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Capacity Expansion Modeling for Storage Technologies

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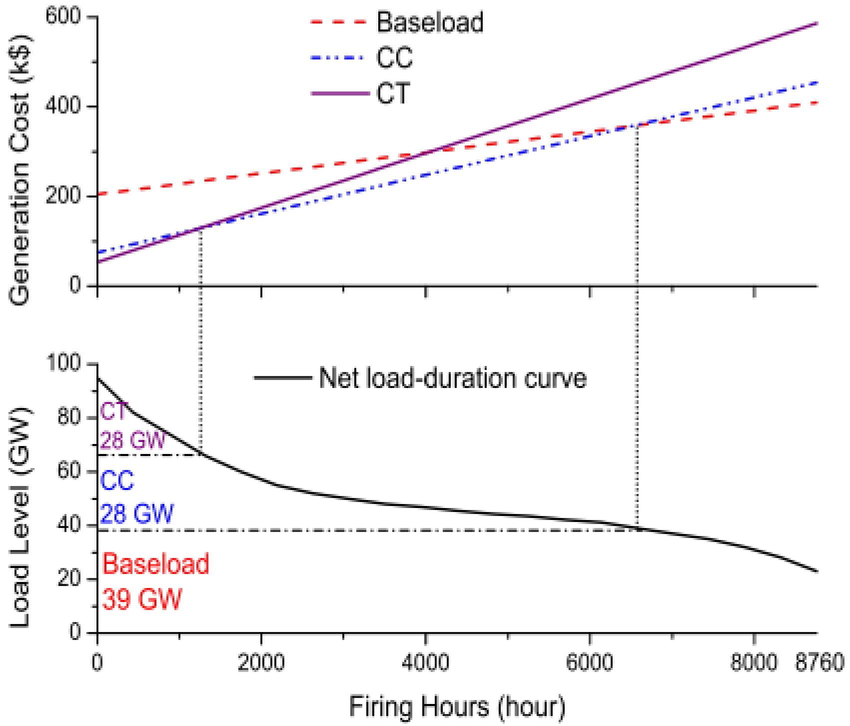
Overview

- Power System Planning
- The Resource Planning Model (RPM)
- Modeling Storage in RPM
- Results
- Related and Current Work

Power System Planning

Primary Question: What resources should be built to meet future electricity demand? (Decadal scale)

Simple Answer:

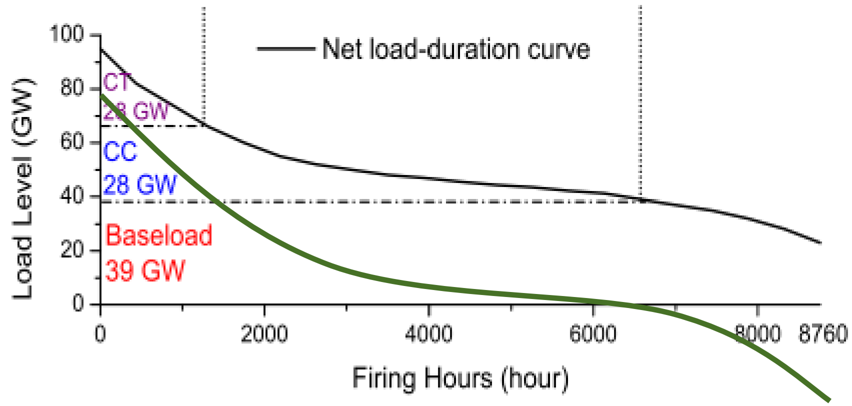


Screening Curves with Merit-Order Dispatch

(Sullivan, Eurek, and Margolis 2014; Zhang 2013)

What Simple Methods Do Not Capture

- Transmission
- Ancillary services
- Ramping constraints
- Minimum generation
- Plant start-ups



Net load curve with additional wind and solar

- How all of the above are impacted by variable generation (wind and solar)
- How flexible technologies (storage, demand response, concentrating solar power with storage) may mitigate these impacts

Planning for More Renewables

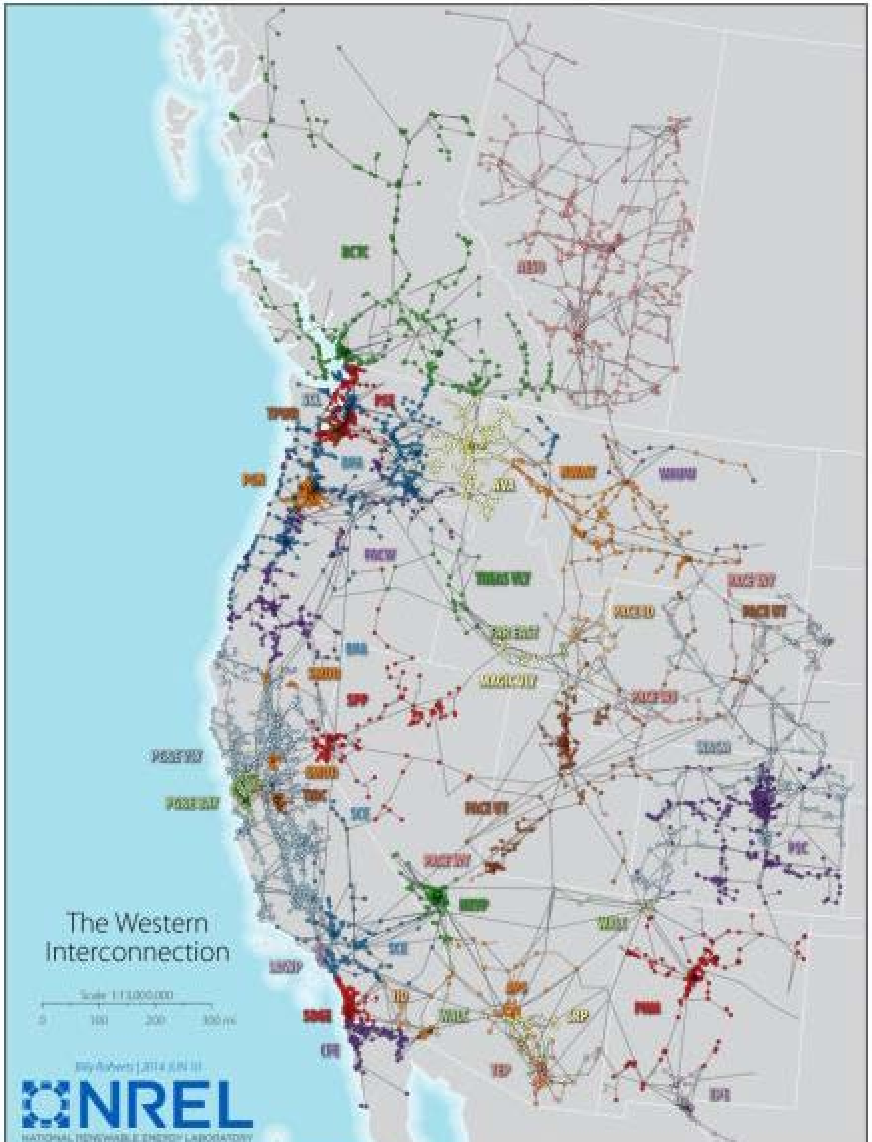
→ Detailed production cost modeling of select portfolios (unit commitment and dispatch to determine operational feasibility and costs)

→ Conventional capacity expansion modeling around candidate net load curves (cost minimization or profit maximization of investment decisions over time around several candidate variable generation portfolios)

→ **Combine capacity expansion modeling with detailed operational modeling (optimally choose from a variety of resources that together serve the needs of the system)**

The Resource Planning Model (RPM)

The RPM is a Mixed Nodal/Zonal Model



The RPM is a Mixed Nodal/Zonal Model

Resource Planning Model

For each model year (2010, 2015, …, 2030)…

min (capital and fixed costs for new generators) +
(capital and fixed costs for new transmission) +
(variable, fuel, start-up, and carbon costs) +
(transmission hurdle rates)

s.t. allowed locations and sizes of new assets
wind and solar resource availability
minimum plant size (optional)
load balancing (hourly chronological, four dispatch periods)
pipe or DC power flow
capacity, reserve, and energy constraints
unit commitment (optional)
policy constraints (RPS and CPP)

