Impact of Thermal Plant Operational Flexibility on VRE Curtailment:

The Curtailment Paradox

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Some context

- This talk draws from a *Joule* article **"The curtailment paradox in the transition to high solar power systems"**
  - https://doi.org/10.1016/j.joule.2021.03.021
  - Deeper dive webinar: https://www.youtube.com/watch?v=TmSE1y7rH28
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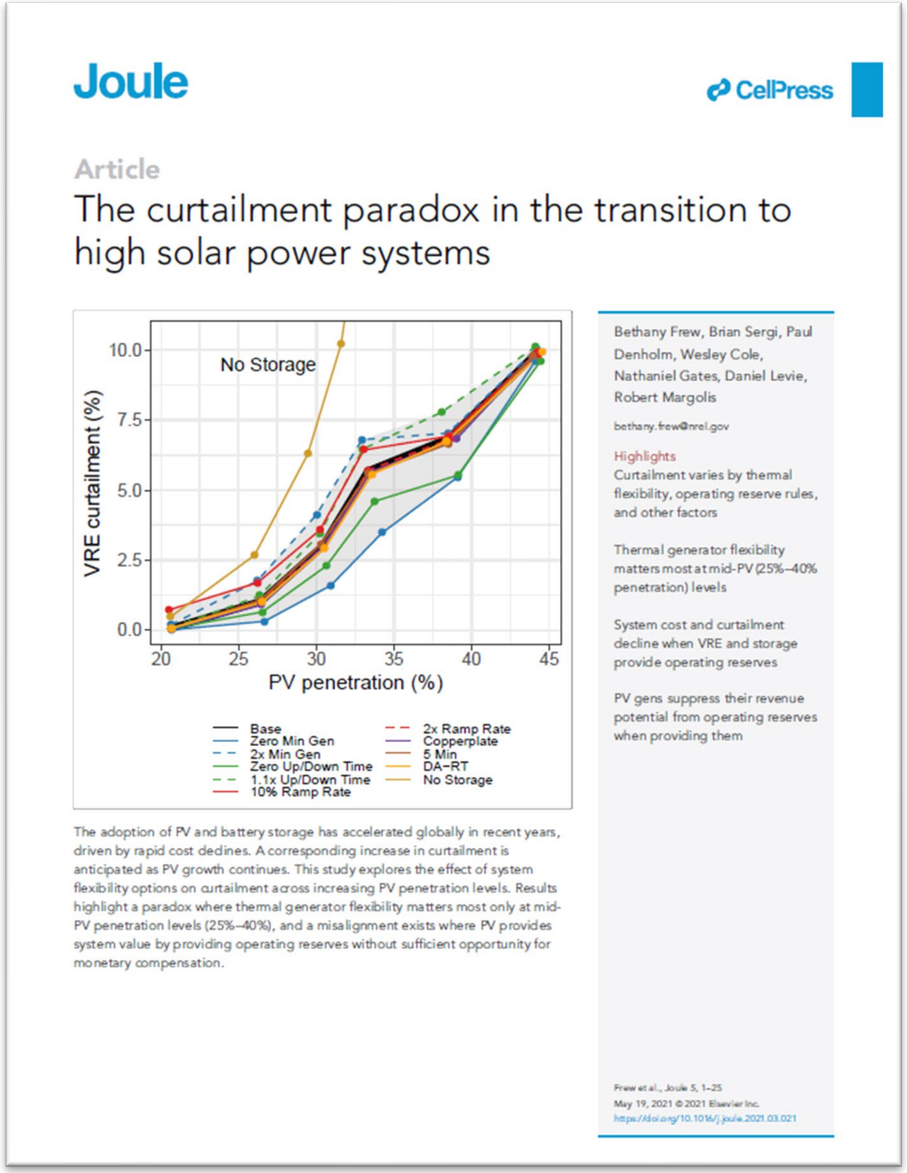
  - Wesley Cole
  - Nathaniel Gates
  - Daniel Levie
  - Robert Margolis
- Funding from U.S. Department of Energy Solar Energy Technologies Office



