Grid Strategies

Changes needed to reliably and affordably achieve very high renewable penetration

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Work in these main areas is needed to reach very high renewable penetration

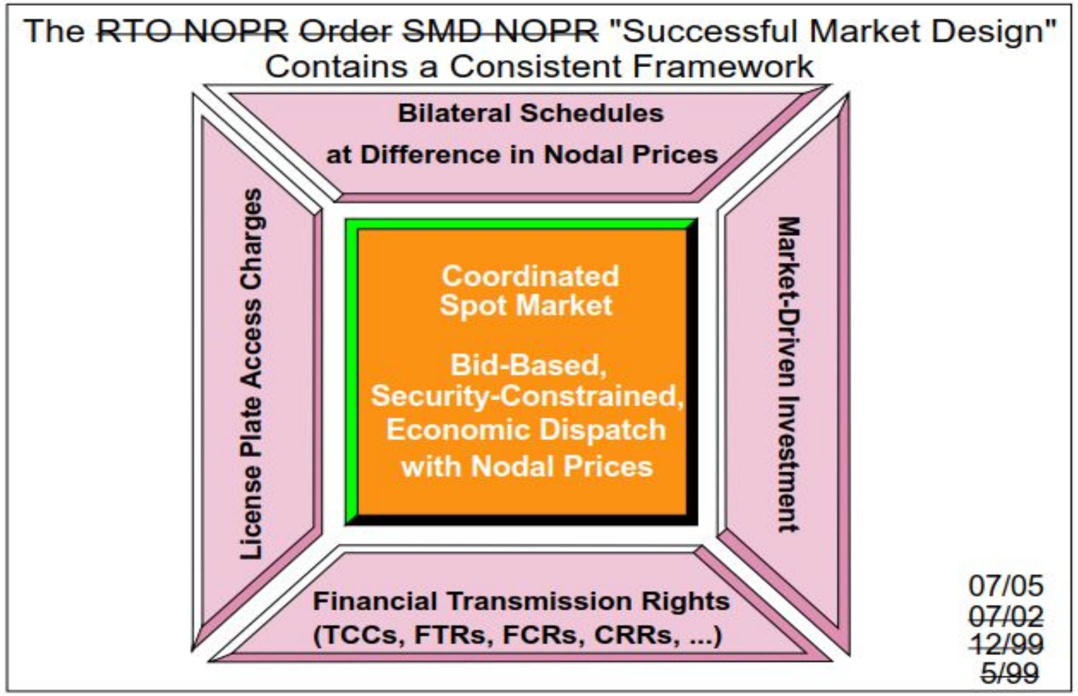
1. Energy markets/seamless regional dispatch
2. Transmission planning/expansion
3. Resource adequacy
4. Power system stability with high inverter-based resource penetration
5. Generation procurement
6. Clean energy policy
7. Integrate DR and DERs with wholesale markets
8. Transmission operational efficiency

1. Energy markets: Preferred Market Structure

- RTO/ISOs balance power system and administer short term spot markets
  - Procures energy and reliability services based on engineering definitions
  - Also plan transmission infrastructure for reliability and efficiency given future resource mix, recovers cost in regional tariff
- Retail suppliers competitively procure power (hedge) with PPAs to serve load. Might be monopoly or competitive retail suppliers (up to the state).
- State PUCs oversee hedging for some or all customers
  - Ensure retail suppliers are credit-worthy buyers of wholesale power
  - Level playing field between retailers and provider of last resort
- Utilities build, own, and operate monopoly T&D (not G) with regulated rates
- Independent Power Producers build and own generation to sell electricity products to retail suppliers/wholesale buyers
- Financial participants provide risk management products

1b. Energy markets: Preferred Market Design

- Flow-based, no physical capacity reservations
- Spot market with bilateral contracts
  - Expect most payments and revenue in long term PPAs, priced at average cost of competitive new unit
  - Spot market for residuals and re-balancing
- Bid-based security constrained economic dispatch
- Energy at each time and location
  - Hourly locational marginal pricing (LMP)
- Reliability Services--technology-neutral
  - Operating reserves, exact needs vary by region
  - Reactive support—non-market compensation
- Scarcity pricing
  - prevents free-riding, encourages contracting,
  - attracts flexible resources
  - Most load hedged, and doesn't pay it.



Source: Bill Hogan, Harvard University

2. Transmission planning/expansion

Address the '3Ps'

- Planning
  - Proactive, all electricity system benefits, probabilistic/scenario based, portfolio of network upgrades, all technology options, community engagement
- Permitting
  - Demonstration of benefits with credible regional authorities leads to high batting average
- Paying
  - Broad beneficiary pays cost allocation

Incorporate all benefits of transmission

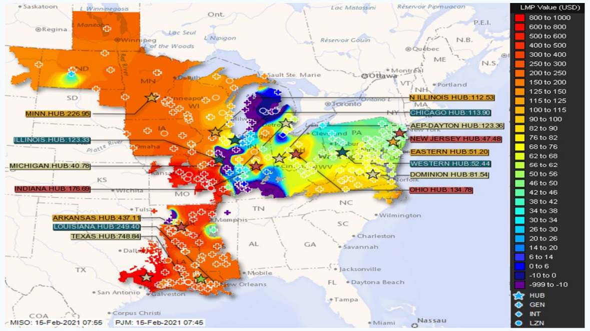
Capacity value

Greater ability to supply when power is scarce with regionally diverse portfolio.

