The value of interregional coordination and transmission in decarbonizing the US electricity system

Patrick R. Brown and Audun Botterud

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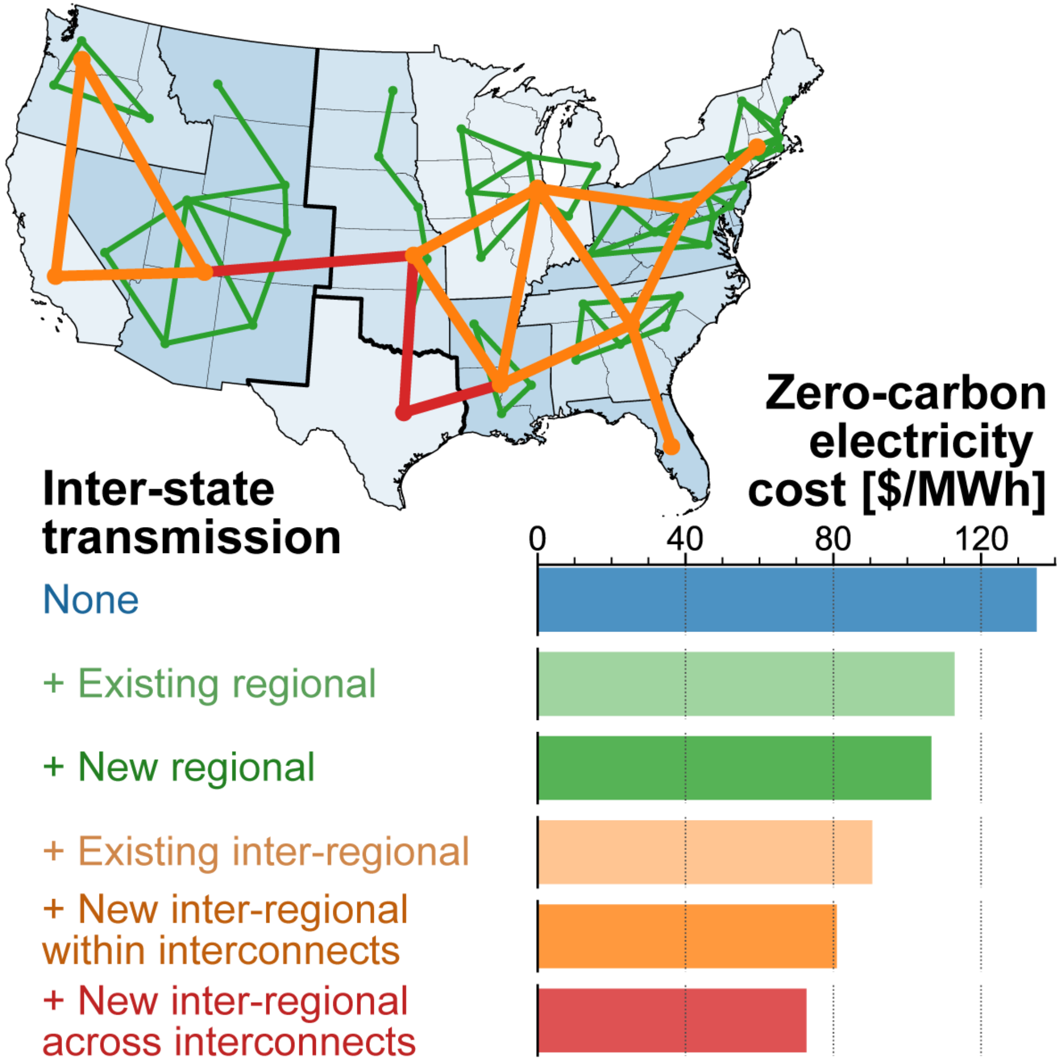
prbrown@mit.edu

MIT Energy Initiative



Brown, P.R.; Botterud, A. *Joule* **2021**, *5*, 115
https://doi.org/10.1016/j.joule.2020.11.013
https://github.com/patrickbrown4/zephyr

Prior work on low- and zero-carbon power systems (USA)

Low carbon (up to ~80% decarbonized)

- Sequential investment pathway
- High geographic coverage
- Multi-node transmission model
- Low temporal resolution for capacity-investment decisions*

NREL 2012 – Renewable Electricity Futures Study
ReEDS: U.S., **80%** [30-90%] emissions reduction

NREL: **RPM**
EPA: **IPM**
EIA: **NEMS**
EPRI: **US-REGEN**

Kammen et al. *Applied Energy* **2016**, *162*, 1001
SWITCH: WECC, **85%** emissions reduction

NREL Interconnections Seam Study **2020**: up to **85%** renewables

MacDonald et al. *Nat. Clim. Change* **2016**, *6*, 526
NEWS: U.S., **up to 80%** emissions reduction

Zero carbon (100% decarbonized)

- Steady-state “snapshot” (not sequential investment pathway)
- Isolated sites/ISOs or copper-plate US
- No transmission (1-node system)
- ≤ 1 hr temporal resolution
- ≥ 1 year of VRE data

Jacobson et al. *PNAS* **2015**, *112*, 15060

Ziegler et al. *Joule* **2019**, *3*, 2134

Caldeira et al. *Energy Environ. Sci.* **2018**, *11*, 914

Sepulveda et al. *Joule* **2018**, *2*, 2403

Princeton Net-Zero America Study **2020**

Vibrant Clean Energy **2020**

NREL LA100 **2021**

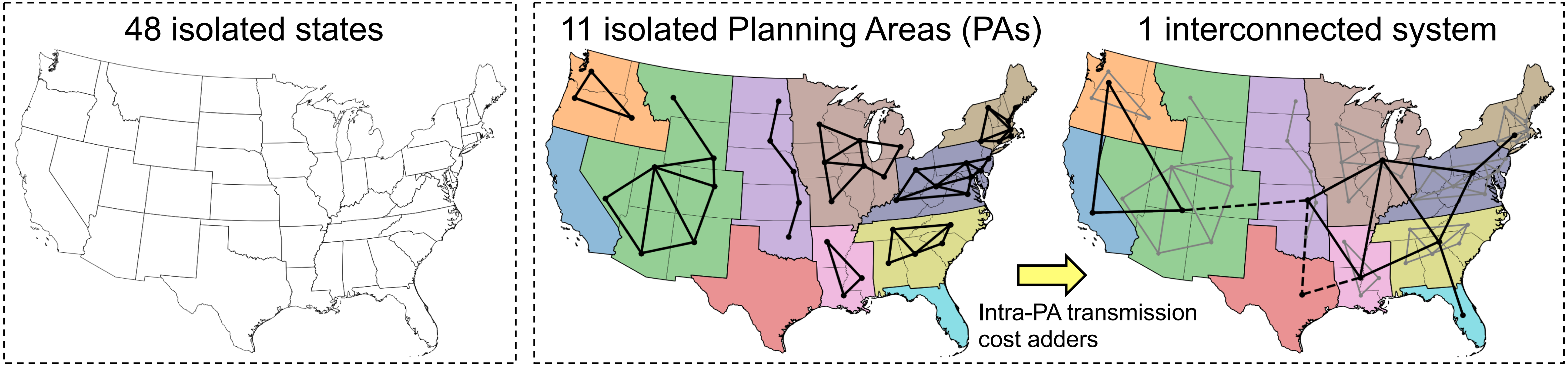
Many studies for Europe

…

This study: Zero-carbon power systems for the US

Our approach:

- Co-optimized **capacity & operation** of generation, storage, and transmission
- Linearized model, chronological hourly weather and load over **7 years** (2007-2013, 61296 hrs)
- **Zero carbon** as central case; sensitivities for nonzero carbon, nuclear, hourly reserves
- Technology costs: NREL Annual Technology Baseline (ATB) 2019, **2030 “mid”** as baseline
- Hourly demand: NREL Electrification Futures Study (**2040 “Reference” electrification** as baseline, other scenarios as sensitivities)



Modeled technologies

Included in all cases:

Zero-carbon technologies **currently** being deployed at **GW** scale in the US

- **PV**
  - Horizontal 1-axis tracking; NREL NSRDB weather
- **Wind**
  - Reference: Gamesa G126/2500 (200 W/m^2), 100m hub (additional turbines in sensitivity); NREL WIND Toolkit weather
- **Li-ion batteries***
  - Independent energy capacity (battery cells) and power capacity (inverter/interconnection)
  - *Left out of long-duration-storage sensitivities
- **Existing hydropower (no new capacity)**
  - Run-of-river: Historical monthly availability (EIA 860 & 923), must-run
  - Reservoir: Historical monthly availability (EIA 860 & 923), flexible dispatch within each day

Included in some sensitivities:

- "Long-duration" energy storage (LDES)
  - Cost & performance based on pumped hydro
- Nuclear
  - Existing/new, variety of cost + performance assumptions
- $9000/MWh load-shedding
- Natural gas combined- and open-cycle

NOT included:

- Offshore wind
- Carbon capture
- Demand flexibility
- Coal / oil
- Concentrated solar thermal
- Geothermal
- Bioenergy

Framing this work

This study is:

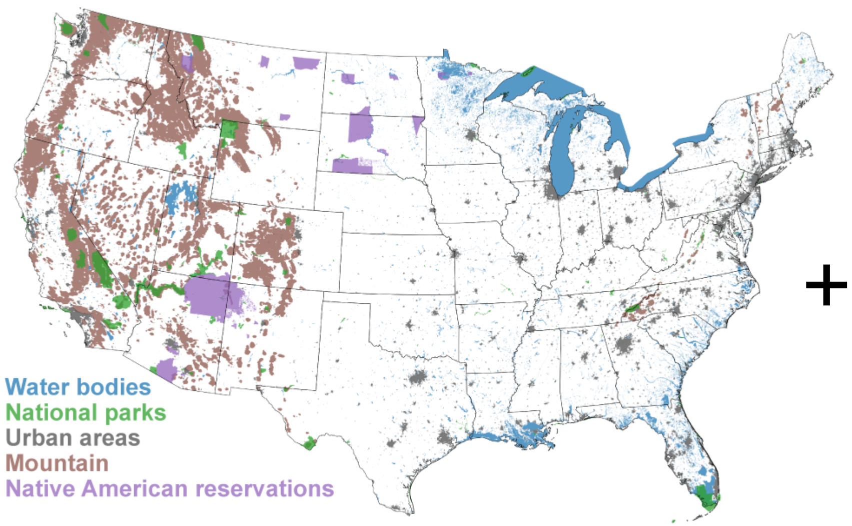
- Primarily concerned with **resource adequacy** in **zero-carbon** systems
- Technologically conservative
  - Only techs currently deployed at **GW scale**
- An improvement on some aspects of previous studies:
  - Copper plate (Caldeira, Jacobson) → Explicit interregional **transmission** flows and capacity
  - Isolated regions (Princeton, Sepulveda, Ziegler) → **Full interconnected US**
  - 1 year of weather data (Princeton, NREL Seams, Sepulveda) → **7 years** in base case, 21 years in sensitivity
  - Seasonal timeslices (NREL ReEDS) → **hourly co-optimized planning & dispatch**

This study is NOT:

- An AC or DC optimal-power-flow or **security**-constrained dispatch study
  - Transmission flows are completely controllable and highly aggregated
- A transmission/generation **siting** study
  - Generation and transmission assets are highly aggregated
- An analysis of specific **policy** or regulatory approaches
- **Economy-wide**
  - We only model the electricity system (with high-electrification sensitivities)
- A **pathway** study
  - System snapshot, 2040 demand; hydro and transmission are the only brownfield assets

Wind + solar supply curves

Filter out excluded areas



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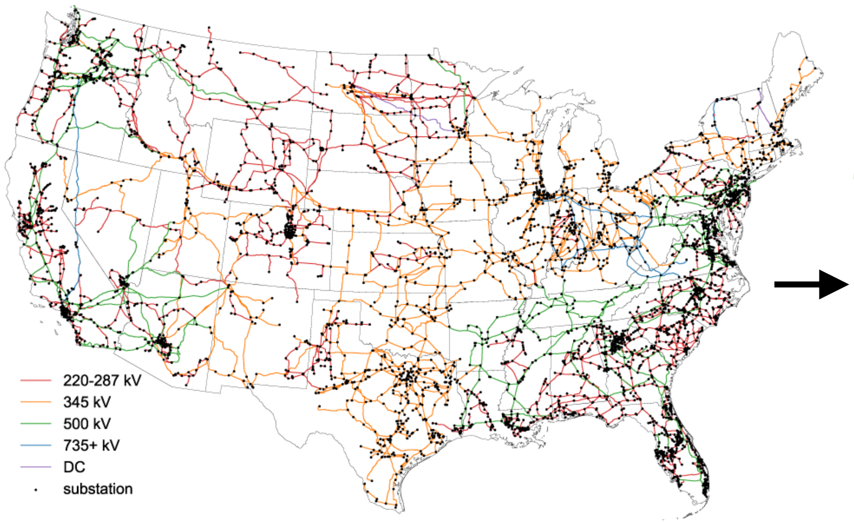
Interconnect to existing substations



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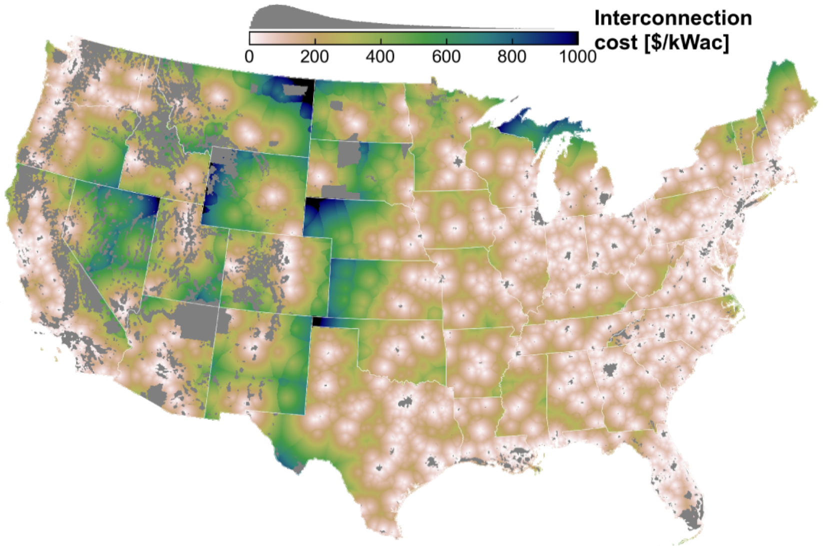
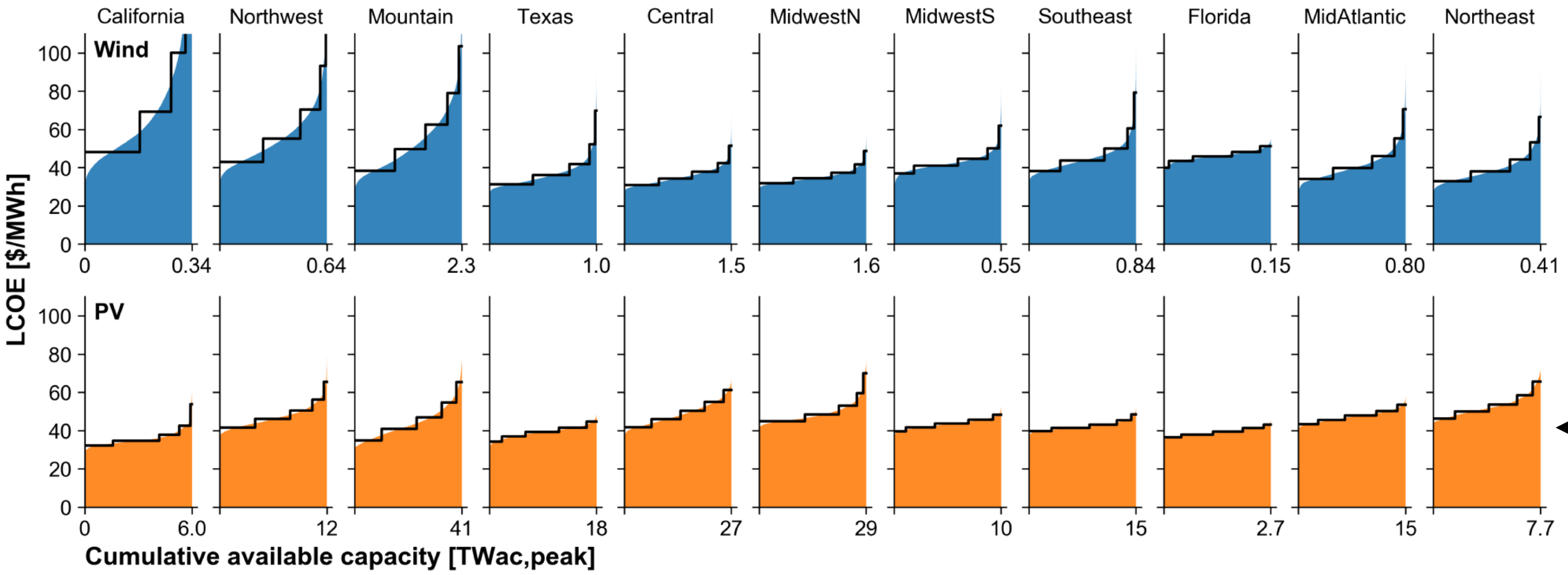
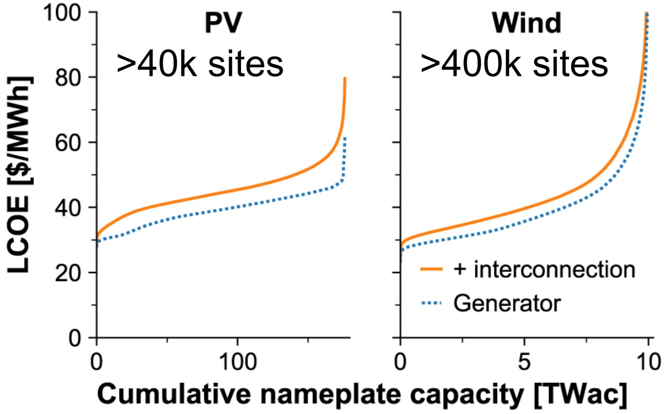
Interconnection cost map







