Modeling storage technologies in Capacity Expansion Models

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• RPM Overview

• Motivation for better storage modeling

• Storage Methodology

• Results
Resource Planning Model (RPM)

- Capacity expansion model that simulates least-cost investments in and operation of a generation and transmission system

- Specialized for analysis of a *regional* electric system over a utility planning horizon (10-20 years)
  - Includes hourly chronological dispatch
  - High spatial resolution of existing and new resources
  - Real-world transmission system
Database: Complete Western Interconnection data for all major generation units and transmission lines

<table>
<thead>
<tr>
<th>Technology</th>
<th>Units</th>
<th>Capacity in 2010 (GW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>143</td>
<td>39</td>
</tr>
<tr>
<td>Gas-CC</td>
<td>208</td>
<td>60</td>
</tr>
<tr>
<td>Nuclear</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Gas-CT</td>
<td>434</td>
<td>20</td>
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<tr>
<td>Other Gas</td>
<td>184</td>
<td>23</td>
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<tr>
<td>Biomass</td>
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<td>2</td>
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<tr>
<td>Geothermal</td>
<td>57</td>
<td>3</td>
</tr>
<tr>
<td>Hydropower</td>
<td>641</td>
<td>70</td>
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<tr>
<td>Pumped Hydro</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>PV</td>
<td>5</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>CSP</td>
<td>10</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Wind</td>
<td>144</td>
<td>12</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,911</strong></td>
<td><strong>243</strong></td>
</tr>
</tbody>
</table>

20,086 Transmission Lines
Flexible data platform allows development of region-specific models

- Aggregated transmission and generation outside of focus region
- Maintains spatial resolution of focus region
- Full transmission model and individual units within focus region
- Represent hurdle-rates between regions
- Temporally consistent with production cost model
Highly detailed renewable resource data is aggregated for high definition in the focus-region.

Solar Resource Regions
Motivation for better storage modeling
Renewable deployment expected based on policy and economics

- State Renewable Portfolio Standards (RPS)
- California AB32
- EPA Clean Power Plan (CPP)

Results from ReEDS 2015 Standard Scenarios (Sullivan et al. 2015)
Increased system flexibility is known to support RE grid integration

(Denholm and Hand 2011)
Challenges for Capacity Expansion Modeling
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• Operational issues. With a given portfolio of assets including variable generation (VG),
  o Is dispatch feasible?
  o Are there enough operating reserves?
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• Resource valuation issues
  o *Flexible, but energy-constrained* resources: capacity value, use for energy and operating reserves, ability to reduce curtailment
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  o Is dispatch feasible?
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• Resource valuation issues
  o Flexible, but energy-constrained resources: capacity value, use for energy and operating reserves, ability to reduce curtailment

• Associated computational limitations
  o Optimization formulation geared toward annual investment decisions
  o Necessitates reduced geospatial and temporal resolution
Methodology
Approach

0. RPM was initially designed with high renewable futures and flexibility in mind
   - Chronological, hourly dispatch
   - Operating reserves based on VG penetration
   - Unit commitment and ramping constraints
   - Unit-level detail and transmission in focus region
   - Dynamic capacity value calculations
Approach

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   - Chronological, hourly dispatch
   - Operating reserves based on VG penetration
   - Unit commitment and ramping constraints
   - Unit-level detail and transmission in focus region
   - Dynamic capacity value calculations
     - RPM can capture many of the key valuations for flexibility.
     - However computational limitations prevent adequate coverage over time (e.g., hourly is not possible).
     - We use time-series and load duration curve techniques outside of the optimization to better capture flexibility during “tail” events.
Approach

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   - Parameterize impacts of VG and flexible technologies on capacity value and curtailment.
Approach

1. “Yoga for capacity expansion models” – capture flexibility needs and provision in models with limited temporal resolution and coverage
   - Hourly time series and load duration curve methods, similar to NREL REFlex model.
   - Parameterize impacts of VG and flexible technologies on capacity value and curtailment.
   - Similar, but less-detailed methods being used in global Integrated Assessment Models
2. Add flexible technology investments
   - Storage with maximum and minimum energy constraints
   - Capture appropriate value streams, some of which require 8760 calculations (e.g. capacity value, curtailment reduction)
   - Current and future cost estimates vary significantly and are uncertain. Thus we include a range of possible costs to determine tipping points for measurable deployment.
Yoga: Storage dispatch heuristic
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• Storage technologies have limitations on when they can be used based on their state of charge and energy capacity
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• Assume grid operators will utilize storage efficiently, particularly during peak periods
Yoga: Storage dispatch heuristic

