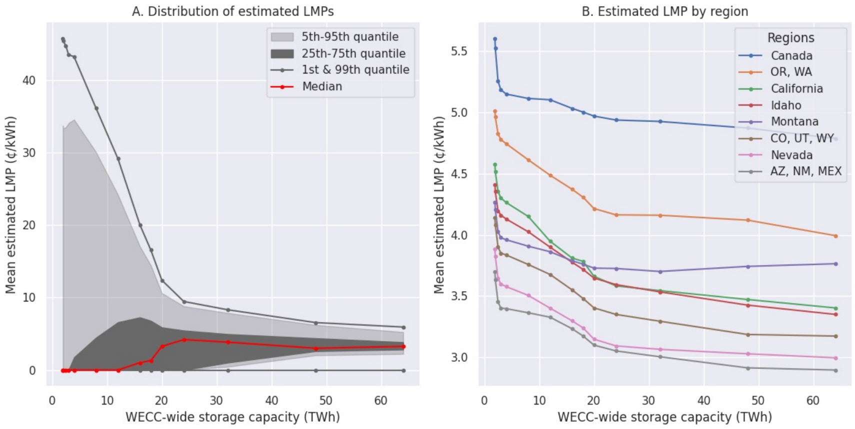
Discussion: LDES energy capacity mandates

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



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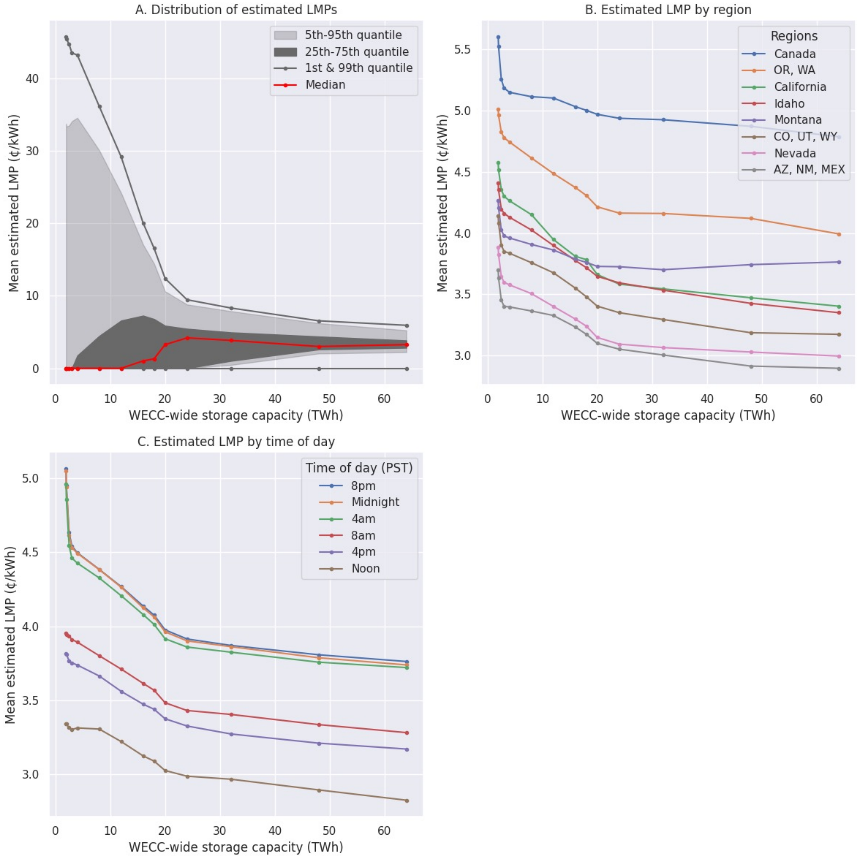
Discussion: LDES energy capacity mandates

- 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



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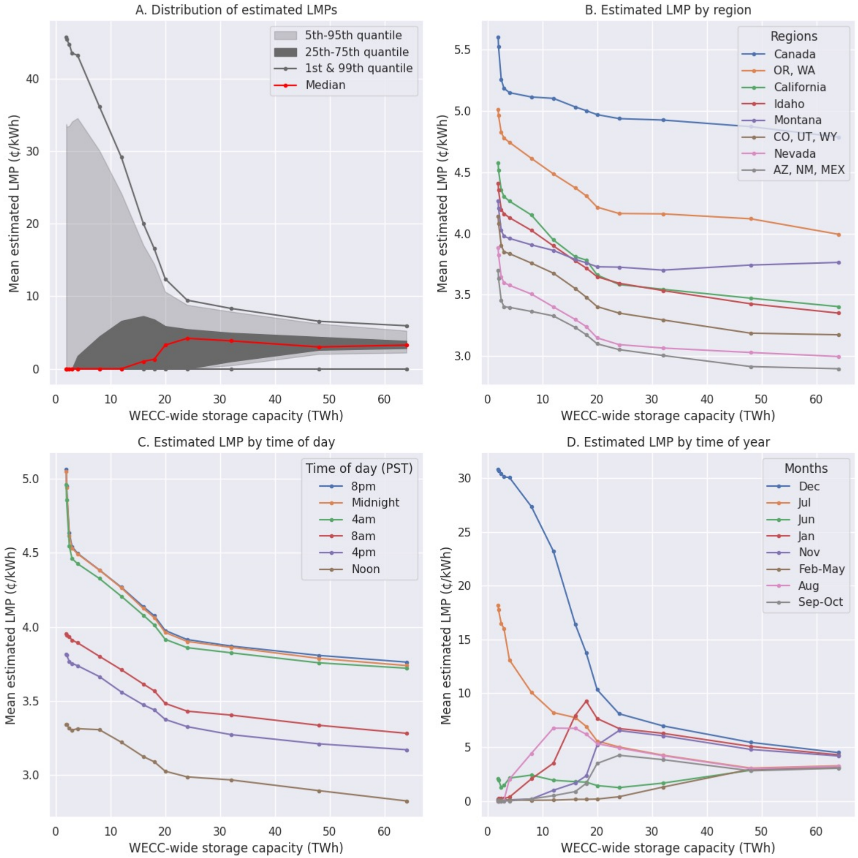
Discussion: LDES energy capacity mandates

