

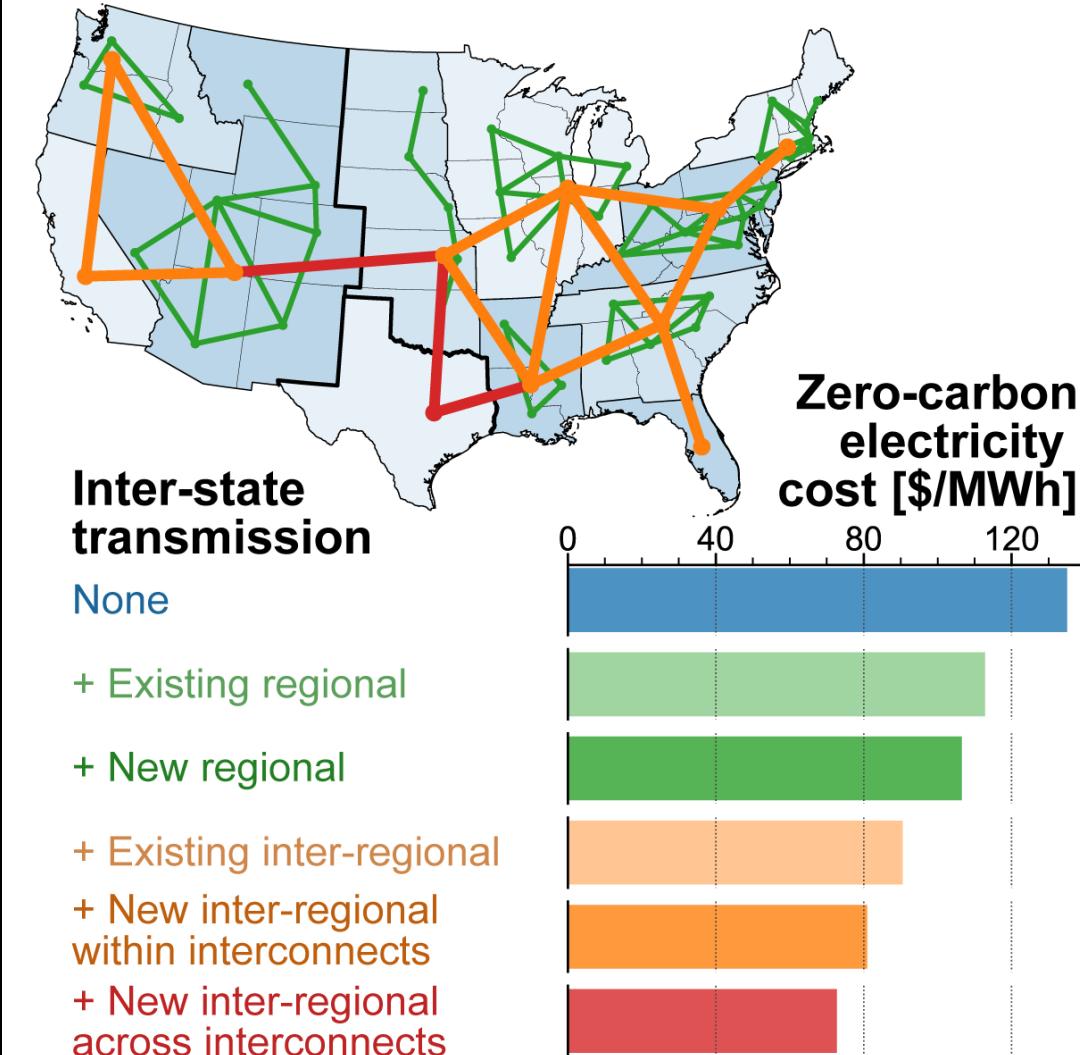
The value of interregional coordination and transmission in decarbonizing the US electricity system

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2022-07-08

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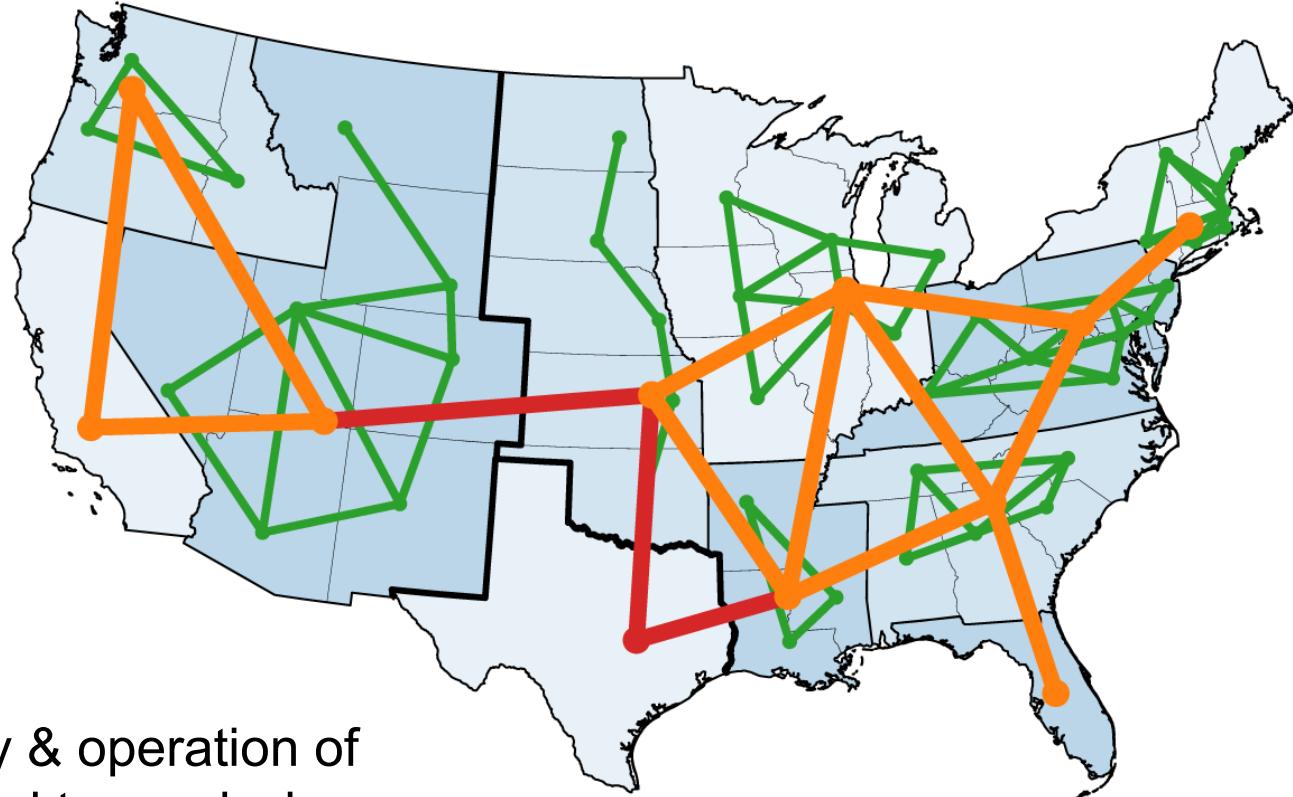
Brown, P.R.; Botterud, A. *Joule* **2021**, 5, 115
<https://doi.org/10.1016/j.joule.2020.11.013>
<https://github.com/patrickbrown4/zephyr>

This study: VRE + transmission + storage

ZEPHYR:

Zero-emissions
Electricity system
Planning with
Hourly operational
Resolution

<https://github.com/patrickbrown4/zephyr>



Brown, P.R.; Botterud, A. Joule 2021, 5, 115
<https://doi.org/10.1016/j.joule.2020.11.013>

- Co-optimized capacity & operation of generation, storage, and transmission
- 7 years of 8760-hour weather (2007–2013)
- 8760-hour demand from NREL Electrification Futures Study
- 100k's of wind/solar sites
- 3 geographic scopes:
states, planning areas (PAs), integrated US

Base case includes zero-carbon technologies **currently** being deployed at **GW** scale in the US:

- | | |
|--|--|
| <ul style="list-style-type: none"> ■ PV ■ Wind | <ul style="list-style-type: none"> ■ Li-ion batteries ■ Existing hydro |
|--|--|