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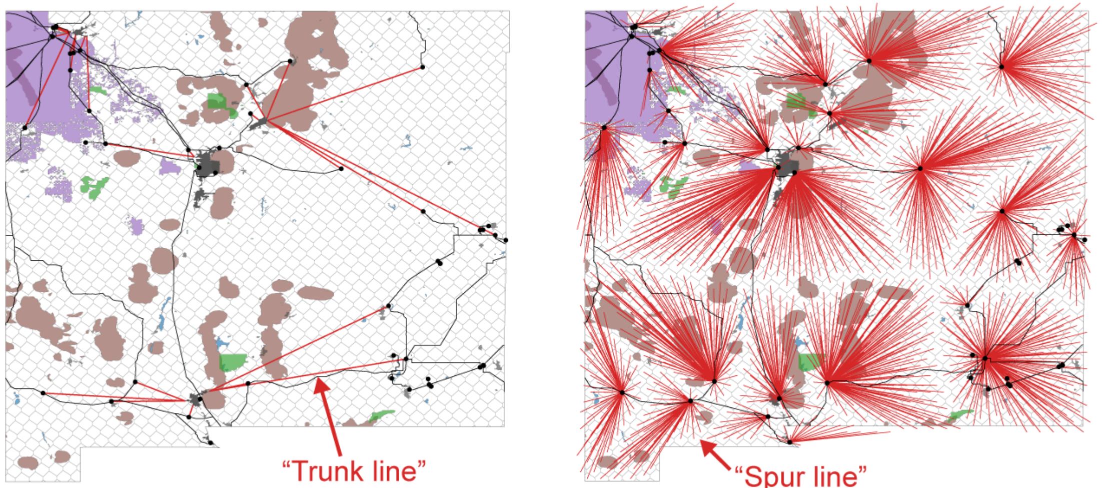
Bin PV and wind sites by state or planning area (PA) and LCOE

→ 7x8760-hour profiles

Three types of transmission modeled

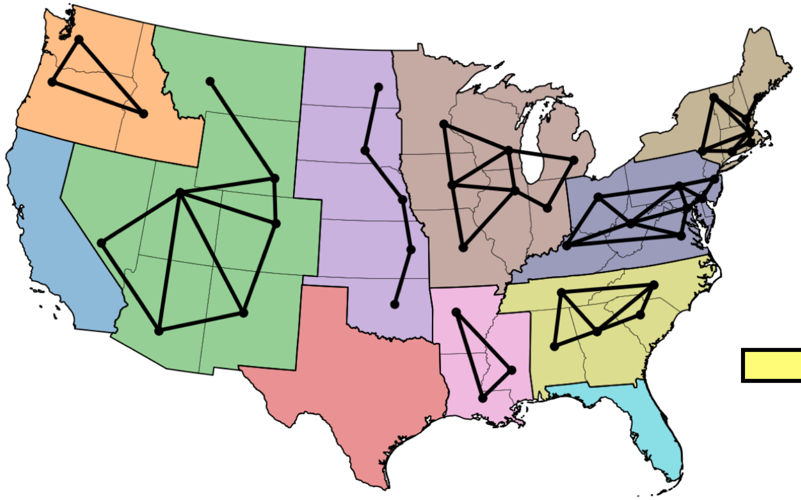
1. Intra-state "interconnection" lines for PV + wind

- Includes "spur lines" to nearest substation and "trunk line" reinforcements to nearest urban edge
- Included in system cost, but not in inter-state transmission capacity [TW-km] totals



2. Inter-state intra-PA

- Existing lines and new builds
- AC only

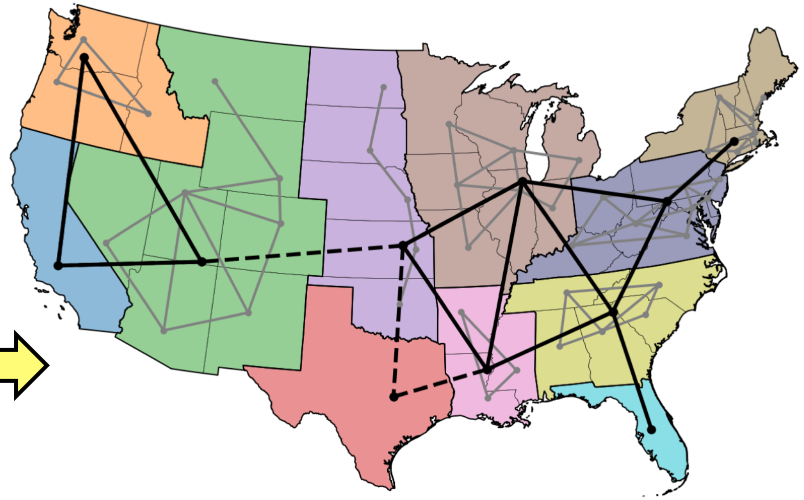


Intra-PA transmission cost adders for PV and wind [$/kWac-yr]:

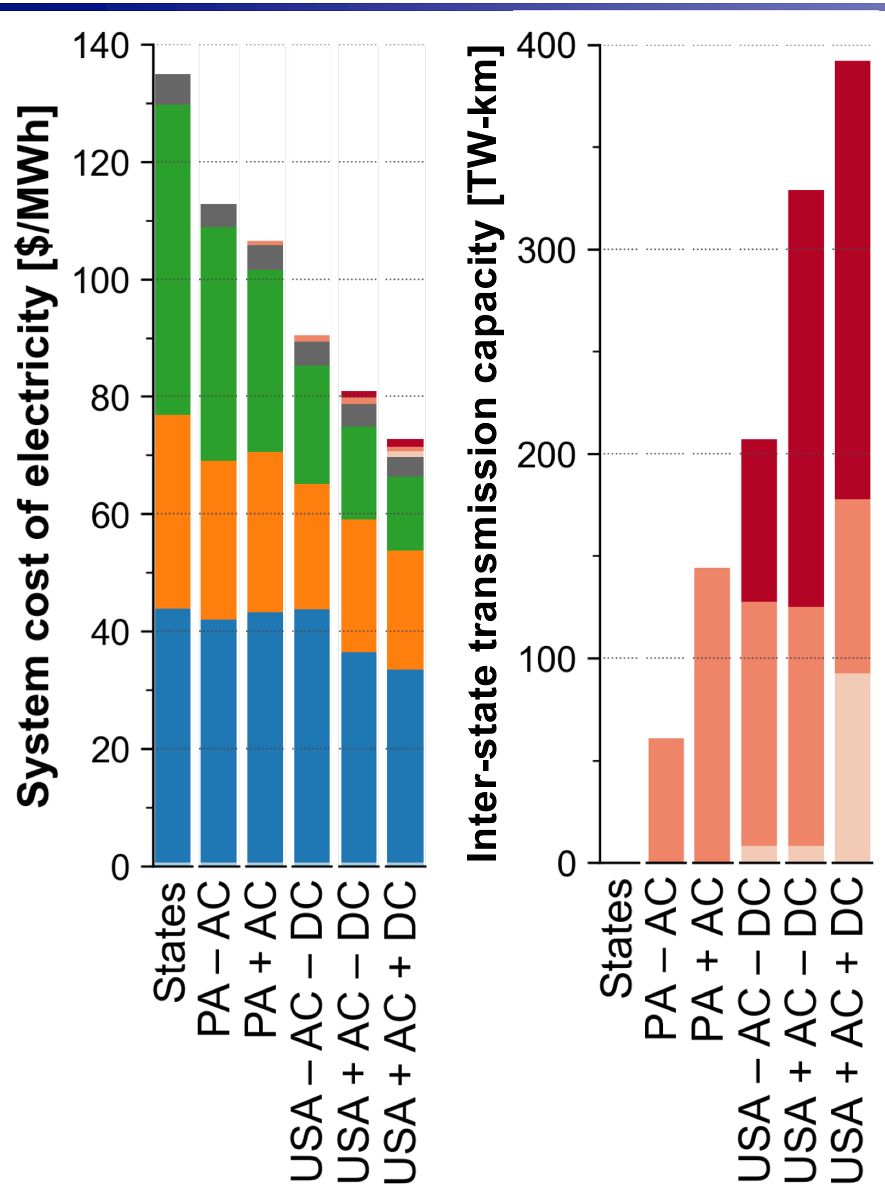
$$\frac{\left(\text{annualized inter-state transmission cost [\$/yr]}\right)}{\left(\text{installed PV and wind capacity within PA [kWac]}\right)}$$

3. Inter-state inter-PA

- Existing lines and new builds
- AC within same interconnect, DC between interconnects



Reductions in cost, storage, & capacity with regional coordination



* SCOE = System Cost of Electricity [$/MWh]
= (annualized capex + opex) / (annual demand)

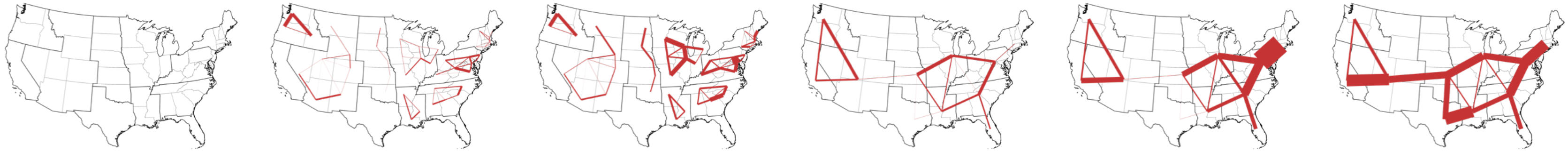
+ 1.0 $/MWh trans.
– 8.2 $/MWh SCOE

+ 0.8 $/MWh trans.
– 6.3 $/MWh SCOE

+ 1.2 $/MWh trans.
– 9.6 $/MWh SCOE

Scenario:

States | **PA – AC** | **PA + AC** | **USA – AC – DC** | **USA + AC – DC** | **USA + AC + DC**



+ Existing regional

+ **New** regional

+ Existing **inter**-regional

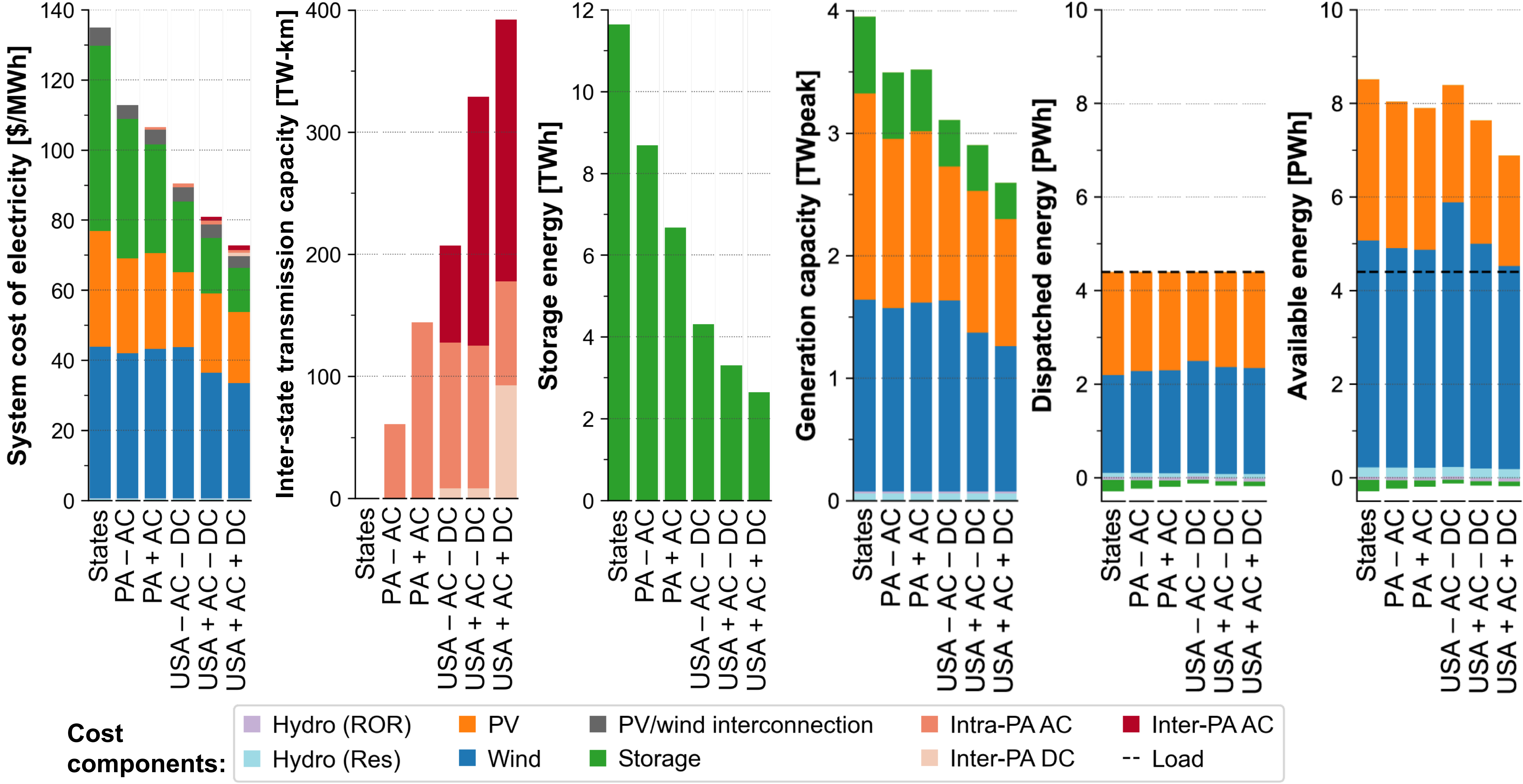
+ **New** AC inter-regional
within interconnects

+ **New** DC inter-regional
across interconnects

Cost components:

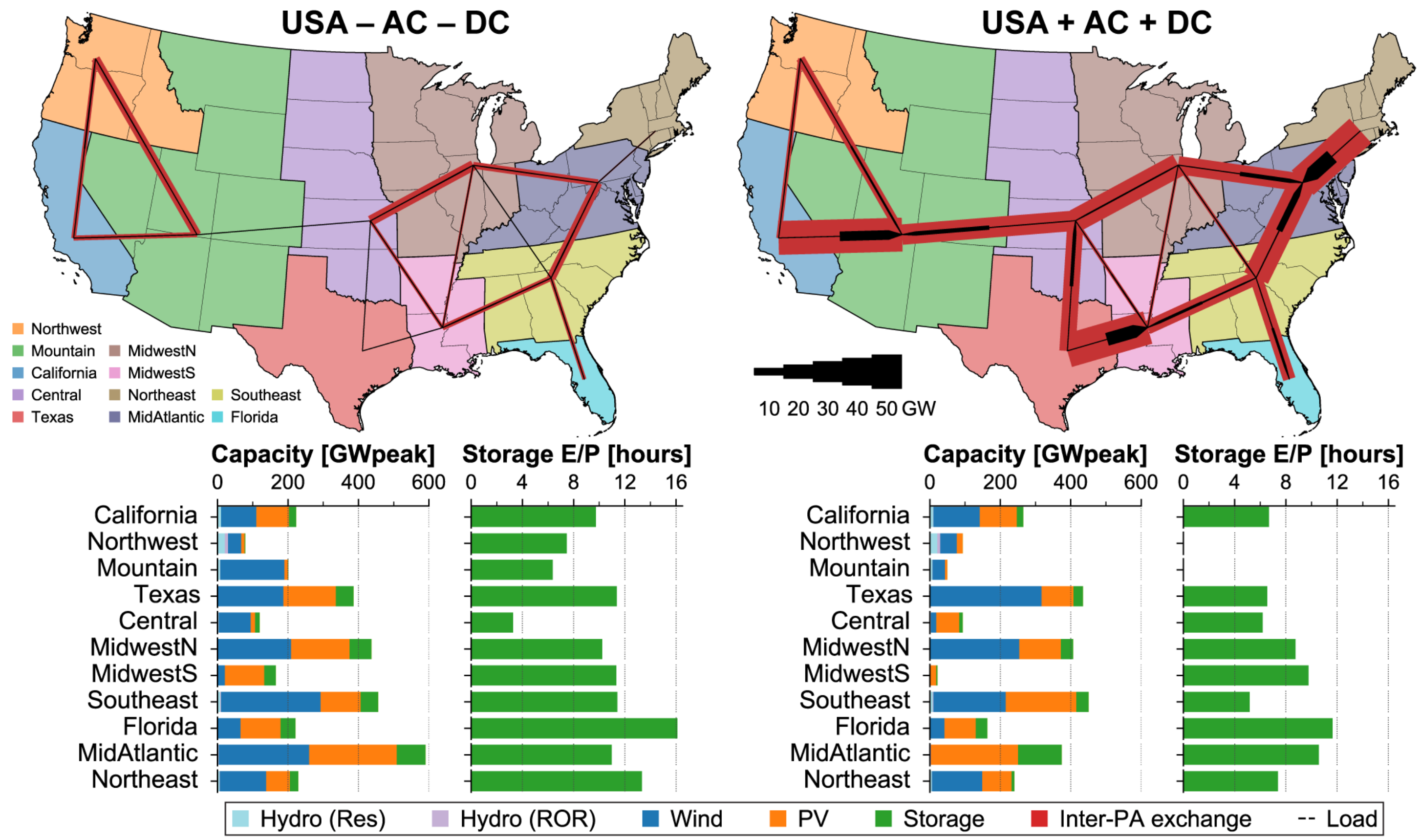
Hydro (ROR)	PV	PV/wind interconnection	Intra-PA AC	Inter-PA AC
Hydro (Res)	Wind	Storage	Inter-PA DC	-- Load

Reductions in cost, storage, & capacity with regional coordination

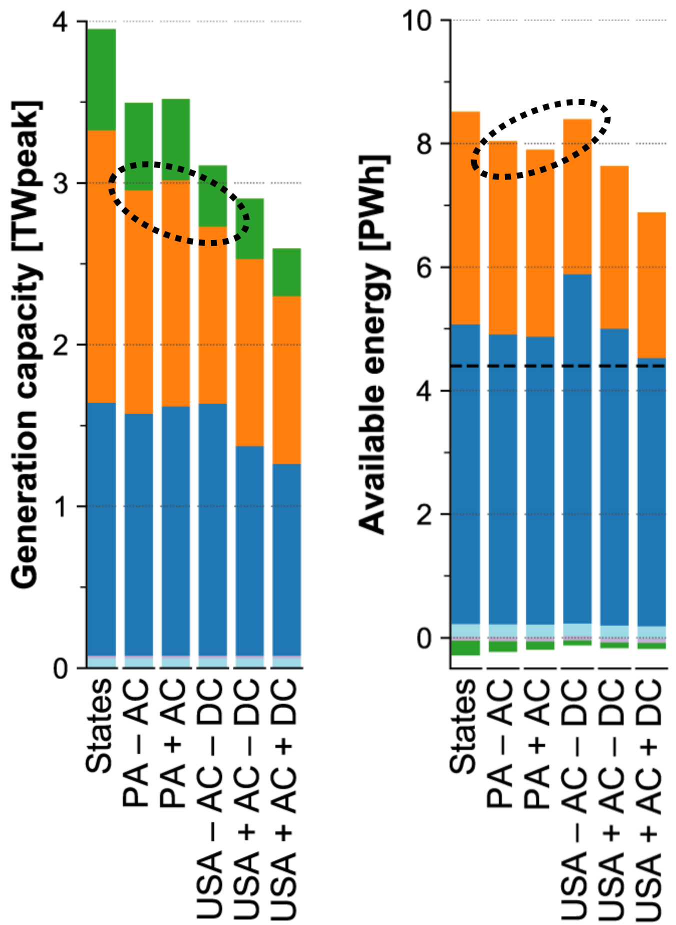


Two main benefits of inter-state transmission*

1. Reduction in aggregate variability through spatial averaging → **Reduction in storage capacity + duration**



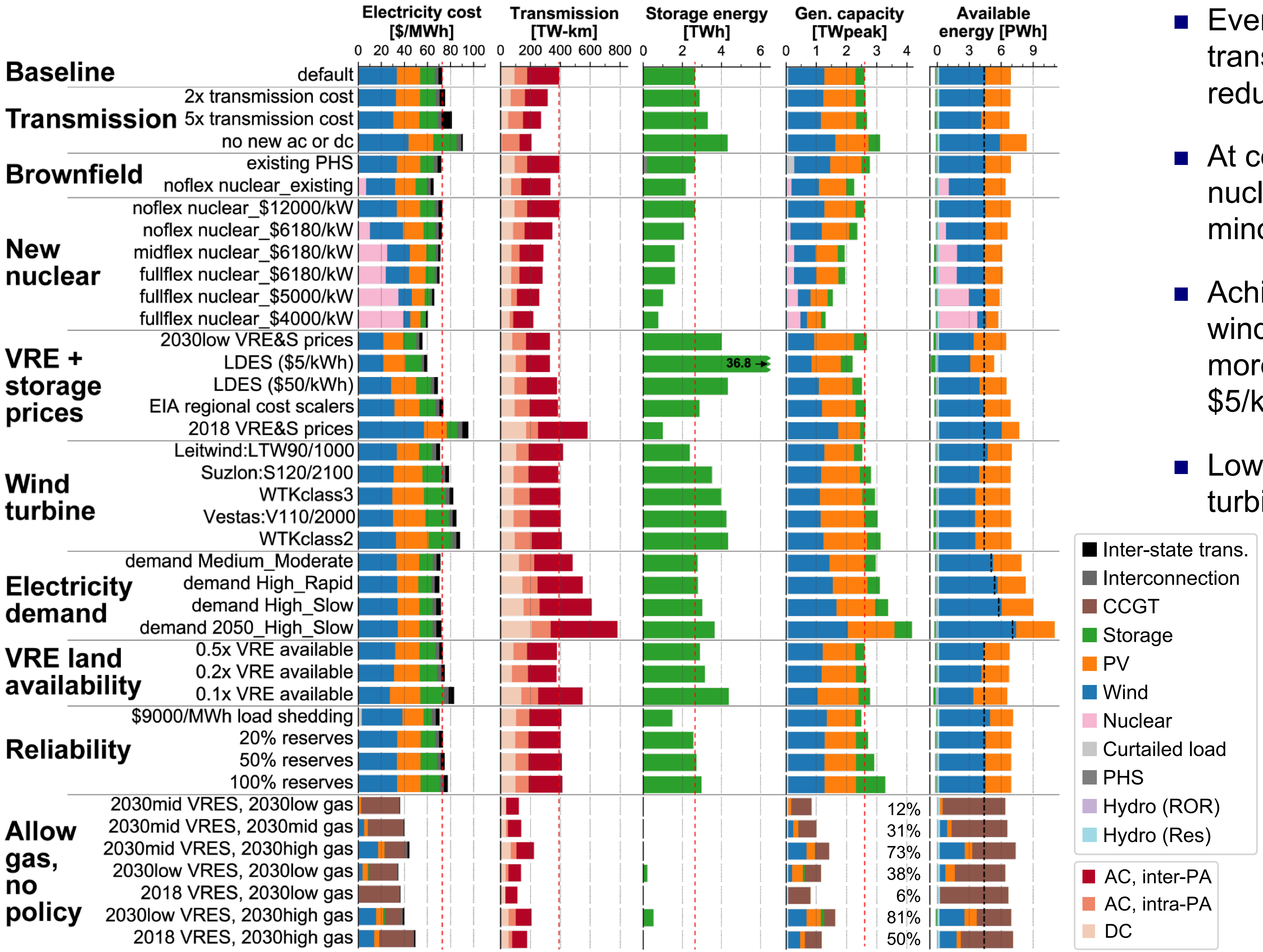
2. Better access to high-quality resource regions → **More energy from less PV/wind capacity**