Joule

CelPress

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

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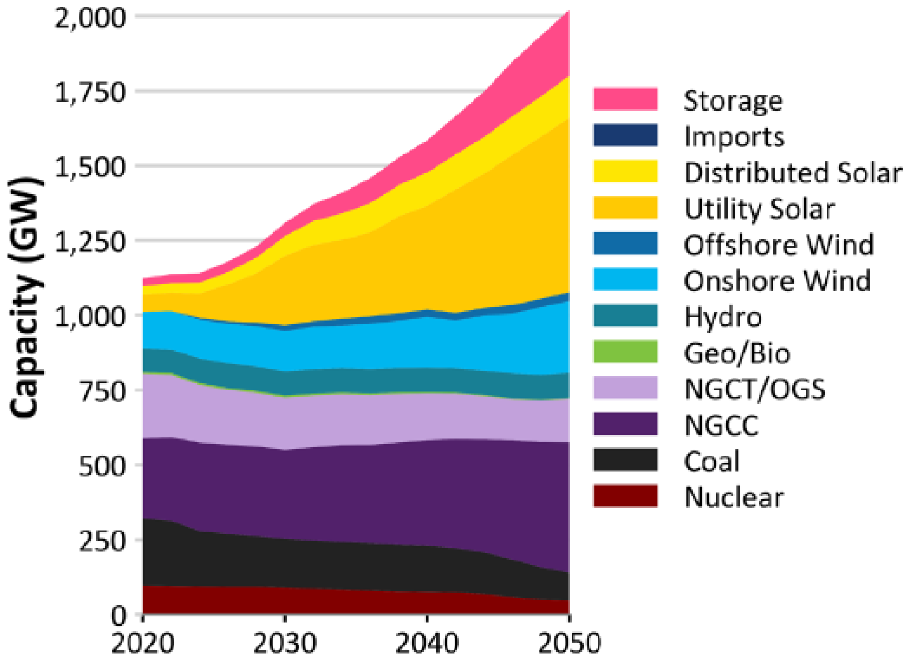
Why focus on curtailment and PV?

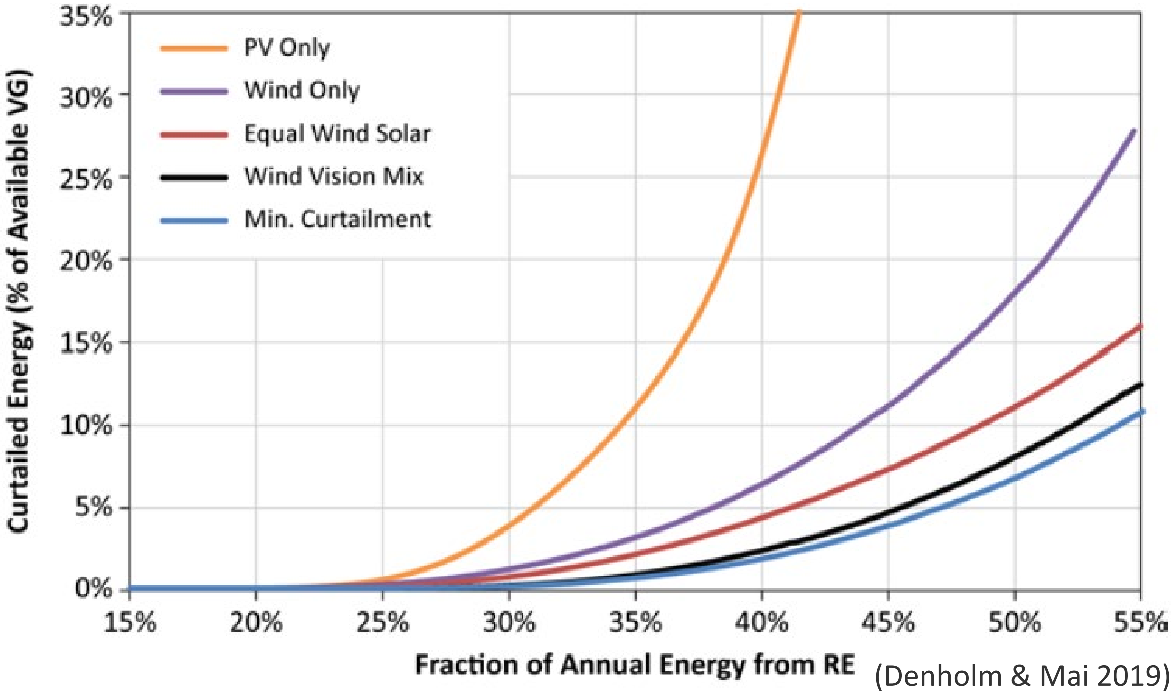
- Economic curtailment (i.e., part of least-cost operations) is a **new normal in grid operations** by providing flexibility to ensure grid reliability
  - Our previous work found many hours of 40+% curtailment (Frew et al. 2019)

- PV is projected to have the **largest share of new renewable deployments**



(Cole et al. 2020)

- PV has a **more rapid increase in curtailment as contribution levels increase** due to its coincident nature



(Denholm & Mai 2019)

