The Solar Curtailment Paradox

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NREL Webinar

Some context

- This talk draws from a recently published *Joule* article **"The curtailment paradox in the transition to high solar power systems"**
  - https://doi.org/10.1016/j.joule.2021.03.021
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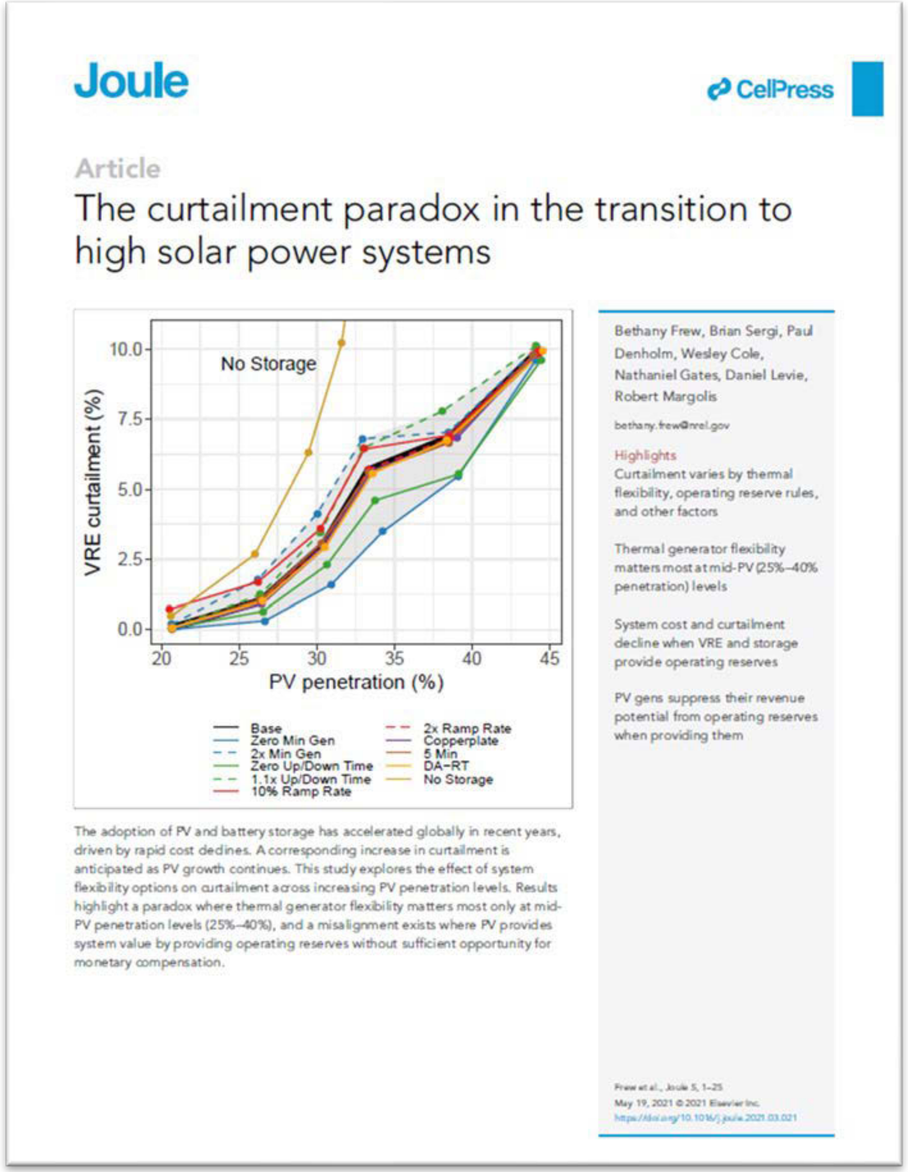
- Funding from U.S. Department of Energy Solar Energy Technologies Office


Joule
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Article

The curtailment paradox in the transition to high solar power systems

The adoption of PV and battery storage has accelerated globally in recent years, driven by rapid cost declines. A corresponding increase in curtailment is anticipated as PV growth continues. This study explores the effect of system flexibility options on curtailment across increasing PV penetration levels. Results highlight a paradox where thermal generator flexibility matters most only at mid-PV penetration levels (25%–40%), and a misalignment exists where PV provides system value by providing operating reserves without sufficient opportunity for monetary compensation.

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Highlights

Curtailment varies by thermal flexibility, operating reserve rules, and other factors

Thermal generator flexibility matters most at mid-PV (25%–40% penetration) levels

System cost and curtailment decline when VRE and storage provide operating reserves

PV gens suppress their revenue potential from operating reserves when providing them

Frew et al., Joule 5, 1–25
May 19, 2021
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Par·a·dox

/ˈperəˌdäks/

noun

a seemingly absurd or self-contradictory statement or proposition that when investigated or explained may prove to be well founded or true

https://www.lexico.com/en/definition/paradox

Two pieces of the solar curtailment paradox

1) Thermal generator parameters, especially by restricting minimum operating levels and ramp rates, **impact variable renewable energy (VRE) curtailment more in mid-PV contribution levels** (~25%–40%) than in lower (~20%) or higher (~45%) PV contribution levels.

2) While allowing VRE and storage to provide operating reserves results in reduced operating cost and curtailment, **the price suppression effect from these resources reduces incentives for PV to provide operating reserves with curtailed energy**.

How did we arrive there?

We:

1. Systematically explored the **impact of flexibility options on curtailment levels as PV contributions grow**, e.g., operational flexibility of thermal generators, battery storage, transmission
2. Assessed the **potential value in allowing VRE and storage to provide operating reserves** with that curtailed energy

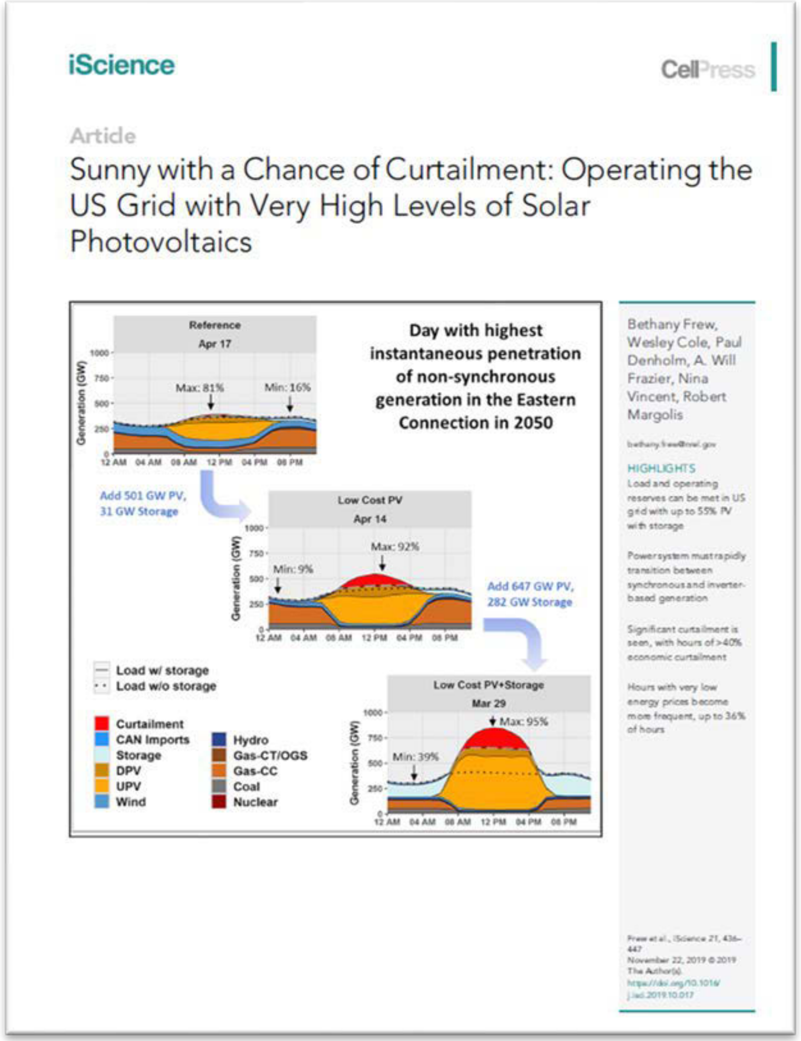
- Existing work has looked at some of these factors, but not all in comparison, and typically at much lower PV contribution levels (generally 5%–20%)
  - Highest PV study was 50% solar, exploring impact of minimum generation levels and startup costs (Bistline 2019)

Why curtailment?