Wind/hydro/geothermal/solar/storage complementarity

Congestion

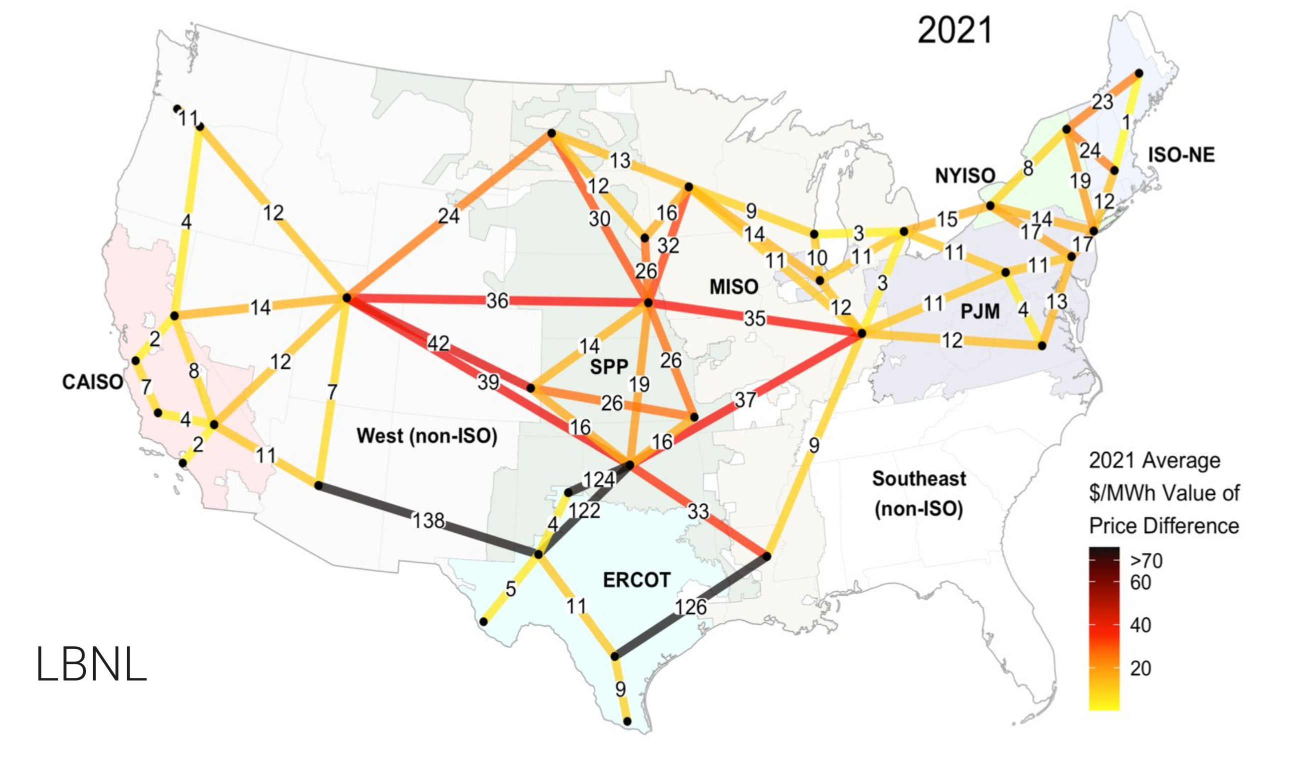
Production cost modeling always under-forecasts congestion, by a lot.



Reliability/resilience

50% of value in 5% of hours (LBNL)

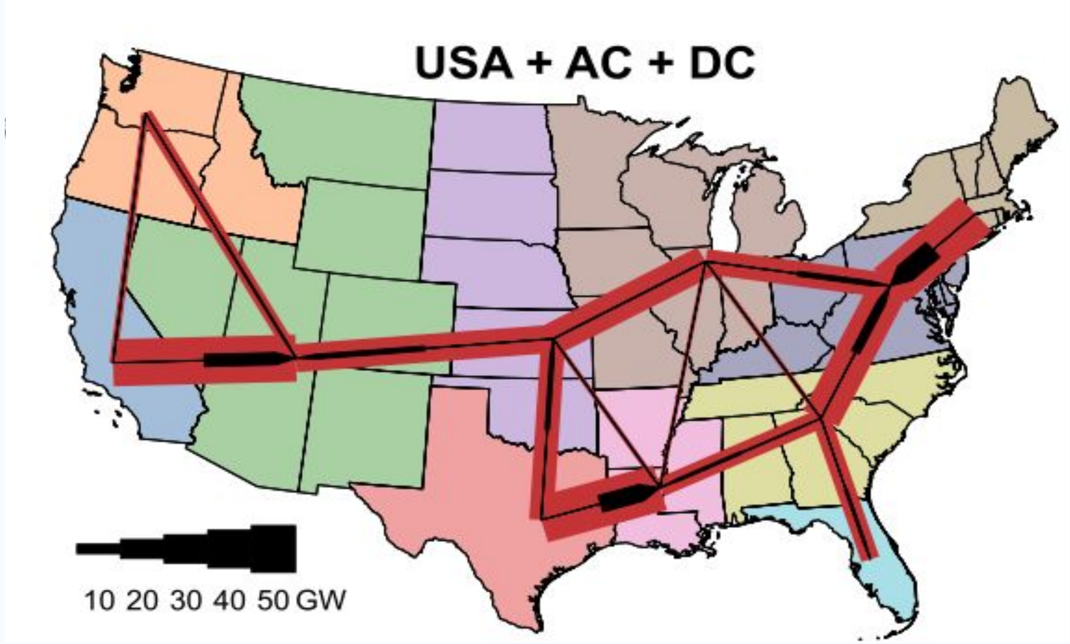
Flows in both directions (winter storms Elliot, Uri, etc)