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 curtailment paradox

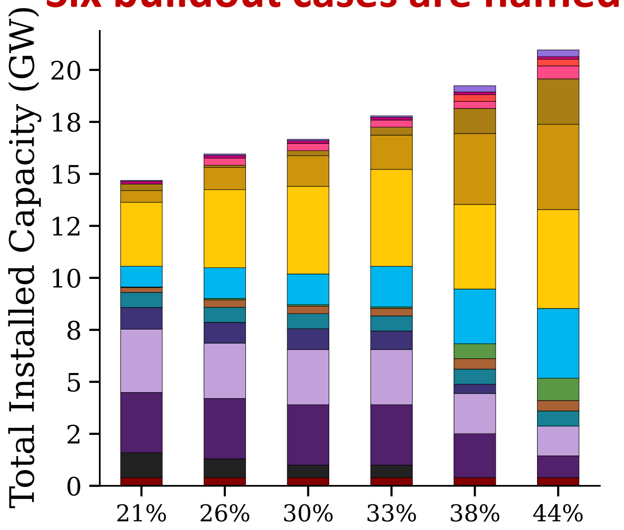
1) Thermal generator parameters, especially by restricting minimum operating levels and ramp rates, **impact variable renewable energy (VRE) curtailment more in mid-photovoltaic (PV) contribution levels** (~25%–40%) than in lower (~20%) or higher (~45%) PV contribution levels

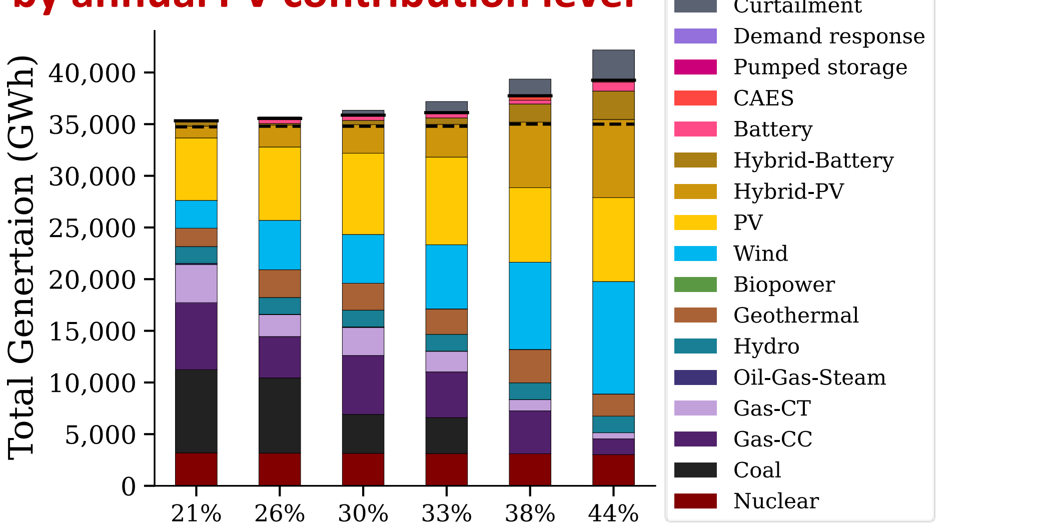
2) While allowing VRE and storage to provide operating reserves results in reduced operating cost and curtailment, **the price suppression effect from these resources reduces incentives for PV to provide operating reserves with curtailed energy**

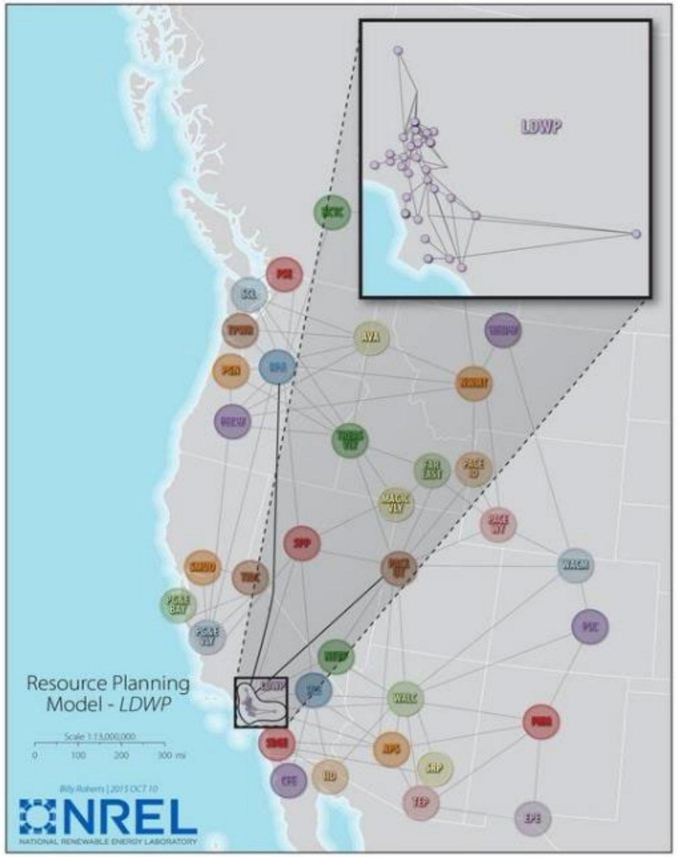
Study system, approach, and buildout cases