- Curtailment occurs **when generation exceeds demand** and/or **system conditions impose operational constraints** that preclude all the available energy from being utilized (Sun et al. 2020, Bird 2016, Bird 2014)
  - Lack of system flexibility includes transmission congestion, minimum generation levels of thermal generators or hydropower, or back-feeding in the distribution system (Lew et al. 2013, Denholm et al. 2018, Bistline 2018, Jorgenson et al. 2017, O'Shaughnessy et al. 2020)

A new normal in grid operations

- Economic curtailment (i.e., part of least-cost operations) is a **new normal in grid operations** by providing flexibility to ensure grid reliability
  - Our previous work found many hours of 40+% curtailment
    (Frew et al. 2019)


iScience CellPress

Article

Sunny with a Chance of Curtailment: Operating the US Grid with Very High Levels of Solar Photovoltaics

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HIGHLIGHTS

Load and operating reserves can be met in US grid with up to 55% PV with storage

Power system must rapidly transition between synchronous and inverter-based generation

Significant curtailment is seen, with hours of >40% economic curtailment

Hours with very low energy prices become more frequent, up to 36% of hours

Frew et al., iScience 21, 436–447
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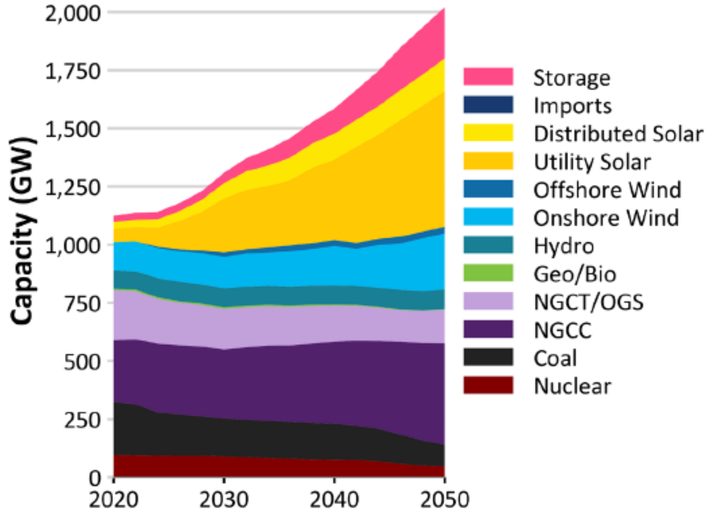
https://doi.org/10.1016/j.isci.2019.10.017

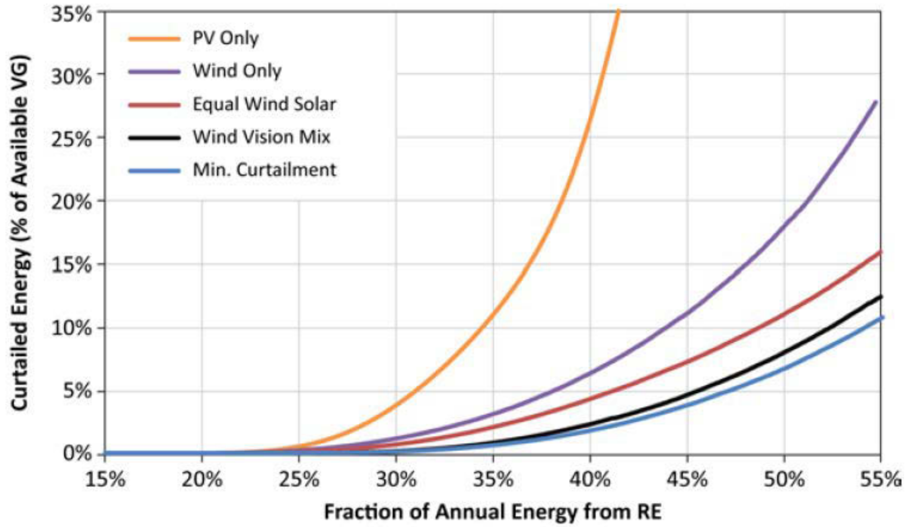
Why PV?

- PV is projected to have the **largest share of new renewable deployments** in the U.S. (Cole et al. 2020) and world (IEA 2020)

- PV has a **more rapid increase in curtailment as contribution levels increase** due to its coincident nature (Denholm & Mai 2019)



(Cole et al. 2020)



(Denholm & Mai 2020)

Who cares?

Overarching question: *What challenges/interactions do grid stakeholders need to confront as PV contributions grow?*

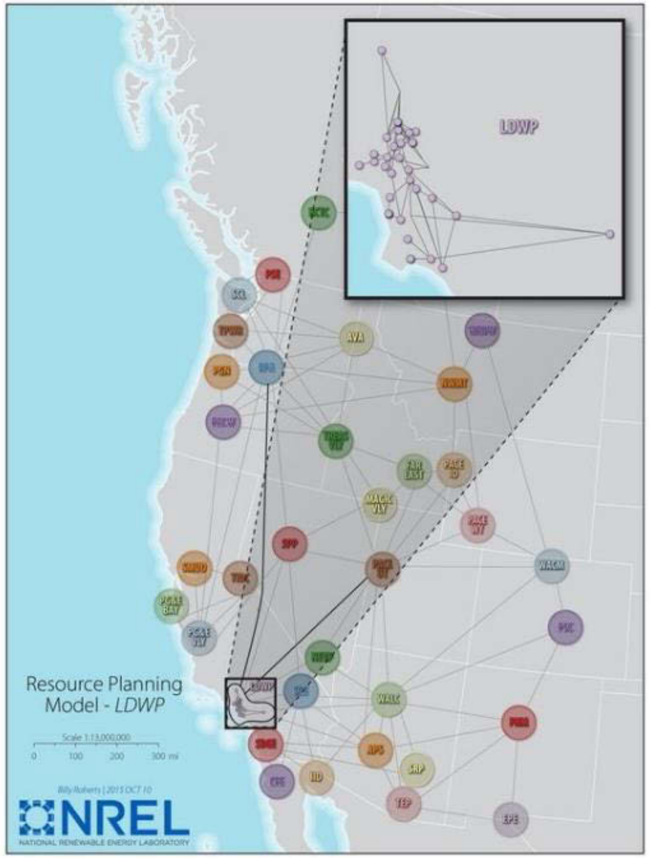
- **System planners and operators**
  - Thermal generator operations are particularly important at mid-PV contribution levels (25%–40%), suggesting a phased approach for the ongoing transformation of the power system
- **Market designers**
  - Potential need to revise operating reserve eligibility rules and compensation structures as PV contributions increase

