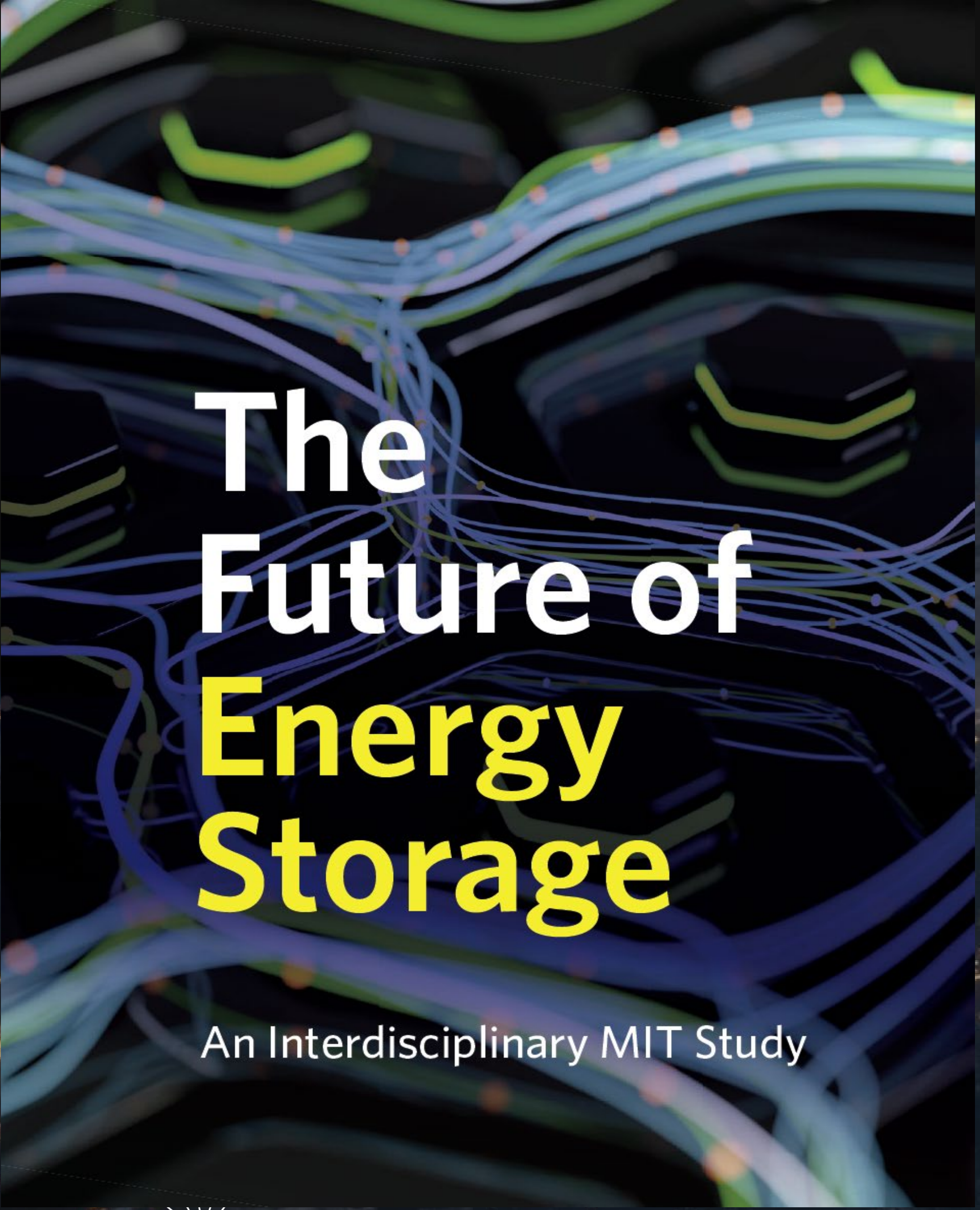

Insights from MIT's Study

Presented by

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The Future of Energy Storage is the latest in the MIT "Future of…" studies, exploring the roles of key energy technologies in a carbon-constrained future

Limiting significant adverse climate impacts will require drastic reductions in global carbon dioxide emissions by mid-century.

Decarbonization of the economy requires electrification, which necessitates achieving a deep decarbonization of the electric power sector at reasonable cost.

A decarbonized electricity sector will rely heavily on intermittent wind and solar generation. This leads to the need for electricity storage for both economic and reliability reasons.

What kinds of electricity storage technologies and policies would make this outcome achievable? How do options and choices vary regionally and nationally?