Framing this work

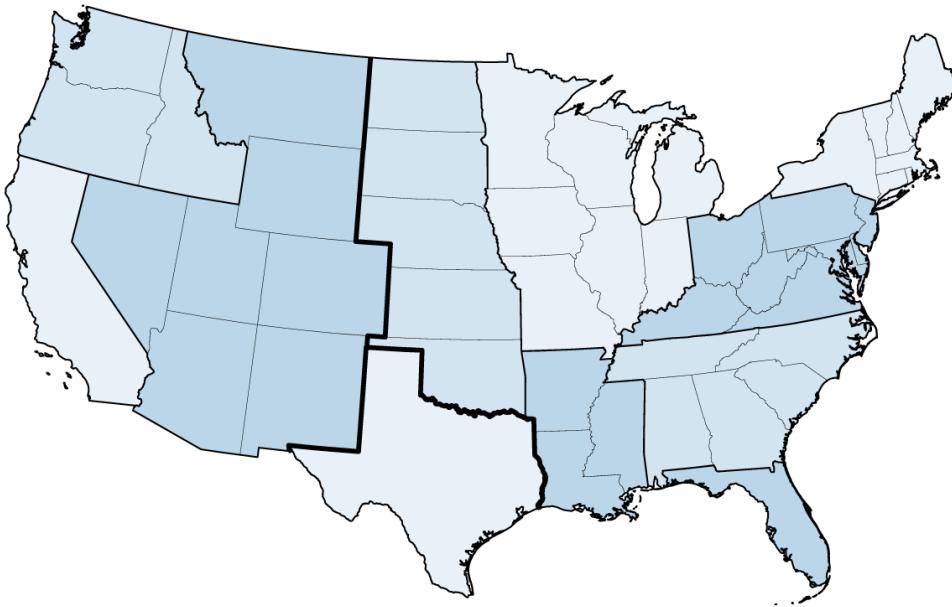
This study is:

- Primarily concerned with **resource adequacy** in **zero-carbon** systems (i.e. the “balancing challenge”¹)
- Technologically conservative
 - Only techs currently deployed at **GW scale**
- An improvement on 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**

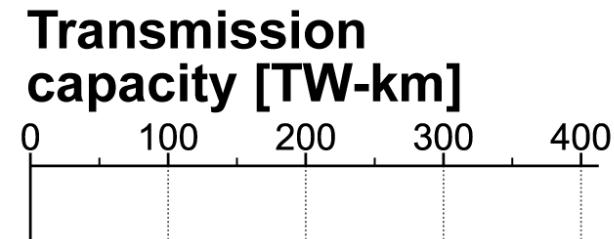
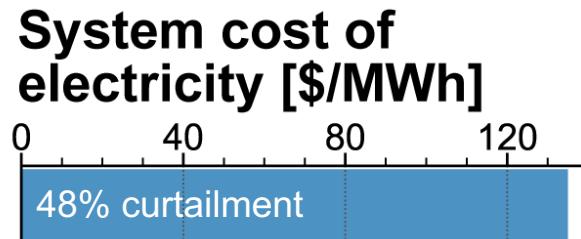
This study is NOT:

- An optimal-power-flow, security-constrained dispatch, or stability study
 - Transmission flows are completely controllable and highly aggregated
- A transmission/generation **siting** study
 - Aggregated generation & transmission
- 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

Transmission reduces system cost & storage requirements

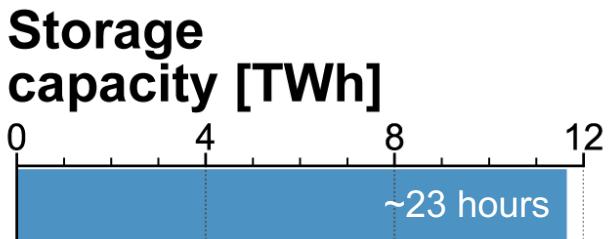


Inter-state transmission included
None

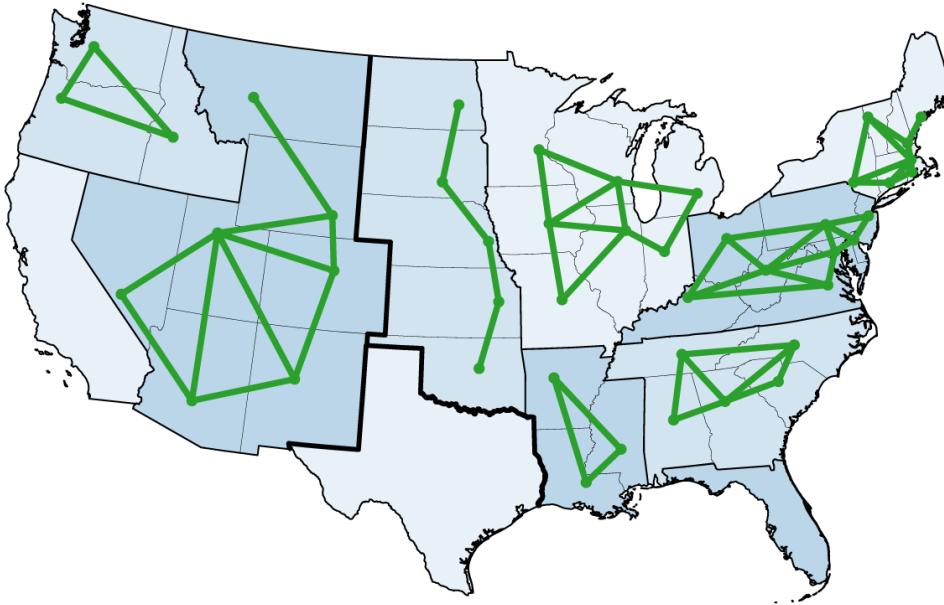


Base case includes zero-carbon technologies **currently** being deployed at **GW** scale in the US, along with existing hydro:

- PV
- Wind
- Li-ion batteries



Transmission reduces system cost & storage requirements



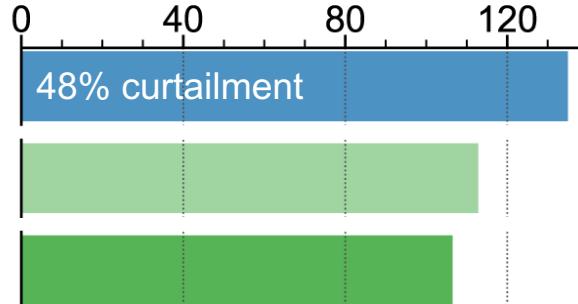
Inter-state transmission included

None

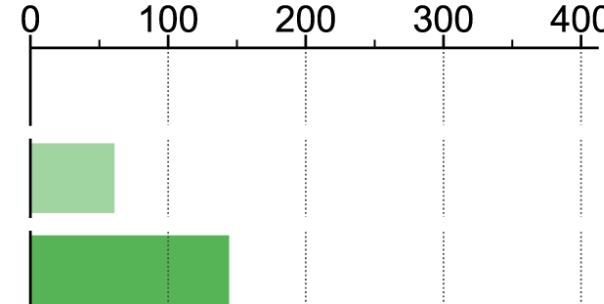
+ Existing regional

+ New regional

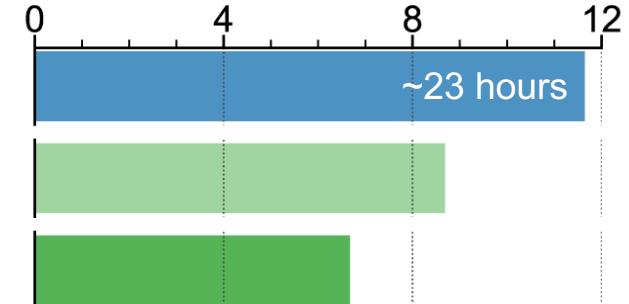
System cost of electricity [\$/MWh]



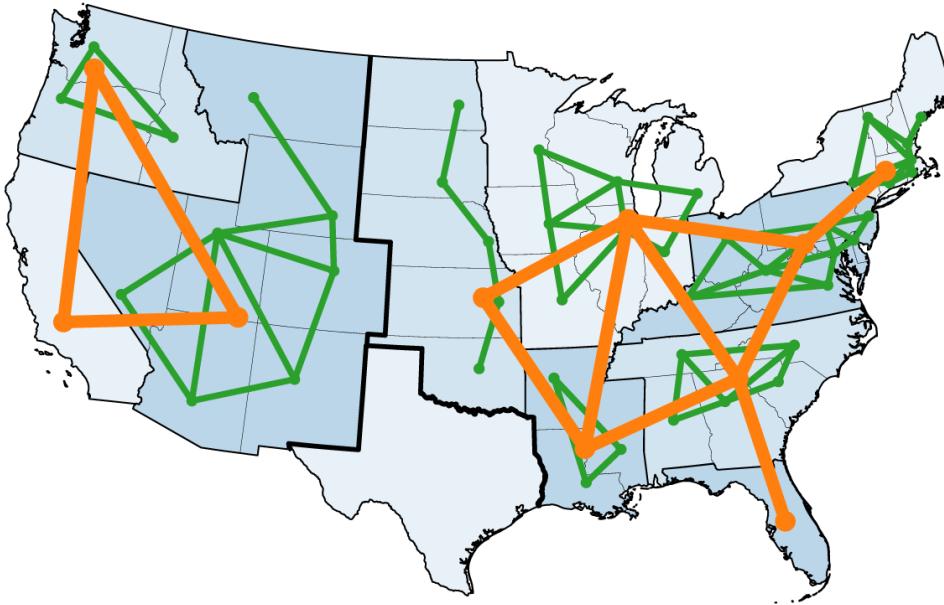
Transmission capacity [TW-km]