Our study system

- **Roughly based on the Los Angeles Department of Water and Power (LADWP)**, leveraging data from the recently released LA100 study (https://maps.nrel.gov/la100)

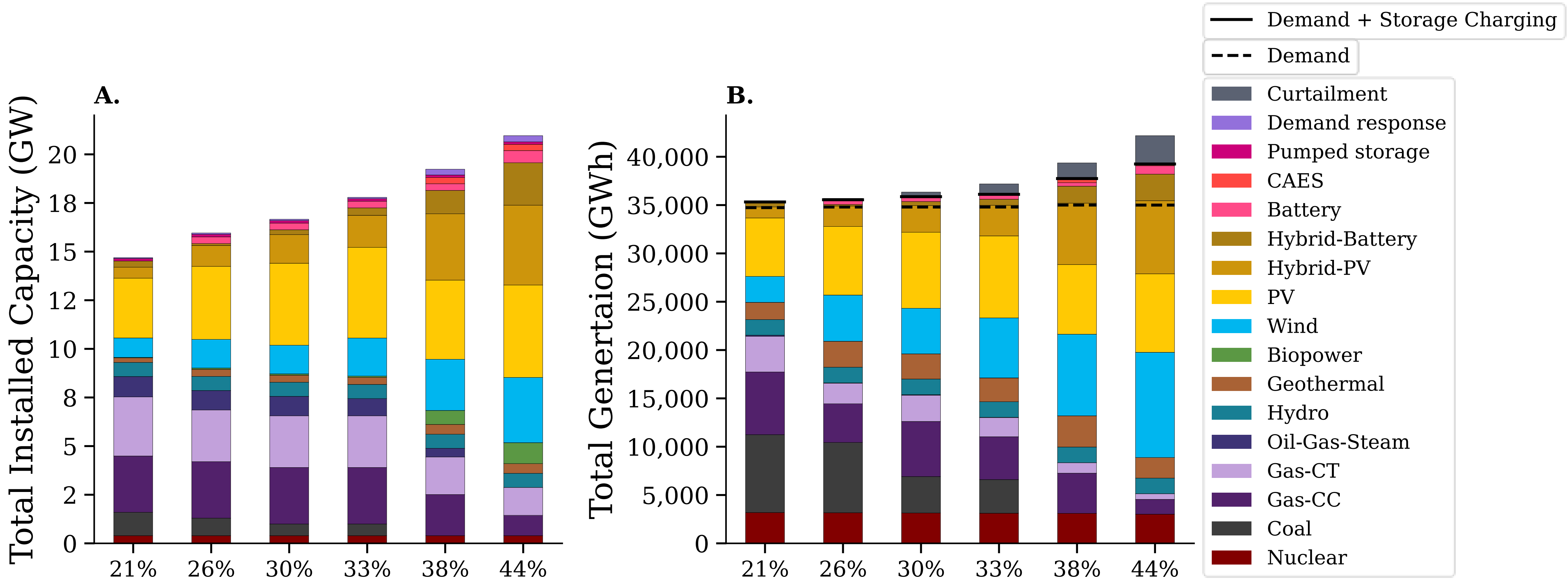
- **Used capacity expansion modeling (CEM) to develop six PV and storage buildout cases (with consistent load)**
  - Captures need to overbuild (declining capacity credit)
  - Guarantees cost recovery for Base case only

- **Used production cost modeling (PCM) with PLEXOS to explore operations with each of those buildout cases**
  - Explore curtailment, generation, cost, and price outcomes for these static cases with different operations parameters
  - Does not guarantee long-run cost recovery for any sensitivity



NREL's Regional Planning Model (RPM) was used to establish six buildout cases for the LADWP footprint

Six buildout cases – named by annual PV contribution level



Notes:

- Generation (and associated PV contribution level naming convention) is shown for Base scenario
- “Hybrid” PV is co-located with a common point of interconnection, shared inverter (PV+storage generation cannot exceed inverter rating), and loosely coupled (can charge from grid or PV)

Base scenario

Renewable contribution Annual avg (max instantaneous) % of total annual generation			Capacity contribution % of peak load	Curtailment Annual avg (max instantaneous) % of available resource	
PV	VRE	RE	Storage	VRE	PV
21% (71%)	28% (79%)	38% (84%)	6%	0.1% (28%)	0.1% (21%)
26% (81%)	40% (90%)	52% (92%)	8%	1.1% (36%)	1.0% (43%)
30% (87%)	44% (92%)	56% (95%)	10%	2.8% (46%)	3.0% (50%)
33% (88%)	51% (93%)	63% (96%)	11%	6.7% (40%)	5.7% (50%)
38% (94%)	63% (96%)	76% (96%)	24%	5.8% (47%)	6.8% (54%)
44% (96%)	75% (96%)	86% (97%)	37%	8.2% (57%)	9.9% (65%)

PV = utility-scale, stand-alone, and hybrid PV systems, as well as distributed PV resources
VRE = wind and PV
RE = all renewable resources = VRE, biopower, geothermal, and hydropower
Storage = batteries (4- and 8-hour duration stand-alone and hybrid) and pumped hydropower
Instantaneous curtailment levels shown are for hours with available VRE generation of at least 1% of installed capacity

Sensitivity scenarios

We explored 14 scenarios across the six buildouts, resulting in **84** unique instances

Category	Sensitivity	Description
Baseline	Base	Hourly resolution real-time operations with base values; utility-scale VRE eligible to provide operating reserves (distributed PV cannot provide reserves)
Thermal plant flexibility	Zero Min Gen	Minimum generation levels for online dispatchable generators set to zero
	2x Min Gen	Minimum generation levels for dispatchable generators increased to double the base value, up to a maximum of 1 (as a fraction of nameplate capacity)
	Zero Up/Down Time	Minimum on/off times for dispatchable generators set to zero
	1.1x Up/Down Time	Minimum on/off times for dispatchable generators set to 1.1 times base value
	10% Ramp	Maximum ramp up/down rates for dispatchable generators set to 10% of base value
	2x Ramp	Maximum ramp up/down rates for dispatchable generators set to double base value
Eligibility of VRE and storage resources to provide reserves	No VRE Reserves	Utility-scale VRE (stand-alone and VRE portion of hybrid systems) ineligible to provide operating reserves
	No Storage Reserves	Battery storage (stand-alone and battery portion of hybrid systems) and PSH ineligible to provide operating reserves
	No Storage or VRE Reserves	All utility-scale VRE and battery and PSH storage ineligible to provide operating reserves
Other operational constraints	5-Min	5-minute resolution real-time operations; other cases use hourly resolution
	DA-RT	Unit commitment for certain units occurs in day-ahead (DA) simulation using forecasted wind and solar time series, with final dispatch determined by a real-time (RT) simulation with actual wind and solar time series
	No Storage	All storage (battery, PSH, and CAES) replaced with equivalent capacity of Gas-CT; serves as counterfactual case
	Copperplate	Transmission limits not enforced

Ramp rate, duration (up/down time), and magnitude (mingen) all impact how much VRE variability and uncertainty the system can absorb before curtailing (a la “Duck Curve”)

Allowing VRE and storage to provide operating reserves enables access to otherwise curtailed energy in the upward direction and additional curtailed energy in the downward direction