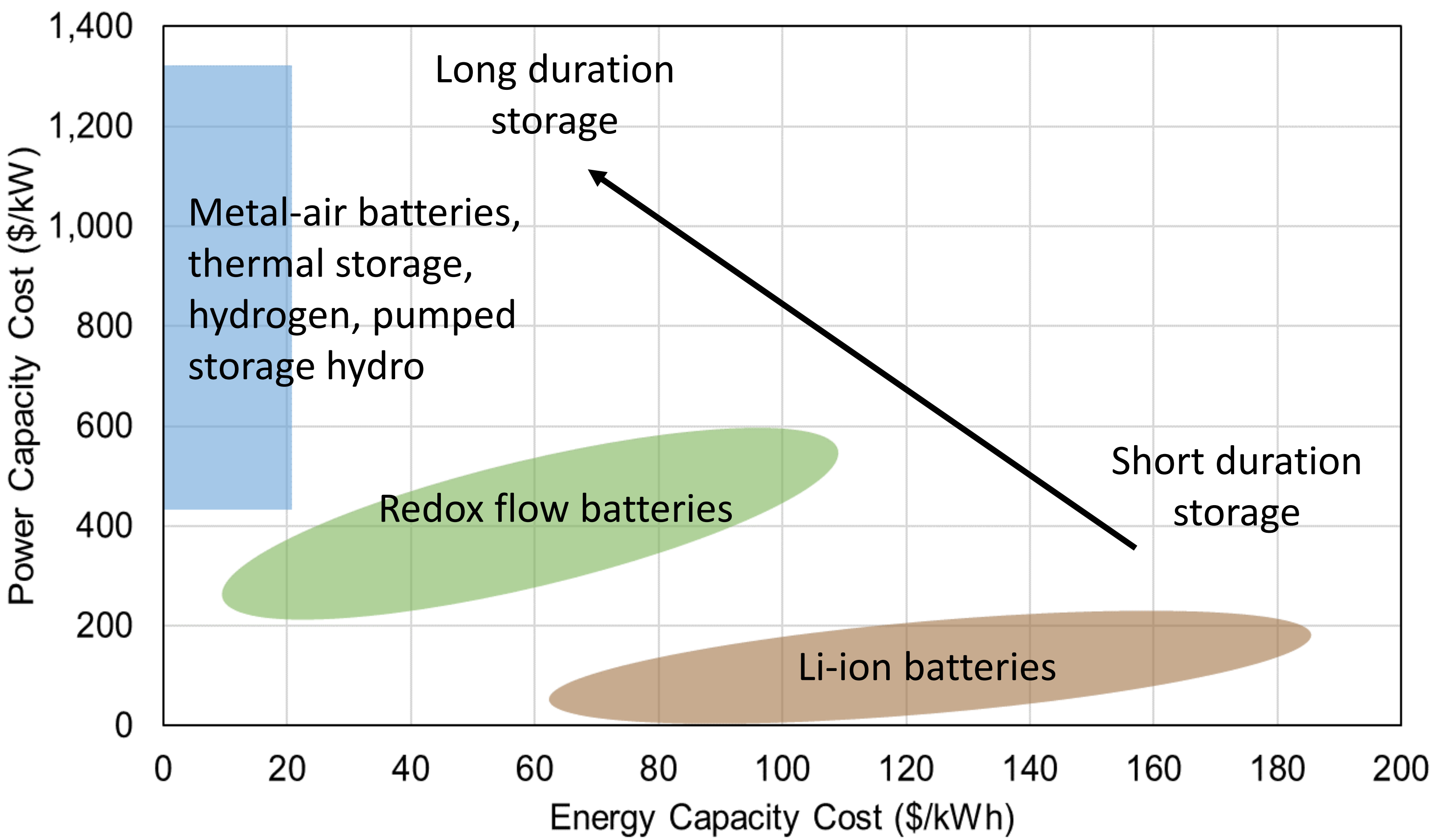
What changes to market designs and regulatory policies are needed to enable equitable & efficient decarbonization of the electricity grid?

Beyond confirming that storage needs to be an integral part of a clean-energy grid, the study's insights also include:

1. The cost trends for many existing and new storage technologies are similar enough within their uncertainty ranges, such that any one of them could become dominant at some point in the next decade(s).
2. Many pathways to a clean-energy grid are feasible, though some are more cost effective than others.
3. A cost-effective decarbonized grid requires an optimal mix of short- and long-duration storage.
4. Renewable generation and storage needs to be combined with increased load flexibility, a mix of utility-scale and distributed resources, and regional and interregional transmission expansion to reduce system-wide costs.
5. We already have the tools to get to a 95-99% decarbonized grid, but achieving the last 1-5% will be challenging and is associated with many economic, reliability, regulatory, and technological uncertainties.
6. Substantial innovations will be needed in regulatory policies, electricity market design, grid planning, and grid operations to achieve a reliable and cost-effective clean-energy grid.

Technologies studied

- **Electrochemical storage**
  - Li-ion
  - Redox flow batteries
  - Metal-air batteries
- **Mechanical storage**
  - Pumped storage hydro
  - Compressed air storage
- **Thermal storage**
  - Molten salt, hot rocks
  - Heat pumps
- **Chemical storage**
  - Hydrogen

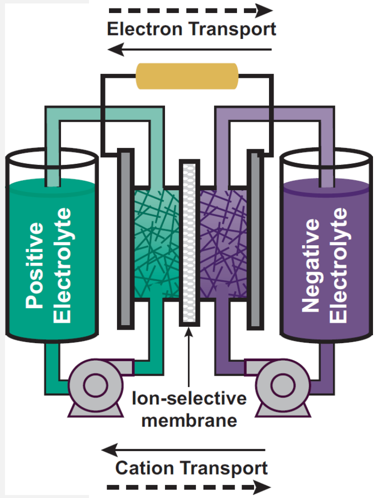


Power capacity cost = cost per MW of maximum instantaneous power
Energy capacity cost = cost per MWh of energy storage capacity
Duration = energy capacity / power capacity

Long-duration energy storage options

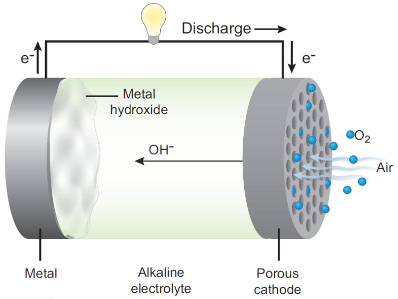
Redox Flow Batteries

- Independent scaling of power (stack) and energy (tanks) makes RFBs tunable for storage duration
- Vanadium redox is most technically advanced but cost and supply challenged
- Awaiting lower-cost highly stable chemistries for long-duration applications