- Los Angeles Department of Water and Power (**LADWP**) footprint, leveraging data from the LA100 study: https://maps.nrel.gov/la100
- Used capacity expansion modeling (CEM) with NREL's Regional Planning Model (**RPM**) to develop **six PV and storage buildout cases**
- Used production cost modeling (PCM) with **PLEXOS** to explore operations for a Base scenario and set of sensitivities with each of the six buildout cases

Six buildout cases are named by annual PV contribution level







Apply RPM to the full Western United States with greater resolution in the LADWP area, then apply PLEXOS to the resulting buildouts for the LADWP footprint

Base scenario at each buildout level

Renewable contribution Annual avg % of total annual generation		Capacity contribution % of peak load	Curtailment Annual avg % of available resource	
PV	VRE	Storage	VRE	PV
21%	28%	6%	0.1%	0.1%
26%	40%	8%	1.1%	1.0%
30%	44%	10%	2.8%	3.0%
33%	51%	11%	6.7%	5.7%
38%	63%	24%	5.8%	6.8%
44%	75%	37%	8.2%	9.9%

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

Base and sensitivity scenarios

We explored 14 scenarios across the six buildout levels, 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”)

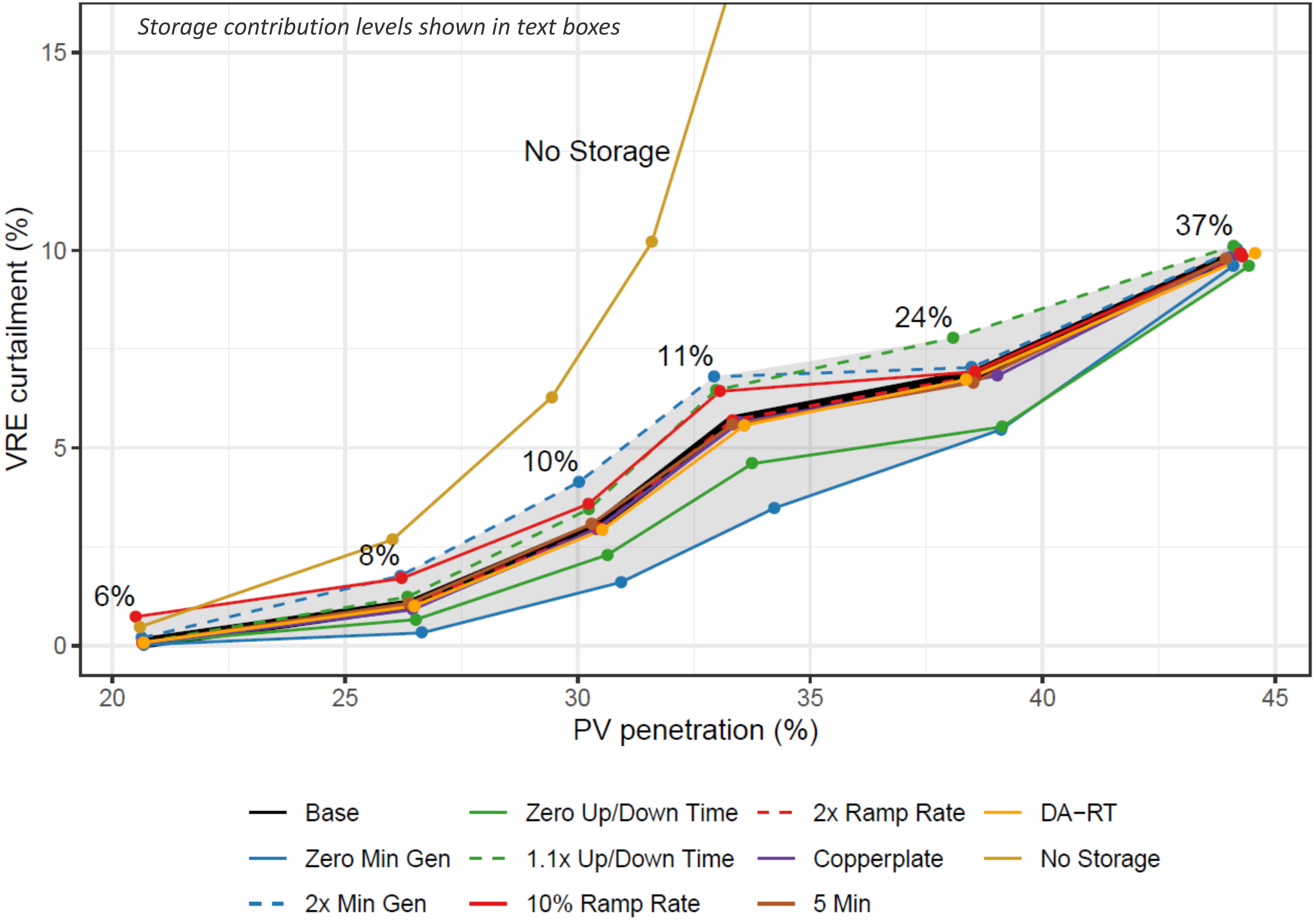
Allowing VRE and storage to provide operating reserves enables access to otherwise curtailed energy in the upward direction and additional curtailed energy in the downward direction