Co-Optimization of Investment and Dispatch

For each model year (2010, 2015, …, 2030)…

min (capital and fixed costs for new generators) +
(capital and fixed costs for new transmission) +
(variable, fuel, start-up, and carbon costs) +
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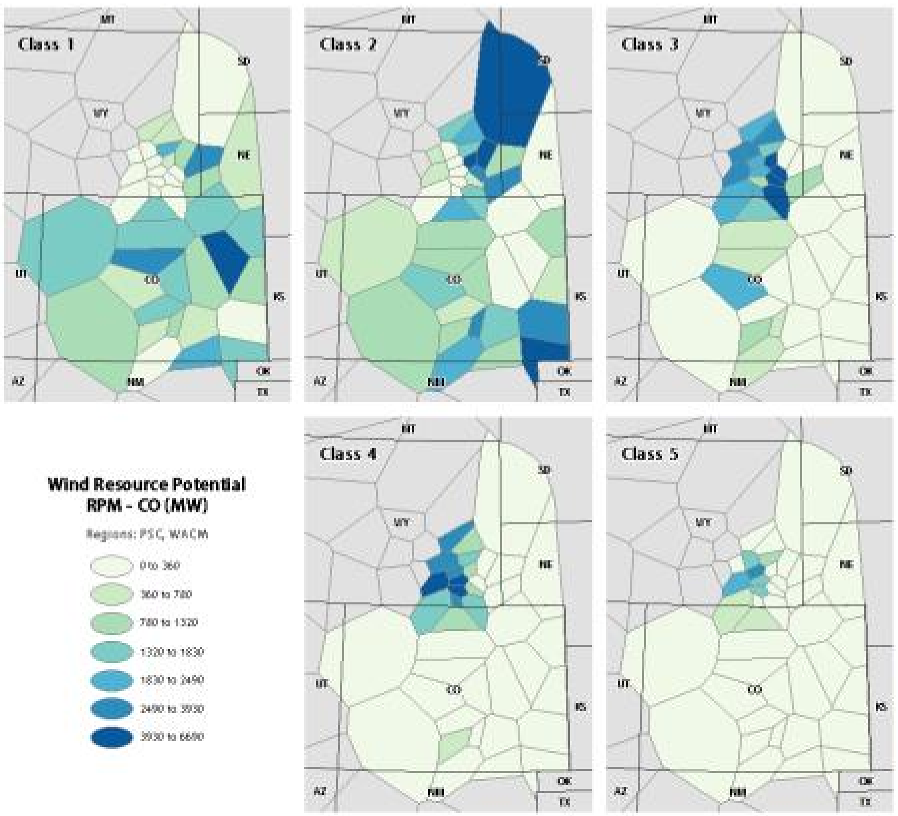
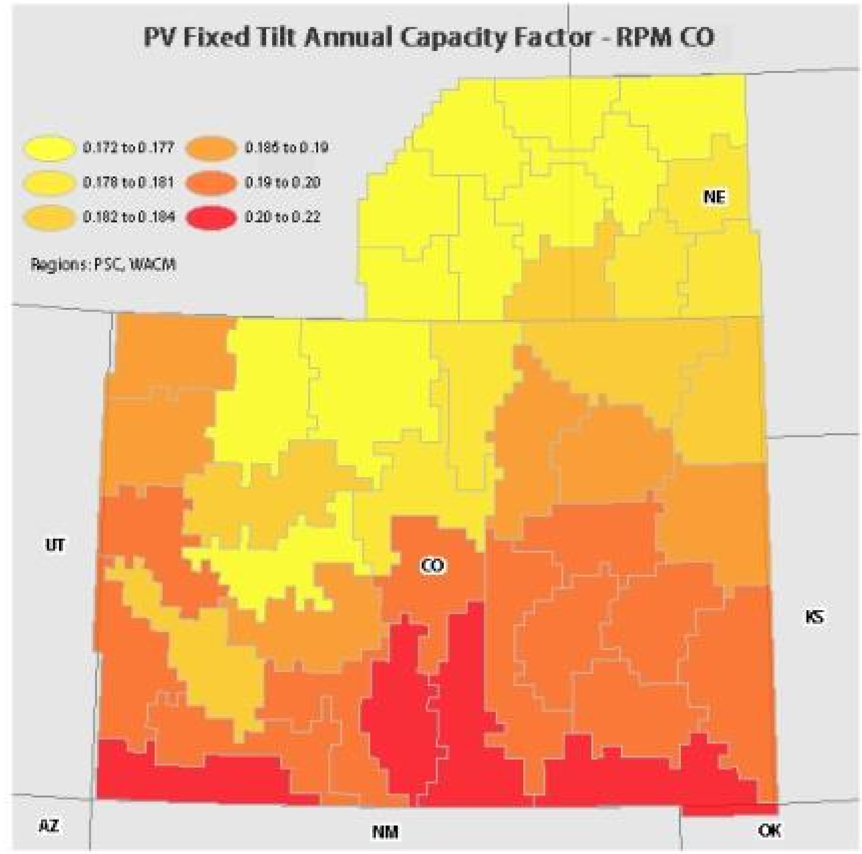
s.t. allowed locations and sizes of new assets
wind and solar resource availability
minimum plant size (optional)
load balancing (hourly chronological, four dispatch periods)
pipe or DC power flow
capacity, **reserve, and energy constraints**
unit commitment (optional)
policy constraints (RPS and CPP)

dispatch model

High Spatial Resolution Modeling to Accurately Represent Renewable Resource Potential and Quality

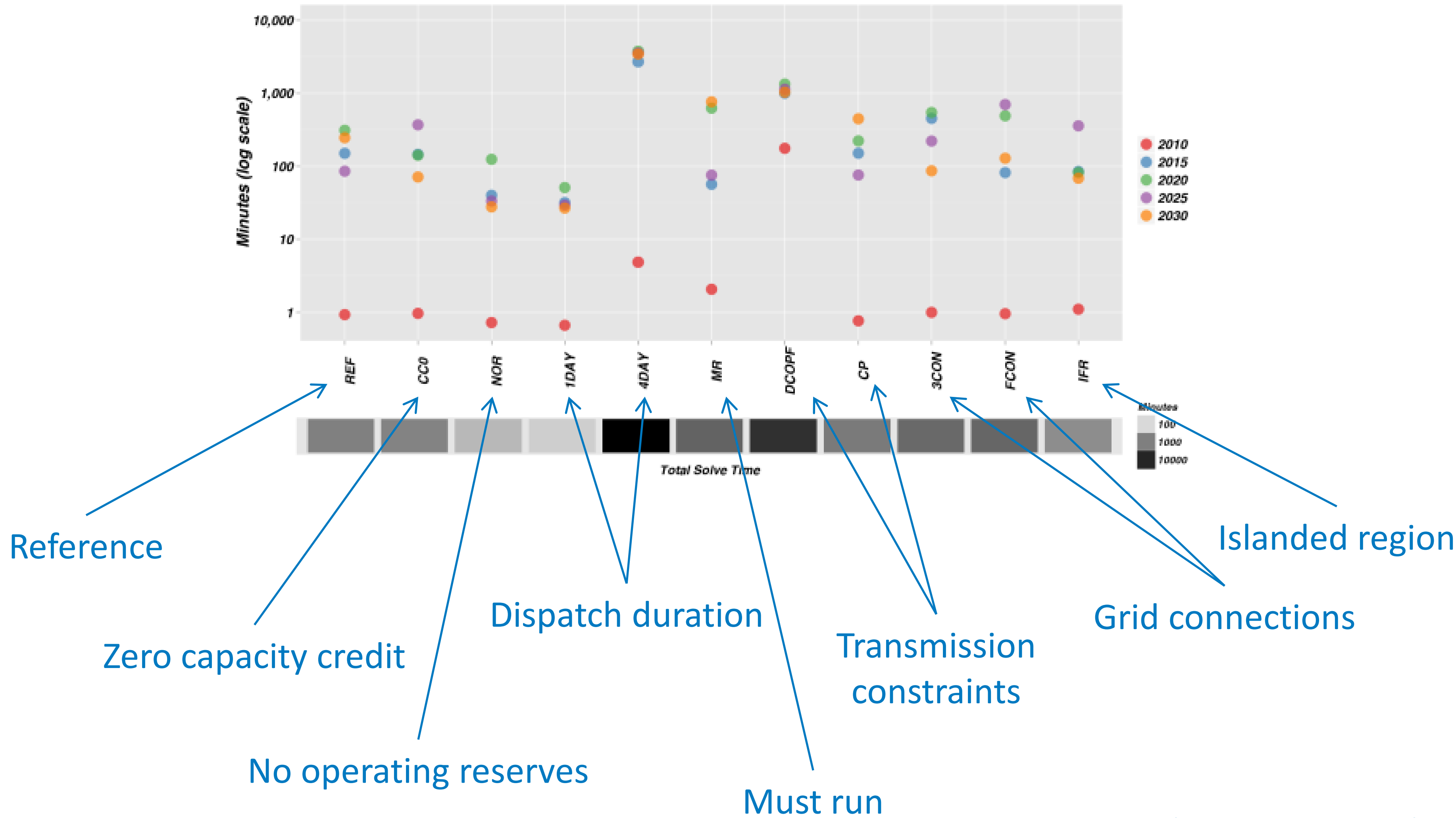




Capacity Expansion Models Have to Balance Operational Detail with Computational Complexity

Computation Time as a Function of Model Configuration

These have generally been improved, but the relative times are still illustrative.



