Operating Reserves in ReEDS

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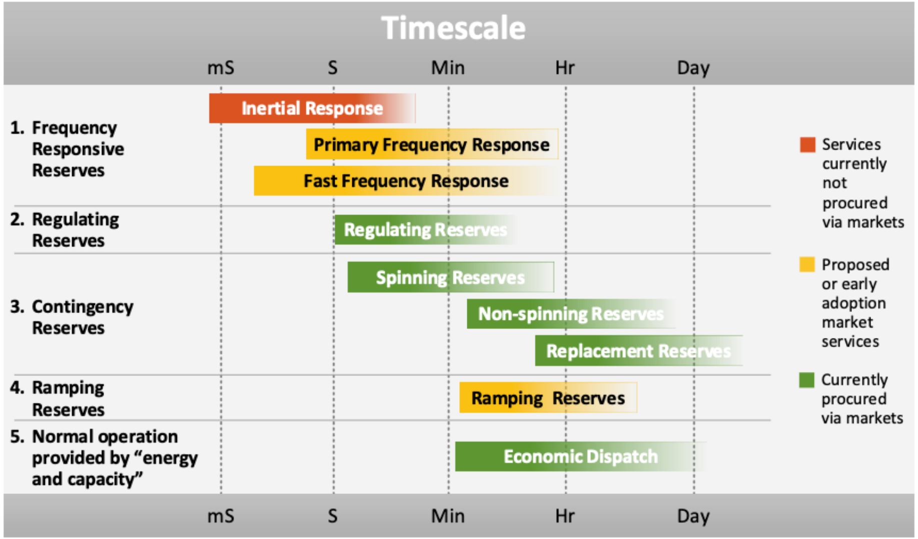
Operating reserves overview

Operating reserve product types:

- **Frequency Responsive Reserves:** the ability to resist or respond to changes in frequency
- **Regulation Reserve (reg):** the ability to respond to regular small fluctuations in load-supply imbalances
- **Contingency (spinning) Reserve (spin):** the ability to respond to a major unit or transmission outage
- **Flexibility Reserves (flex):** the ability to provide following and ramping needs (also known as "ramping reserves")

Reserves are designed to maintain reliability despite inherent variability and uncertainty in demand and supply, including variable renewable energy (VRE)



Source: Denholm, Paul L., et al. *An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind*. National Renewable Energy Laboratory, Golden, CO, 2019, https://www.osti.gov/biblio/1493402.

Operating reserves in ReEDS

ReEDS models three categories of reserves (reg, spin, and flex)

- Reserve requirements quantities are functions of load and VRE share and vary by product.
- Requirement levels are calculated based on methods from the WECC TEPPC*, outlined in Lew et al. (2013) and reproduced in the table below.
- Reserves effectively modeled as “up” reserves.

Operating reserve requirements as a function of load or VRE generation/capacity

	Load (% of load)	Wind (% of generation)	PV (% of capacity)
reg	1%	0.5%	0.3%
spin	3%	--	--
flex	--	10%	4%

*Western Electricity Coordinating Council Transmission Expansion Planning Policy Committee

Operating reserves in ReEDS

Ability of generation technology to supply reserves is dependent on their ability to ramp

- Response time requirements by reserve type:

	reg	spin	flex
Response time (minutes)	5	10	60

- [Ramp rate] x [Response time] = fraction of resource than can provide reserve (`reserve_frac`)
- By default, ReEDS modeling does not allow pre-curtailment of VRE resources (wind/solar) to provide operating reserves

Availability of technologies to provide operating reserves

	Assumed Ramp Rate (%/min)	Ramp Rate * Ramp Time = Upper Bound (% of online capacity)		
		Spinning	Regulation	Flexibility
Gas-CT	8	8*10=80	8*5=40	8*60=480, so 100
Gas-CC	5	5*10=50	5*5=25	5*60=300, so 100
Coal	2	2*10=20	2*5=10	2*60=120, so 100
***Nuclear**	2	2*10=20	2*5=10	2*60=120, so 100
****Geothermal**	4	4*10=40	4*5=20	4*60=240, so 100
CSP w/ Storage	10	10*10=100	10*5=50	10*60=600, so 100
****Biopower**	4	4*10=40	4*5=20	4*60=240, so 100
Oil/Gas Steam	4	4*10=40	4*5=20	4*60=240, so 100
Hydro (dispatchable)	100	No Upper Bound		
*****Storage**	100			

Upper bound determines maximum fraction of online capacity that generators could provide as reserves (`reserve_frac`)

* By default nuclear is precluded from providing operating reserves in ReEDS, but this can be enabled using the GSw_NukeFlex switch

**Geothermal and biopower values are assumed to be the same as oil/gas steam units. In practice, geothermal plants typically do not ramp given their zero or near-zero variable costs, and therefore only provide energy and not operating reserves.

***Storage includes batteries, pumped storage hydropower (PSH), and compressed air energy storage (CAES).

Sources:

Bloom, Aaron, et al. *Eastern Renewable Generation Integration Study*. National Renewable Energy Laboratory, Golden, CO, 2016, https://www.osti.gov/biblio/1318192. See Table 6 for NG-CT, NG-CC, Coal, Oil/Gas Steam

Jorgenson, Jennie, et al. E*stimating the Performance and Economic Value of Multiple Concentrating Solar Power Technologies in a Production Cost Model*. National Renewable Energy Laboratory, Golden, CO, 2013, https://www.osti.gov/biblio/1260920. See Table 3 for CSP.