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

Paradox 1: Thermal flexibility matters most in the middle

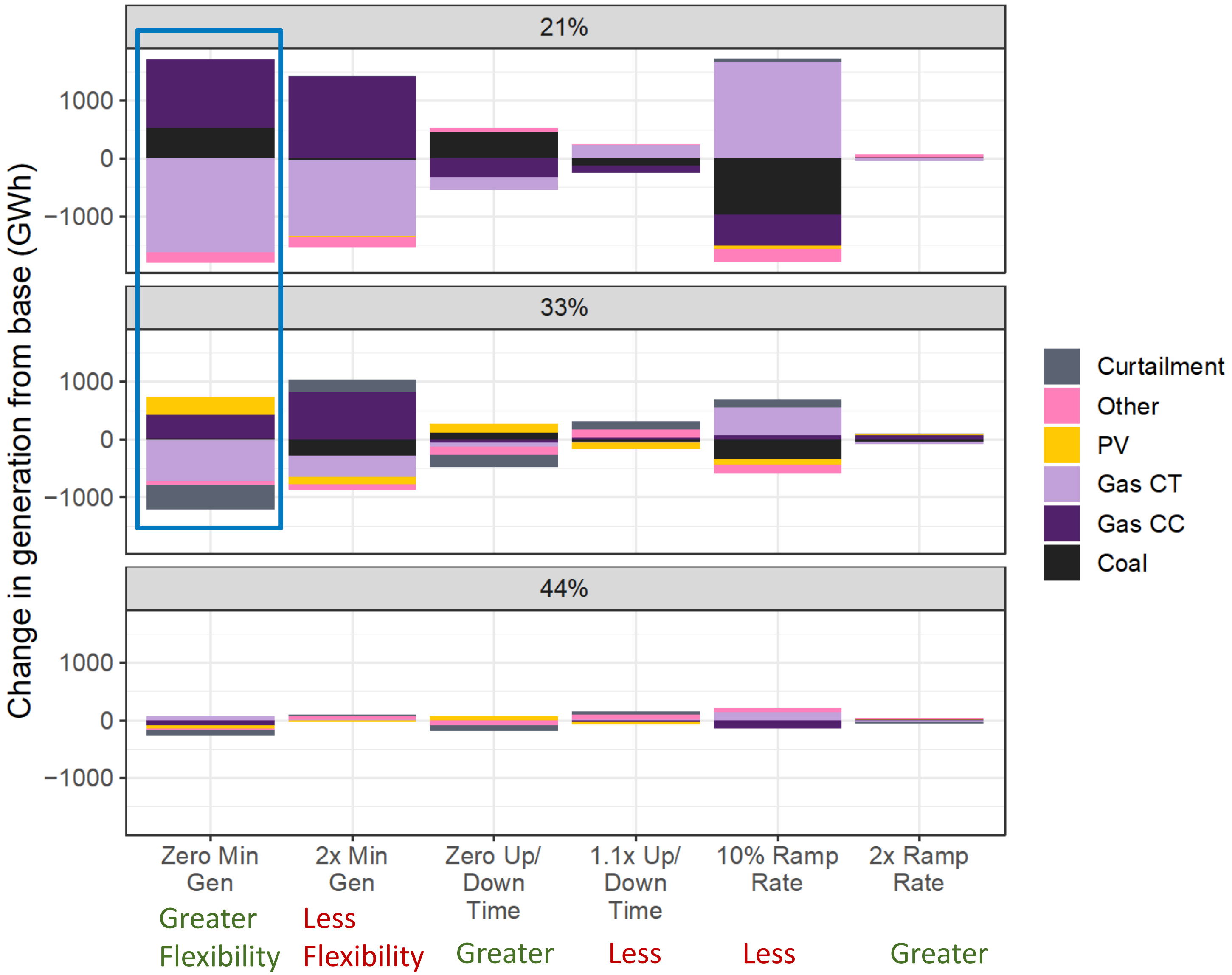
VRE curtailment

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)
  - Suggests need for phased approach for ongoing grid transformation
- Significantly smaller curtailment impacts are observed from transmission constraints, forecasting errors, or temporal resolution
  - Future work could explore impact on inter-regional systems and different buildouts