* Additional benefits of transmission not resolved here:

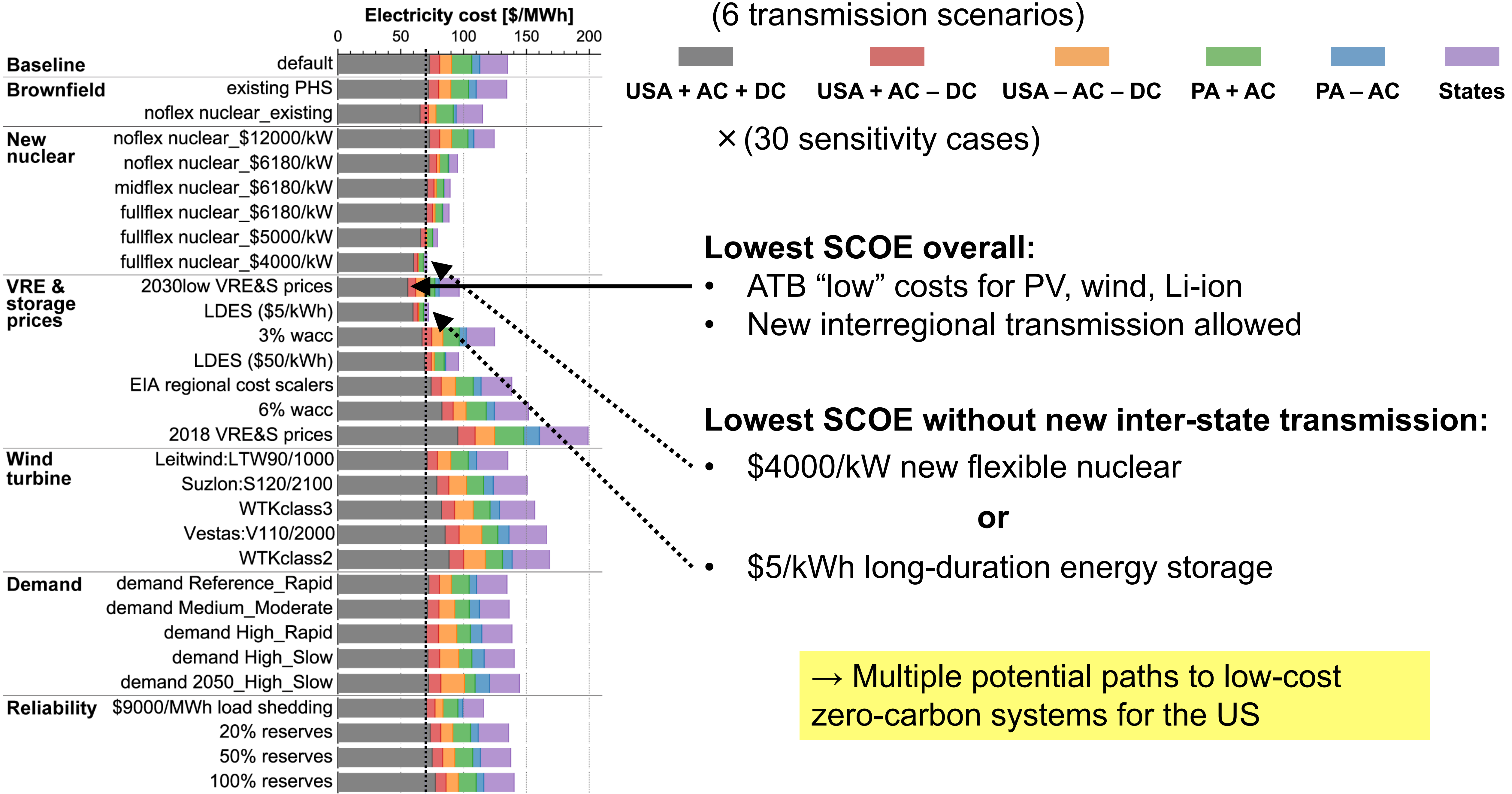
- n-1 security
- Inertia / stability
- Reduction in forecast uncertainty [Pfeifenberger 2020]
- Sub-hourly balancing
- Mitigating regionally-correlated unmodeled outages (e.g. icing, fuel scarcity)

Sensitivity analysis (USA + AC + DC)



- Even at 5x transmission cost, installed transmission capacity increases ~30% and reduces SCOE by ~6 $/MWh
- At central projected prices ($6180/kW), some nuclear is installed when available, but with minor impact on electricity cost (~$2/MWh)
- Achieving 2030 “low” price projections for wind, PV, and Li-ion reduces system cost more than $4000/kW flexible nuclear or $5/kWh long-duration storage
- Low-specific-power (low-windspeed) wind turbines reduce electricity cost
- Cross-sector electrification increases capacity, but insignificant impact on electricity cost
- Extent of “overbuilding” is similar between zero-carbon and no-policy
- **Every** USA scenario is cheaper than isolated-PA scenario (107 $/MWh)

Sensitivity analysis with limited transmission



Lowest SCOE overall:

- ATB “low” costs for PV, wind, Li-ion
- New interregional transmission allowed

Lowest SCOE without new inter-state transmission:

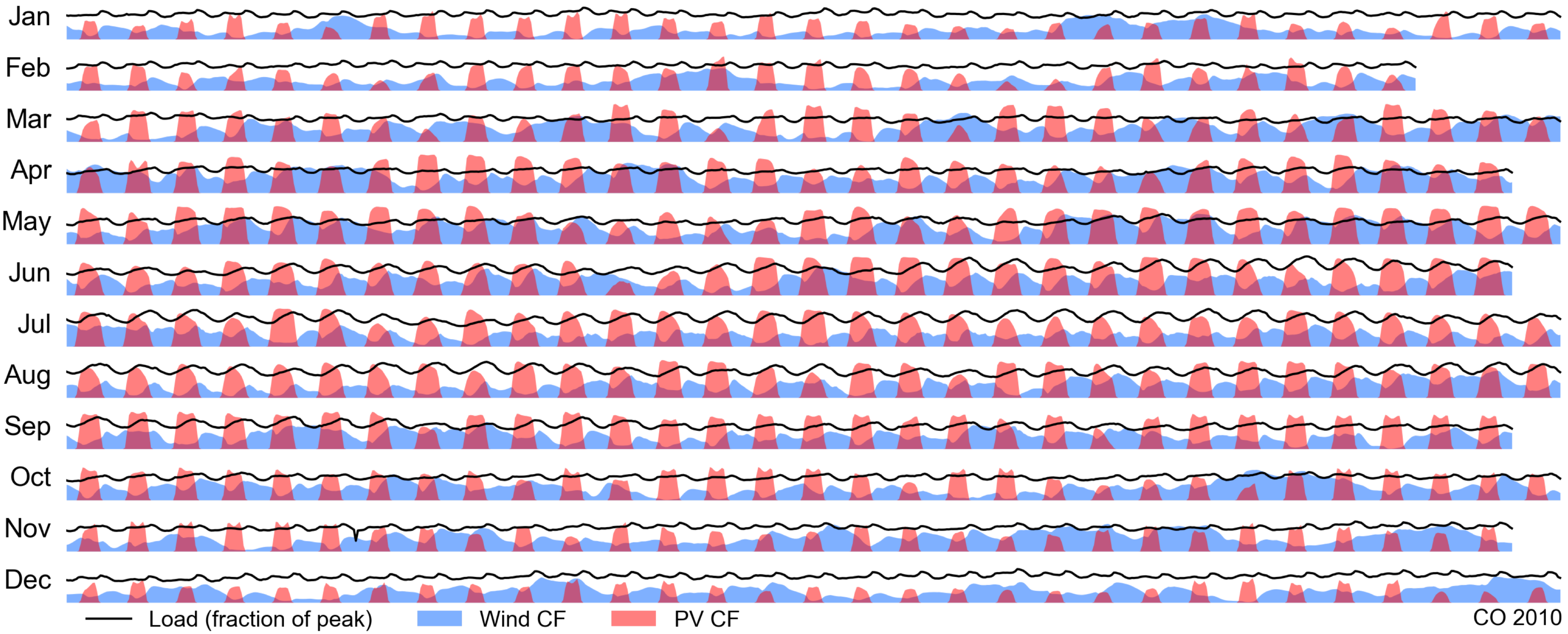
- $4000/kW new flexible nuclear

or

- $5/kWh long-duration energy storage

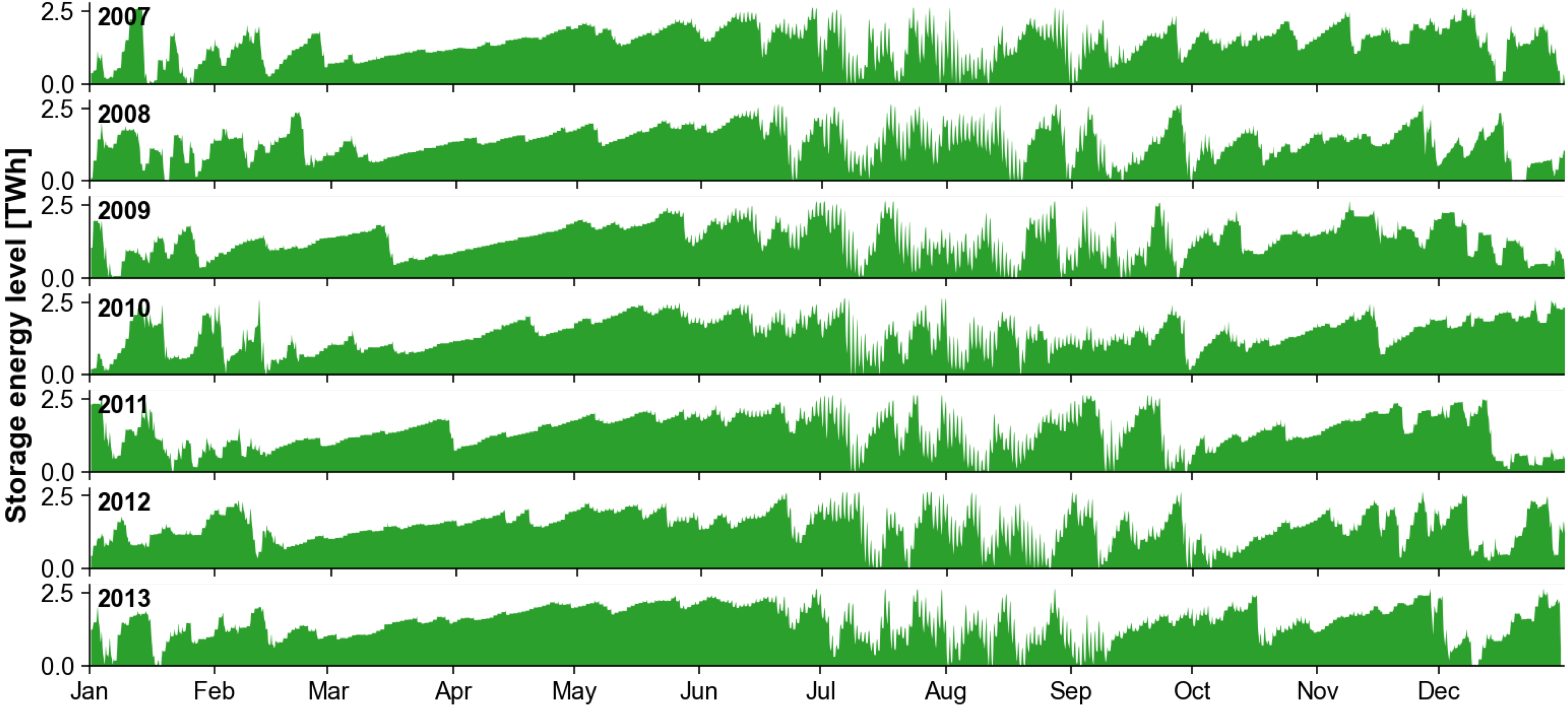
→ Multiple potential paths to low-cost zero-carbon systems for the US

Hourly resource variability



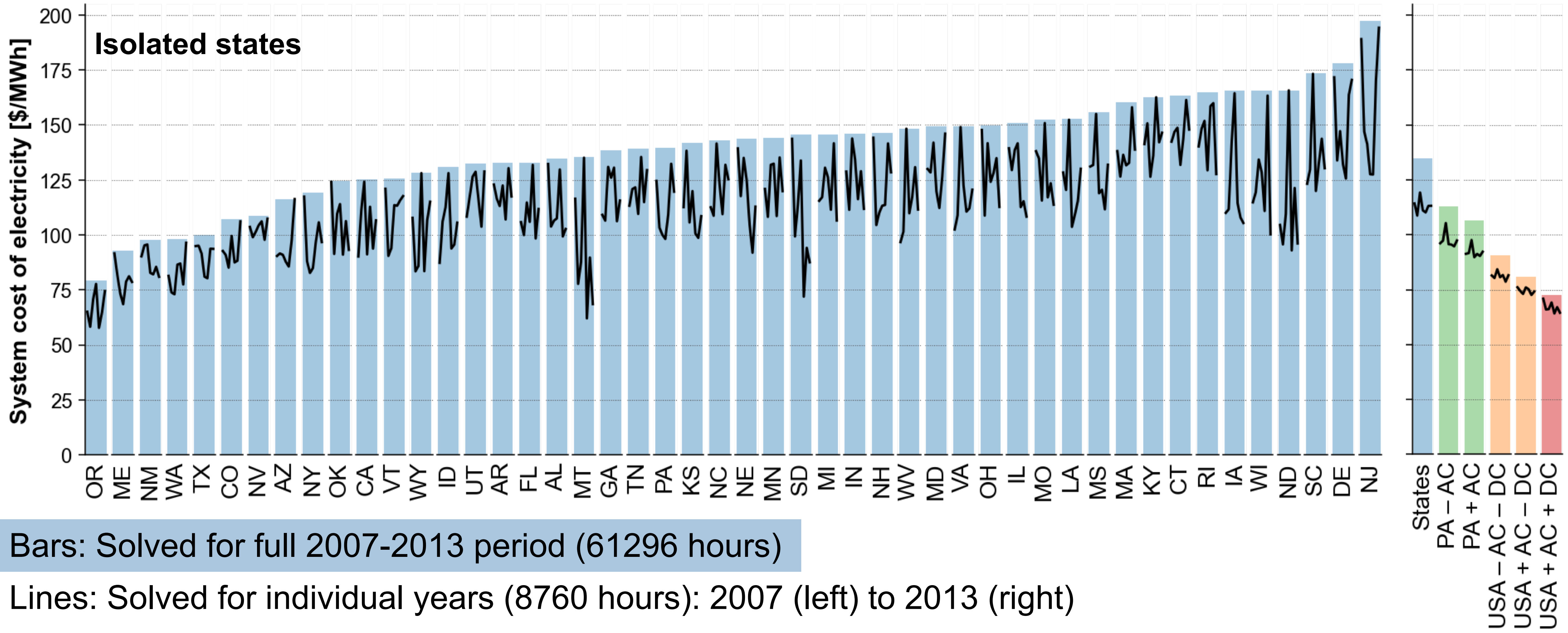
Interannual resource variability → Storage operation