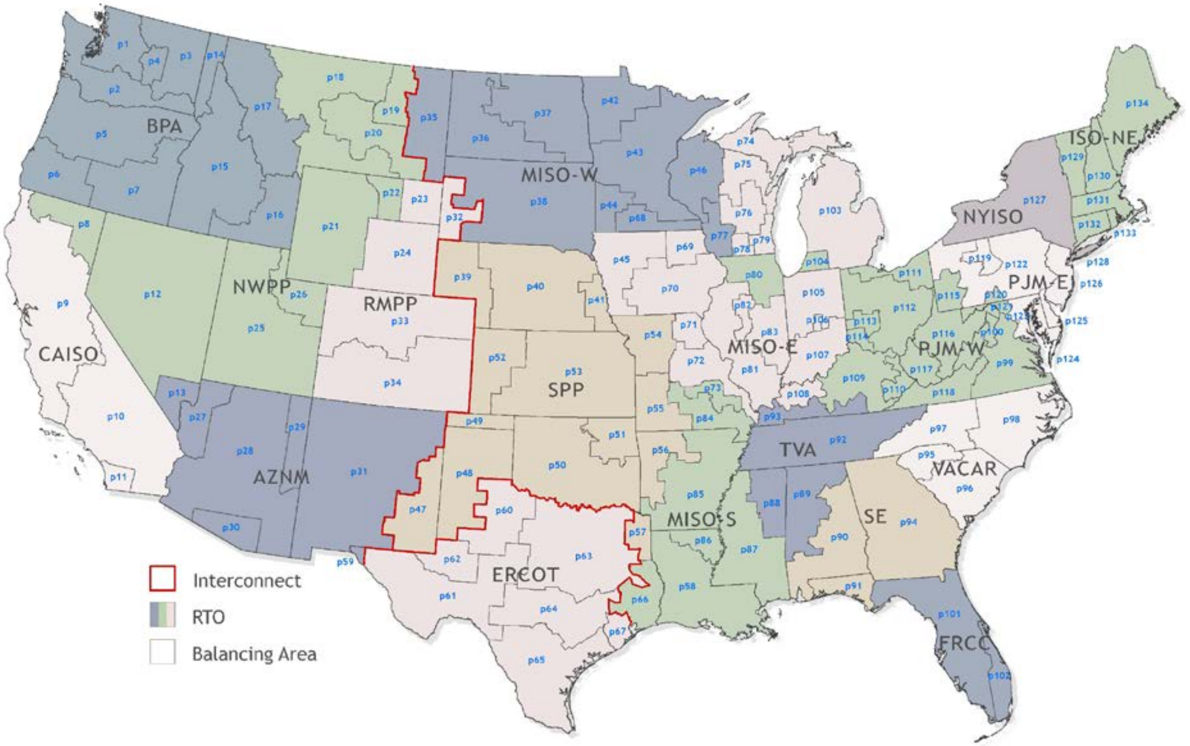
Regional considerations

All operating reserves must be supplied within one of 18 model-defined Regional Transmission Organization (RTO) regions.

Reserves cannot be traded between RTO regions (e.g., prohibits New York hydro from meeting regulation reserve requirement in Florida)

By default, reserves can be traded between balancing areas (BAs) within an RTO

- Model switches allow for testing sensitivities that preclude or penalize inter-BA reserve trading



Source: Ho, Jonathan, et al. *Regional Energy Deployment System (ReEDS) Model Documentation: Version 2020*. National Renewable Energy Laboratory, Golden, CO, 2021, https://www.osti.gov/biblio/1788425.

Cost for providing regulation reserves

Opportunity costs are captured in the ReEDS formulation for all reserve products. However, additional costs are included for regulation reserves to account for the cost of following a rapidly changing signal.

Generator costs are taken from Table 3 in Hummon et al. (2013) (reproduced here).

- These costs are in 2013$.
- Because ReEDS does not clearly distinguish between coal type, we use $12.5/MW-h for all coal technologies.
- Gas-CT, geothermal, biopower, land-fill gas, and CAES are all assumed to provide regulation reserves at the same cost as gas/oil steam.

Generator Type	Cost ($/MW-h)
Supercritical Coal	15
Subcritical Coal	10
Combined Cycle	6
Gas/Oil Steam	4
Hydro	2
Pumped Storage Hydropower	2

Source: Hummon, Marissa, et al. *Fundamental Drivers of the Cost and Price of Operating Reserves*. National Renewable Energy Laboratory, Golden, CO, 2013, https://www.osti.gov/biblio/1220216.

Recent modeling changes related to operating reserves

1. Accounted for efficiency losses for any storage technology that provides regulation reserves.
2. Included a requirement that storage have sufficient energy to cover reserves + generation in a timeslice.
3. Refined constraints governing whether generators must be on to provide reserves.
4. Added a cost to provide spinning reserves for generators that have heat rates.

1. Storage efficiency losses

Motivation: ReEDS accounts for storage losses when charging to provide energy, and therefore should also consider losses for any charging associated with providing regulation reserves.

Storage losses from provided regulation reserves calculated as:

```
reg_provided / 2 * (1 - storage_eff(i,t)) * reg_energy_frac
```

- Assuming an energy neutral signal (i.e., the storage will return to its state of charge at the end of the time period), storage is only expected to be charging half the time when providing regulation reserve. Accordingly, we calculate efficiency losses for half of the regulation reserve provided (`reg_provided`).
- `storage_eff(i,t)` is the round-trip efficiency for storage of technology i in year t
- reg_energy_frac is the fraction of regulation reserves that will result in generation, also known as the dispatch to contract ratio (assumed to be 15% based on Ferreira et al., 2013)

Example: A battery with 85% roundtrip efficiency provides 10 MW of regulation reserves for 1 hour. The losses from providing these reserves are 10/2*(1-0.85) * 0.15 = 0.1125 MW-h

2. Storage state of charge

Motivation: Previously, the model would allow for storage to provide operating reserves even if it had no available state-of-charge. This might overstate storage's ability to provide reserves.

A new constraint was added to ensure that storage has sufficient state of charge to provide operating reserves (`eq_storage_opres`)

- Formulation included in appendix to this presentation (slide 31)

If storage is also discharging, it can only provide operating reserves using the remaining energy

- E.g., if the starting state of charge of a battery is 100 MWh, and it discharges 60 MWh, then it can use the remaining 40 MWh for operating reserves in the same timeslice.

3. Generator dispatch and reserves

Motivation: Generators with minimum generation levels may not be able to provide reserves without being committed.

ReEDS' representation of "unit commitment" was expanded to two constraints to better control the online status of generators when providing operating reserves:

- Based on generators ability to respond (`reserve_frac`; see table on slide 5).
- Generators with `reserve_frac` <= 0.5 must generate during the same timeslice (these are the less-flexible generators).
- Generators with `reserve_frac` > 0.5 must generate sometime during the same day (these are the more flexible generators).

Prior to this change, all generators were treated using the more flexible generation option, which may have overstated the ability of inflexible generators to provide reserves.