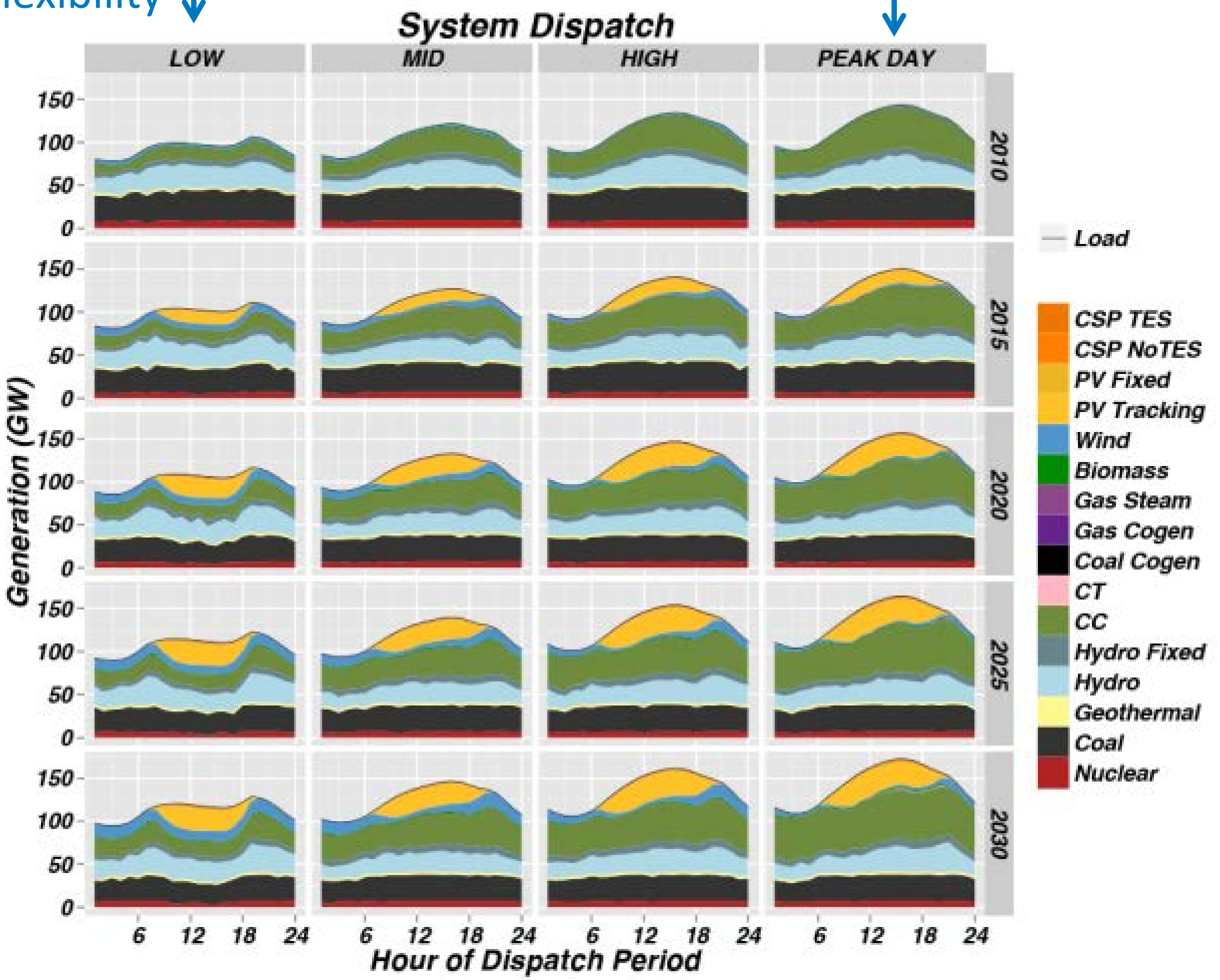
(Mai et al. 2015)

Reduced Order Dispatch Does Not Fully Address the Variability Seen Throughout the Year

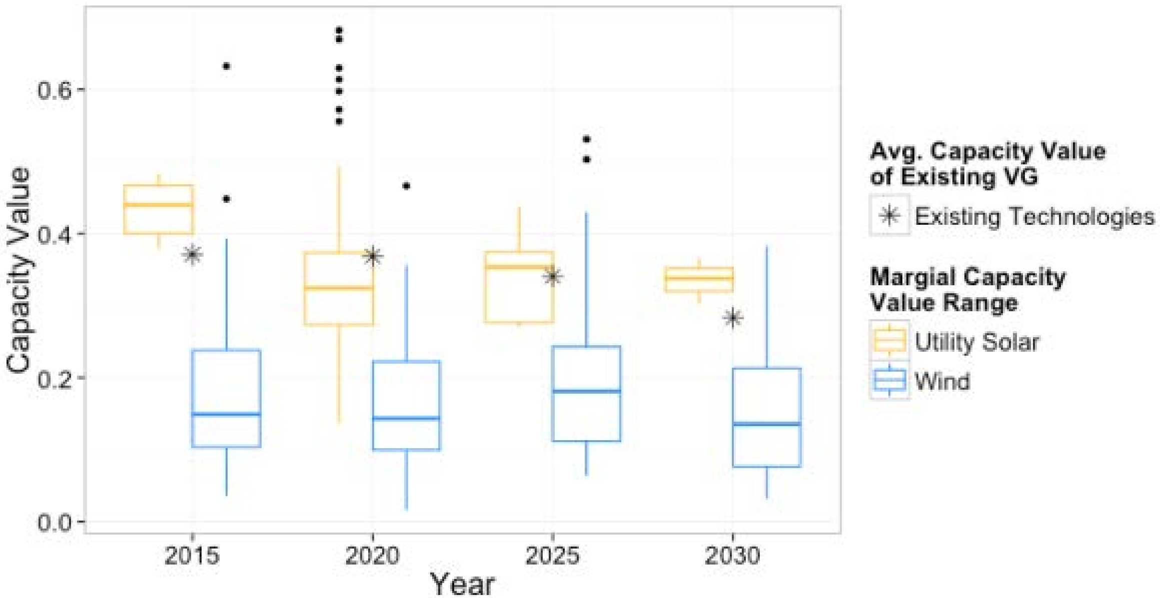
Low period does not fully capture conflict between wind, solar, and thermal fleet inflexibility ↓

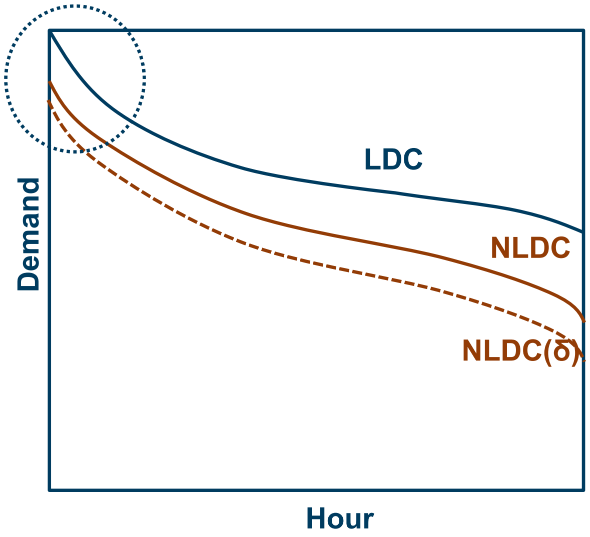
Peak day does not fully capture capacity value ↓