Transmission Vision—Full Macro Grid

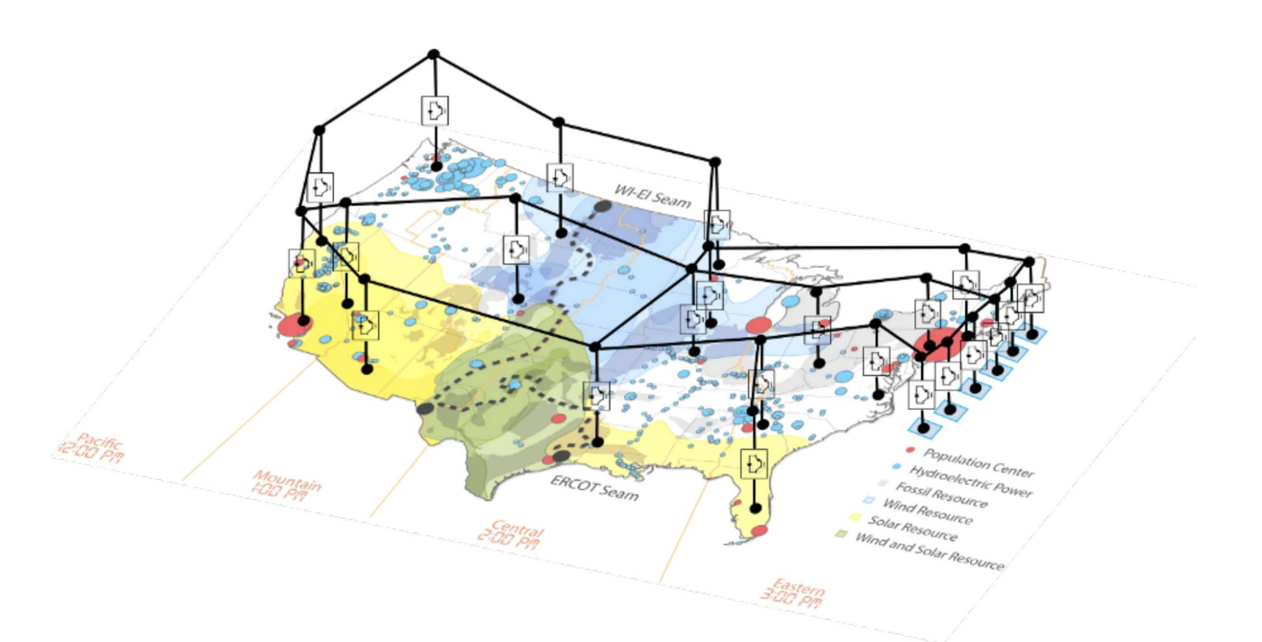
10s of GWs of power transfer back and forth across and between regions
Benefit > cost with 2-3x increase in national transmission capacity

MIT Value of Interregional Transmission Study



Brown (MIT), https://www.cell.com/joule/fulltext/S2542-4351(20)30557-2

NREL Seams Study (updated by Jim McCalley)



Bloom (NREL),
https://cleanenergygrid.org/wp-content/uploads/2020/11/Macro-Grids-in-the-Mainstream-1.pdf