Storage capacity [TWh]



Transmission reduces system cost & storage requirements



Inter-state transmission included

None

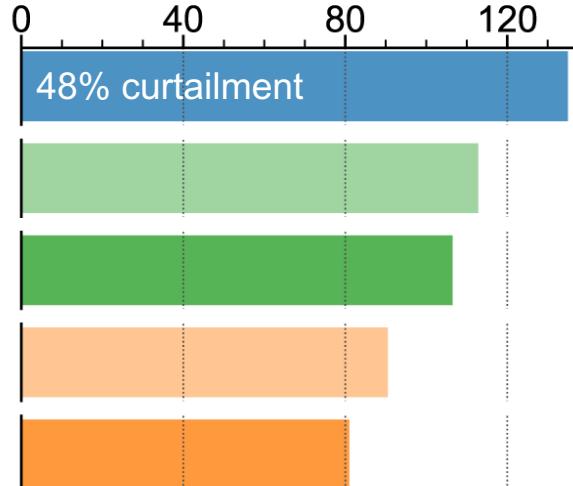
+ Existing regional

+ New regional

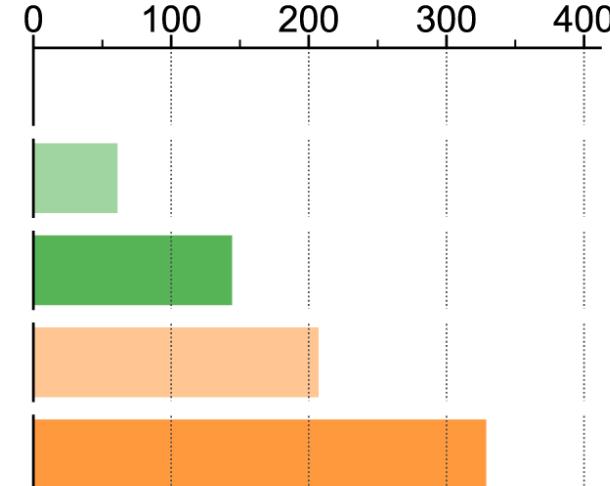
+ Existing inter-regional

+ New inter-regional within interconnects

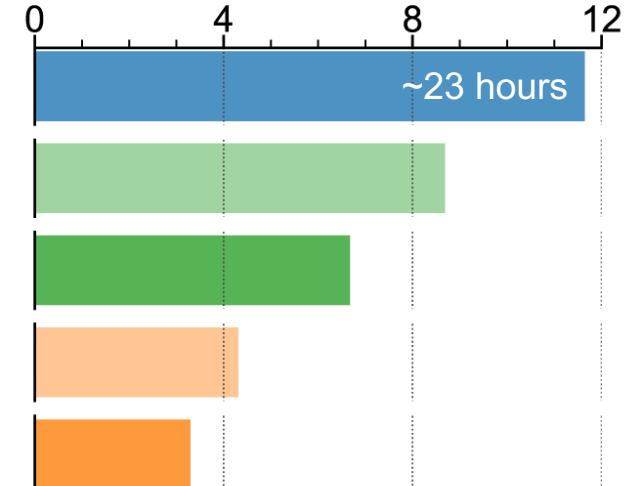
System cost of electricity [\$/MWh]



Transmission capacity [TW-km]



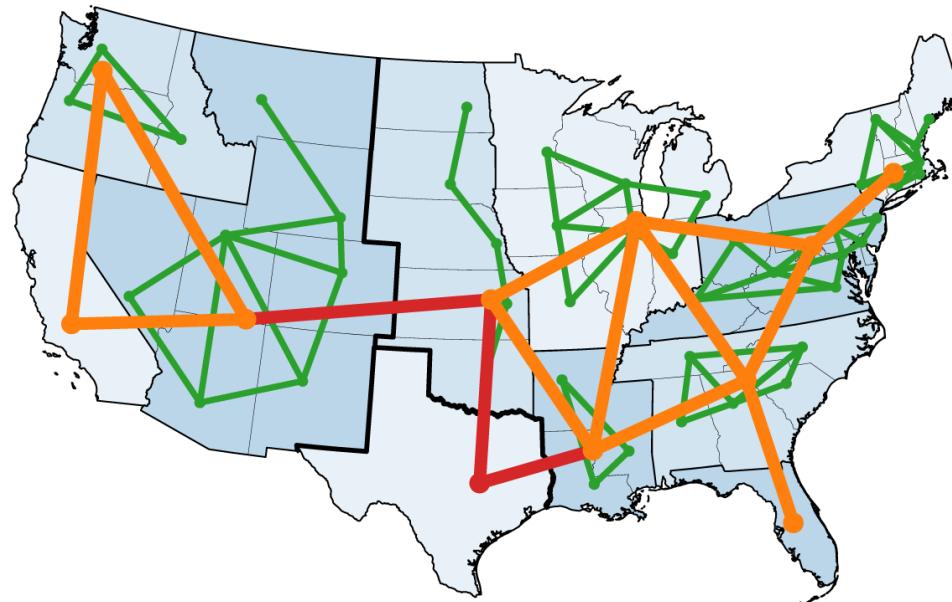
Storage capacity [TWh]



Transmission reduces system cost & storage requirements

Is 36% curtailment a lot?

- Peak/mean demand = 1.6
- Capacity utilization in a completely dispatchable system is $1/1.6 = 63\%$
- 63% utilization = 37% “curtailment”



Inter-state transmission included

None

+ Existing regional

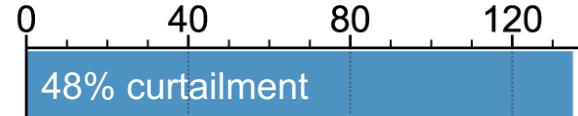
+ New regional

+ Existing inter-regional

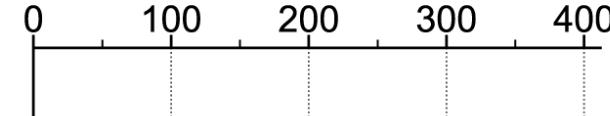
+ New inter-regional within interconnects

+ New inter-regional across interconnects

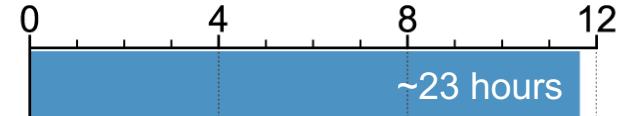
System cost of electricity [\$/MWh]



Transmission capacity [TW-km]



Storage capacity [TWh]