Impact on rest-of-system operations (e.g., unit commitment) from greater operational resolution, forecast uncertainty, no storage, and no transmission constraints

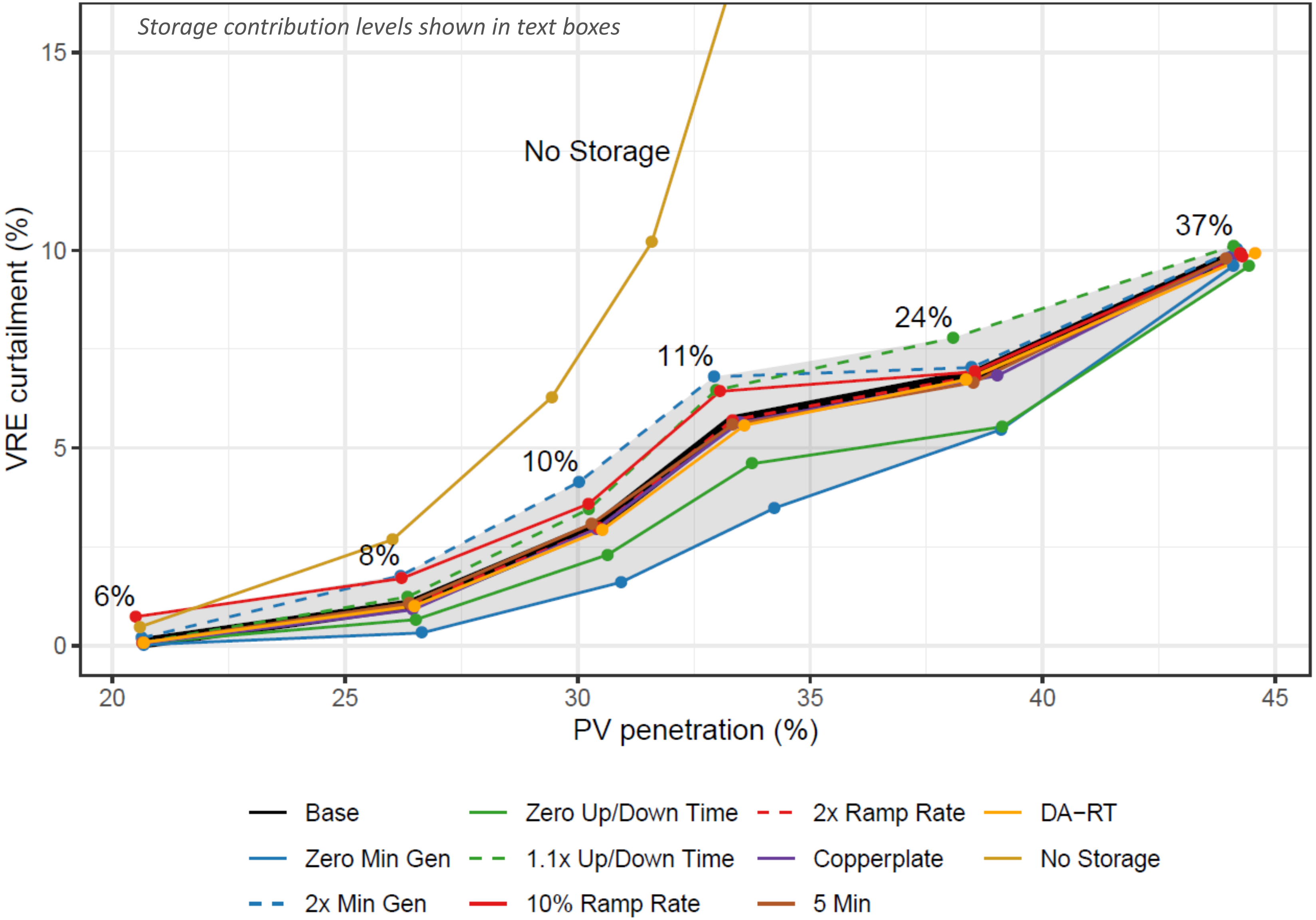
Operating reserve scenarios

- Eligible generators may provide operating reserves up to their operating limits (i.e., within ramping, maximum resource availability, and online status constraints)
- Six products:
  - **Regulation up/down** (upward/downward, 5 min response, $4,100/MW shortage price)
  - **Spinning** (upward, 10 min response, $4,000/MW shortage price)
  - **Non Spinning** (upward and/or offline, 10 min response, $4,000/MW shortage price)
  - **Flexibility up/down** (upward/downward, 20 min response, $3,900/MW shortage price)