4. Heat rate penalty

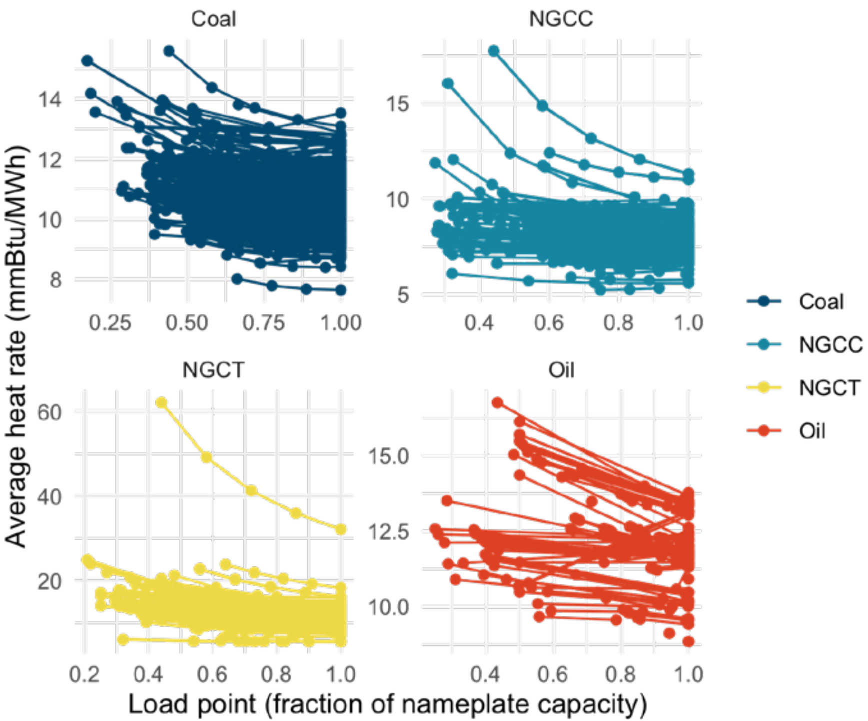
Motivation: Generators that have heat rates may be less efficient if they reduce their set points to ensure headroom for reserves. Capturing this dynamic better captures the cost of providing operating reserves.

Fossil generators are given an additional penalty on cost to provide spinning reserves

- Intended to represent costs of operating at lower efficiencies (i.e., less efficient point on heat rate curve)

Penalty factor is derived from the increase in heat rate at 50% load relative to 100% load

- Based on heat rate curves in the PLEXOS database used for the North American Renewable Integration study (NARIS, 2021), depicted in the chart to the right



Release of model with updated reserve formulations

All model changes described above have been included in the 2021 version of the ReEDS model.

This model version was made publicly available in November with the release of the 2021 Standard Scenarios.

- Available at https://www.nrel.gov/analysis/reeds/.

Operating reserve switches in ReEDS

To facilitate operating reserve analysis, these switches were added to the model:

Switch name	Description	Values
GSw_OpRes	Turn on/off operating reserve constraints	**0** = off, **1** = on (default)
GSw_OpResCost	Suffix for filename of inputs for operating reserve costs; users can use one of two included files or create their own cost input file	**default** = costs only included for regulation reserves (default) **market** = cost of providing spinning, regulation, and flexibility for all generators given value of clearing prices in 2017*
GSw_OpResReqMult	Multiplier for total requirement of operating reserves	Any positive number (default is 1)
GSw_OpResTrade	Turn on/off the ability to trade operating reserves across balancing areas	**0** = off, **1** = on (default)
GSw_OpResTradeMult	Multiplier on how much transmission capacity is required for each unit of operating reserves traded between balancing areas	Any positive number (default is 1)
GSW_OpresFromVRE**	Turn on/off the ability of VRE resources to provide operating reserves	**0** = off (default), **1** = on
GSW_OpresFromStorage**	Turn on/off the ability of storage to provide operating reserves (includes batteries, pumped storage hydro, and CAES)	**0** = off, **1** = on (default)

*Based on findings in Denholm et al., *An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind*. National Renewable Energy Laboratory, Golden, CO, 2019, https://www.osti.gov/biblio/1493402.

** These switches are not included in the 2021 open access version of ReEDS but will be available in the next release. When turned on, it is assumed that VRE can ramp 100% of its capacity and thus has a reserve_frac = 1.

Testing Performed

We compared operating reserve outcomes in ReEDS with hourly dispatch from PLEXOS, a production cost modeling tool (PCM).

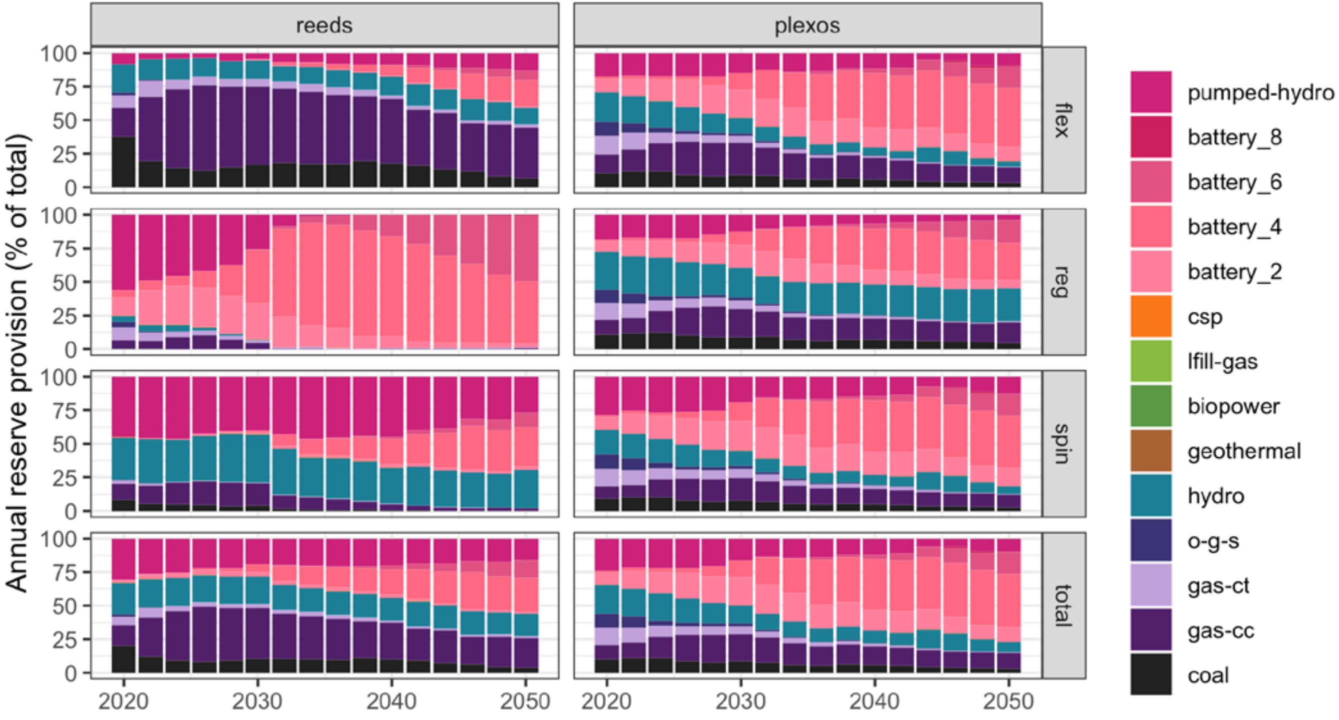
- Finer temporal resolution (hourly), with chronological modeling of storage state-of-charge.
- Better representation of fossil generator constraints (e.g., min stable levels, ramping).