Thermal generator flexibility



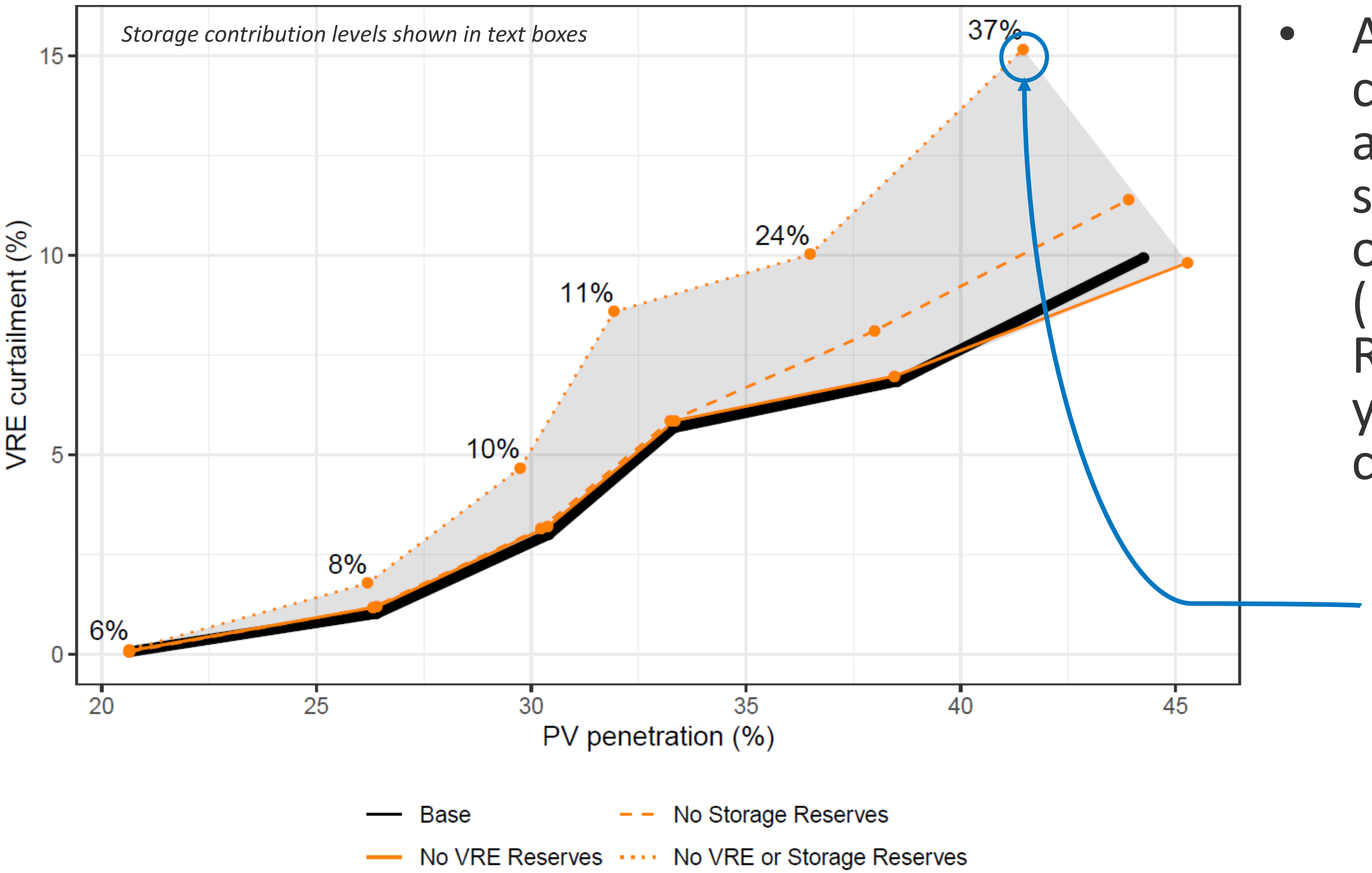
- Minimum generation levels and ramp rates yield largest differences in dispatch
- In scenarios with **greater** thermal generator flexibility, there is generally more solar, Gas-CC, and coal generation and less Gas-CT generation
- In scenarios with **less** thermal generator flexibility, there is generally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

Paradox 2: Curtailed PV eats its own lunch

(with respect to operating reserves)