Paradox 1: Thermal flexibility only really matters in the middle

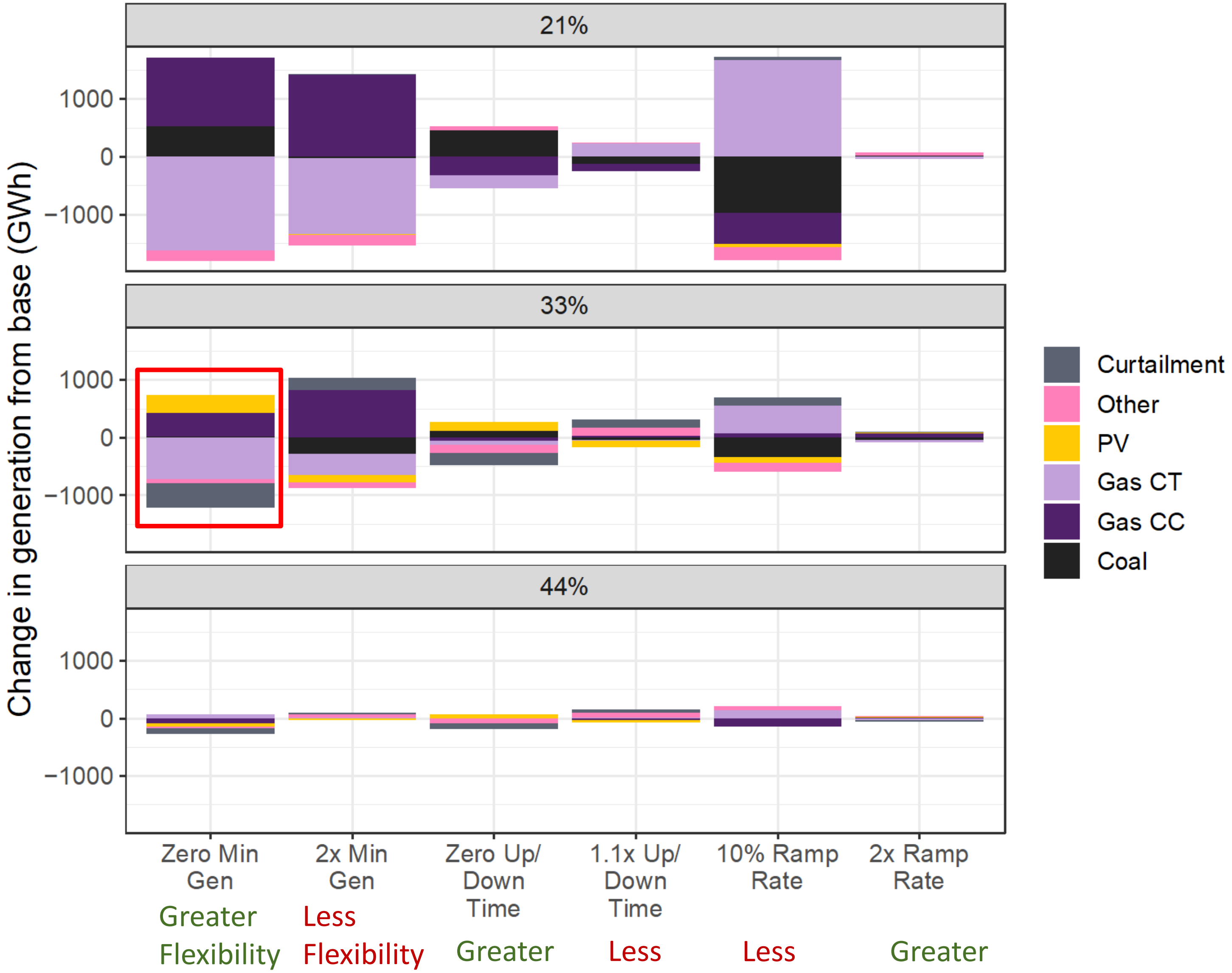
VRE curtailment

all scenarios except operating reserves sensitivities



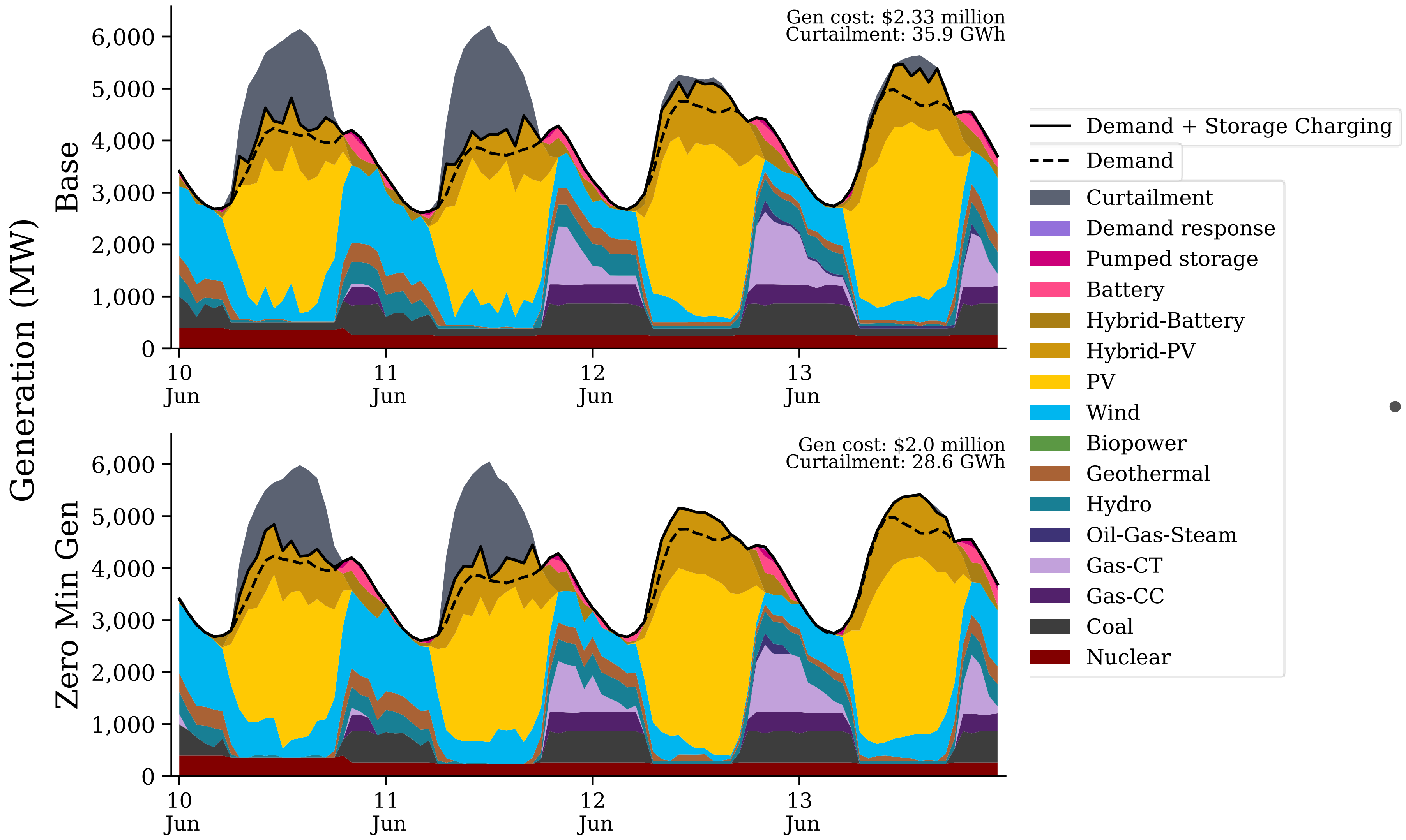
- No Storage serves as a counterfactual case
- “Transition zone” or “Goldilocks zone” exists at **mid PV levels** (roughly 25%–40% in this system)
  - Thermal generator flexibility (ramp rate, minimum generation levels, and minimum up-and-down time) impacts VRE curtailment more than at lower (about 20%) or higher (about 45%) contribution levels
- Significantly less curtailment impacts are observed from transmission constraints, forecasting errors, or temporal resolution

Thermal generator flexibility



- In scenarios with **greater** thermal generator flexibility, there is generally more solar, Gas-CC, and coal generation and less Gas-CT generation
- In scenarios with **less** thermal generator flexibility, there is generally less coal and solar generation, with nuanced trade-offs among natural gas-fired generation
- Tradeoff in cost and flexibility
  - Coal is cheap but inflexible, Gas CT is expensive but flexible, and Gas CC is in the middle
- Minimum generation levels and ramp rates yield largest differences in dispatch