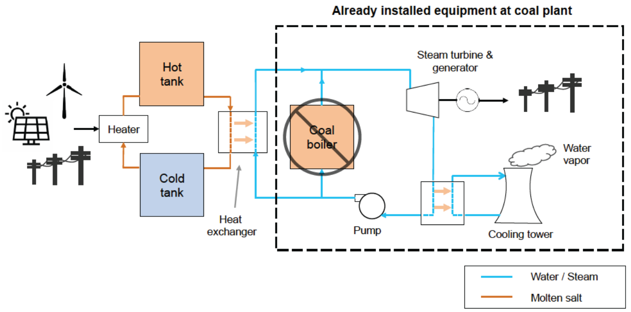
Metal-Air Batteries

- Very low energy cost makes metal-air attractive despite high power cost and low round-trip efficiency
- Best suited for long-duration storage applications
- Can use low-cost earth-abundant elements such as Zn and Fe with large existing supply chains



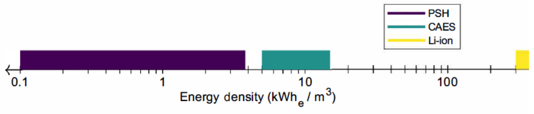
Thermal Energy Storage

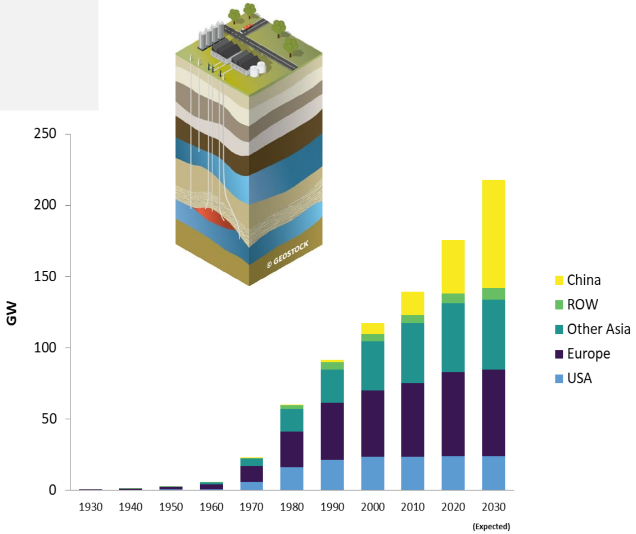
- Key challenge: conversion of heat to electricity
- Identified a new low-cost option: Steam turbine retrofit with TES at existing coal plants



Mechanical Energy Storage

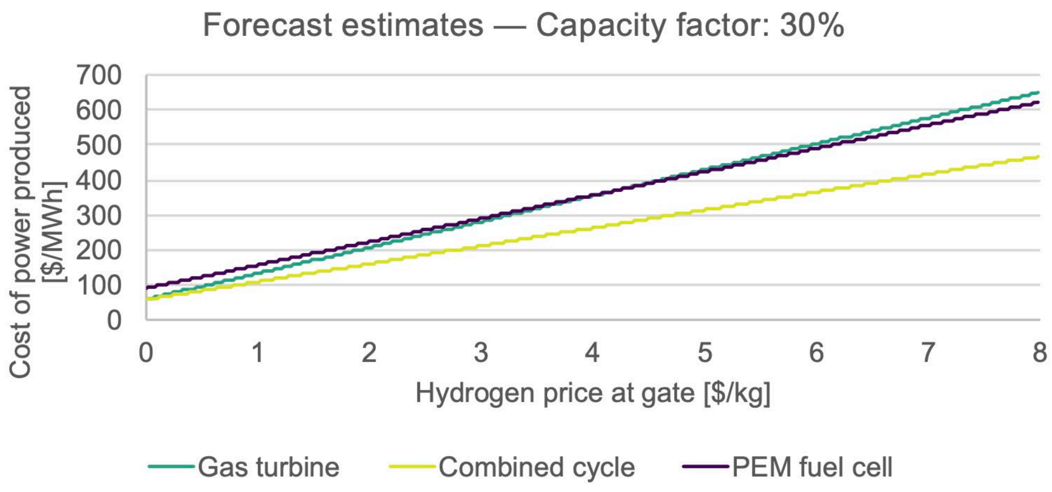
- Constrained by low energy density, geology
- Pumped storage hydropower is expanding rapidly in China but not U.S.