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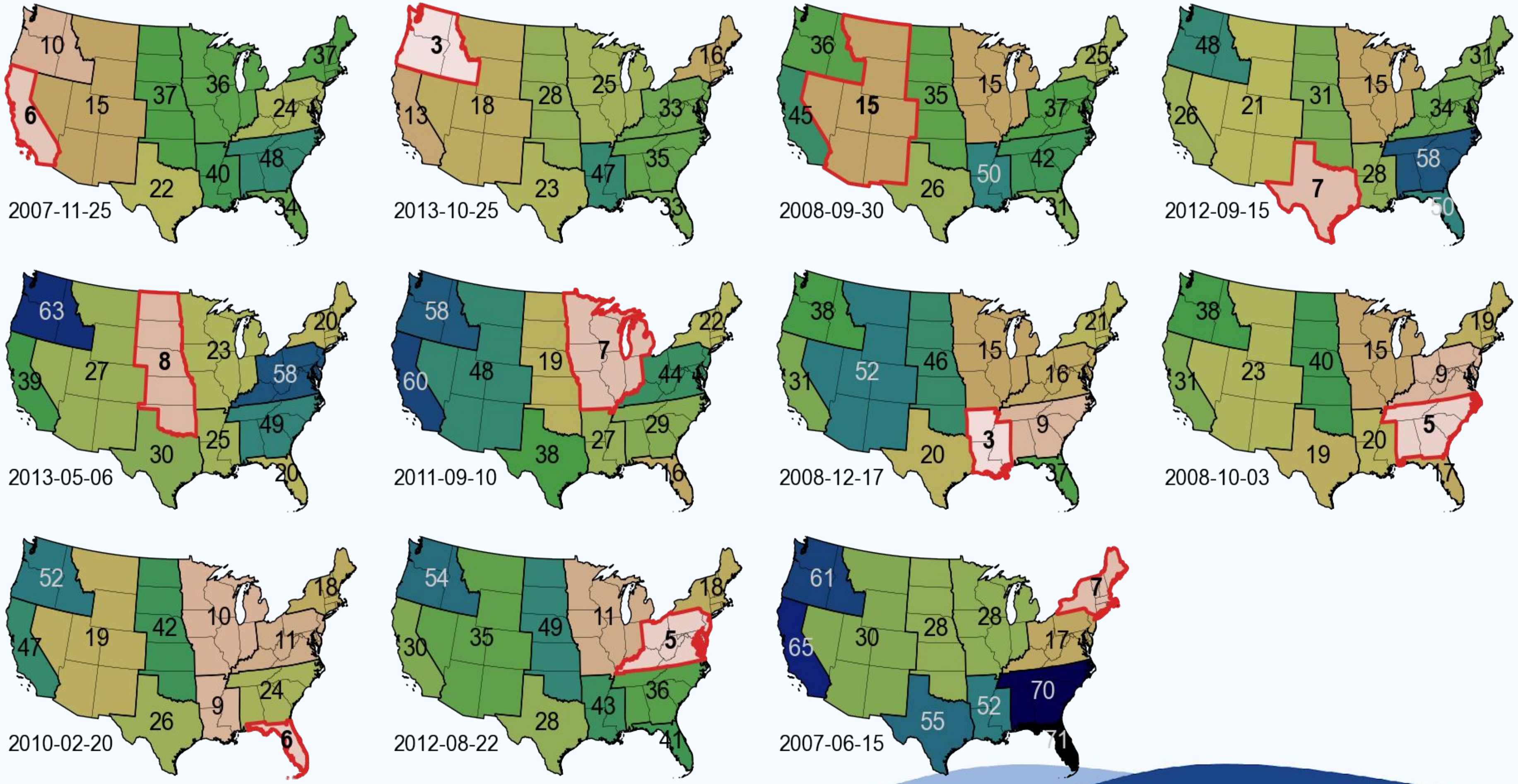
Renewables can contribute to resource adequacy and reduce costly generation reserve margins. Output is steady across wider areas

Take the least-windy day in each planning area from 2007–2013.

How windy are each of the other planning areas on that day?

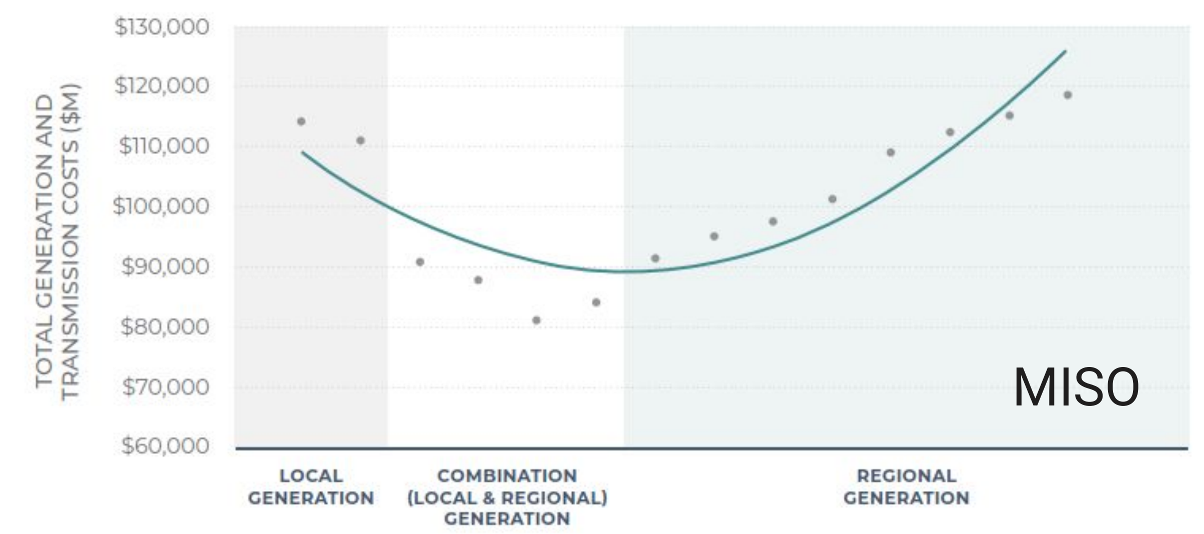
Single-day wind capacity factor [%] at top quintile of sites

(Patrick Brown, MIT, NREL)



Economically sound transmission planning

- "Just and reasonable" has to mean maximize net benefits
  - Any other decision rule raises costs to consumers
  - Not least cost of transmission but least cost of delivered energy (generation + transmission)
  - Not benefit/cost ratio
- Dr. William Hogan: "A forward-looking cost-benefit analysis provides the gold standard for ensuring that transmission investments are efficient."
- Overcome generator protectionism with strong independent planning