96 dispatch hours per year →



Variable Generation (Wind and Solar) Capacity Value

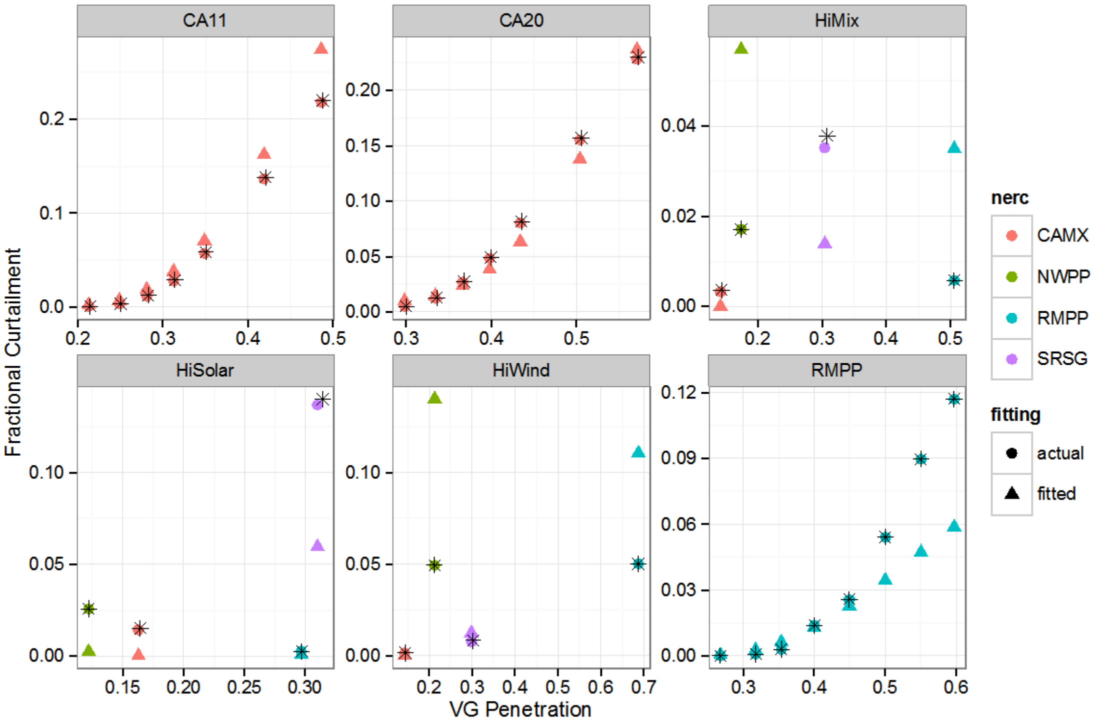


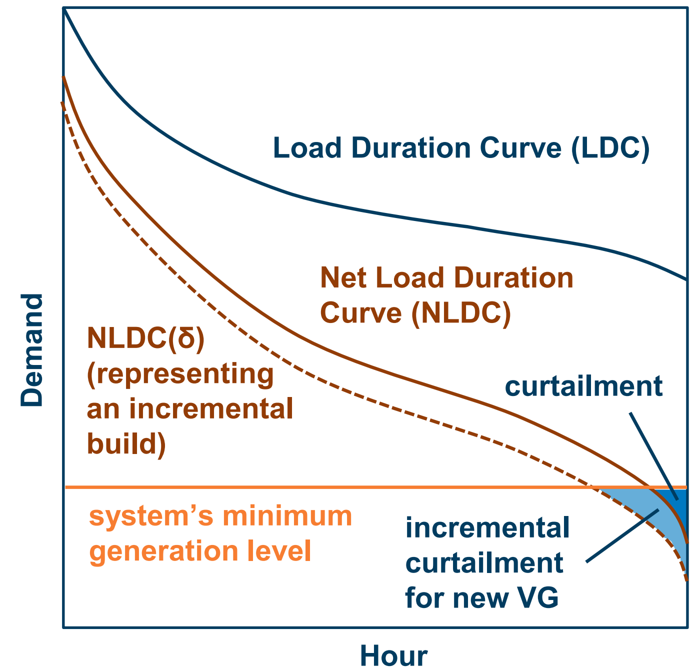


- Capture shift in net peak load based on top 100 hours
- Values geospatial and technology diversity
- For each NERC region:
  - Capacity value of existing VG = <LDC – NLDC>$_{\text{top 100}}$ / (existing VG capacity · 100)
- For each VG resource region:
  - Marginal capacity value of new VG = <NLDC(δ) – NLDC>$_{\text{top 100}}$ / (δ · 100)

Fractional capacity values used in planning reserve constraints

Minimum Curtailment of Variable Generation





- Curtailment of wind and solar arises when the thermal fleet cannot be turned down enough to accommodate their full output
- RPM's curtailment estimates are based on regression analysis of curtailment seen in production cost model runs as a function of system composition

Modeling Storage in RPM

Modeling Approach

0. RPM was initially designed with high renewable futures and flexibility in mind
1. "Yoga for capacity expansion models"—capture system-dependent capacity values, minimum curtailment, and curtailment mitigation with parameters calculated with regression models, load duration curve, and heuristic dispatch methods
2. Model the storage investment decision with a dispatch model that allows value stacking

Storage Technologies are Defined By

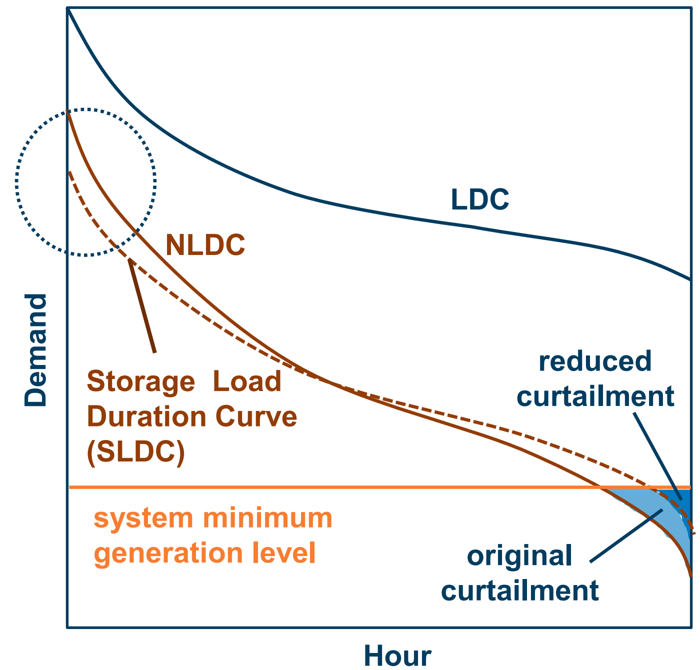
- **Amount of storage per unit power capacity** (h, that is, MWh/MW)
- **Capital and fixed O&M** per unit power capacity ($/kW and $/kW-yr, respectively)
- **Variable O&M** per unit energy discharged
- **Roundtrip charging efficiency**

Storage Value Stacking

- **Capacity** – Fraction of nameplate that can contribute to planning reserves
- **Energy arbitrage** – Shift energy generation from times of low net load/price to times of high net load/price
- **Curtailment reduction** – A specific form of energy arbitrage
- **Operating reserves**
  - Spinning contingency
  - Flexibility (forecast uncertainty over hours)
  - Regulation (balancing over seconds)

Yoga for Storage Technologies: Capacity Value and Curtailment Mitigation

- A heuristic dispatch algorithm is used to simulate storage optimizing its capacity value and curtailment reduction potential
  - Whenever there is curtailment, storage is charged
  - Whenever the net load is in the peak hours, storage is discharged
  - At all other times, storage is used to ensure capacity to charge or discharge is available during curtailment periods or peak hours, respectively



- Capacity value of storage is estimated from the Storage Load Duration Curve (SLDC) in the same way the capacity value of variable generation is estimated from the NLDC
- Curtailment reduction is calculated as the fraction of the original curtailment that storage helps the system avoid

Storage Dispatch Model

storage level(t) =

storage level(t-1) + charge(t) * efficiency

– generation(t)

– 0.25 [flexibility(t) + regulation(t)] * (1 – efficiency)

storage level(t) ≤ capacity * energy capacity

generation(t) + charge(t) + spin(t) + flexibility(t) + regulation(t)

≤ capacity

storage level is required to balance over the year

storage imbalances for each dispatch period cannot exceed the energy capacity

spin, flexibility, and regulation are all limited by ramp rate

new storage reduces required curtailment from existing wind and solar

storage must charge at least as much as the calculated curtailment reduction effects require

Results

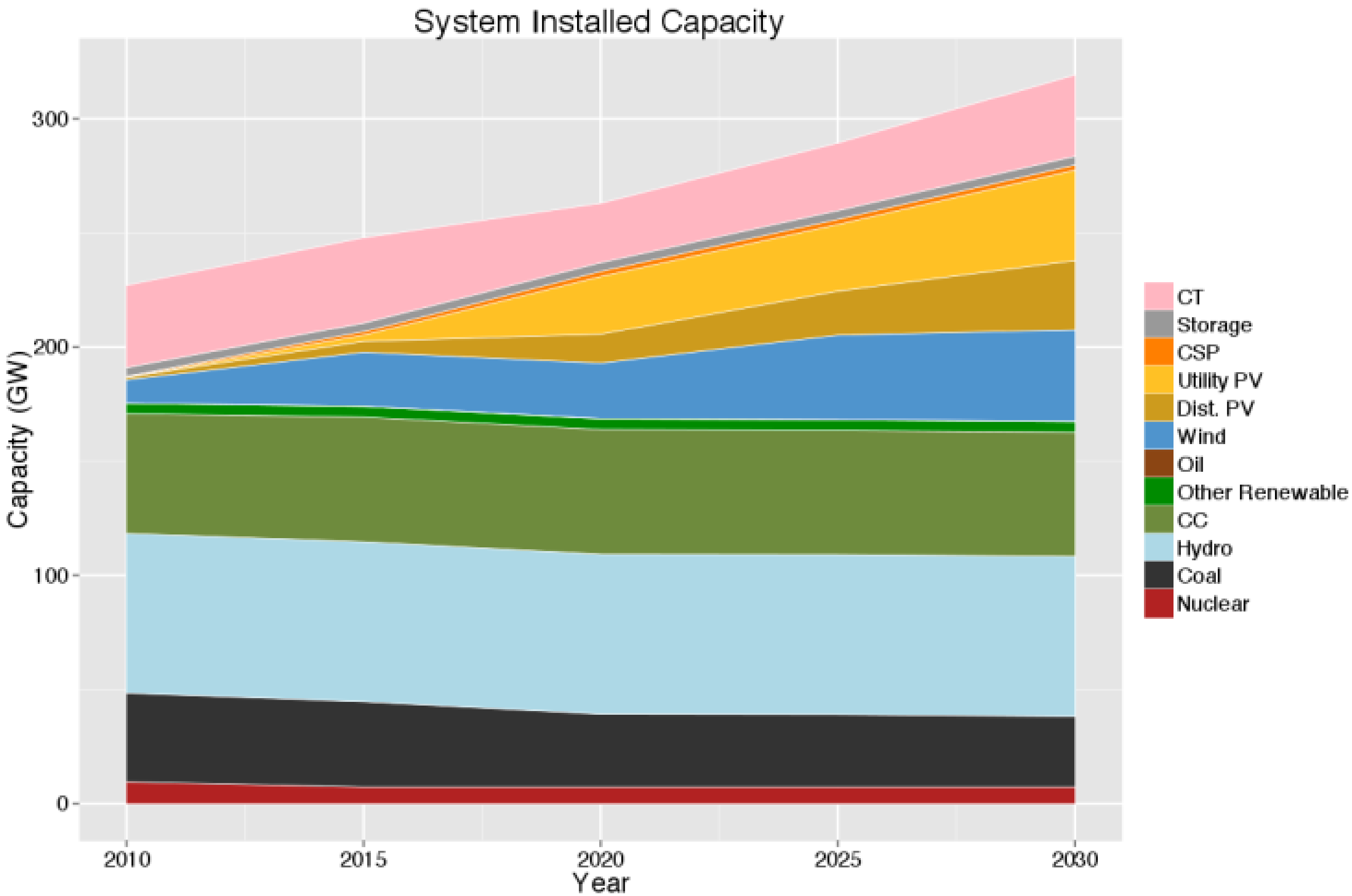
Storage Technologies and Costs: An Initial Experiment