Example (greater flexibility): Zero Min Gen at 33% PV



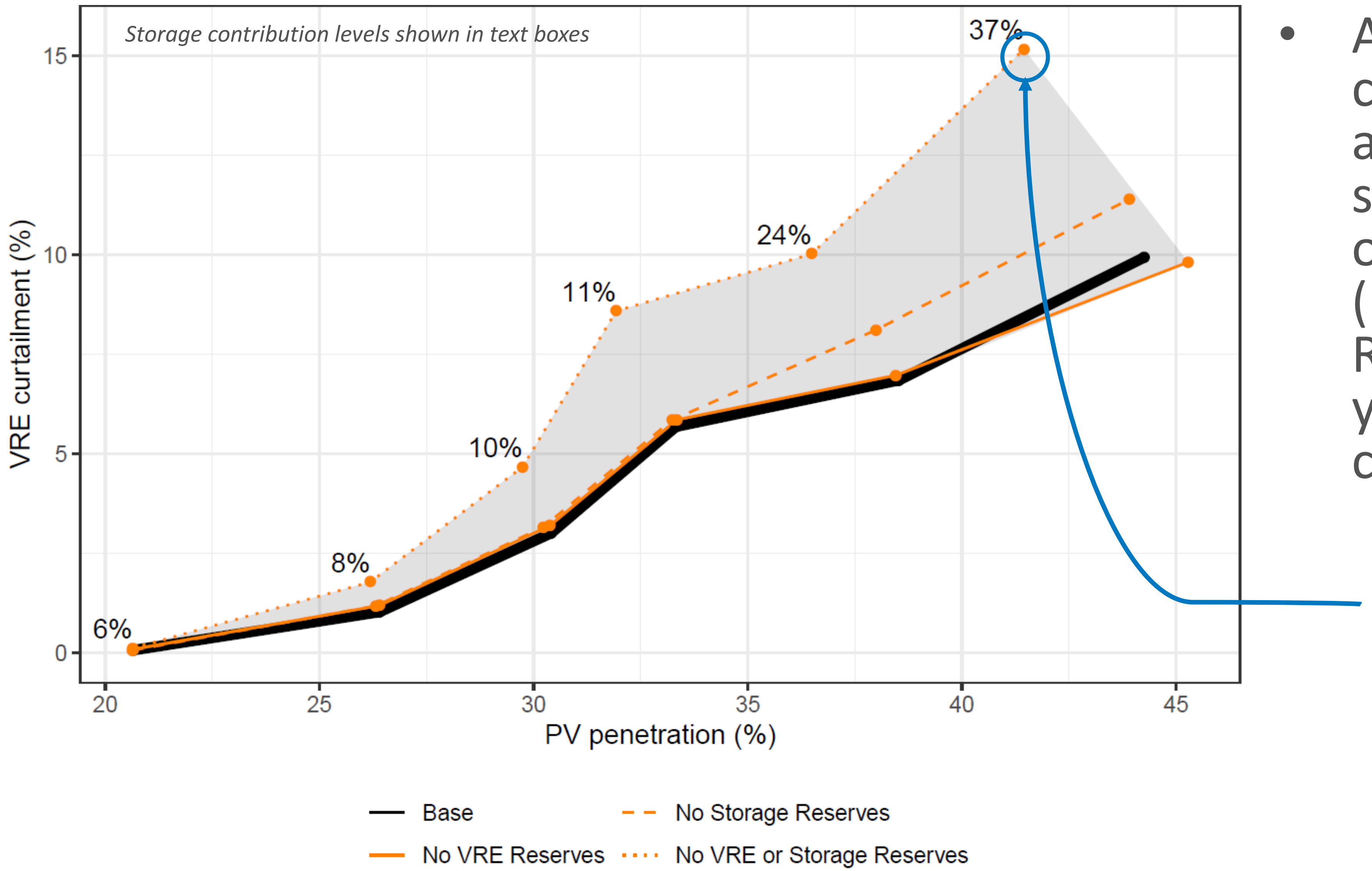
- With the additional flexibility afforded to the coal generators, the system can utilize more of the zero-marginal-cost solar and relatively low-marginal-cost coal and Gas-CC
- Relative to the Base case for these 4 days:
  - 3.2% greater utilization of solar
  - 20% less curtailment
  - 16.5% operating cost savings ($0.33 million)

Paradox 2: Curtailed PV eats its own lunch

(with respect to operating reserves)

VRE curtailment

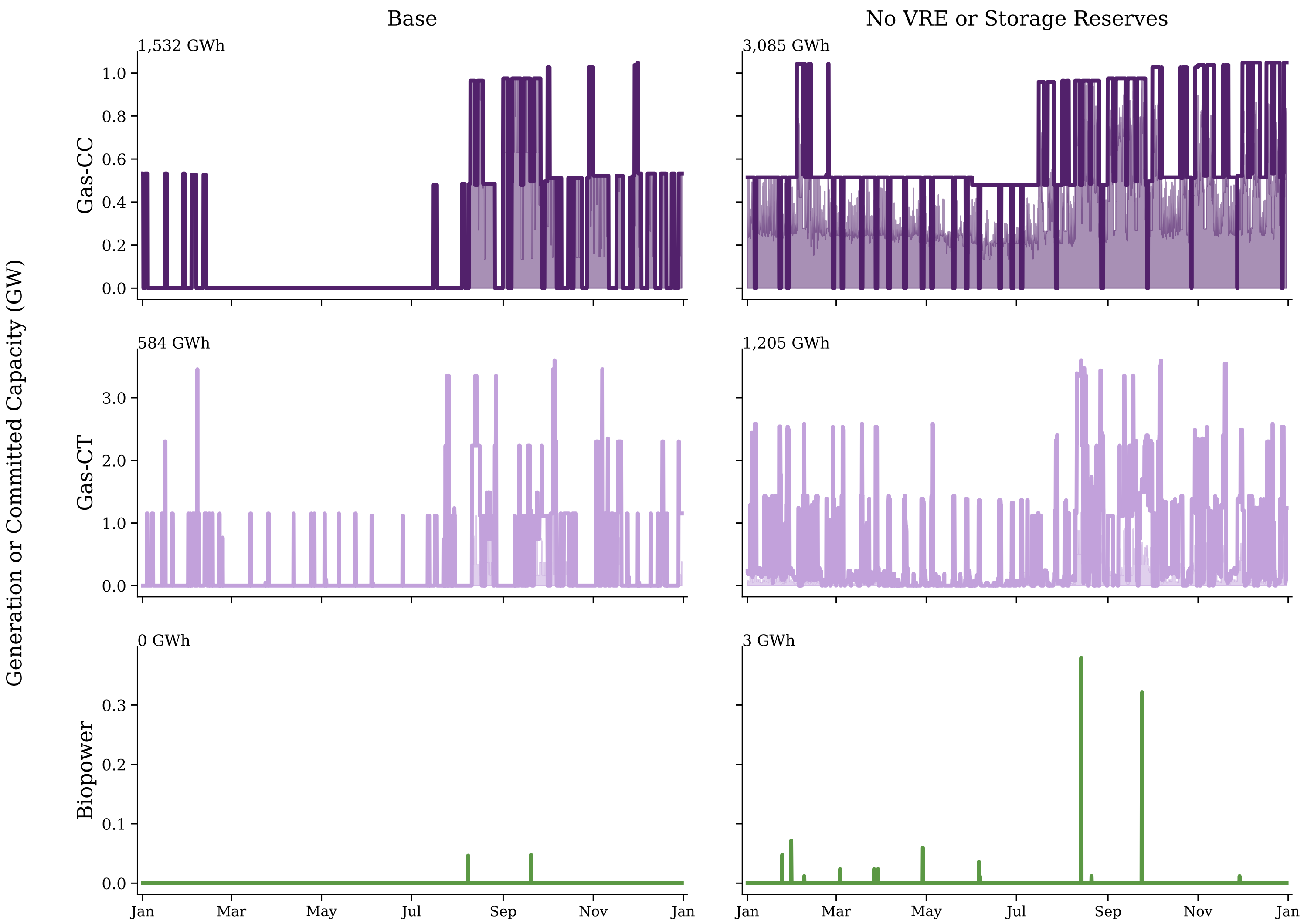
for operating reserve sensitivities



- At high PV contributions, not allowing VRE and storage to provide operating reserves (No VRE or Storage Reserves scenario) yields significant curtailment increases
  - 53% more curtailment relative to the Base case at 44% PV level

What’s driving the difference?