PLEXOS model developed using the ReEDS-to-PLEXOS translation tool

- Based on reference case ReEDS scenario for the continental U.S., run biennially through 2050.
- PLEXOS model run zonally, with spatial resolution matching ReEDS BAs.

Despite some of the enhanced resolution and detail, PLEXOS doesn’t necessarily represent the “ground truth” for these models. However, it is a helpful source of comparison.

Comparison with PLEXOS



ReEDS and PLEXOS show some differences in which technologies are dispatched for specific reserve products.

- ReEDS overestimates hydro provision of spinning reserve and underestimates regulation.
- ReEDS utilizes more gas generation for flex reserves than PLEXOS.

Despite differences by product, the total share of reserve provision by technology across is comparable.

- More gas used for reserves in ReEDS than in PLEXOS; may reflect impact of additional generator constraints.
- Storage is the largest provider of reserves across both modeling approaches, particularly for future scenarios.

Some differences expected given the difference in temporal resolution and generation characteristics between capacity expansion (ReEDS) and production cost (PLEXOS) models

Testing Performed

We also performed sensitivities on some of the new operating reserve switches to understand how they affect capacity buildouts and costs in ReEDS. These sensitivities included:

1. Penalties on trading operating reserves across regions (**GSw_OpResTradeMult**)
2. Allow/disallow VRE to provide reserves (**GSW_OpresFromVRE**)
3. Allow/disallow storage to provide reserves (**GSW_OpresFromStorage**)
4. Allow ReEDS to endogenously determine reserve prices / pay for operating reserves at the 2017 market clearing prices (**GSw_OpResCost**)

We test different combinations of sensitivities 2-4 for both a reference case and a case with a 100% clean energy requirement by 2050*.

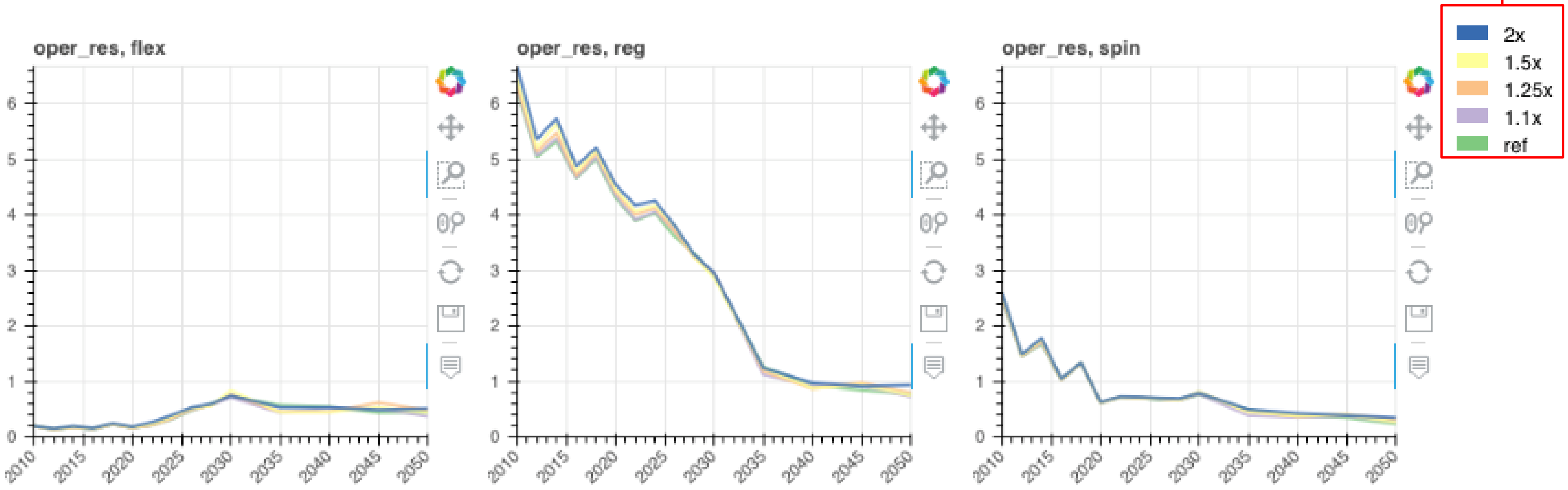
VRE buildout		VRE reserve eligibility		Storage reserve eligibility		Reserve cost method
Reference	X	VRE reserves	X	storage reserves	X	Endogenous
High VRE		no VRE reserves		no storage reserves		Based on 2017 market prices

*For these runs "clean" includes all VRE and renewable generation as well as bio- or H2- powered combustion turbines, but excludes nuclear.

ReEDS sensitivity testing: Penalty on trading reserves

Multipliers for how much transmission must be allocated to for reserves to be traded between BAs (ref: 1 means trading 1 MW required 1 MW of transmission)

National average reserve prices by product ($/MW-h)