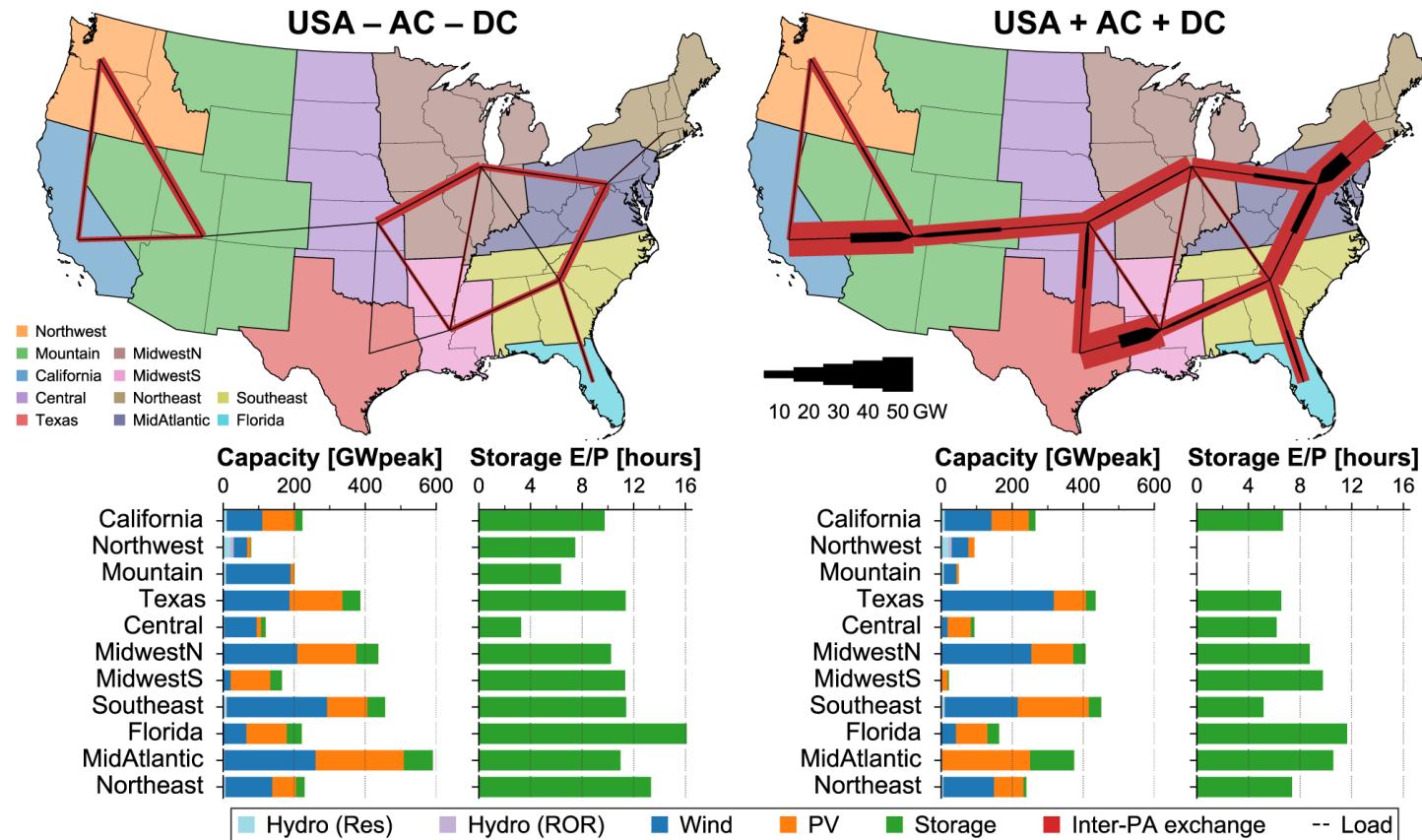


36% curtailment

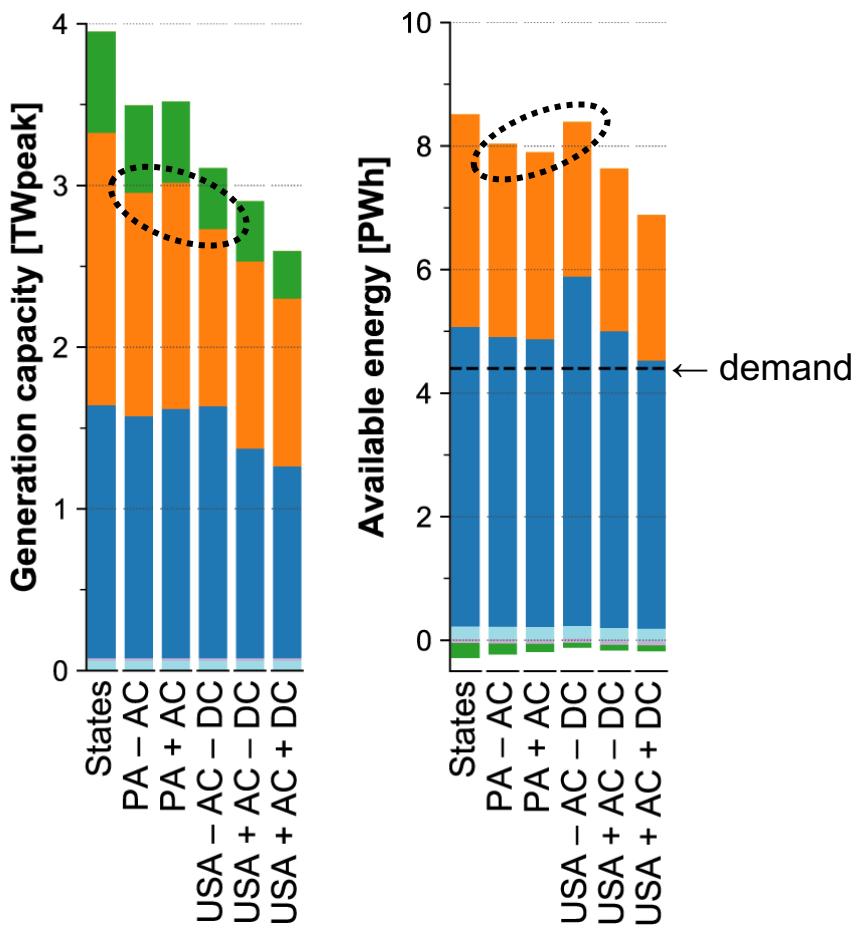
~5 hours

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 interregional 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)