Technologies Selected from the DOE/EPRI 2013 Electricity Storage Handbook

Storage Subclass	Description	Energy Capacity (h)	Roundtrip Efficiency	Capital Cost ($/kW)	FOM ($/MW-yr)	VOM ($/MWh)
c0	Li-Ion for regulation	0.25	0.9	1,038	6,403	1.04
c1	Lead-acid for reserves	0.5	0.9	1,633	5,917	0.49
c2	Li-Ion	1	0.9	1,426	6,984	3.72
c3	Li-Ion	2	0.93	4,570	26,800	2.70
c4	NaCl-Ni	2	0.85	2,040	10,137	2.62
c5	Lead-acid	4	0.9	4,261	13,320	0.97
c6	Iron-chromium	4	0.75	1,500	8,924	1.36
c7	Zinc-air	6	0.8	1,663	7,404	0.74
c8	Pumped hydro	8	0.81	2,350	6,603	0.30
c9	Lead-acid	10	0.9	5,023	9,200	0.50
c10	Iron-chromium	10	0.75	2,484	7,596	0.40
c11	Pumped hydro	16	0.8	2,200	6,130	0.30

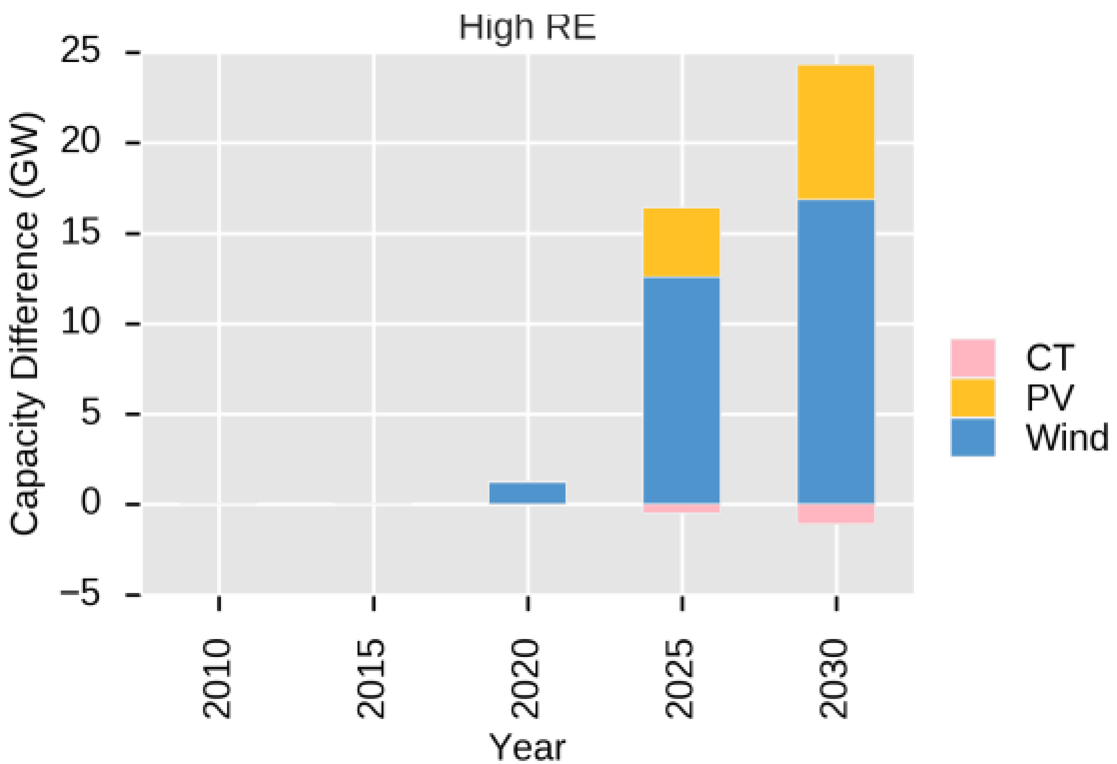
- Single-point costs—Reduced capital costs by a fraction less than one in a number of scenarios to see how costs impact storage deployment and use
- For each technology, implemented a floor of $100/kWh—except for pumped hydro whose costs were kept constant

Base Scenario for the Western Interconnect



(Hale et al. 2016)

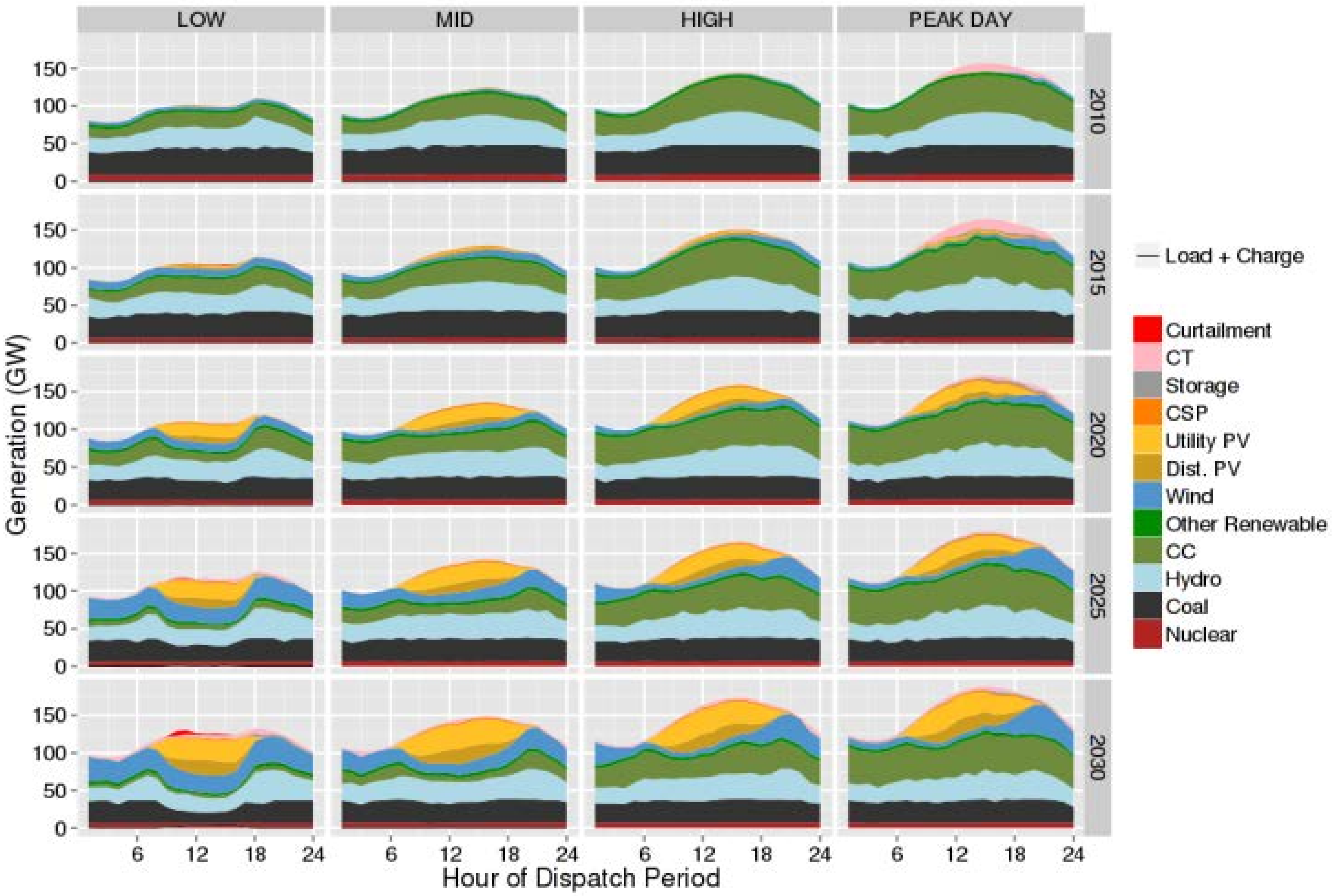
High Renewable Energy Scenario, Difference with Base Case



Capacity expansion changes induced with high gas price trajectory and a non-zero carbon price trajectory.