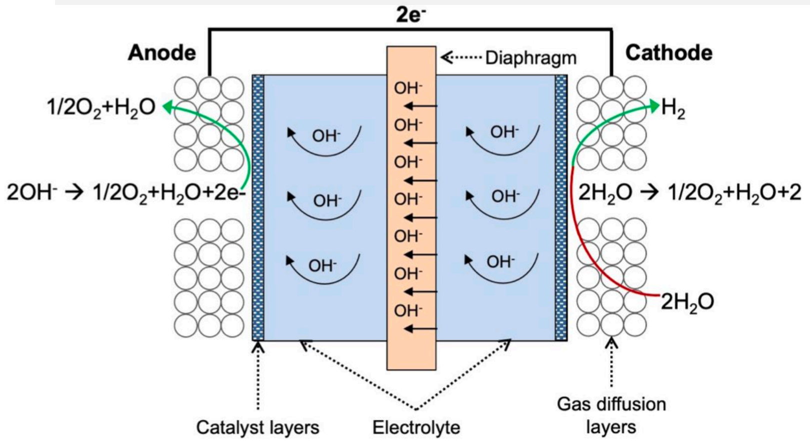


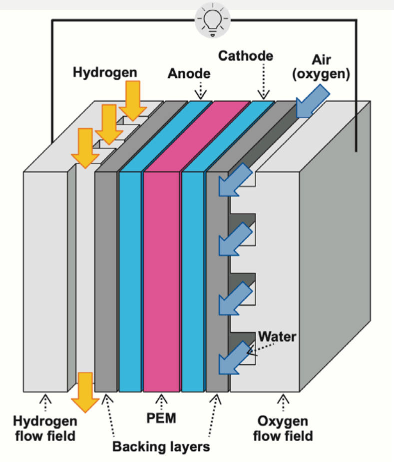


Hydrogen

- Commercially proven technologies exist for all aspects of the hydrogen value chain except for electricity production via hydrogen.
- Hydrogen is currently produced, transported, and sold to industry as a feedstock for numerous industrial processes. There is no significant consumer market.





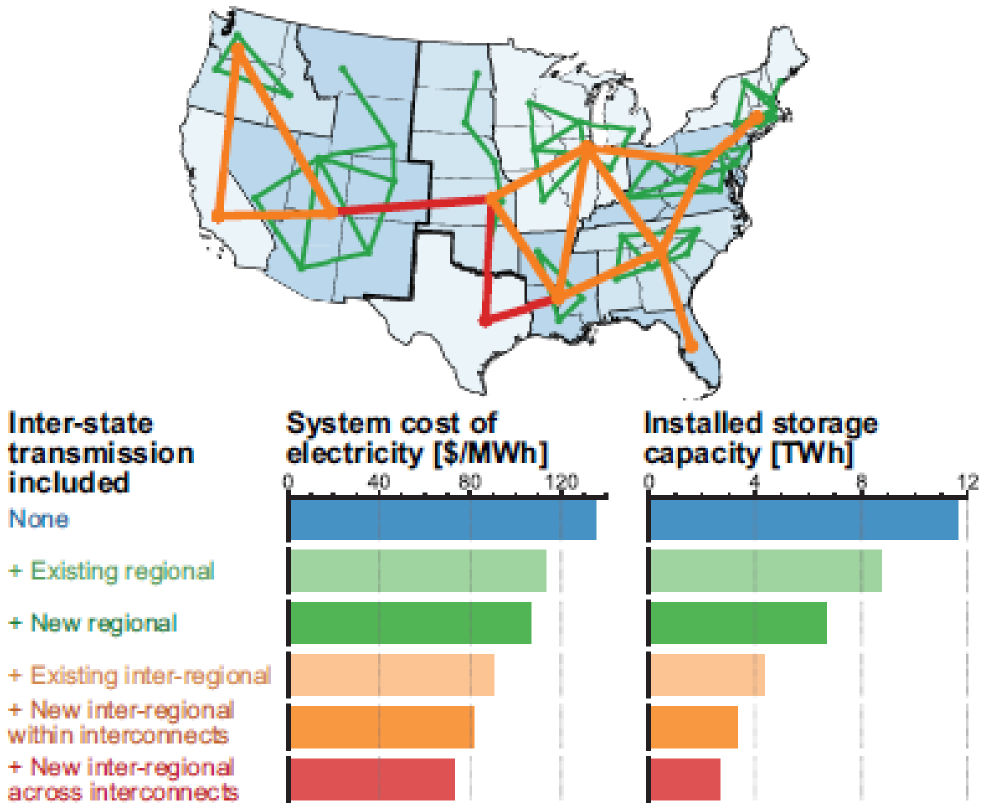


- While low costs to store hydrogen make hydrogen an appealing energy storage medium for long-duration applications, using hydrogen as a fuel to produce power is very expensive relative to similarly positioned thermal power generation assets.
- Long-duration energy storage will likely not be the main driver of hydrogen demand in a future decarbonized energy system for the simple reason that hydrogen will be more valuable as a way to indirectly electrify otherwise difficult-to-electrify energy end uses.

Grid Simulation Results

NATIONAL PERSPECTIVE

Transmission expansion can greatly reduce cost of decarbonization and lower the required amount of storage



Scenarios show the impacts on SCOE and optimal storage deployment if the country is modeled as isolated states (blue bars), isolated zones without and with new regional transmission (green bars), and a fully interconnected system with different levels of inter-regional transmission (orange and red bars) (Brown and Botterud 2021). The transmission assumptions in the regional case study discussed above are most similar to the "new regional" transmission scenario shown here.

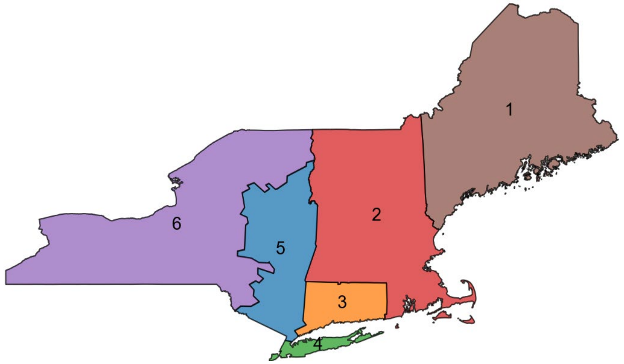
Transmission

- Transmission expansion can play an important role in reducing grid decarbonization costs, in part by reducing the need for storage
- Unlike natural gas transmission pipelines, which are primarily regulated at the federal level, states play a dominant role in the approval process for new electricity transmission
- Under the current regulatory structures it is difficult and time consuming to plan and get approval for major transmission lines, particularly when those lines cross states that do not perceive significant benefits from the project
- Reducing regulatory barriers to the planning and permitting new transmission will need to be a high priority for cost-effective decarbonization