Flexible operation of interregional transmission

9

USA + AC + DC scenario

Modeled 2040 flows with 2010 weather



California|Northwest

↑ 50 GW

California|Mountain

Mountain|Northwest

Central|Mountain

Central|Texas

Central|MidwestN

Central|MidwestS

MidwestN|MidwestS

MidwestN|Southeast

MidwestS|Texas

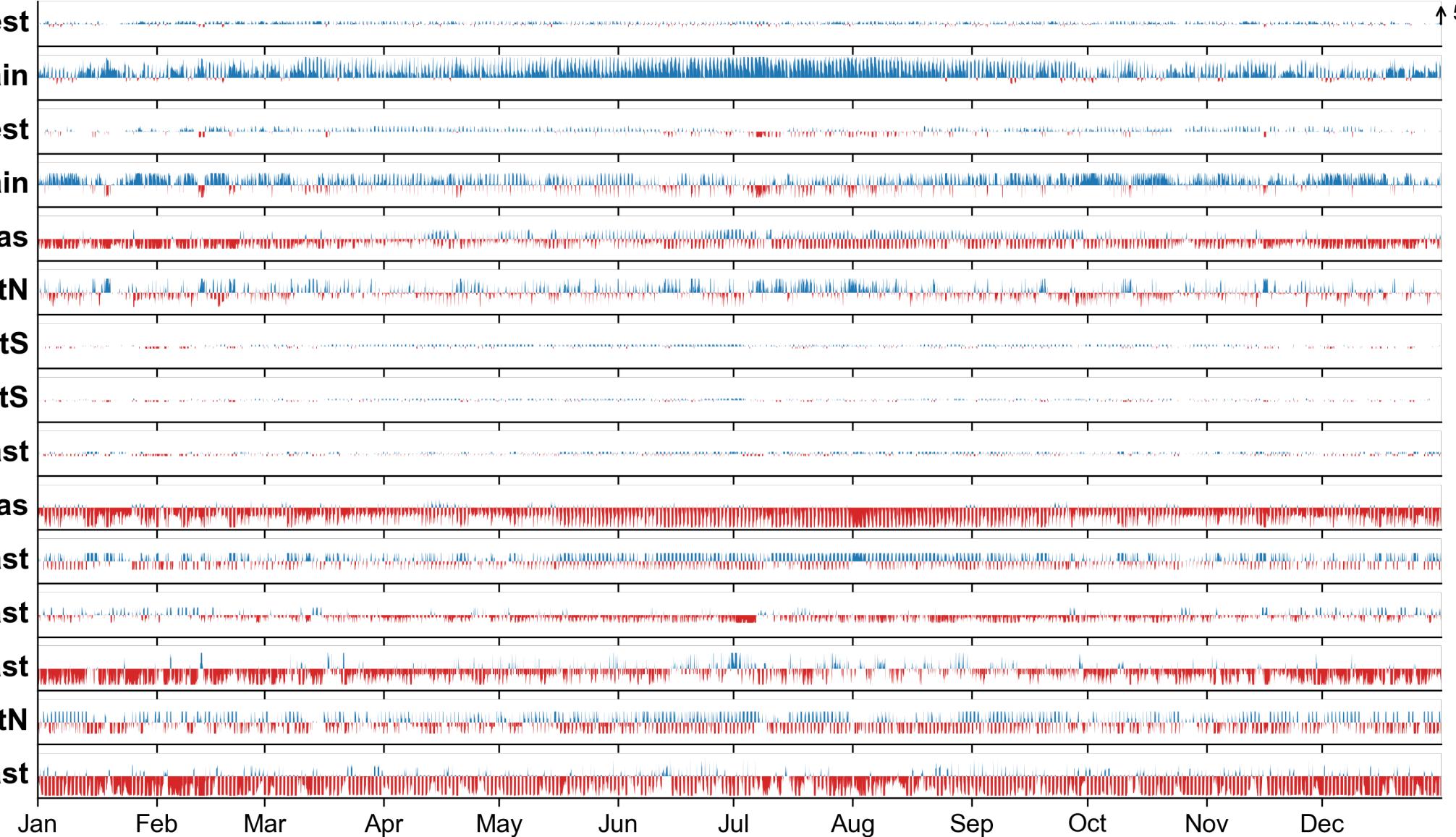
MidwestS|Southeast

Florida|Southeast

MidAtlantic|Southeast

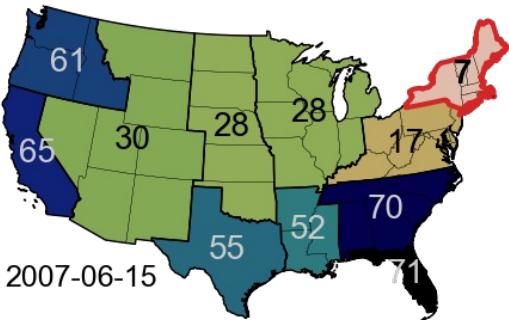
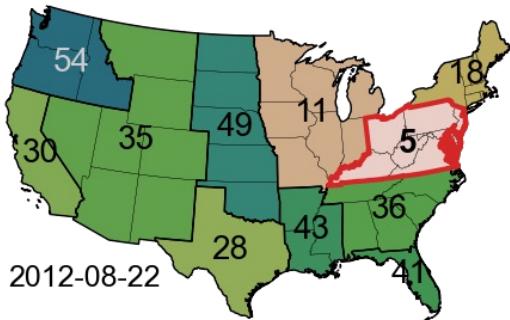
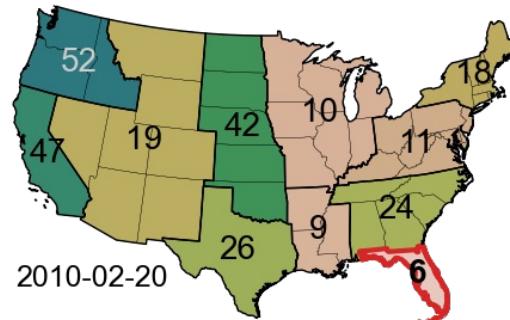
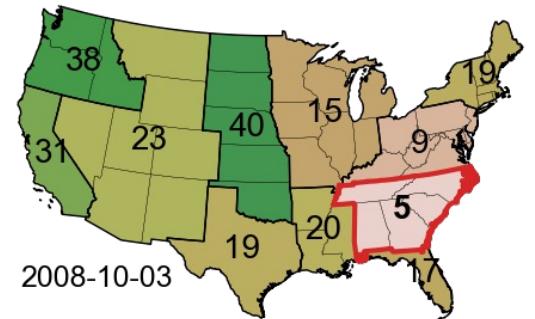
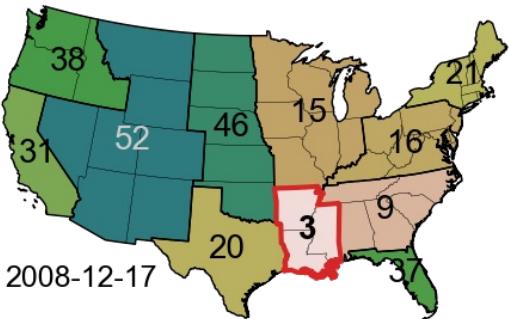
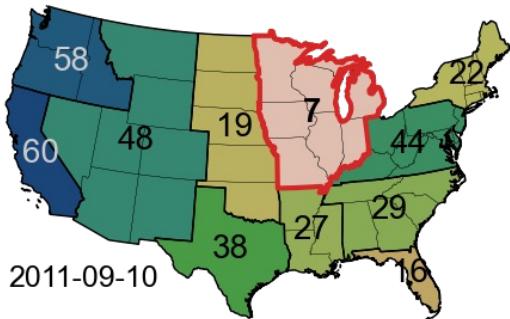
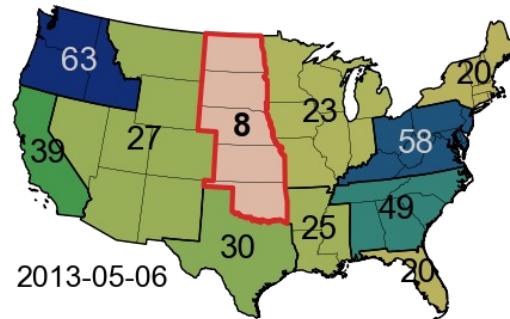
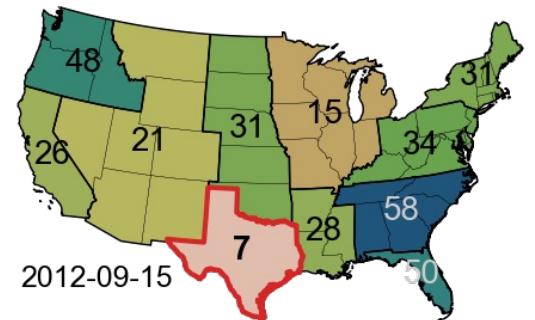
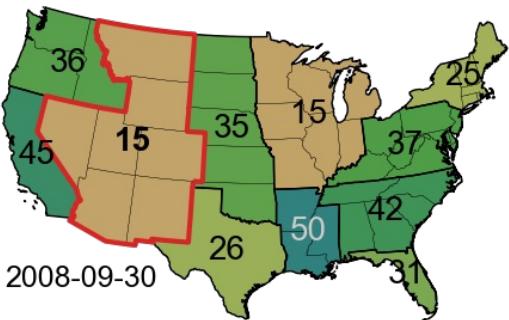
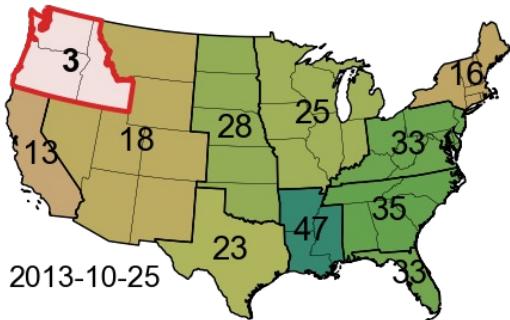
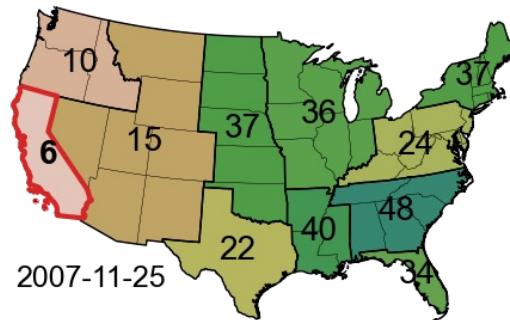
MidAtlantic|MidwestN