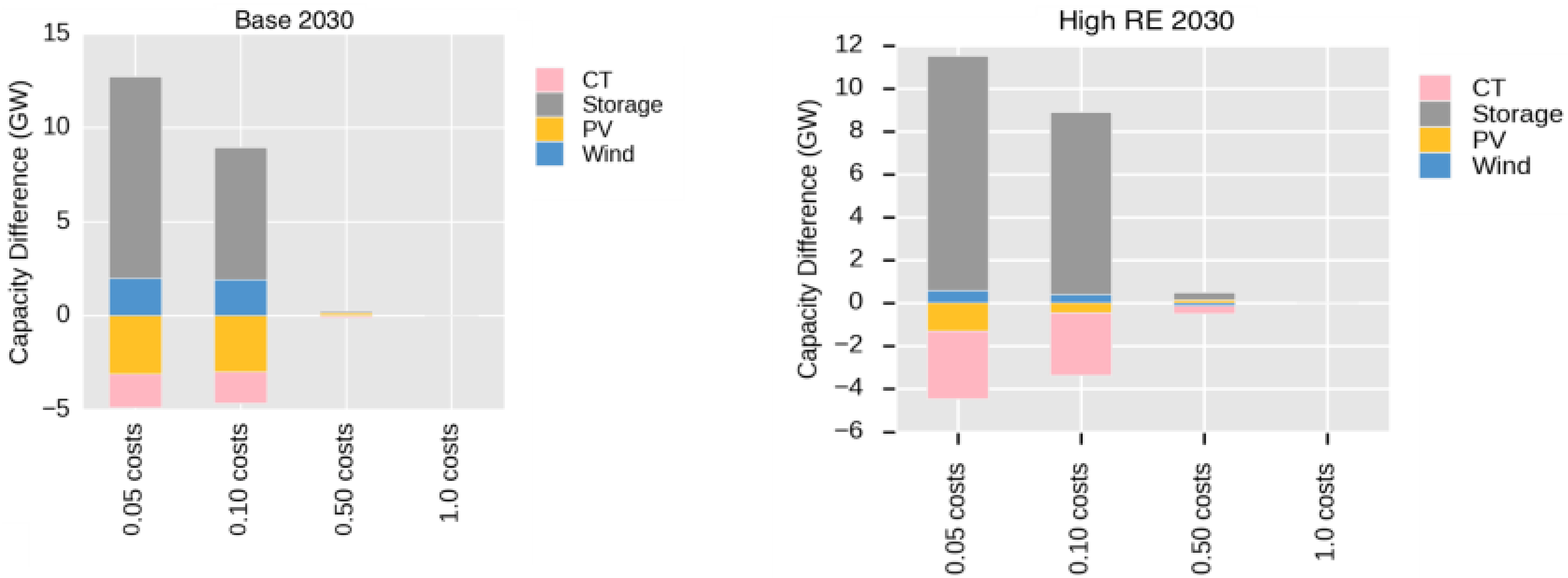
(Hale et al. 2016)

High Renewable Case Dispatch



(Hale et al. 2016)

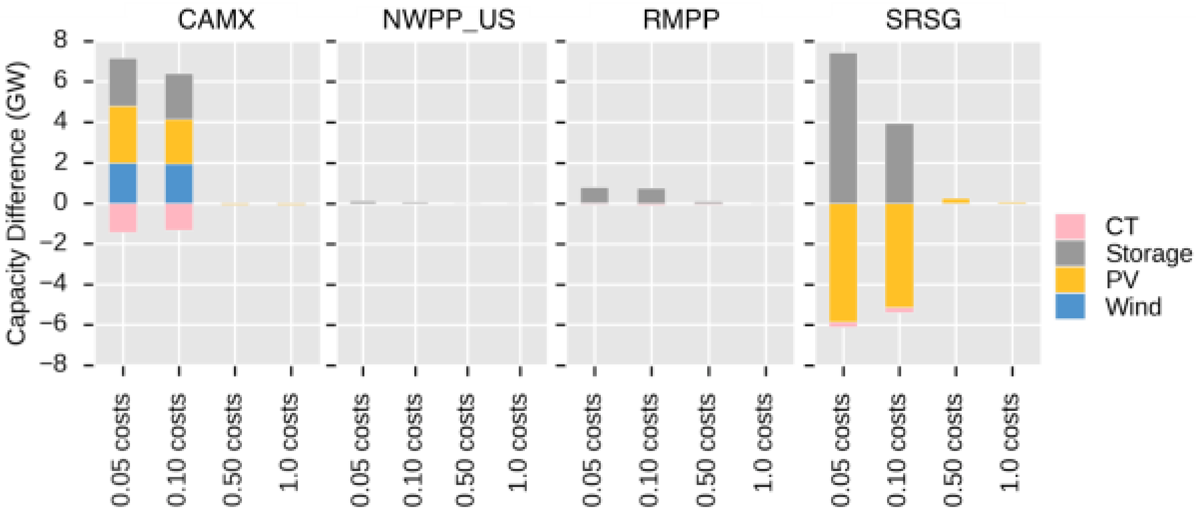
Storage Deployment as a Function of Cost Reductions

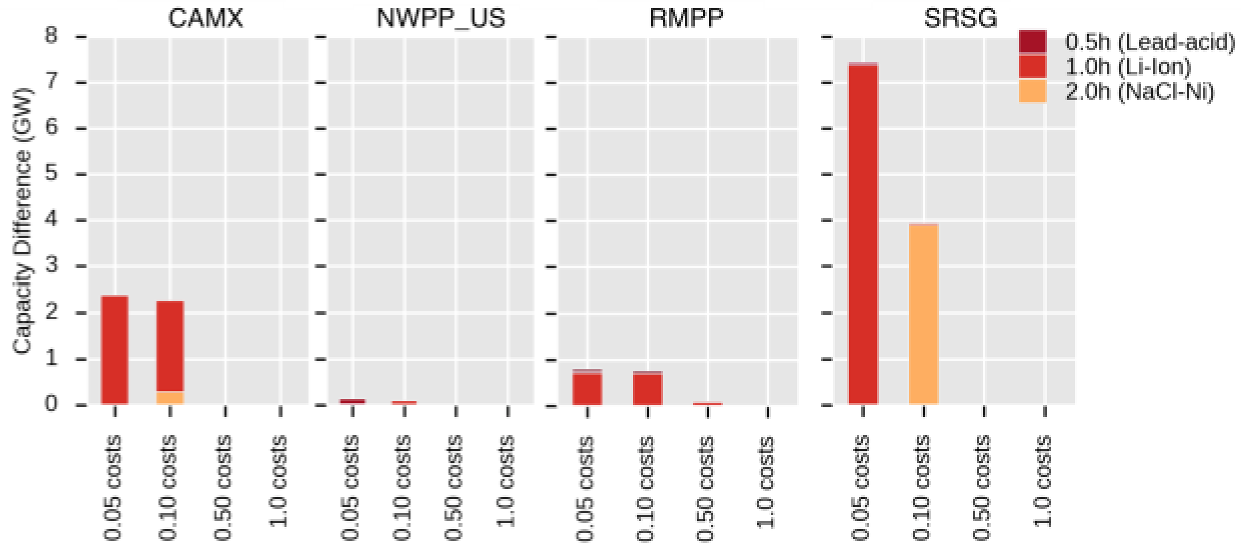


(Hale et al. 2016)

Deployment Depends on Regional Needs – Base Scenario

- CAMX and SRSG need capacity
- RMPP and NWPP-US need reserves
- Storage helps CAMX import fewer renewable energy credits