- Co-optimize transmission and generation

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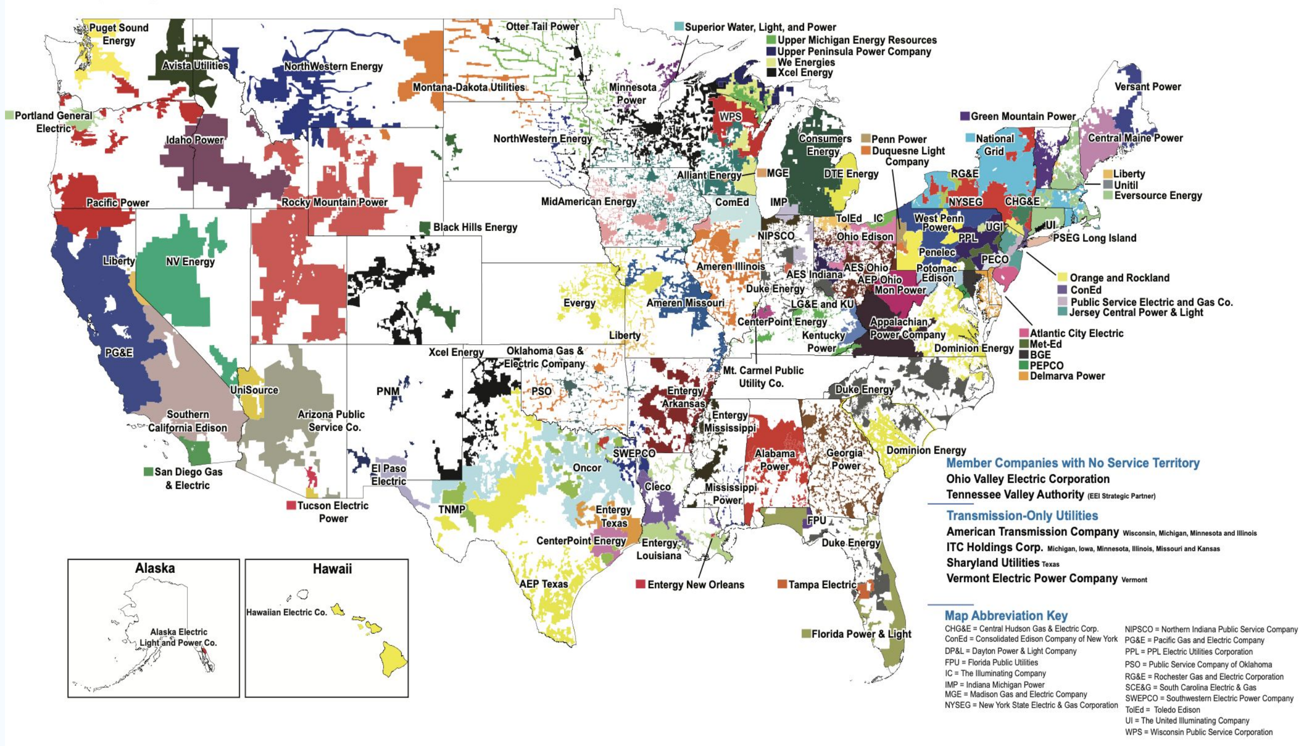
Transmission infrastructure expansion—why is it so hard?

- The electric industry grew up as ~3000 separate utilities focused on their own small areas.
- Utilities and the regulatory structure were not designed to plan, permit or pay for interstate highway-type lines.
- Linear infrastructure is always hard because it must string together contiguous pieces of land, each of which is important to someone.



High-Performance Conductors: modern conductor technologies which have greater performance characteristics when compared to traditional conductors

Carbon and composite core conductors

are overhead, bare conductors that use a trapezoid shaped wire of annealed aluminum to carry electrical current and use a carbon or composite core for support, reducing sag and increasing power-flow capacity.

Superconductors use a class of metallic compounds that exhibit negligible resistive losses when cooled using liquid nitrogen, enabling very low losses and very high power-flow capacities.