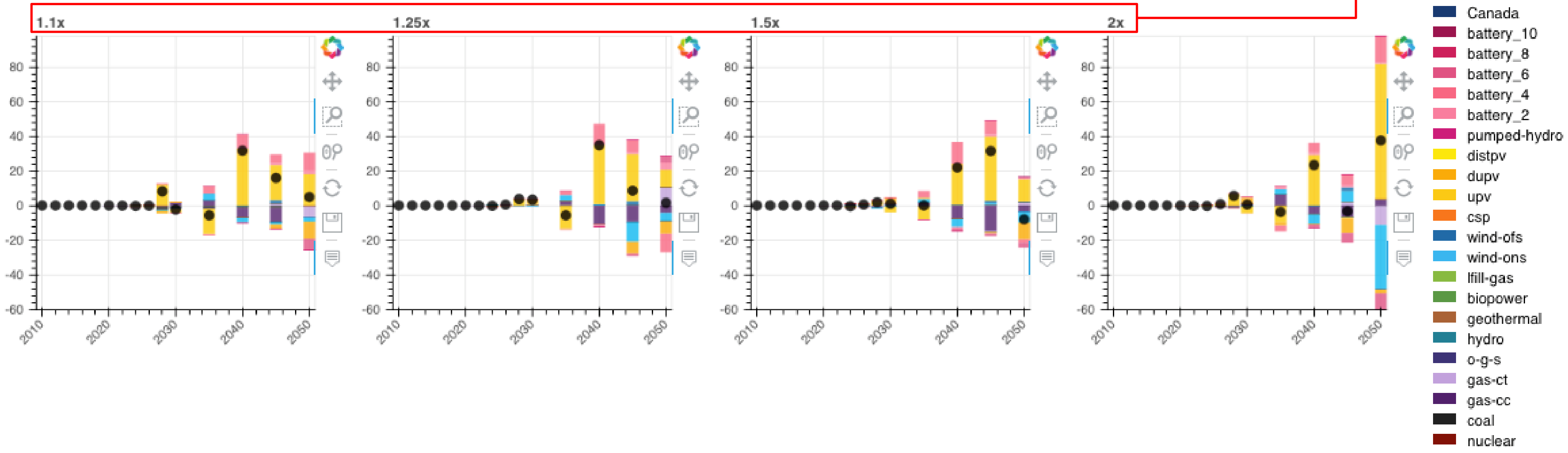


Multipliers for trading operating reserves have little impact on reserve prices or installed capacity

ReEDS sensitivity testing: Penalty on trading reserves

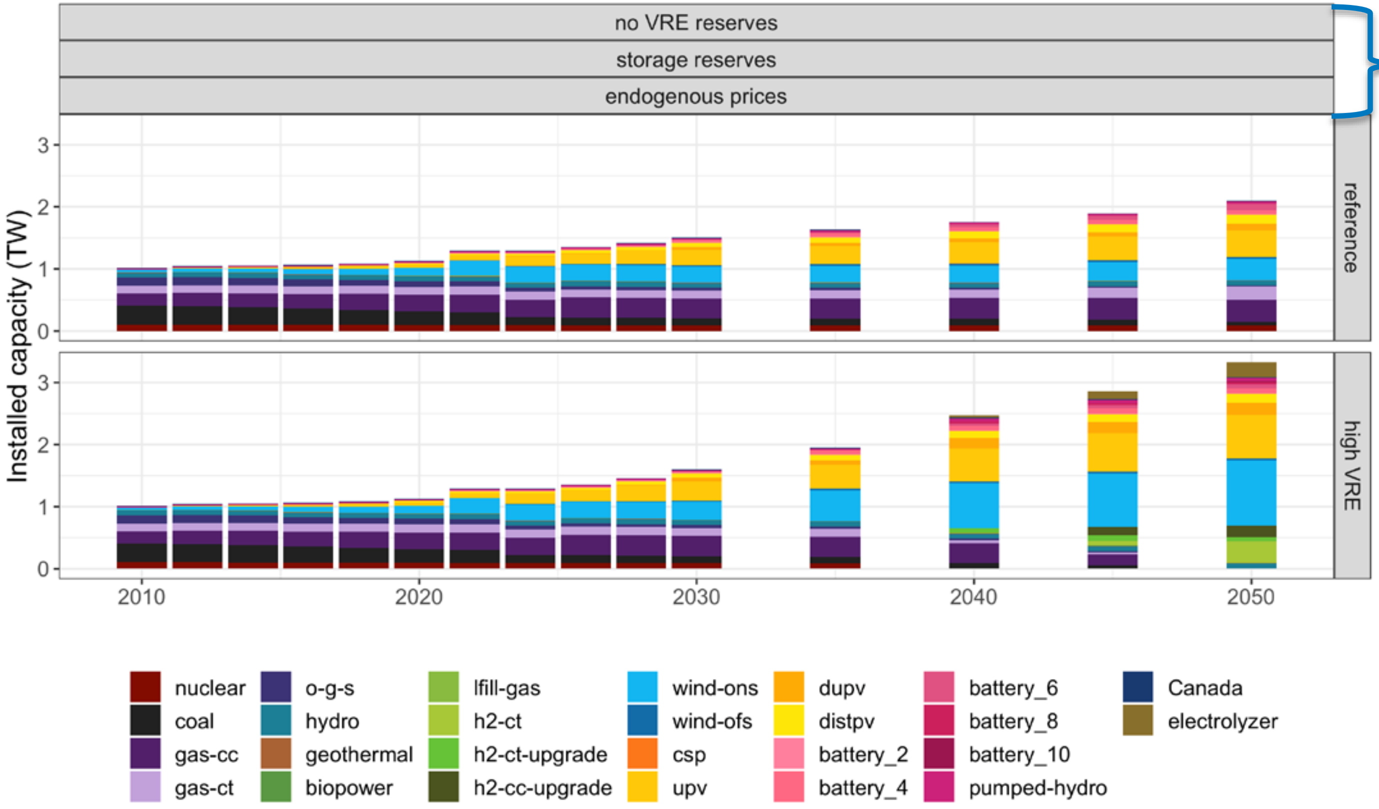
Multipliers for how much transmission must be allocated to for reserves to be traded between BAs (ref: 1 means trading 1 MW required 1 MW of transmission)

U.S. installed capacity (GW, difference from reference)



Multipliers for trading operating reserves have little impact on reserve prices or installed capacity