MidAtlantic|Northeast



It's always windy or sunny somewhere

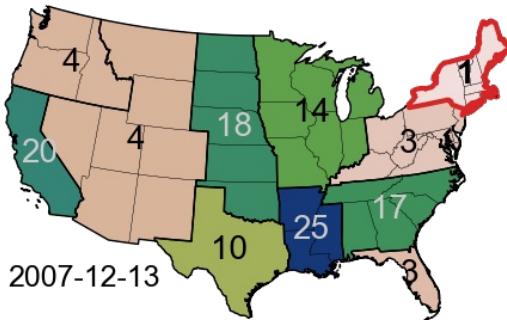
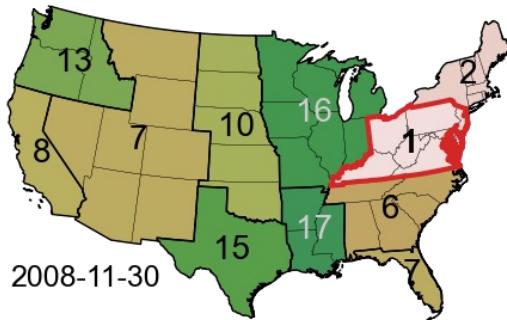
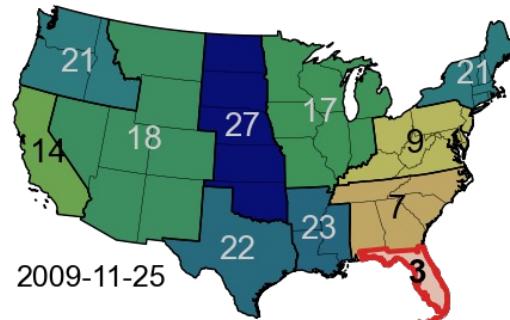
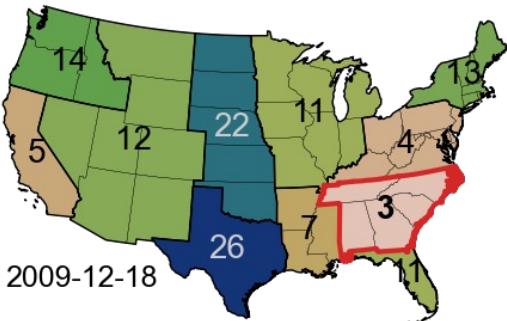
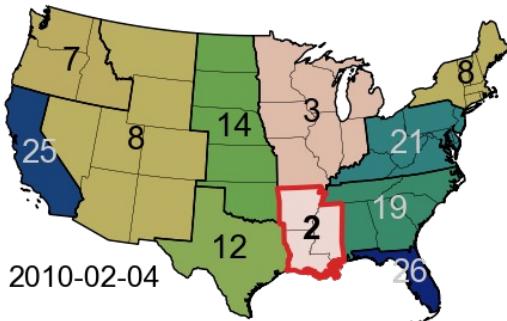
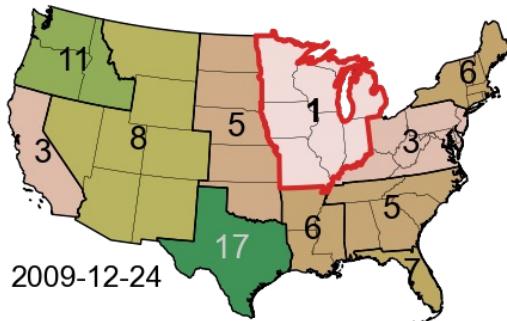
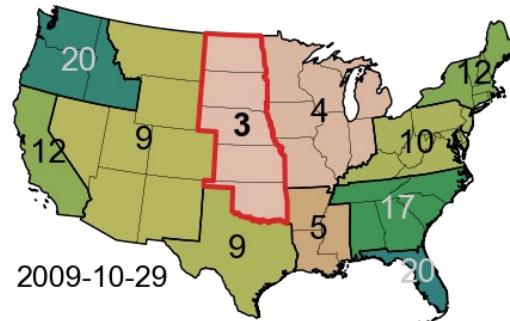
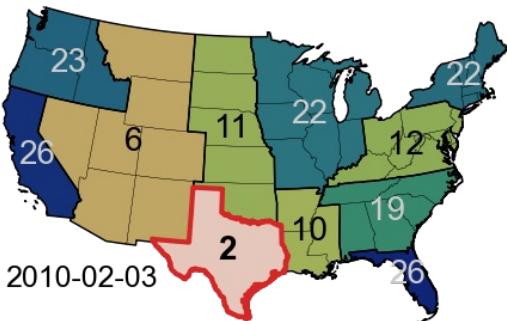
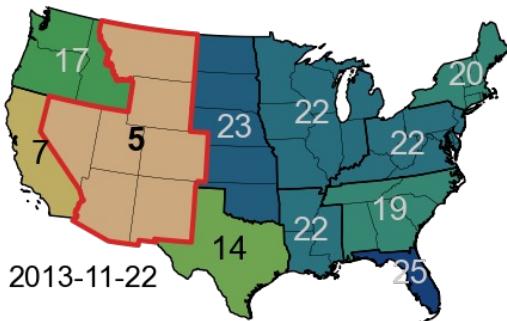
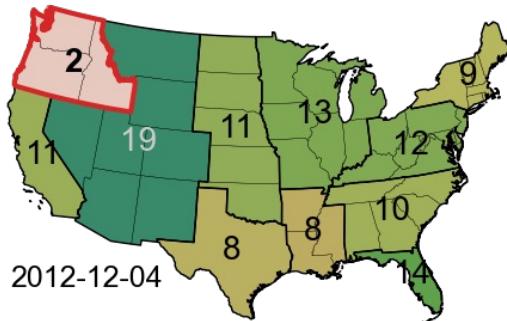
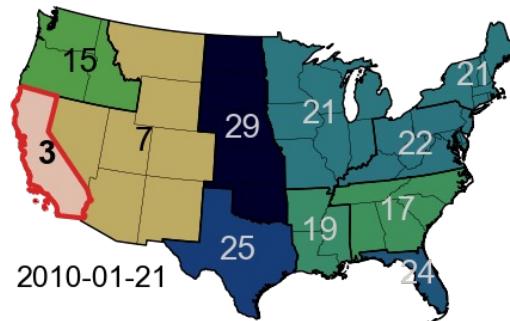
Take the **least-windy** day in each planning area from 2007–2013.
How windy are each of the other planning areas on that day?



Single-day wind
capacity factor [%]
at top quintile of sites

It's always windy or sunny somewhere

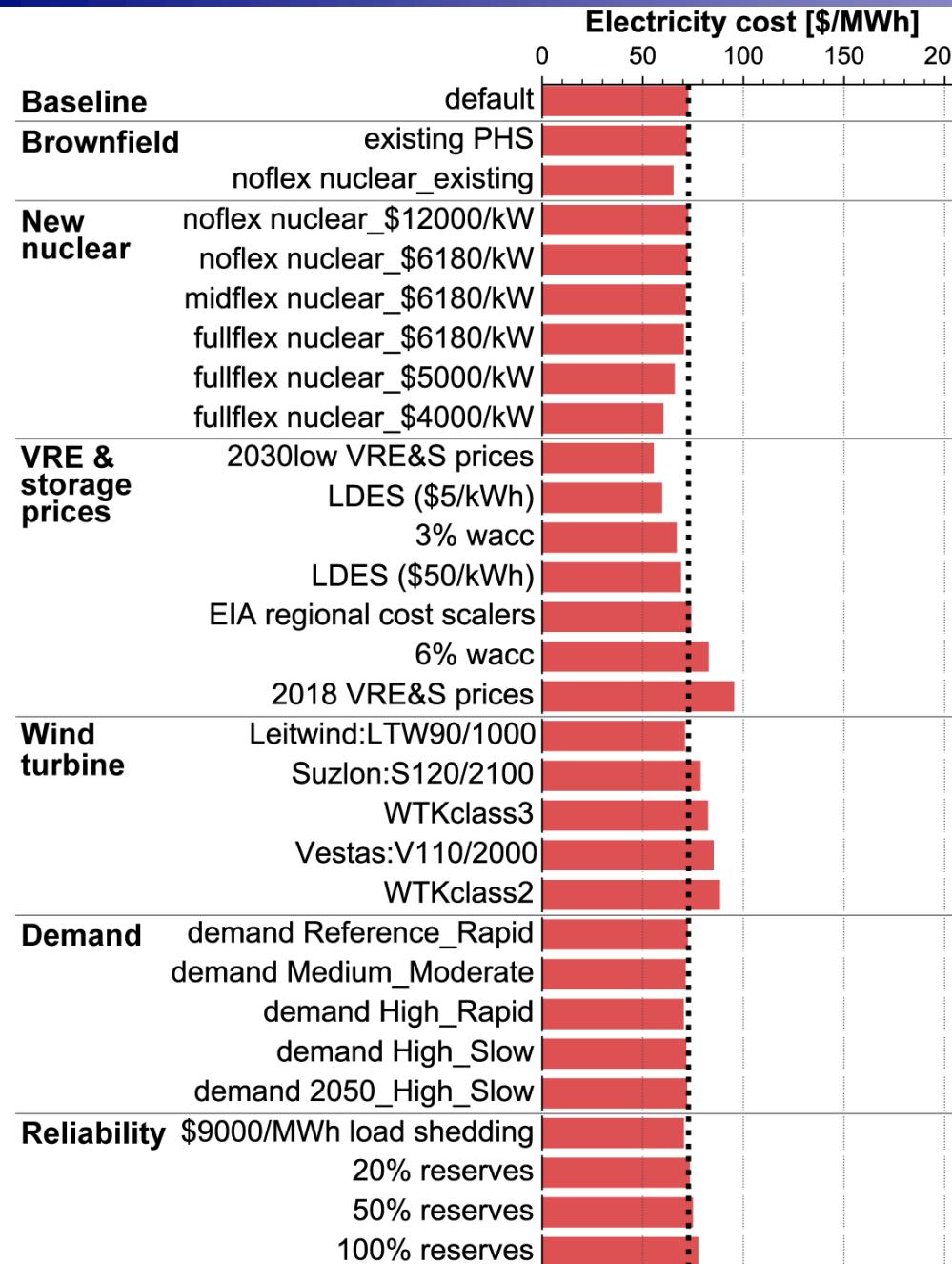
Take the **least-sunny** day in each planning area from 2007–2013.
How **sunny** are each of the other planning areas on that day?