• Storage technologies have limitations on when they can be used based on their state of charge and energy capacity

• Assume grid operators will utilize storage efficiently, particularly during peak periods

• Create a heuristic dispatch to maximize capacity value and minimize curtailment, which is used to create a modified ‘storage load curve’
Yoga: Capacity Value
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• Capture shift in net peak load based on top 100 hours
Yoga: Capacity Value

• Capture shift in net peak load based on top 100 hours
• Values geospatial and technology diversity
Yoga: Capacity Value

• Capture shift in net peak load based on top 100 hours
• Values geospatial and technology diversity
• At the NERC level and by storage technology:
  o capacity value of existing storage = \( \frac{<NLDC - SLDC>_{top 100}}{\text{existing capacity}} \)
  o marginal capacity value of new storage = \( \frac{<SLDC(\delta)>_{top 100}}{\delta} \)
Yoga: Curtailment
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• Curtailment based on interplay of NLDC, min-gen, and storage dispatch.
Yoga: Curtailment

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- We use a regression based on PLEXOS production cost simulations to calculate the effective min-gen and identify how storage impacts curtailment below that line.
Yoga: Curtailment

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- We use a regression based on PLEXOS production cost simulations to calculate the effective min-gen and identify how storage impacts curtailment below that line.
Scenarios
Capacity Expansion for Baseline Scenarios

### Base

- Existing policies
- Mid-line PV and wind costs
- Mid Storage costs
- AEO Reference Natural Gas prices
- No Carbon price

### High Renewable

- Existing policies
- Mid-line PV and wind costs
- Mid Storage costs
- AEO High Natural Gas prices
- Median Carbon price
Annual Generation for Baseline Scenarios

Base

- Solar growth starts in 2020
- Mild wind growth
- Significant curtailment doesn’t start until 2035
- Increase in gas CC generation in 2035

High Renewables

- Solar growth starts in 2020
- Significant wind generation in 2025
- Significant curtailment starts in 2030
Storage cost trajectories

Trajectories from Cole et. al. for several storage capacities

Capital Cost, $/W

2010 2015 2020 2025 2030 2035

- Li-ion Battery; 0.25h
- Li-ion Battery; 0.5h
- Li-ion Battery; 1h
- Li-ion Battery; 2h
- Li-ion Battery; 4h
- Li-ion Battery; 8h

- High Cost Storage
- Mid Cost Storage
- Low Cost Storage
Storage capacity built by RPM

- **Base**
- **Base, HSC**
- **Base, LSC**

- Li-Ion Battery; 0.25h
- Li-Ion Battery; 0.5h
- Li-Ion Battery; 1h
- Li-Ion Battery; 2h
- Li-Ion Battery; 4h
- Li-Ion Battery; 8h
Storage capacity built by RPM

- **Base**
  - Capacity, GW
  - Years: 2015-2035

- **Base, HSC**
  - Capacity, GW
  - Years: 2015-2035

- **Base, LSC**
  - Capacity, GW
  - Years: 2015-2035

- **High RE**
  - Capacity, GW
  - Years: 2015-2035

- **High RE, HSC**
  - Capacity, GW
  - Years: 2015-2035

- **High RE, LSC**
  - Capacity, GW
  - Years: 2015-2035

Legend:
- Red: Li-Ion Battery; 0.25h
- Blue: Li-Ion Battery; 0.5h
- Green: Li-Ion Battery; 1h
- Purple: Li-Ion Battery; 2h
- Orange: Li-Ion Battery; 4h
- Yellow: Li-Ion Battery; 8h
Storage Cost Impacts on Annual Generation, Base

High Storage Costs
- Reduction of wind and increase of gas CC
- Reduction of curtailment largely from lower renewable dispatch

Low Storage Costs
- Large increase solar and storage generation
- Reduction in solar curtailment and coal generation
Storage Cost Impacts on Annual Generation, Base