Available committed thermal capacity (dark lines) and generation (light lines) at 44% PV



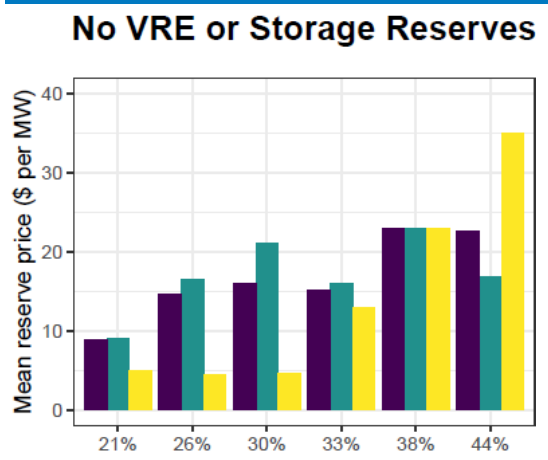
- When VRE and storage can provide reserves (Base scenario), **thermal capacity that is otherwise committed only to meet operating reserve requirements is no longer needed**, resulting in large portions of the year when Gas-CC, Gas-CT, and biopower are not committed
  - Reduces generation for these technologies by about 50%
  - **Enables greater utilization of lower-cost VRE and storage resources** for not only operating reserves, but also energy, thereby reducing curtailment
  - Reduces systemwide operating costs by about 50%

Operating reserve price trends

- Despite these curtailment and system cost benefits when VRE and storage provide operating reserves ("Base"), **they do not necessarily translate to increased revenues**
- Higher curtailment levels associated with increasing contribution of PV resources, and the interaction with storage, lead to **lower prices for reserves**, especially during times of PV curtailment
- Operating reserve shortage conditions **generally only affect operating prices during non-curtailment periods in the transition zone**

Operating reserve prices

No VRE or Storage Reserves



- All three price metrics **generally increase as PV contribution levels increase**, driven by thermal generator commitments

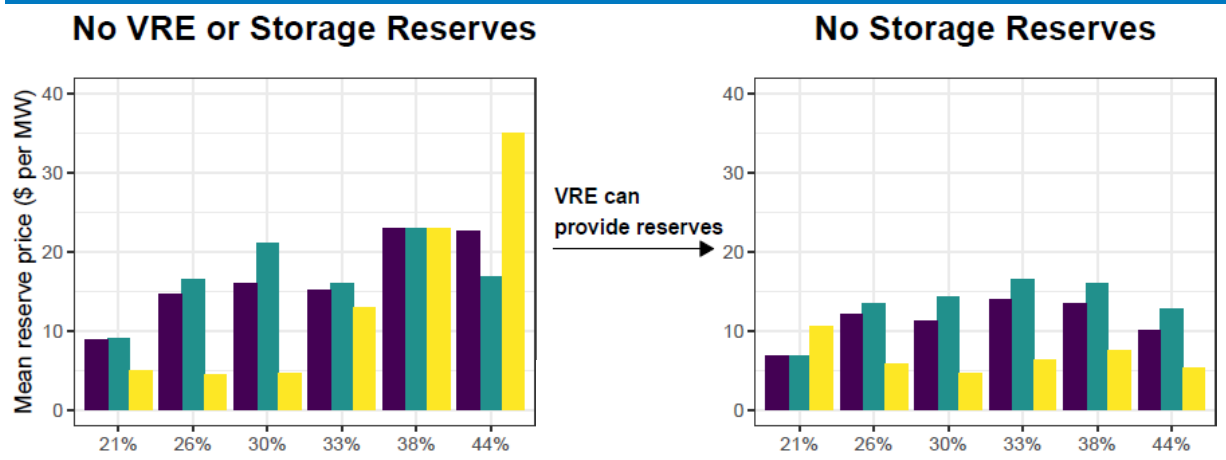
- A much smaller secondary effect is the presence of operating reserve shortage events during periods without PV curtailment (teal bars)
  - Largest absolute impact in the transition zone
  - Comprise only a small portion (<1%) of system operating cost

Spinning reserve is shown as an example

All hours Hours with no PV curtailment Hours with PV curtailment

Operating reserve prices

No Storage Reserves



- Operating reserve prices **generally drop** because curtailed VRE can provide operating reserve capacity with zero cost instead of higher cost thermal resources
  - Particularly prominent during periods of PV curtailment (yellow bars)

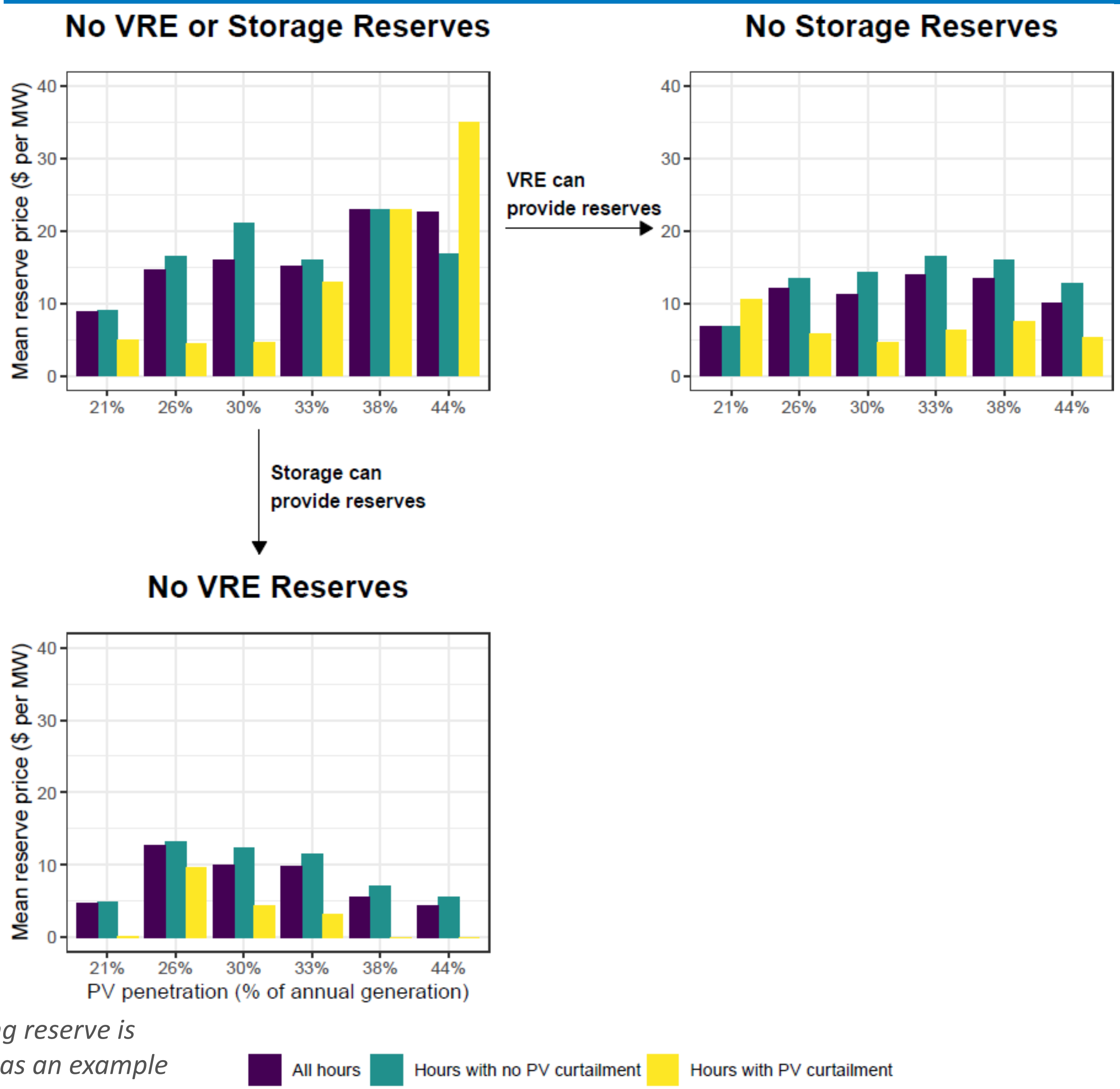
- Operating reserve shortage events play a much smaller role