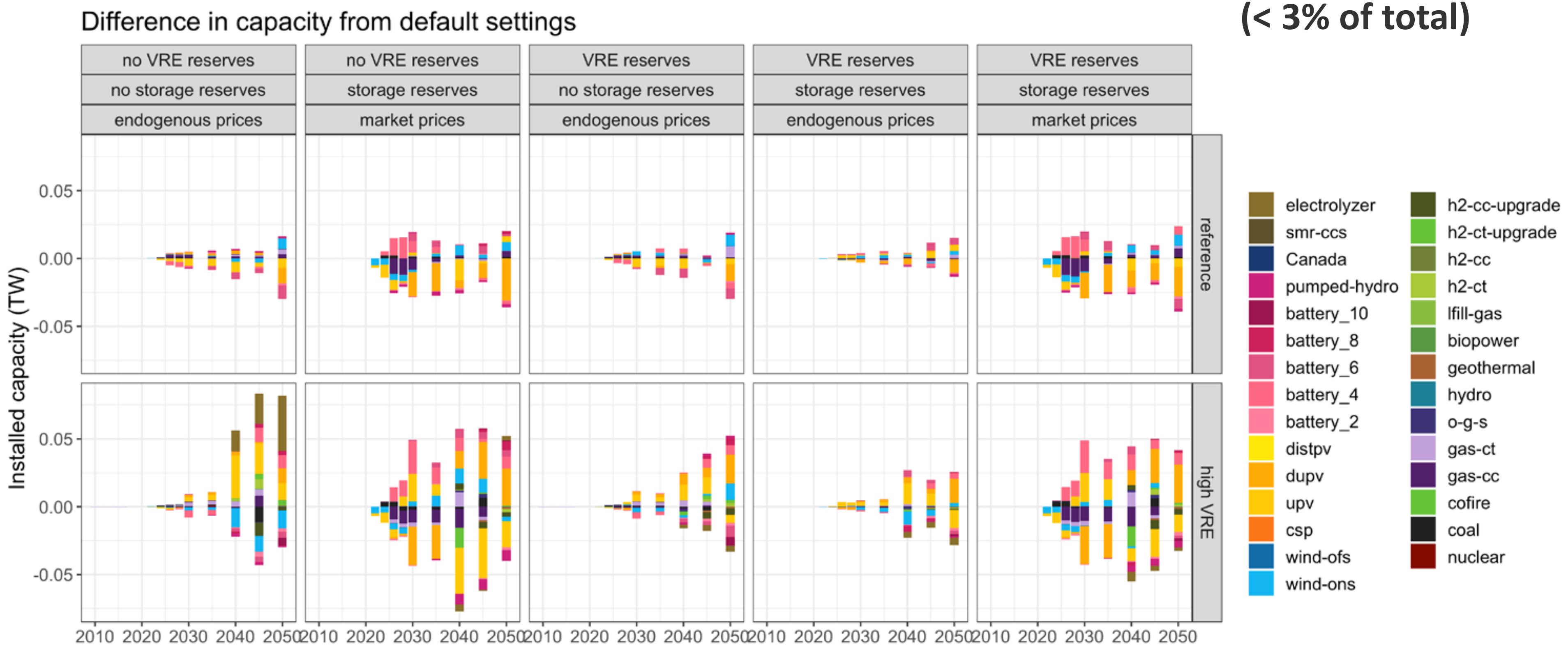
ReEDS sensitivity testing: Installed capacity



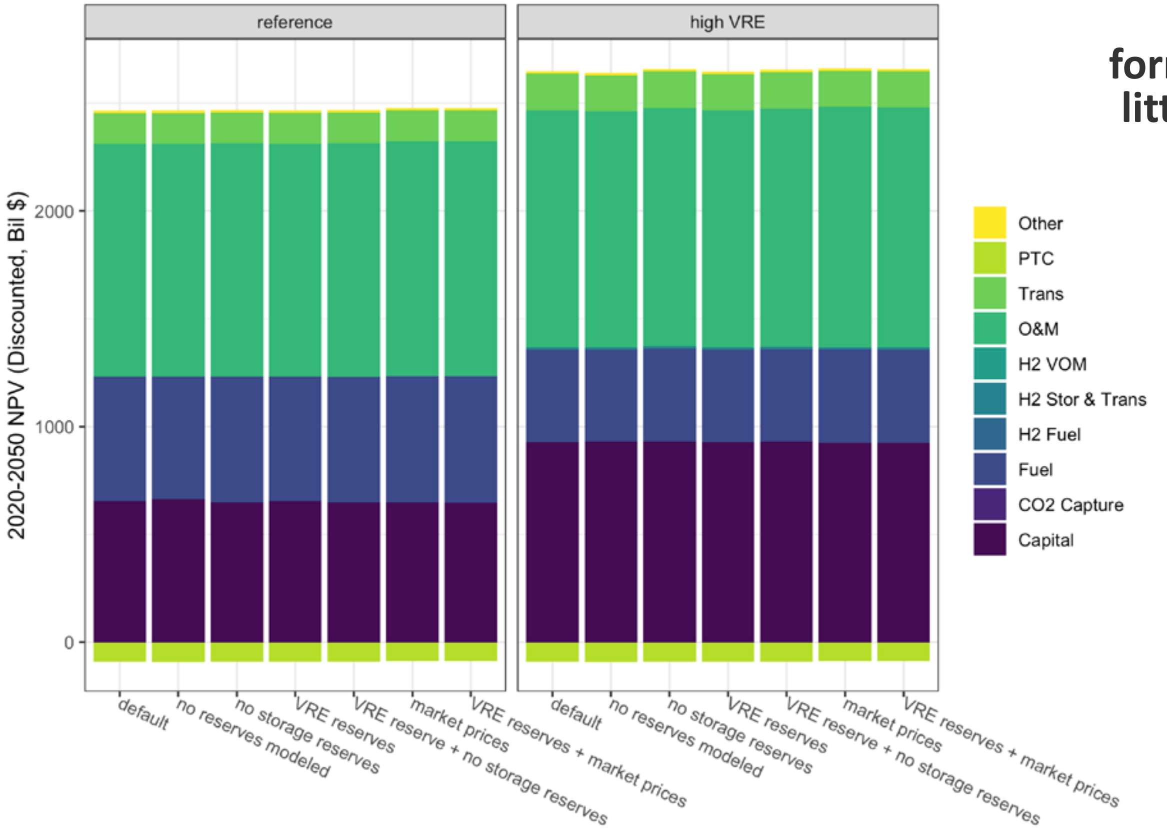
Default settings in ReEDS for operating reserves switches

ReEDS sensitivity testing: Installed capacity

Capacity differences are small relative to system size (< 3% of total)