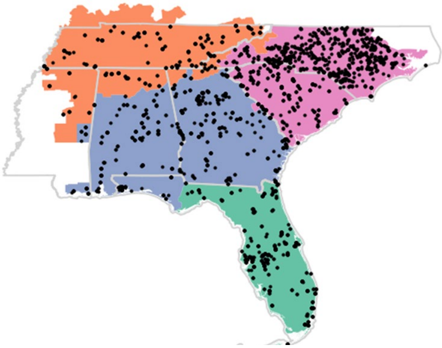
REGIONAL PERSPECTIVE – The study explored the role of storage in carbon-constrained, mid-century power systems for 3 very different US regions

U.S. Regions

U.S. Northeast



U.S. Southeast



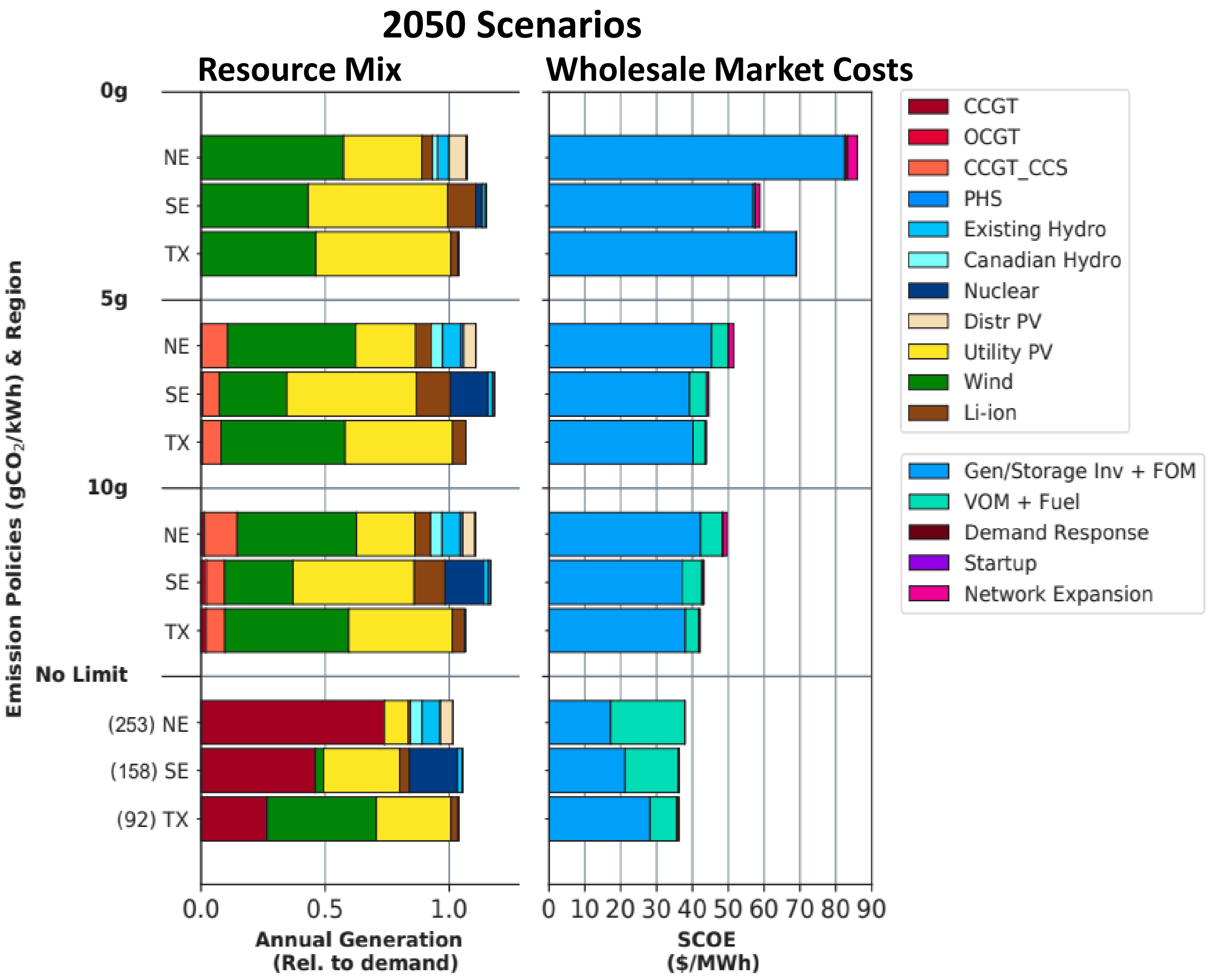
Texas

Grid CO_2 emissions intensity (2018)[1]:	U.S. Northeast	U.S. Southeast	Texas
	249 gCO_2/kWh	387 gCO_2/kWh	481 gCO_2/kWh

Findings are based on modeling **economically efficient net-zero emissions power systems** under a wide range of technological and policy assumptions, including:

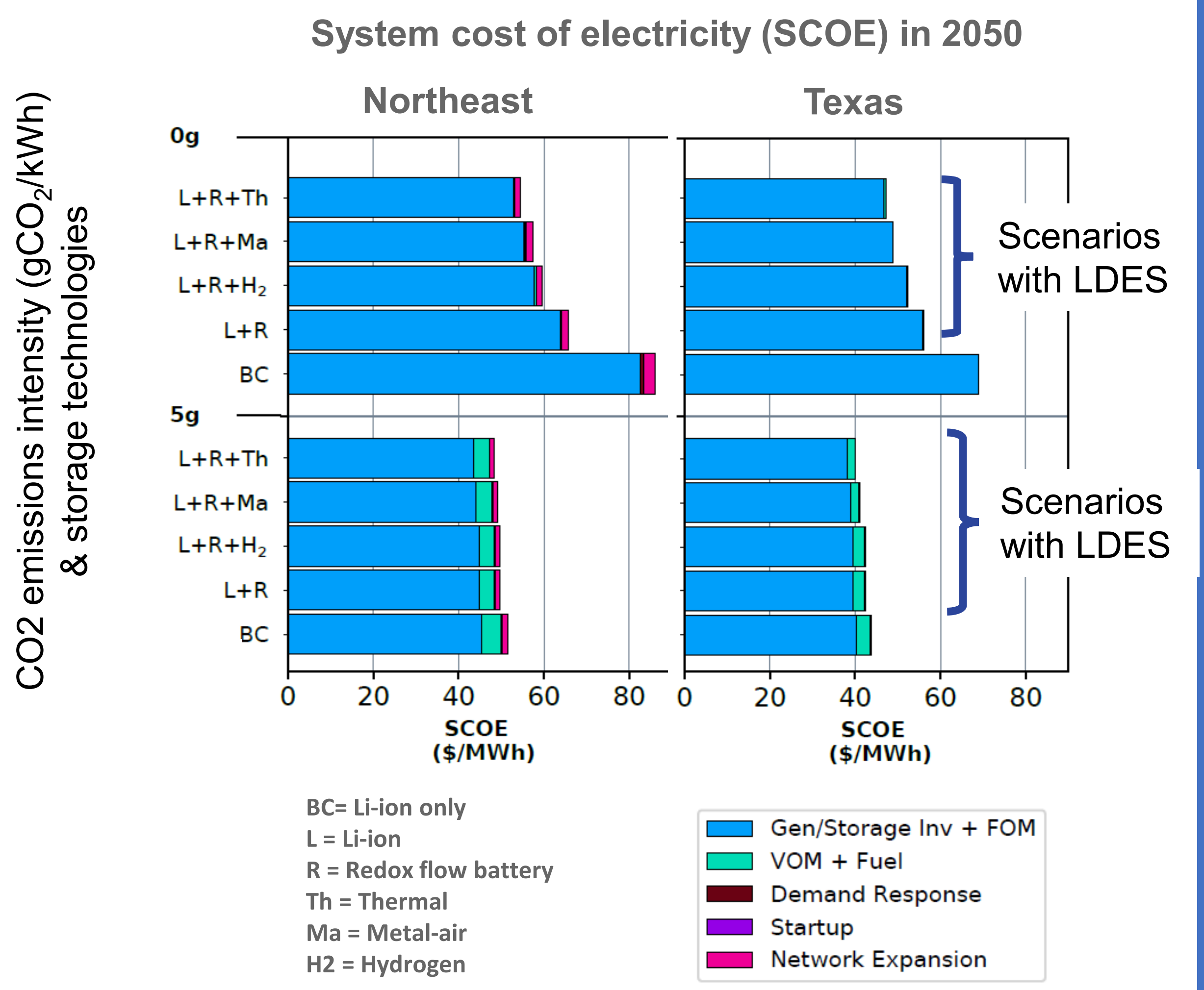
- CO_2 emissions intensity limits ranging from 50 gCO_2/kWh to 5 gCO_2/kWh
- Projection of **substantial increase in electricity demand** consistent with a highly electrified economy
- **Continued cost reductions for VRE and Li-ion storage** by 2050
- Continued availability of existing zero-carbon supply (e.g. nuclear in Southeast, hydro in Northeast)
- Sparing use of natural gas generation with carbon capture and sequestration (CCS)
- Perfect foresight assumed throughout. No tractable alternative, but could understate the value of storage

Study results suggest that near-complete decarbonization of major US regions by mid-century is feasible without sacrificing reliability or incurring higher costs using VRE and Li-ion storage – *and some gas with CCS*



- Challenges of "getting to net-zero" vary across regions based on their resource endowments and demand patterns
  - Note: high VRE penetration in Texas with no carbon limit (CO_2/kWh down 81%, all coal plants closed). NE up from nuclear closing. SE down 57%
- Energy storage can substitute or complement all other elements of a power system (distribution, transmission, generation, demand management)
- Storage can (and should be able to) earn revenues from providing a variety of products: energy arbitrage, ancillary services, transmission services, and capacity/resource adequacy
- Plausible demand shifting (hours) mainly substitutes for short-duration storage
- These regional simulations did not consider transmission links to other regions expansion, which play an important role in reducing grid decarbonization costs