VRE curtailment

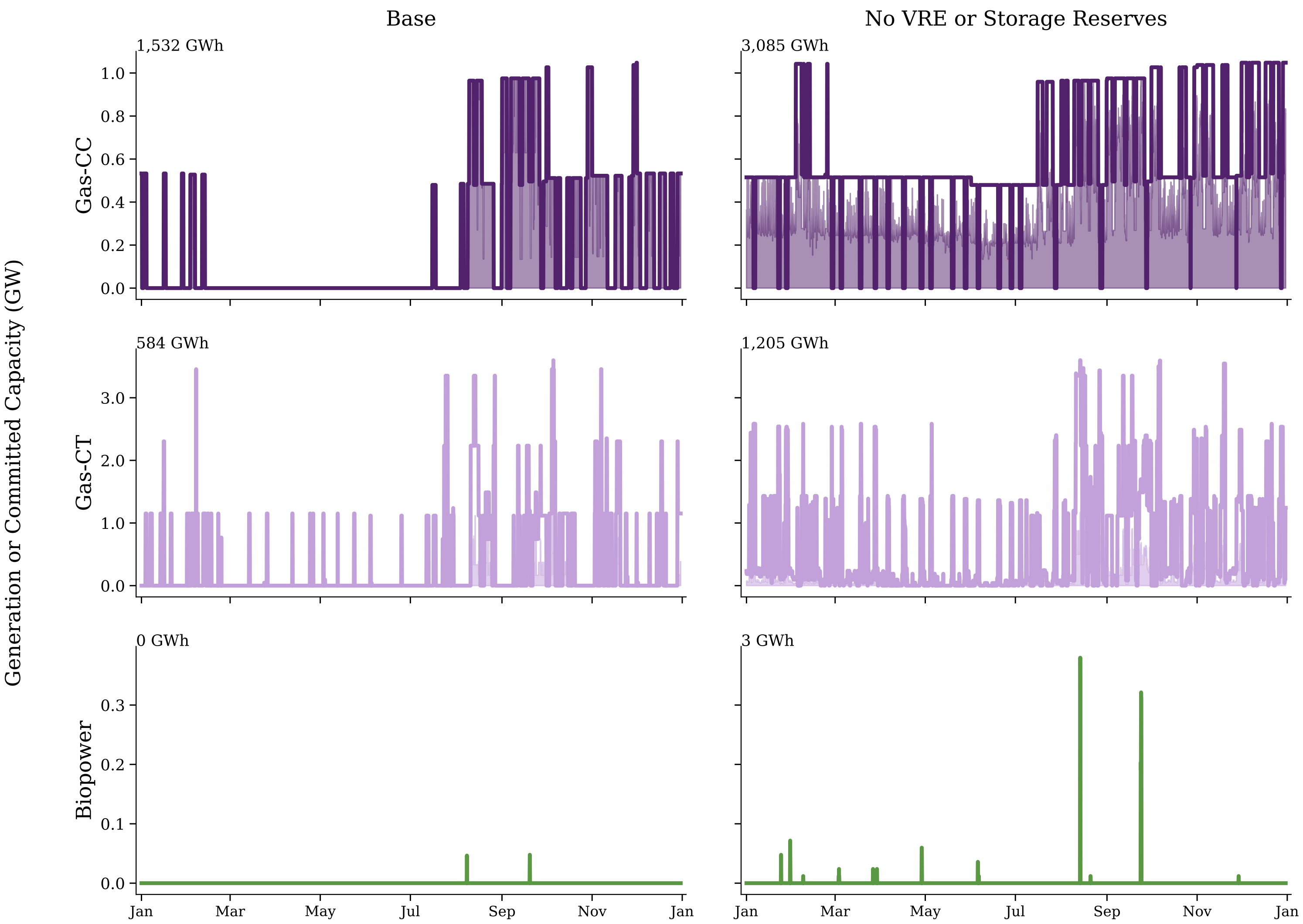
for operating reserve sensitivities



- 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?