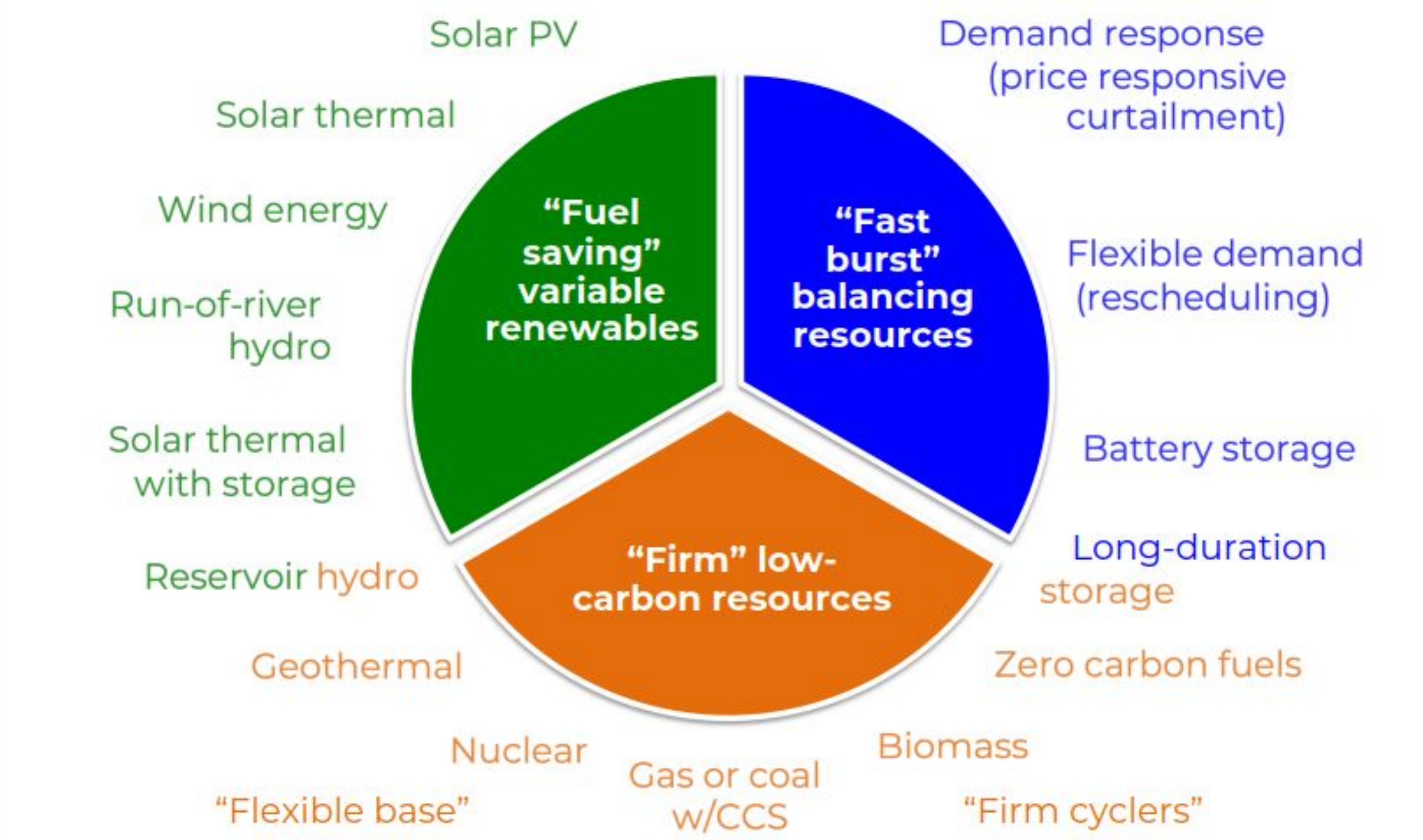
Capacity Expansion with High-Performance Conductors

Reconductoring with high-performance conductors replaces existing transmission lines with high-performance conductors using the original tower and right-of-way. In some cases, upgrades to terminal equipment may be required.

For rebuilds, transmission towers along with the conductor are replaced, either due to age or to accommodate larger conductors within an existing right-of-way.

Reconductoring generally takes 1-3 years and can 2x the capacity of a corridor at approximately half the cost of a new transmission line, while rebuild options can add significantly more capacity.

3. Resource adequacy: Reliable Carbon-Free Electricity Portfolios



Sepulveda, N., Jenkins, J.D., et al. (2018), "The role of firm low-carbon resources in deep decarbonization of electric power systems," Joule 2(11).

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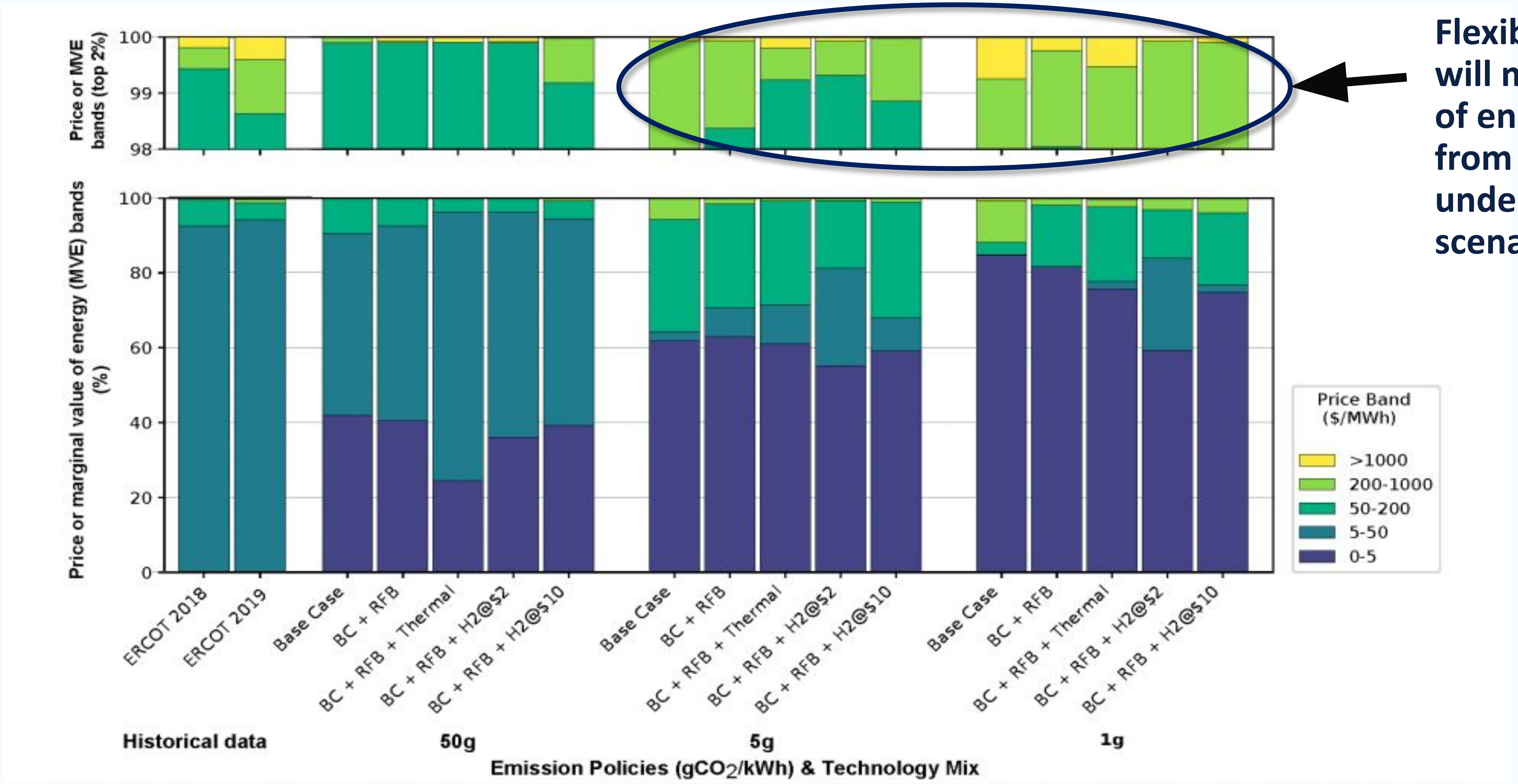
Dispatchable/capacity resources will run less and be paid in a small number of hours, or paid a reservation fee