- 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
- D: LMPs are highest in July and December (highest demands) while near zero for in other months due to excess renewable energy



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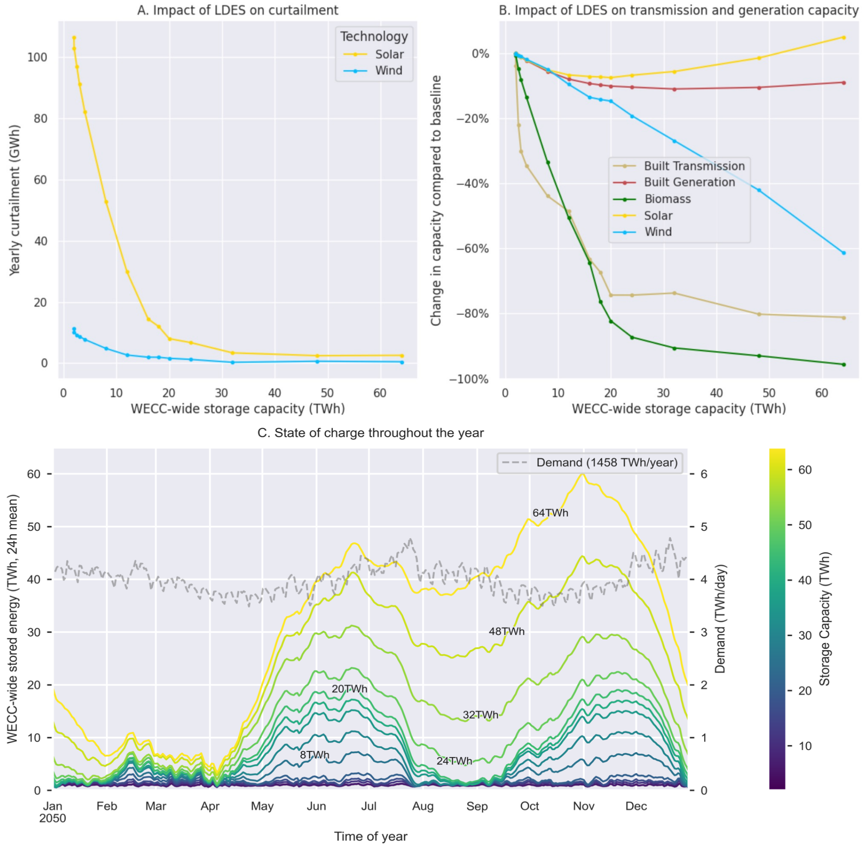
Discussion: LDES energy capacity mandates

- 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: Transmission deployment drops by ~75% when 20 TWh are added
- C: Seasonal use of LDES to serve winter and summer peaks



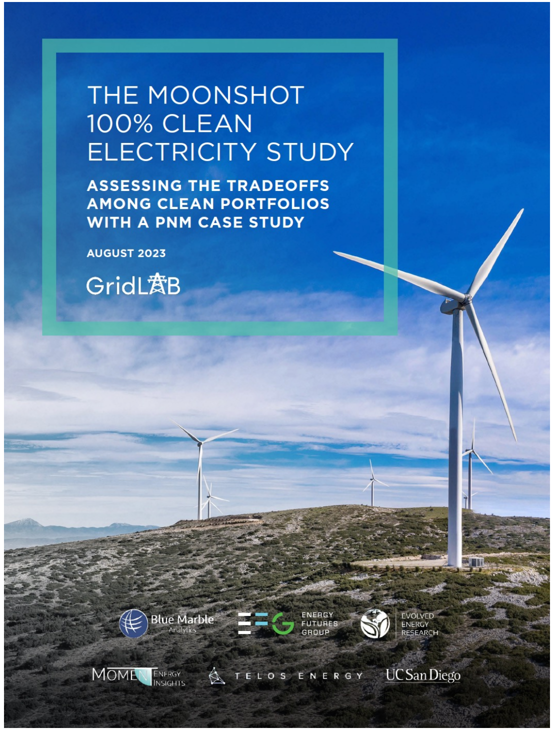
Discussion

What are your thoughts?

1. Storage energy mandates
    - Reduction of prices, variability, and volatility
    - Reduction of curtailment, transmission and total installed generation
    - Business model for stakeholders?

2. Market designs for long-duration storage
    - New ancillary services?

3. Open-source capacity expansion to support electric utility tools/planning
    - In parallel to support utilities/ISOs?
    - Provide generation portfolio from capacity expansion for utilities to study dispatch and iterate?
    - Or other synergies?



THE MOONSHOT
100% CLEAN
ELECTRICITY STUDY

ASSESSING THE TRADEOFFS
AMONG CLEAN PORTFOLIOS
WITH A PNM CASE STUDY

AUGUST 2023

GridLAB

Thank you

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