Spinning reserve is shown as an example

All hours   Hours with no PV curtailment   Hours with PV curtailment

Operating reserve prices

No VRE Reserves

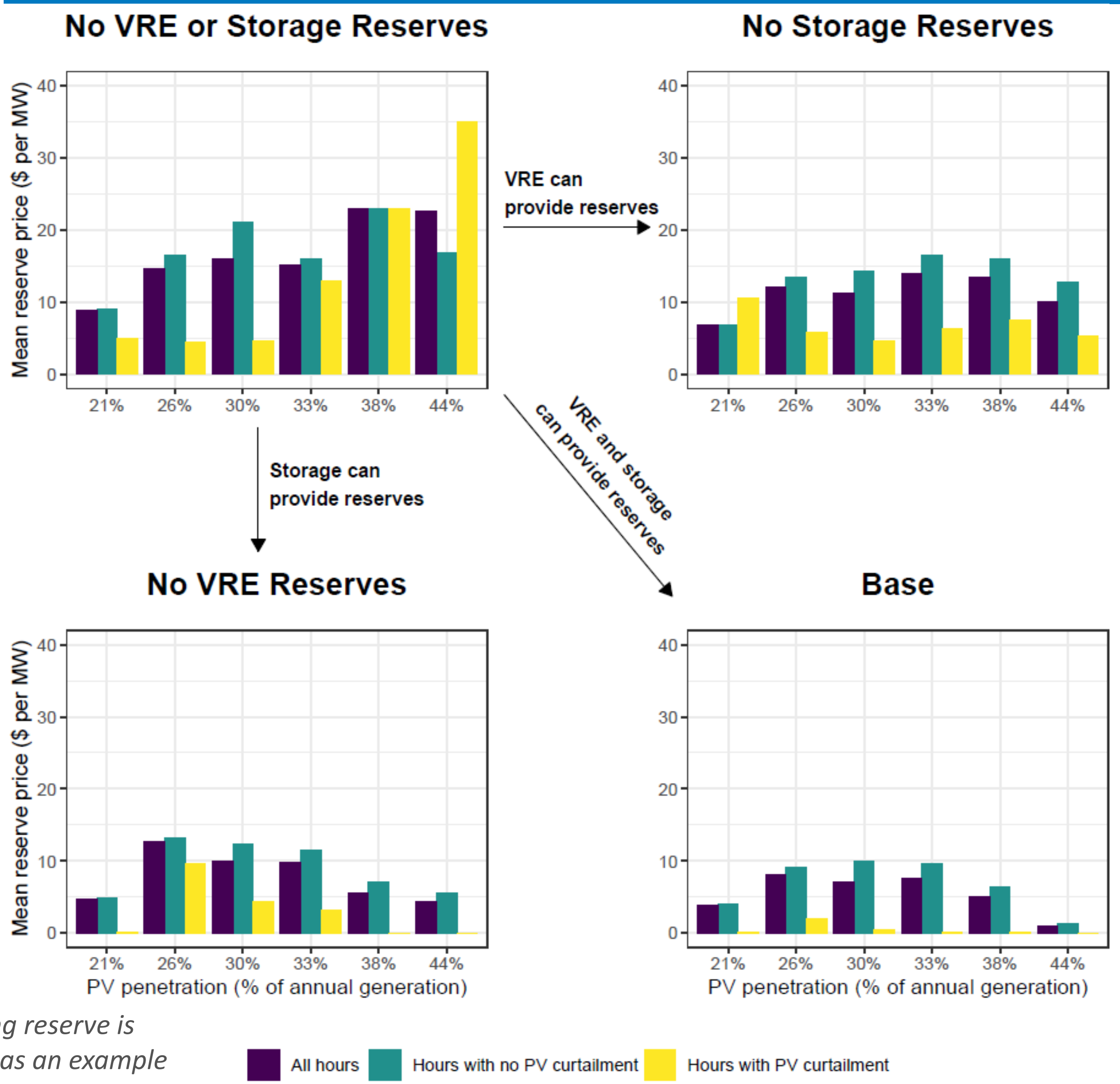


Spinning reserve is shown as an example

- Operating reserve prices **significantly decrease**
  - Driven by storage, which has near-zero cost and ample capacity to provide reserves, especially during periods of curtailment (yellow bars)
- Operating reserve shortage events play a small role
- Total curtailment MWh and number of hours of curtailment is reduced by 36%, implying that there are **fewer periods when PV could use curtailed energy to provide operating reserves** if it were permitted to do so

Operating reserve prices

Base



Spinning reserve is shown as an example

- Operating reserves prices consistently **remain nearly zero** during periods of PV curtailment
  - Storage has already reduced prices to nearly zero during periods of curtailment and has reduced the number of time periods with curtailment
  - Highlights the **importance of understanding the role of storage for provision of operating reserves** under increased PV deployment

Wholesale market design considerations

<u>Caveat</u>: Though we do not simulate a formal wholesale market, we demonstrate the potential impact of high PV scenarios and operating reserve eligibility rules on reserve prices and associated revenues that result from the modeled least-cost system operations

- **Market structures and policies that allow all VRE resources to provide operating reserves yield lower-cost operations and curtailment**
  - Currently not common practice in competitive wholesale markets

- **Operating reserve markets may not provide a significant revenue source to compensate for reduced revenues resulting from greater levels of curtailment and declining energy prices**
  - Low operating reserve prices could limit the incentive for PV to provide operating reserves with curtailed energy
  - Proper alignment of grid system value and compensation may require market modifications

Wholesale market design considerations (cont'd)

- **Markets may need to continually update pricing structures to better reflect value of reliability, flexibility, externalities, and the true lost opportunity cost**
  - Shortage pricing (e.g., ORDCs)
  - Bidding practices to reflect full set of considerations (wear and tear, battery degradation, market participation models, RPS, or other policy goals)
  - Avoided emissions pricing
  - Role of uplift payments (e.g., thermal plants forced on for reliability purposes)

- **Markets may need to consider factors that can impact how rest of system is operated (e.g., mingen levels)**
  - Role of emerging technologies, e.g., hybrids, distributed energy resources
  - Resources that are effectively self-scheduled (e.g., resources that operate through bilateral contracts)

Wrap up

Future work could look at:

- **System dimensions**
  – Different systems, different buildouts (including transmission), a wider range of storage/hybrid contribution levels and durations

- **Flexibility causes and supplies (including tradeoffs in options)**
  – Full cost-benefit analysis of thermal generator flexibility upgrades (in both CEM and PCM with unit-level accounting)
  – A larger role of demand response/responsive demand, especially as an alternate to thermal generator upgrades (e.g., could demand response result in same outcome as Zero Min Gen scenario?)
  – Consideration of other end-uses for curtailed energy (ESI, etc.)
  – More robust evaluation of the role of uncertainty (e.g., wider range of forecast errors, stochastic forecasts, lookahead treatment, etc.)

Future work could look at (cont’d):

- **Technology and market representation**
  - Improvements to storage/hybrid representation (e.g., what value to bid into market, degradation costs, participation models/rules
  - Improvements to operating reserve treatment (e.g., additional costs for wear and tear for regulation reserves, disincentives for down-direction reserves where RPS-type goals exist)

- **Linkages to investment**
  - Feedback of operational sensitivities on investment decisions over multi-year evolution of system
  - How market design could change to support revenue sufficiency for the resources needed for reliability

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Thank You

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