Flexible generators will make majority of energy revenue from 2% of hours under low-emission scenarios

Source: Mallapragada, Jung, Wang, Pfeifenberger, Joskow, and Schmalensee, Electricity Pricing Problems in Future Renewables-Dominant Power, MIT CEEPR

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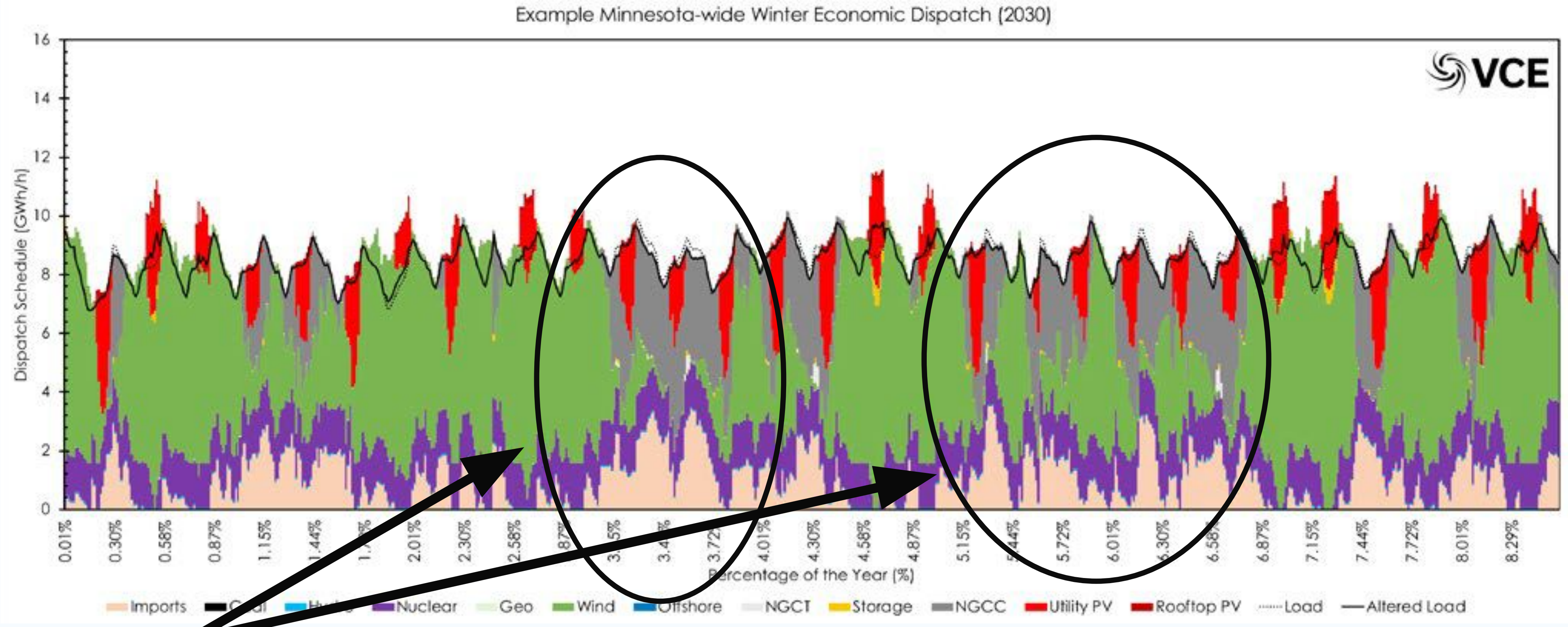
Resource Adequacy Challenge:
60-80 percent renewable systems require other resources for multi-day periods with low renewable output such as imports (beige) and firm dispatchable resources (gray).



Multi-Day periods of low wind+solar, usually winter.