High Storage Costs
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- Large increase solar and storage generation
- Reduction in solar curtailment and coal generation
Storage Cost Impacts on Annual Generation, High RE

High Storage Costs

- Increase in curtailment and gas generation
- Reduction in solar and storage generation
Storage Cost Impacts on Annual Generation, High RE

High Storage Costs
- Increase in curtailment and gas generation
- Reduction in solar and storage generation

Low Storage Costs
- Increase in solar, storage and gas generation
- Decrease in curtailment, and wind generation from reduced installations
Dispatch, High RE, low storage costs
Storage Operation, long-duration

- Charging largely occurs during high solar hours
- Dispatch largely occurs during afternoon peak
- Long-duration storage provides spinning and regulation reserves
Storage Operation, short-duration

- Short-term batteries are mostly used for regulation reserves
- Generation provided occasionally
Value of Storage, Base, mid storage costs

- Storage is only installed in 2020 and 2025 to meet AB32
- Reserves provision enables higher energy capacities in these years
- No economic storage installed until 2035
- 2-hour storage installed for capacity, curtailment reduction, and reserves
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Value of Storage, High RE, low storage costs

- Storage is only installed in 2020 to meet AB32, with reserves provision enabling higher energy capacities
- 30-min to 1-hour storage are installed largely for reserves provision
- By 2030, 4 and 8 hour storage are installed for capacity, curtailment reduction, and energy shifting
Conclusions

- RPM represents renewables and flexible technology with high resolution in resource availability and dispersion
- Use methodology designed to fully capture the tails of operation to ensure we capture the full value flexible technologies provide
- RPM represents multiple value streams available to storage technologies in planning and operations of an electric grid
Questions?
### Who are we?

<table>
<thead>
<tr>
<th>Name</th>
<th>Degree(s)</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clayton Barrows</td>
<td>Ph.D. Energy and Mineral Engineering</td>
<td>Pennsylvania State University</td>
</tr>
<tr>
<td>Anthony Lopez</td>
<td>M.S. Geographic Information Science</td>
<td>University of Denver</td>
</tr>
<tr>
<td>Elaine Hale</td>
<td>Ph.D. Chemical Engineering</td>
<td>University of Texas, Austin</td>
</tr>
<tr>
<td>Trieu Mai</td>
<td>Ph.D. Theoretical Physics</td>
<td>University of California, Santa Cruz</td>
</tr>
<tr>
<td>Dylan Hettinger</td>
<td>B.S. Geography</td>
<td>Appalachian State University</td>
</tr>
<tr>
<td>Brady Stoll</td>
<td>Ph.D. Mechanical Engineering</td>
<td>University of Texas, Austin</td>
</tr>
</tbody>
</table>
Storage Cost Impacts on Capacity, Base

High Storage Costs
- Approximately the same total storage capacity, but smaller energy capacities
- Reduction of wind capacity gets built, with increase in gas CC units

Low Storage Costs
- Large increase in total storage capacity built, with larger energy capacities built starting in 2025
- Increase in solar capacity, reduction of wind and both gas technologies
Storage Cost Impacts on Capacity, High RE

High Storage Costs

- Reduction in storage capacity starting in 2030
- Increase in wind and gas technologies and decrease in solar PV

Low Storage Costs

- Large increase in total storage capacity built, with larger energy capacities built starting in 2030
- Decrease in wind and gas technologies
For each model year (2010, 2015, …, 2030)...

\[
\begin{align*}
\text{min} & \quad \text{(capital and fixed costs for new generators) + } \\
& \quad \text{(capital and fixed costs for new transmission) + } \\
& \quad \text{(variable, fuel, start-up, and carbon costs) + } \\
& \quad \text{(transmission hurdle rates)}
\end{align*}
\]

s.t. \text{ allowed locations and sizes of new assets} \\
\text{wind and solar resource availability} \\
\text{load balancing (hourly chronological, 4 dispatch periods)} \\
\text{transmission constraints} \\
\text{capacity, reserve, and energy constraints} \\
\text{policy constraints (RPS and CPP)} \\
\text{unit commitment (optional)} \\
\text{minimum plant size (optional)}