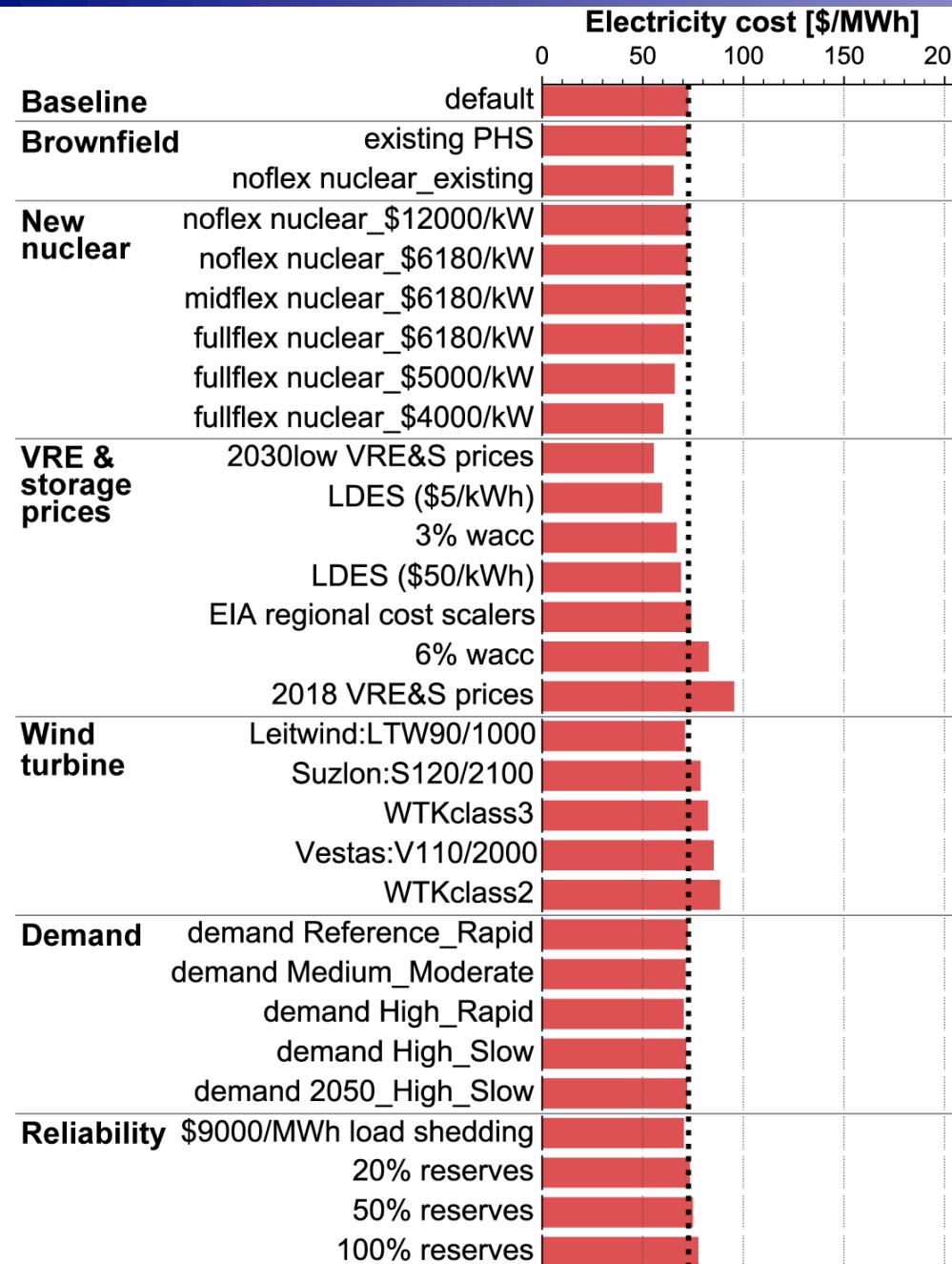
Single-day **PV**
capacity factor [%]
at top quintile of sites

Sensitivity analysis: New interregional transmission allowed

12



Sensitivity analysis: Limited transmission



Interstate transmission included:

+ New
interregional
across
interconnects

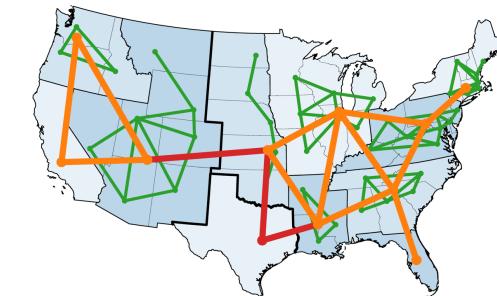
+ New
interregional
within
interconnects

+ Existing
interregional

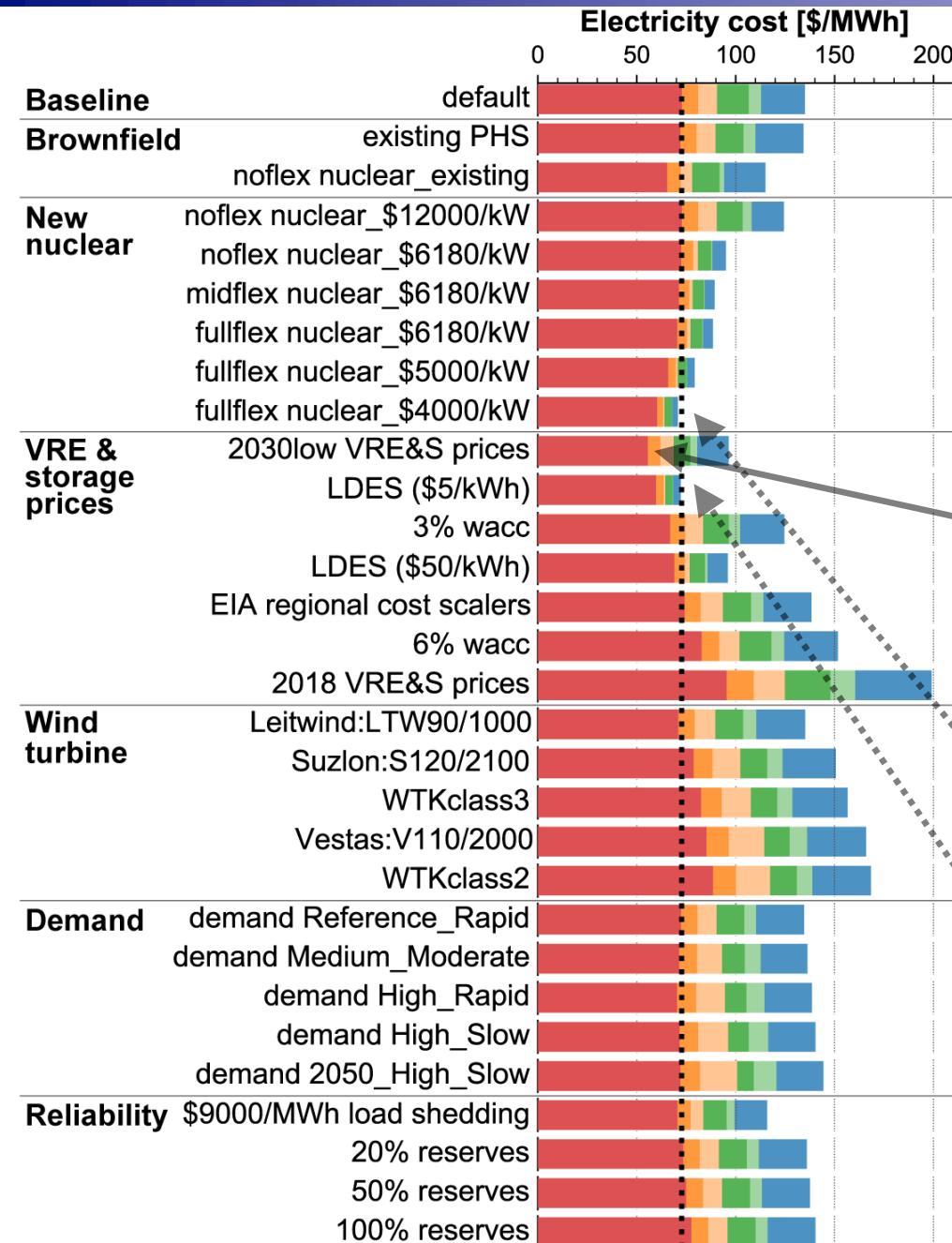
+ New
regional

+ Existing
regional

None



Sensitivity analysis: Limited transmission



Interstate transmission included:

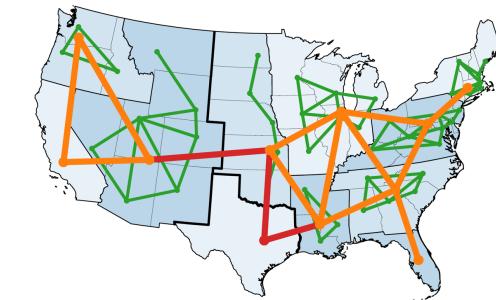
+ New interregional across interconnects

+ New interregional within interconnects

+ Existing interregional

+ New regional

+ Existing regional None



Lowest SCOE overall:

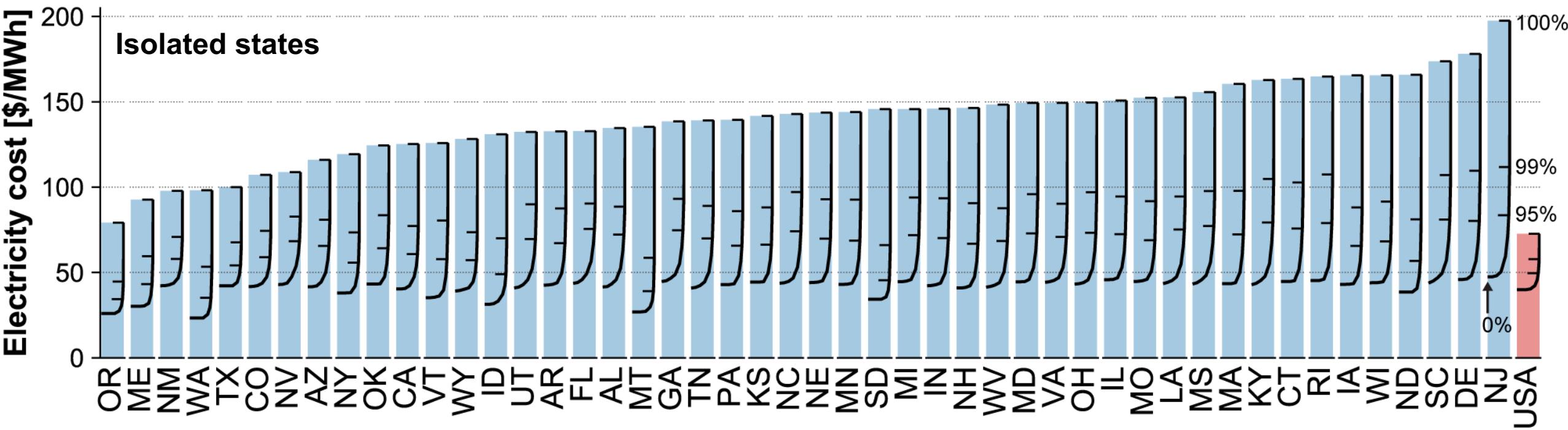
- ATB₂₀₁₉ “low”* costs for PV, wind, Li-ion
- New interregional transmission allowed

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

Lower decarbonization costs for interconnected system¹⁵



Bars: 100% CES, full 2007-2013

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

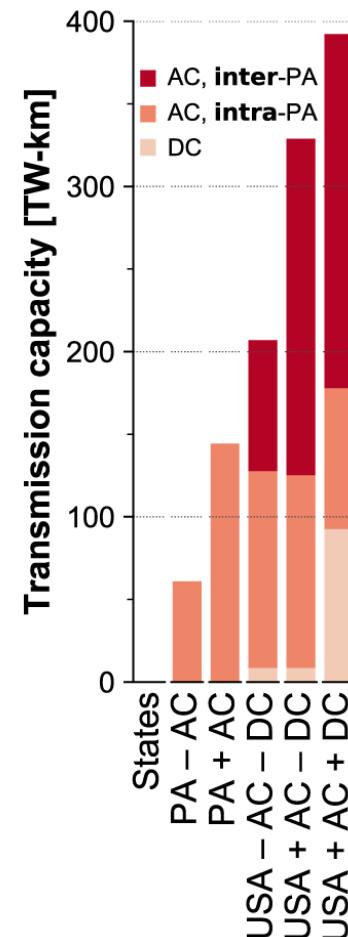
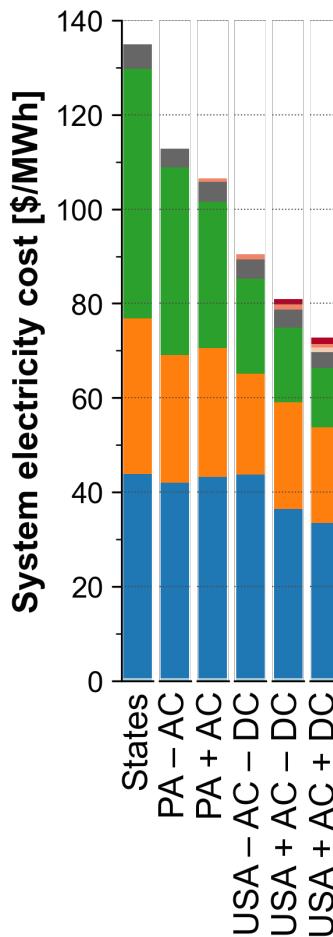
– ticks: 95%, 99%, 100% CES

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

Reaching **95%** for the full US with new interregional transmission adds ~\$10/MWh to no-policy cost

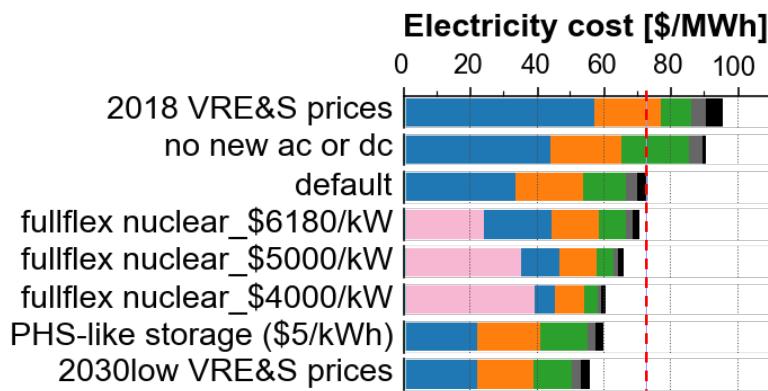
Primary findings

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

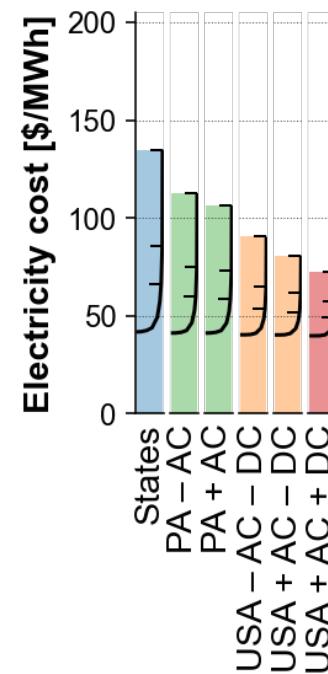


- Zero-carbon electricity system for contiguous US is feasible with today's tech at 1-hour multi-year resolution

- Nuclear and long-duration storage have the potential to reduce system cost, but are not required; **reduction in VRE + Li-ion prices** has a larger impact on system cost



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



Thanks to many for helpful discussions
(errors and opinions are mine):

A. Botterud, H. Pfeifenberger, 
H. Gruenspecht, P. Joskow,
R. Schmalensee, D. Mallapragada,
R. Stoner, J. Jenkins, N. Sepulveda,
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