Source: Clack, VCE, Minnesota/Eastern Interconnection study. See also E3, EFI, Telos, Brattle, Jenkins, MIT EI, Princeton NZA, Gridlab/UC Berkeley, NREL, LBNL, IEA, ESIG, other studies

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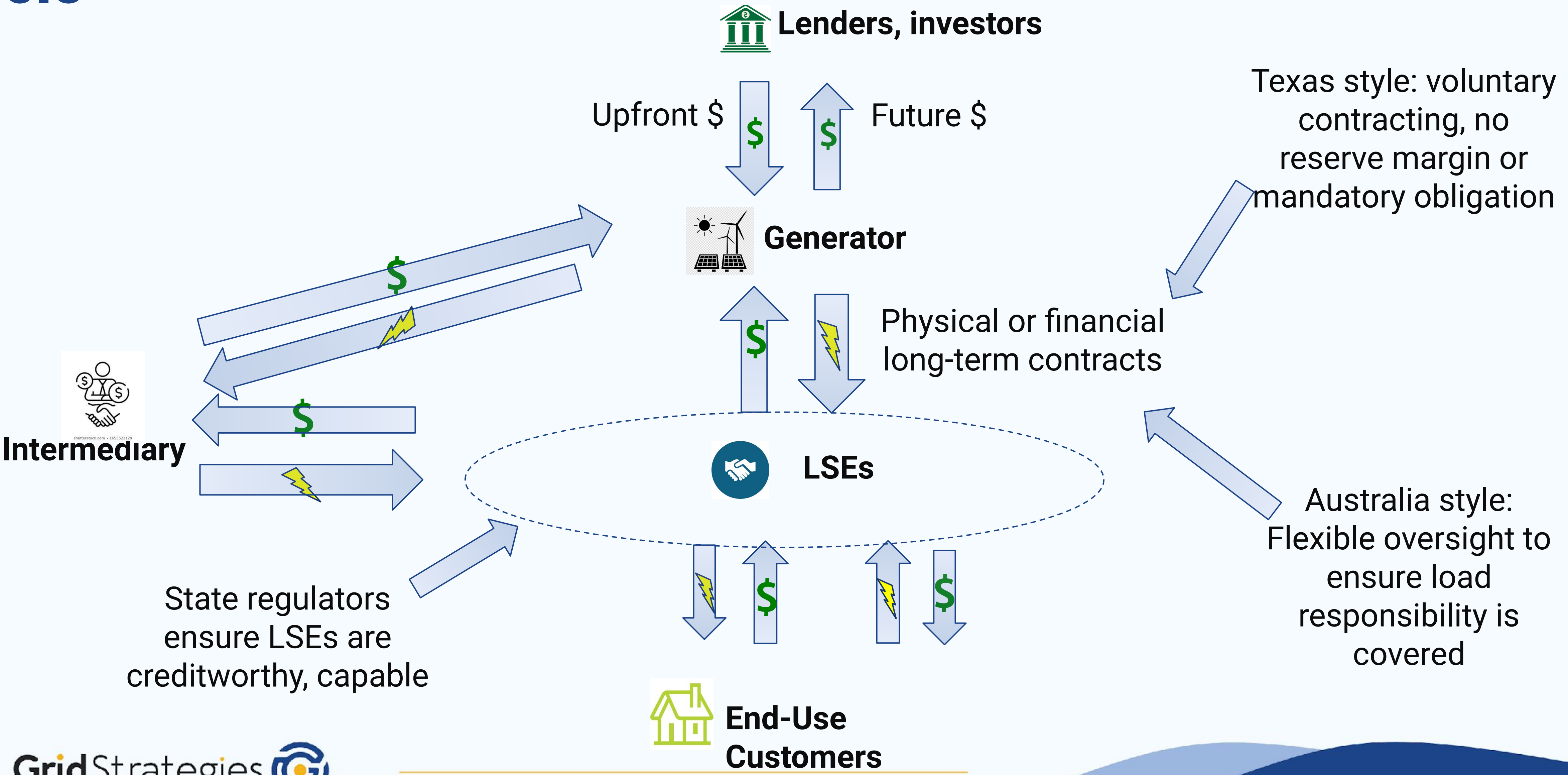
4. Power System Stability with high IBR penetration

- **Frequency Stability, Voltage and Angular Stability**
- **Solutions**
  - Grid-forming inverters—industry and government leadership to solve the chicken and egg problem.
  - Transmission
  - Synchronous condensers
  - IBR standards
  - IBR control tuning
- **Join ESIG!**

5. Generation procurement: Load-Serving Entities' key role



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6. Clean energy policy

- Lawmakers and environmental regulators internalize externalities through incentives and requirements.
- Carbon tax is most efficient
- Renewable requirements and incentives also beneficial

7. Integrate DR and DERs with wholesale markets

- More ground-up system planning with resources close to load
- Learn from Bryan Hannegan/Holy Cross, and other utilities doing this!
- Remove barriers to on-site and community-based resources

8. Transmission operational efficiency

Advanced Power Flow Control	Topology Optimization	Dynamic Line Ratings
2022 UK: Unlocked 1.7 GW network capacity in UK, saving ratepayers $500M	**2016 PJM analysis:** could reduce day-ahead energy costs by $145m/year	**2022 Pennsylvania:** DLR increases line capacity by 25% on average.
2023 New York: Unlocked capacity for 185 MW of generation, with $10M+ savings over legacy tech	**2022 SPP ex-post:** could resolve 98% of overloads in utility's territory	**2012 Belgium:** DLR increases capacity by 20%+ over 90% of the time