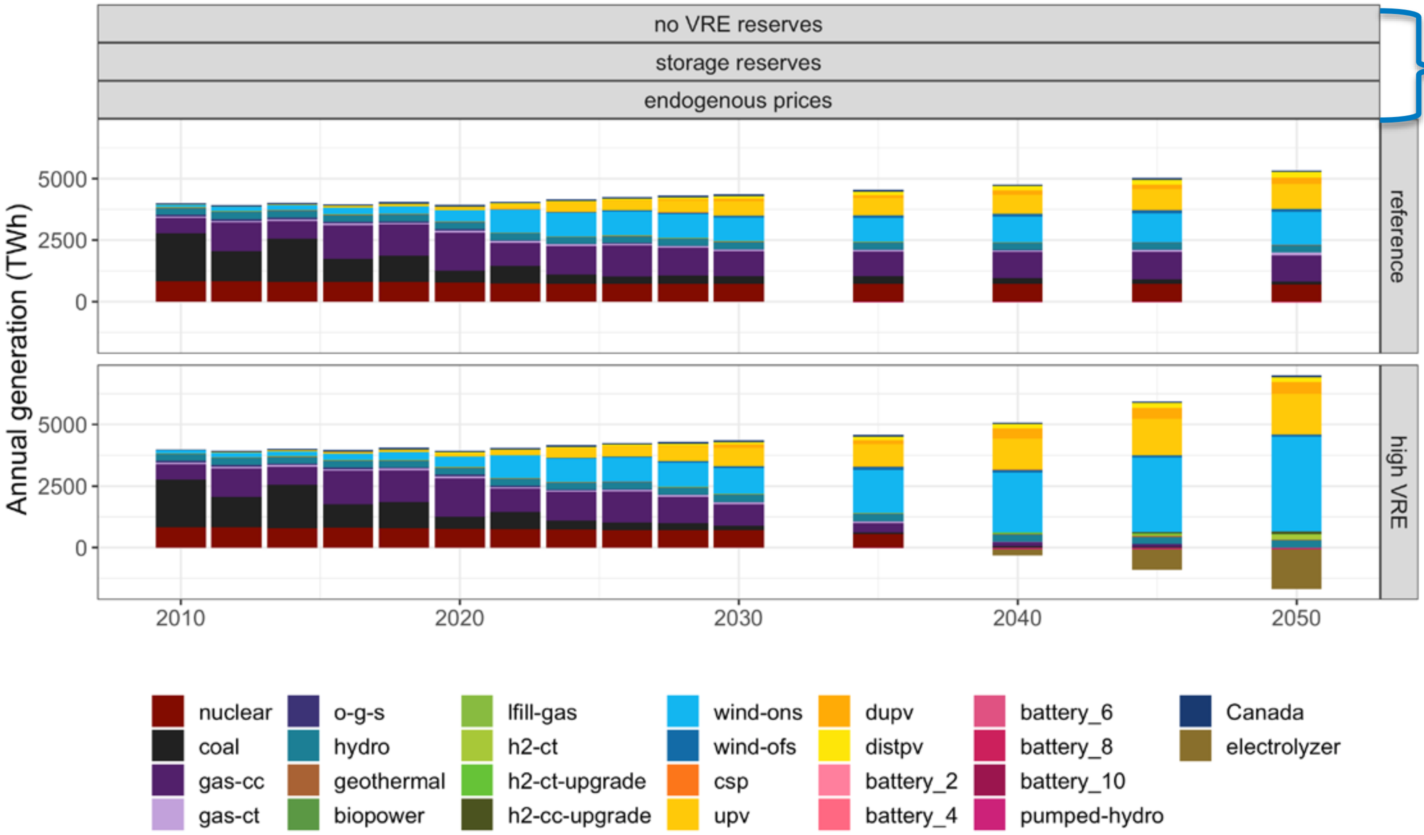


ReEDS sensitivity testing: System Costs



Reserve eligibility/pricing formulations tested have relatively little impact on total system costs

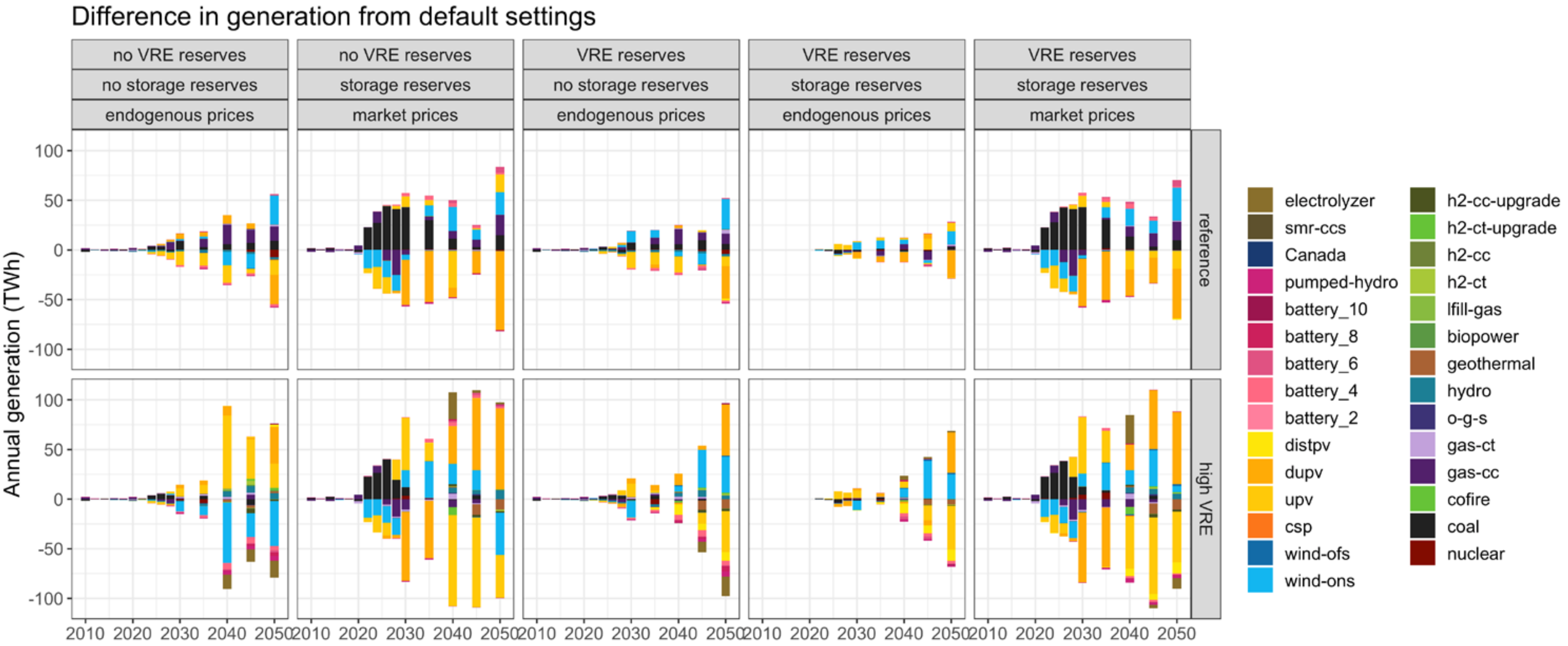
ReEDS sensitivity testing: Annual generation



Default settings in ReEDS for operating reserves switches

ReEDS sensitivity testing: Annual generation

Generation differences are small relative to total (< 3%)