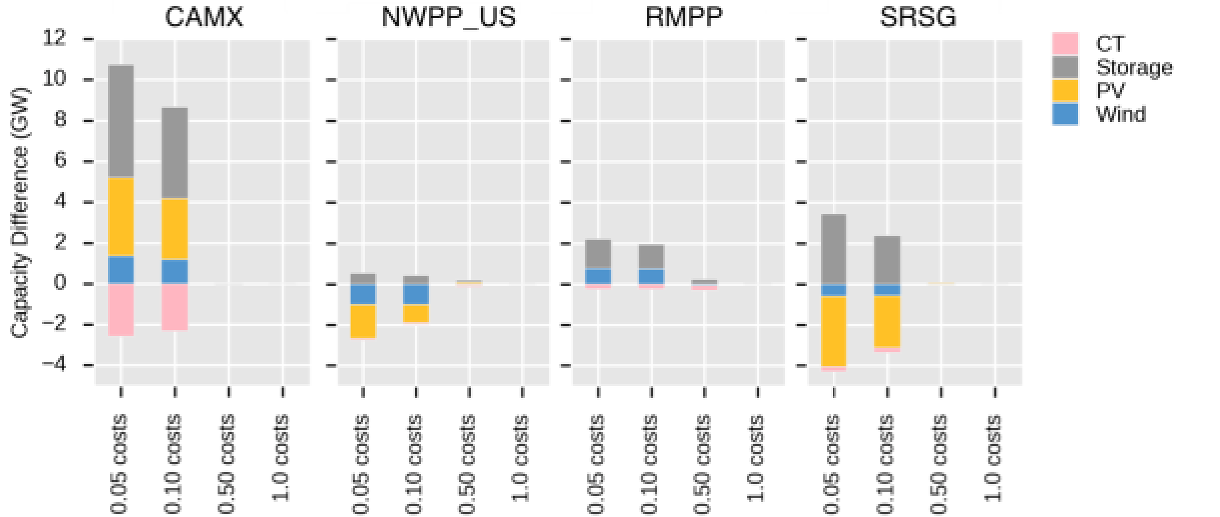


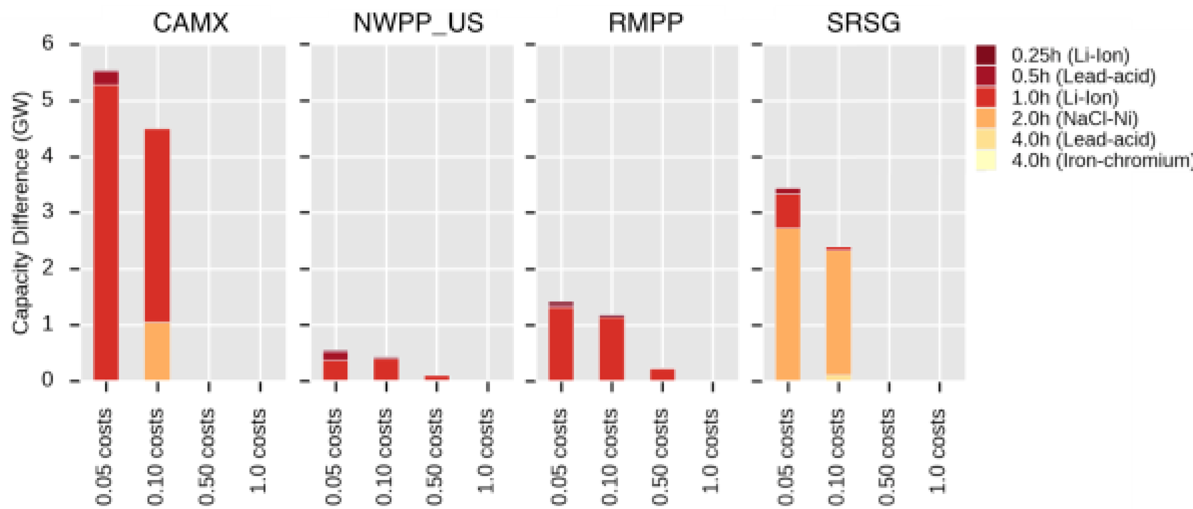


Deployment Depends on Regional Needs – High RE Scenario

- Additional renewables put more pressure on reserves, which favors some short-duration technologies