Central scenario: USA + AC + DC; zero carbon; Li-ion batteries



Interannual resource variability → cost

System cost of electricity (SCOE) [$/MWh], 2007-2013 VRE



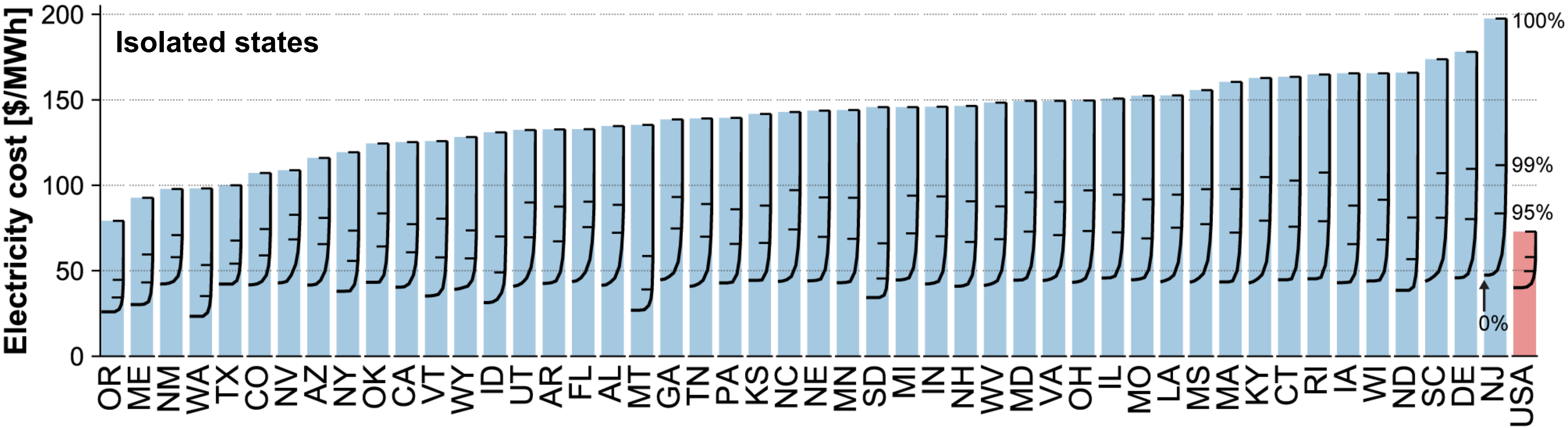
Bars: Solved for full 2007-2013 period (61296 hours)

Lines: Solved for individual years (8760 hours): 2007 (left) to 2013 (right)

SCOE can vary by 2x between years for isolated states; most expensive year varies between states

Interannual variability is smaller at the scale of the contiguous US, but still important

Lower decarbonization costs for interconnected system



Bars: 100% CES, full 2007-2013

Lines: 0% (left) to 100% (right) CES

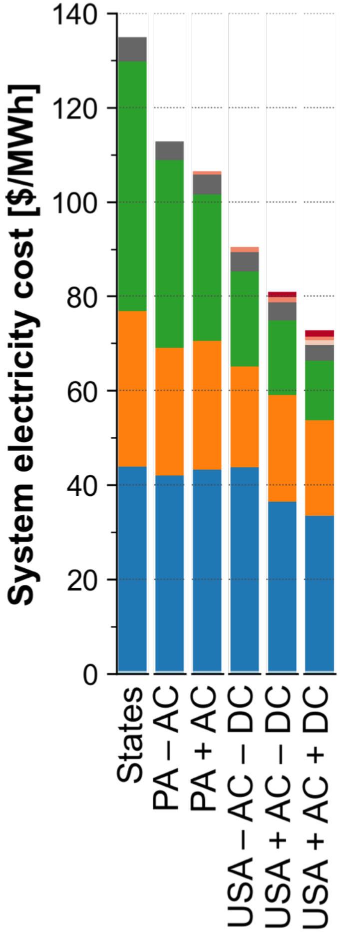
– ticks: 95%, 99%, 100% CES

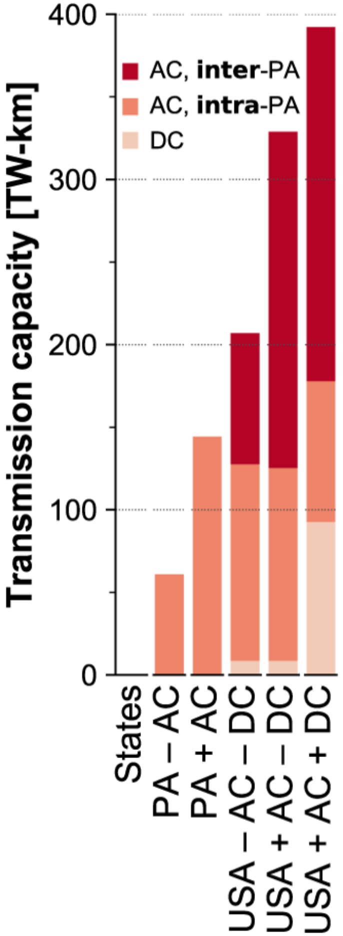
Electricity cost increases significantly on approach to zero carbon for individual states,
but to a **much smaller extent for full-US system**

Reaching **100%** for the full US with new interregional transmission is roughly as expensive as reaching **95%** on an isolated state-by-state basis

Primary findings

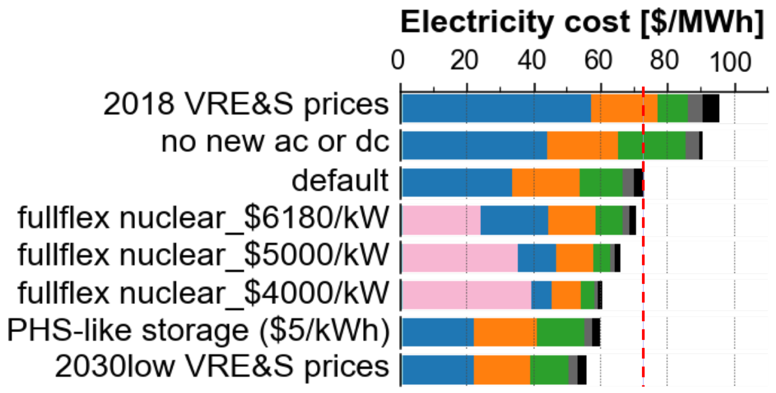
- Inter-regional **transmission** significantly reduces costs and storage needs in high-VRE systems
- Interannual variability is important, especially for isolated systems





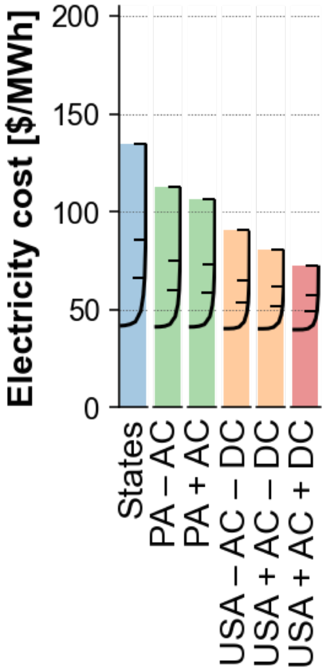
- Zero-carbon electricity system for contiguous US is feasible with today's tech at 1-hour multi-year resolution

- Nuclear and "long-duration" storage have the potential to reduce system cost, but are **not required**, and have less impact than reduction in VRE + Li-ion prices



https://doi.org/10.1016/j.joule.2020.11.013

- Decarbonization costs are significantly lower for **integrated** US-scale system than for isolated states



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MIT Energy Initiative

prbrown@mit.edu