ReEDS sensitivity testing: Reserve provision

ReEDS sensitivity testing: Reserve provision

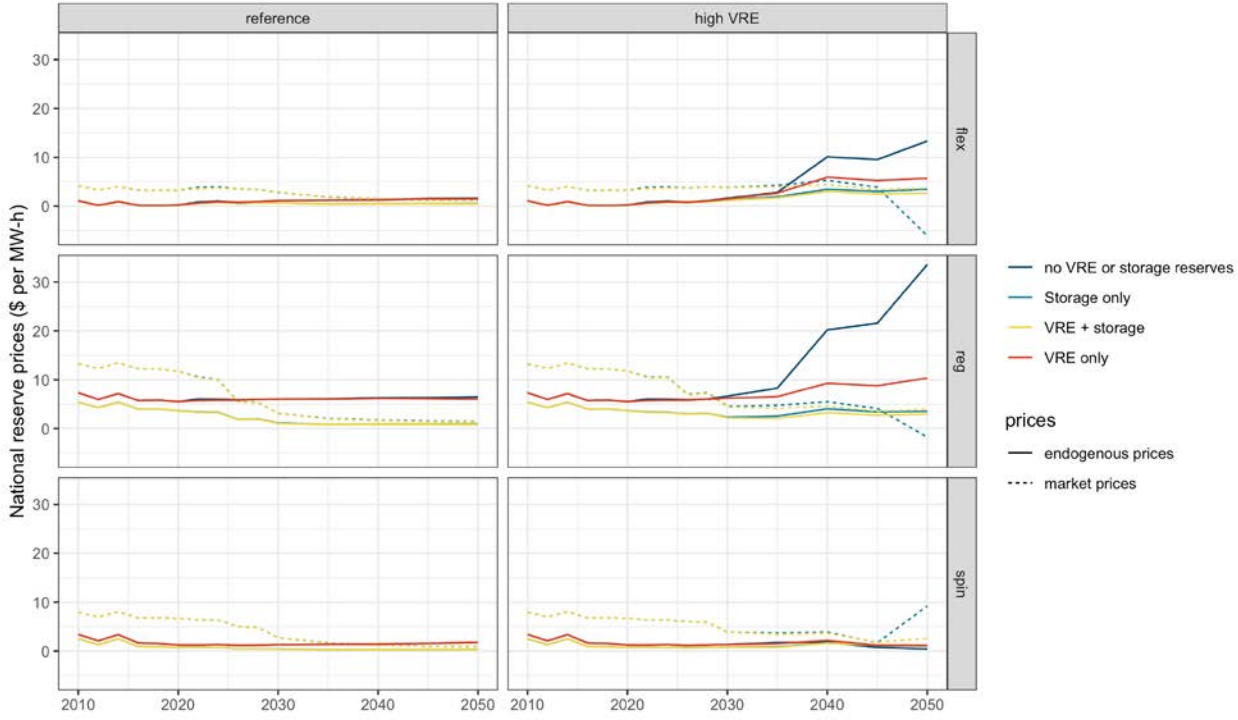
Reference cases

- Disallowing storage from providing operating reserves increases the amount provided from fossil and hydro.
- There is little VRE used for reserves, even in scenarios where it is allowed.
- Using historical market prices for reserves shifts reserve provision away from thermal resources and toward storage.

High VRE cases

- H2-CTs are used to provide operating reserves in all cases; reliance on these resources increases dramatically if storage cannot provide reserves.
- VRE is used to provide reserves when allowed, but provides a smaller share than storage and H2-CTs

ReEDS sensitivity testing: Reserve prices



National average reserve prices computed by multiplying the price of reserves (the marginal value of the reserve constraint) with the quantity of reserves provided by BA, summing across all BAs to get total national cost of reserves, and then dividing by the total quantity of reserve procured nationally

Highest prices occur when storage is not allowed or able to provide reserves.

- Biggest impact occurs in regulation reserves.
- The price impacts are higher in high VRE case.
- Aligns with previous findings on curtailment/reserve provision (see Frew et al. "The Curtailment Paradox in the Transition to High Solar Power Systems")

Market price estimates are generally higher than the endogenous estimates in the short term but lower than them in future cases.

- ReEDS likely not capturing all of the costs for thermal resources to provide reserves.
- Prices for operating reserves might be expected to rise as systems move to higher shares of wind and solar.

Summary

This project enhanced ReEDS' formulation for operating reserves:

- Improved representation of storage.
- Better constraints on generator commitment.
- Revised costs for generators with heat rates.
- More switches to enable users to test different aspects of reserves.

Comparison against PLEXOS runs indicates general alignment in the types of generators that provide reserves.

- There are differences between the two in which resources supply which operating reserve product, but total provision by technology is similar across the two.
- Some differences are expected between capacity expansion and production cost models due to differences in temporal resolution, chronological modeling, and thermal generator constraints.

Sensitivity testing suggests reserve formulations exert little influence over the solution of the model (i.e., installed capacity, total system cost)

- However, the operating reserve formulation does impact what technologies are used to provide reserves, and thus may be important for certain analyses.
- Future work might further investigate the conditions in which operating reserves exert more influence over the model solution (e.g., does a capacity expansion model with higher temporal resolution better capture some of the challenges involved in procuring operating reserves?).

References

For documentation and access to the latest ReEDS model, see https://www.nrel.gov/analysis/reeds/about-reeds.html

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NREL Transforming ENERGY

eq_storage_opres formulation

```
* ---------------------------------------------------------------------------

*there must be sufficient energy in storage to provide operating reserves
eq_storage_opres(i,v,r,h,t)$[valgen(i,v,r,t)$tmodel(t)$Sw_OpRes
                            $(storage_standalone(i) or pvb(i) or hyd_add_pump(i))]..

*[plus] initial storage level
    STORAGE_LEVEL(i,v,r,h,t)

*[minus] generation that occurs during this timeslice
    - hours_daily(h) * GEN(i,v,r,h,t) $[not pvb(i)]

*[minus] generation that occurs during this timeslice
    - hours_daily(h) * GEN_PVB_B(i,v,r,h,t) $[pvb(i)$Sw_PVB]

*[minus] losses from reg reserves (only half because only charging half
*the time while providing reg reserves)
    - hours_daily(h) * OPRES("reg",i,v,r,h,t) * (1 - storage_eff(i,t)) / 2 * reg_energy_frac

    =g=

*[plus] energy reserved for operating reserves
    + hours_daily(h) * sum{ortype, OPRES(ortype,i,v,r,h,t) }
;

* ---------------------------------------------------------------------------
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