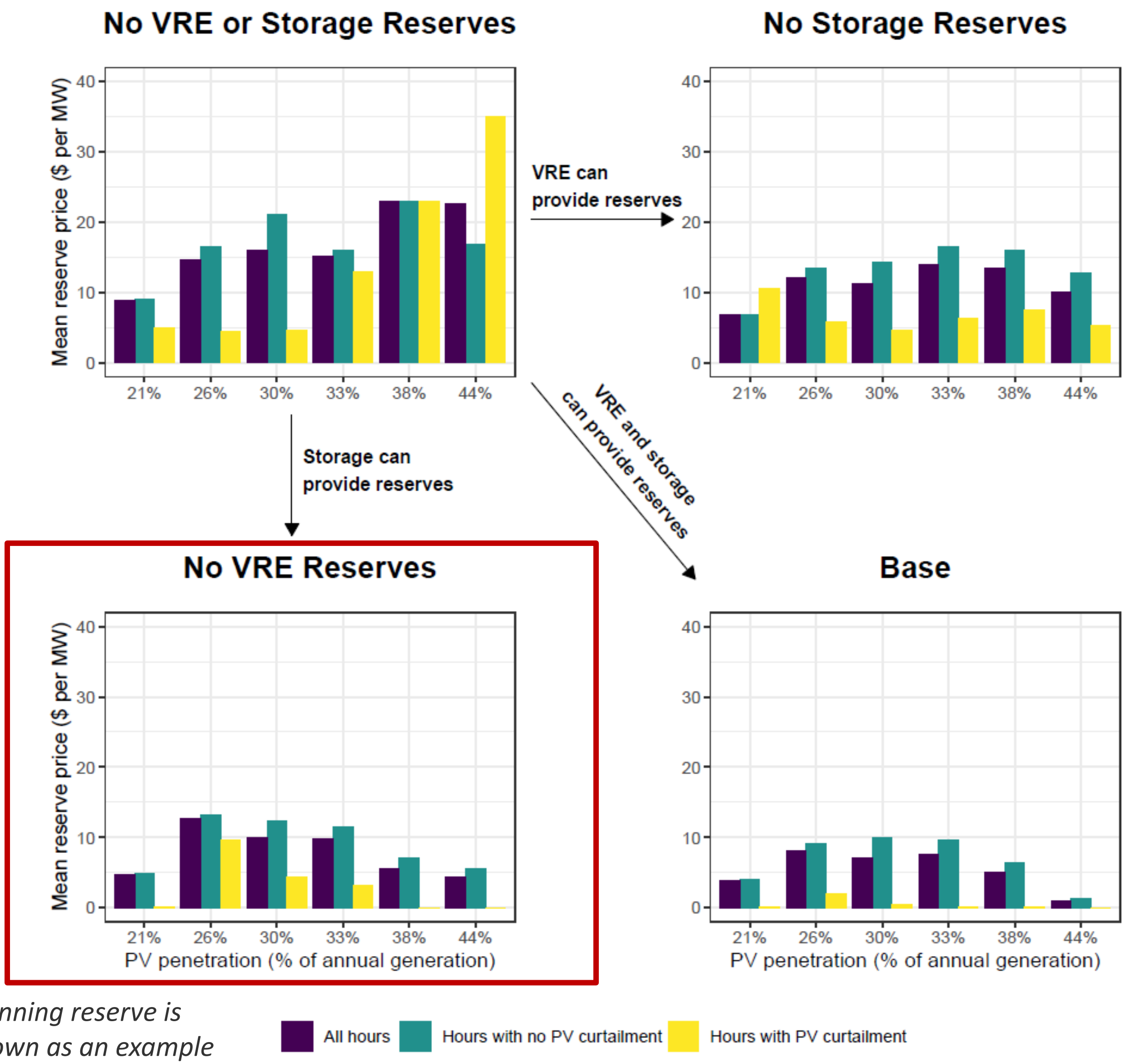
Available committed thermal capacity (dark lines) and generation (light lines) at 44% PV level



- 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

Base



Spinning reserve is shown as an example

- Despite these curtailment and system cost benefits when VRE and storage provide operating reserves ("Base"), **they do not necessarily translate to increased revenues**
- Operating reserve **shortage conditions generally only affect operating prices during non-curtailment periods** (teal bars) in the transition zone
- Larger PV levels and interaction with storage lead to **lower prices for reserves, especially during times of PV curtailment** (yellow bars)
  - Storage drives prices to nearly zero during periods of curtailment and also reduces frequency of curtailment
  - Highlights the need to understand the **role of storage in providing operating reserves** under increased PV deployment

Wrap up

Some parting thoughts on flexibility

- **Markets may need to continually update pricing structures to better reflect the true value of flexibility, reliability, externalities, and lost opportunity costs**
  - Our results reveal a potential misalignment between system value (plus additional externalities from avoided emissions) and compensation for certain resources
  - Operational flexibility could be signaled through refined ORDC approaches or new flexibility reserve products
  - Bidding practices that reflect the full set of physical costs and lost opportunity costs are critical for emerging resources
  - Flexibility and/or price outcomes can be impacted by operational practices elsewhere in the system (e.g., self-scheduled units or reliability-induced commitments that yield uplift payments)
- **Future work could further explore flexibility sources, drivers, and tradeoffs**
  - Full cost-benefit analysis of thermal generator flexibility upgrades (CEM and PCM with unit-level accounting)
  - A larger role of price-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 (energy systems integration, etc.)
  - More robust evaluation of the role of uncertainty (e.g., wider range of forecast errors, stochastic forecasts, lookahead treatment, etc.)

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Thank You

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