- CAMX moves even more renewable generation within its borders

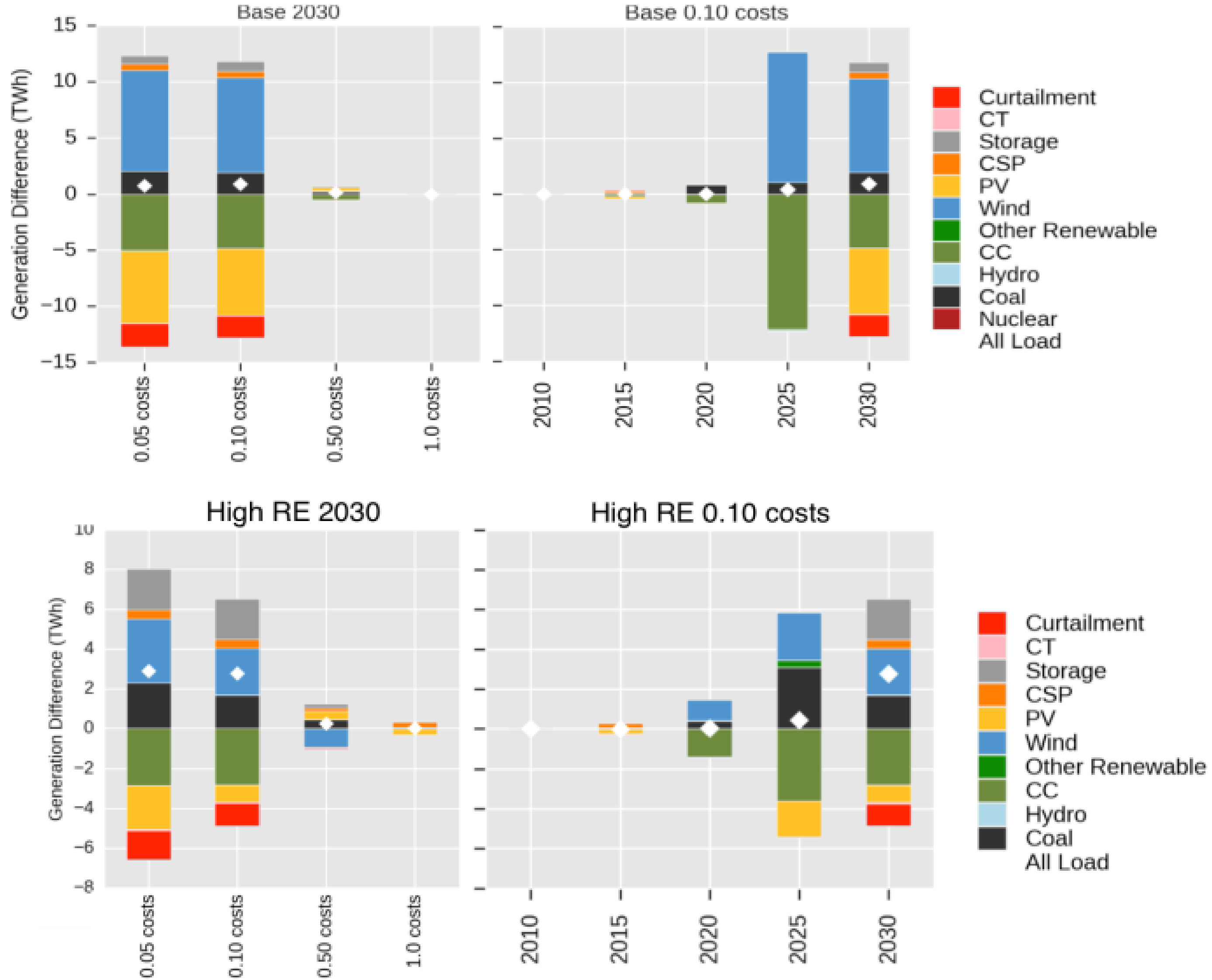




Net Effects of Shifting Capacity and Energy Arbitrage

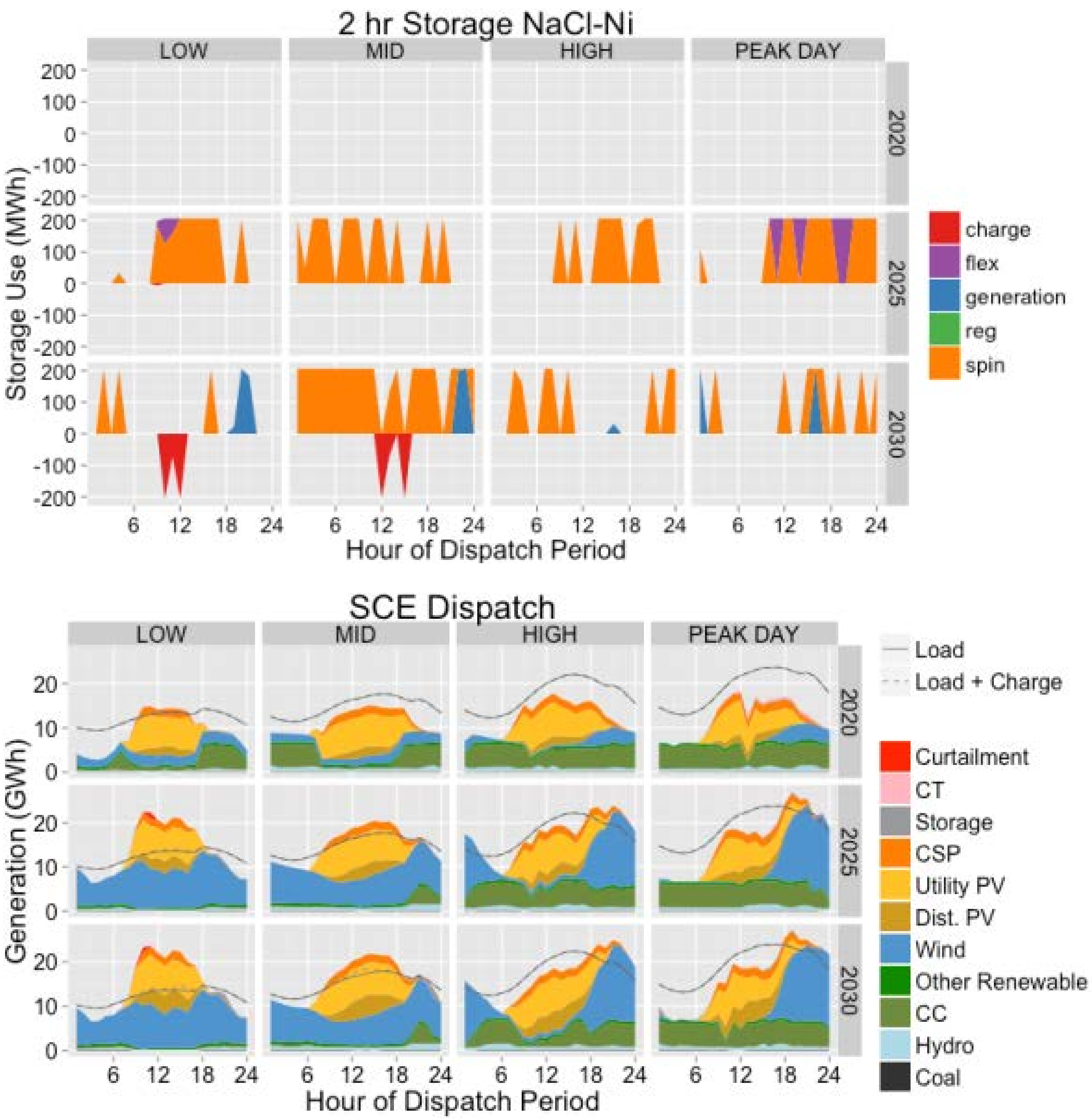
- Base case has more renewable generation on net

- Higher renewable penetrations lead to more active arbitrage



(Hale et al. 2016)

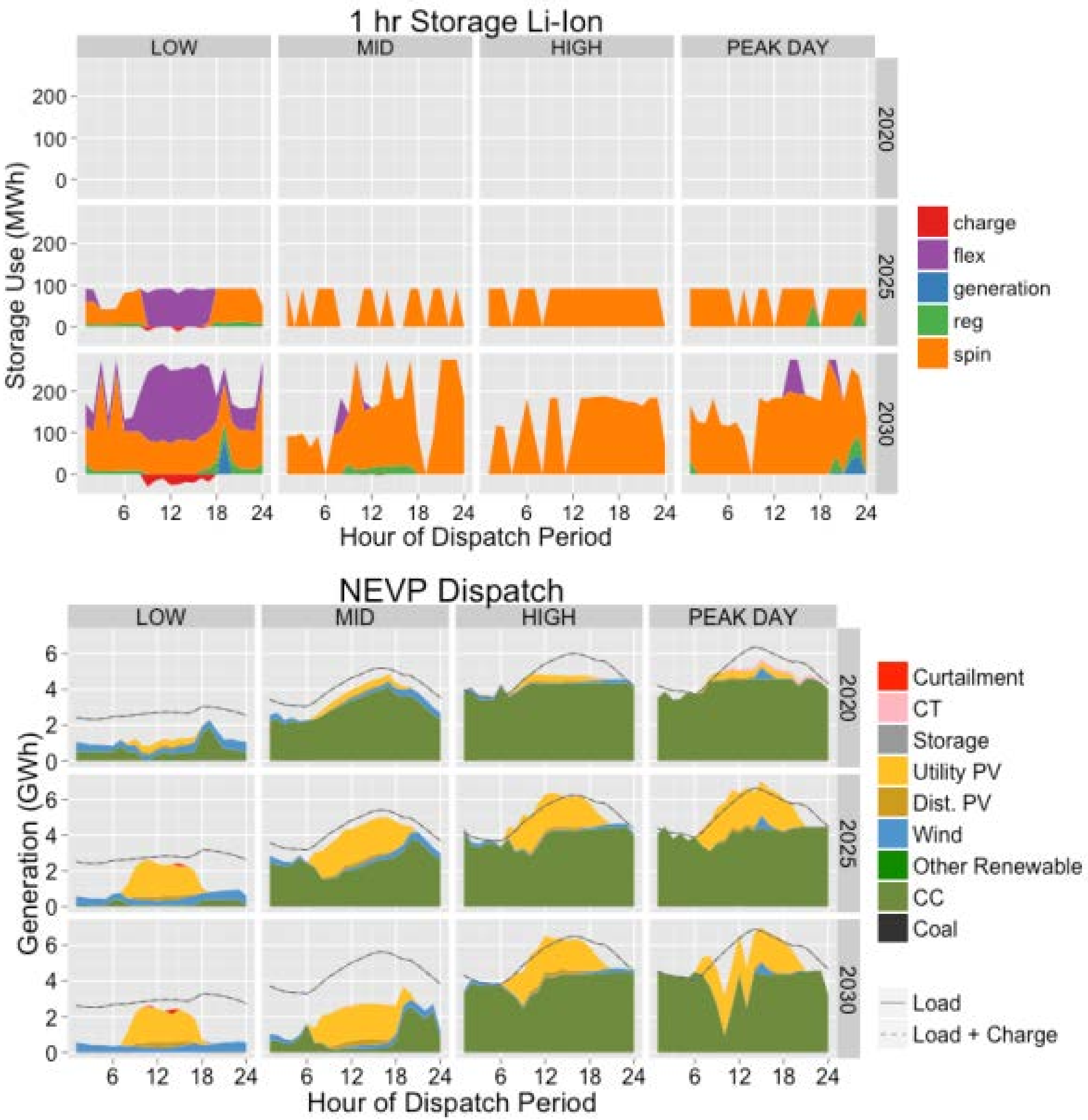
Usage Example: SCE, Base, 10% Capital Cost Scenario



- When first built in 2025, storage provides reserves necessary to integrate wind
- As an existing resource in 2030, the storage provides active arbitrage, charging during high-PV hours, and discharging during high net-load hours in the evening

(Hale et al. 2016)

Usage Example: NEVP, High RE, 10% Capital Cost Scenario



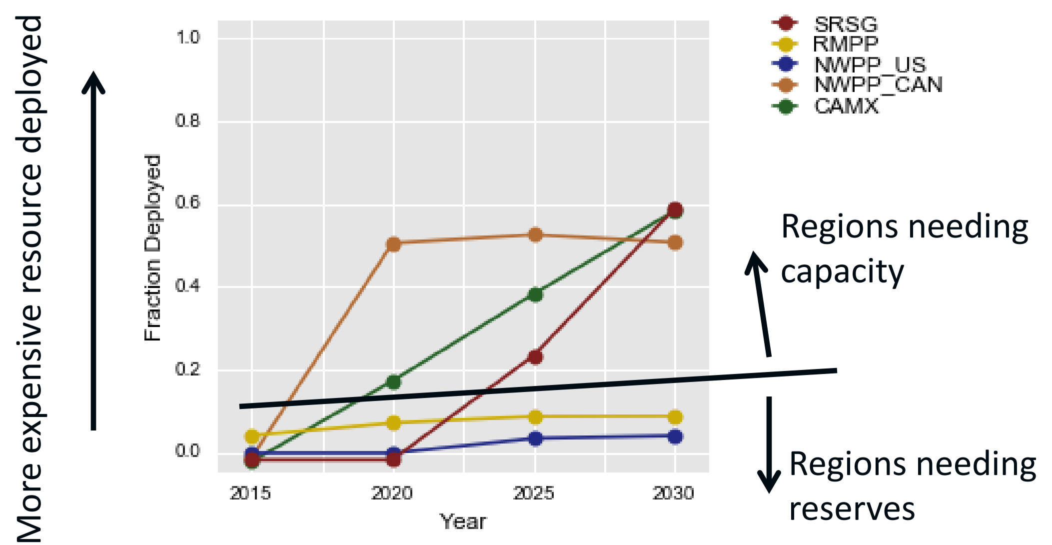
- The primary use for this storage resource is reserves
- Note the high use for flexibility reserves during the low dispatch period, daylight hours

(Hale et al. 2016)

Related and Future Work

Interruptible Load Roles as a Function of Price Point

- Modeled with a yearly cost and energy constraints per day (1–8 h) and per year (50–150 h)
- Interruptible load is a capacity service—capacity value, generation during peak times, spinning contingency reserves
- As with storage, regional deployment depends on regional needs



(Hale et al. 2016)

Concentrating Solar Power with Thermal Energy Storage

- Configurations determined by solar multiple and energy capacity
- Charging is based on incoming solar thermal energy
- Losses are one-time and dissipative
- Curtailment is a slightly different beast

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- Forthcoming analysis for the Western Interconnect looking at different CSP configurations and cost trajectories, along with different PV and battery storage cost trajectories

Thank you!

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