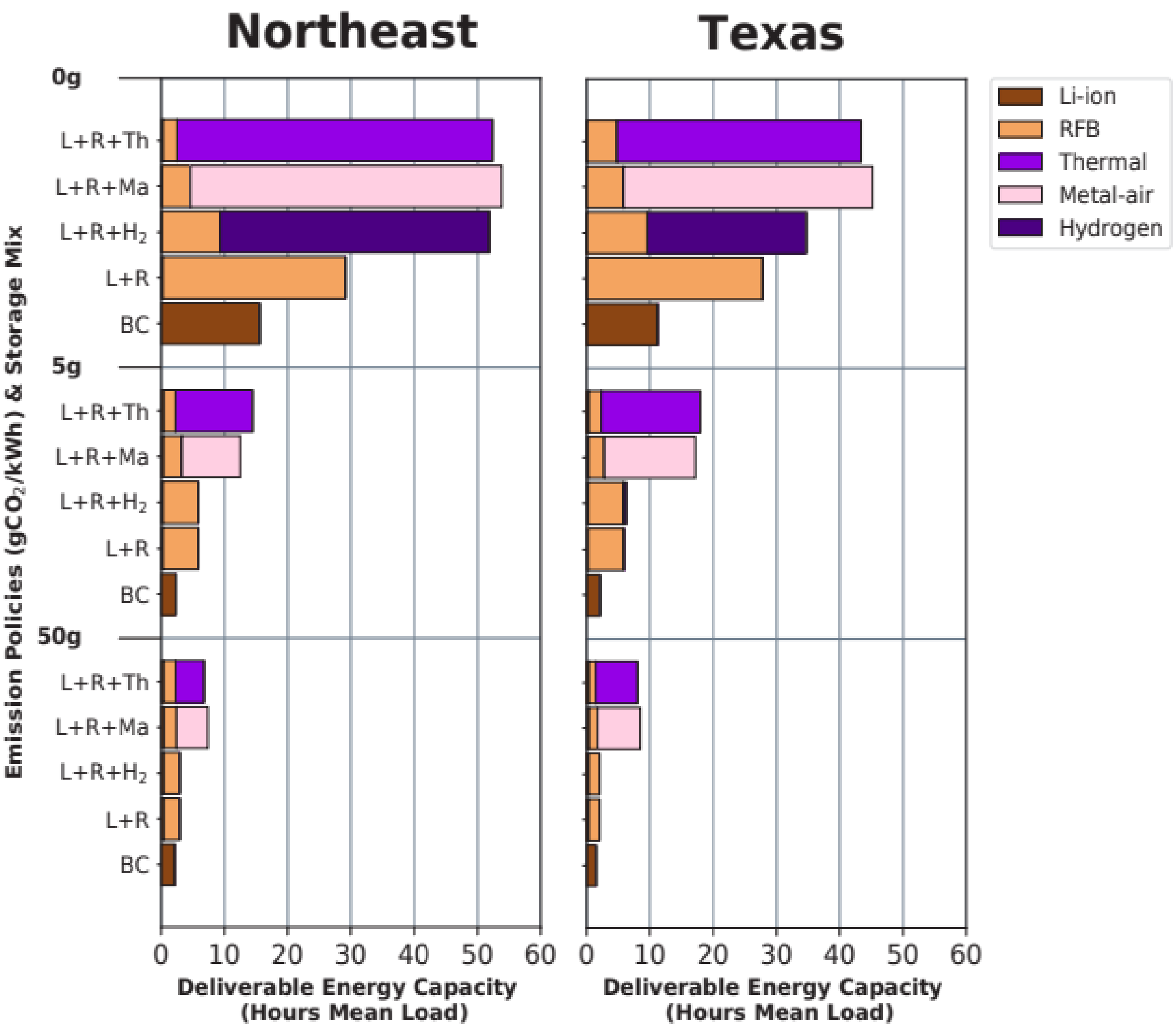
The availability of emerging long-duration energy storage (LDES) technologies can reduce the cost of full decarbonization



Cost impacts of long-duration storage are greatest when natural gas generation is not an option even with CCS (i.e. zero gCO_2/kWh, full decarbonization)

→ Focus public and private RD&D on improving cost and performance attributes of emerging LDES

The role of hydrogen and other long-duration storage technologies vs. Lithium-Ion batteries



2050 simulations with different storage technologies show:

Very similar total system costs across storage technologies: given today's uncertainties about future costs, any of the storage technologies may dominate all others

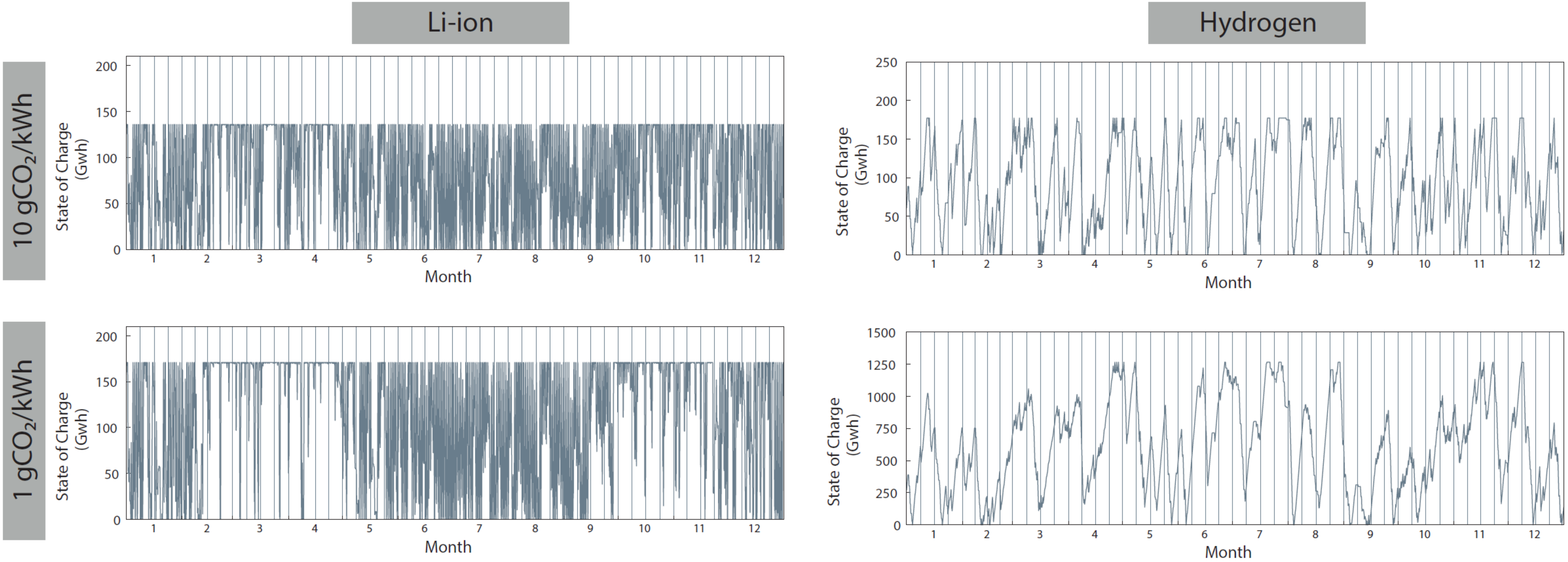
- New storage technologies appear to outcompete Li-Ion, but projected cost savings are similar for anything but full decarbonization (absolute zero)

Hydrogen may be challenged:

- Uneconomic unless full decarbonization?
- Even in an absolute-zero carbon grid, significant competition from other long-duration technologies (redox-flow, metal-air, thermal)

Long-duration storage (e.g., hydrogen) is most valuable when natural gas with CCS is not available, though optimal use is intra-month (not seasonal)

Example state of charge (SoC) of Li-ion battery and hydrogen storage in Texas for 1g and 10g emissions targets



Note: Simulation results for Texas: hourly state of charge (SoC) for Li-ion and hydrogen storage for the scenario with mid-cost Li-ion, RFB (not shown), and hydrogen storage technologies for two emissions constraints.

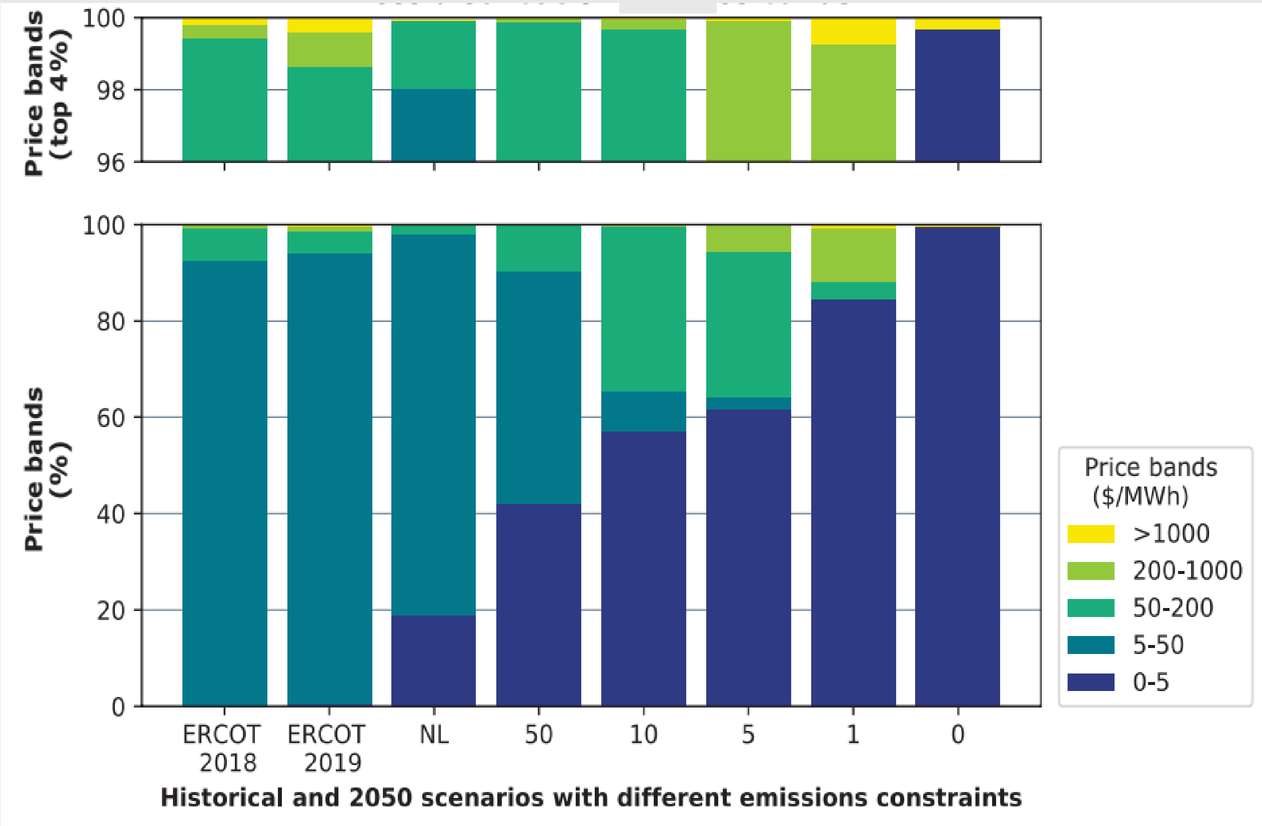
Two Important Features of Future Efficient Decarbonized Electric Power Systems that will Require Significant Regulatory Reform:

Wholesale spot prices will be MUCH more volatile than spot prices in today's markets

- "Excess" VRE capacity substitutes for storage & transmission on the margin, and curtailment is common, which implies a zero marginal value of energy. More near-zero prices occur as carbon constraint tightens.
- To cover higher investment costs despite more frequent low prices, need either more frequent price spikes than today or (if price caps or other out-of-market actions), capacity payments of some kind, including long-term contracts with credit-worthy counterparties.

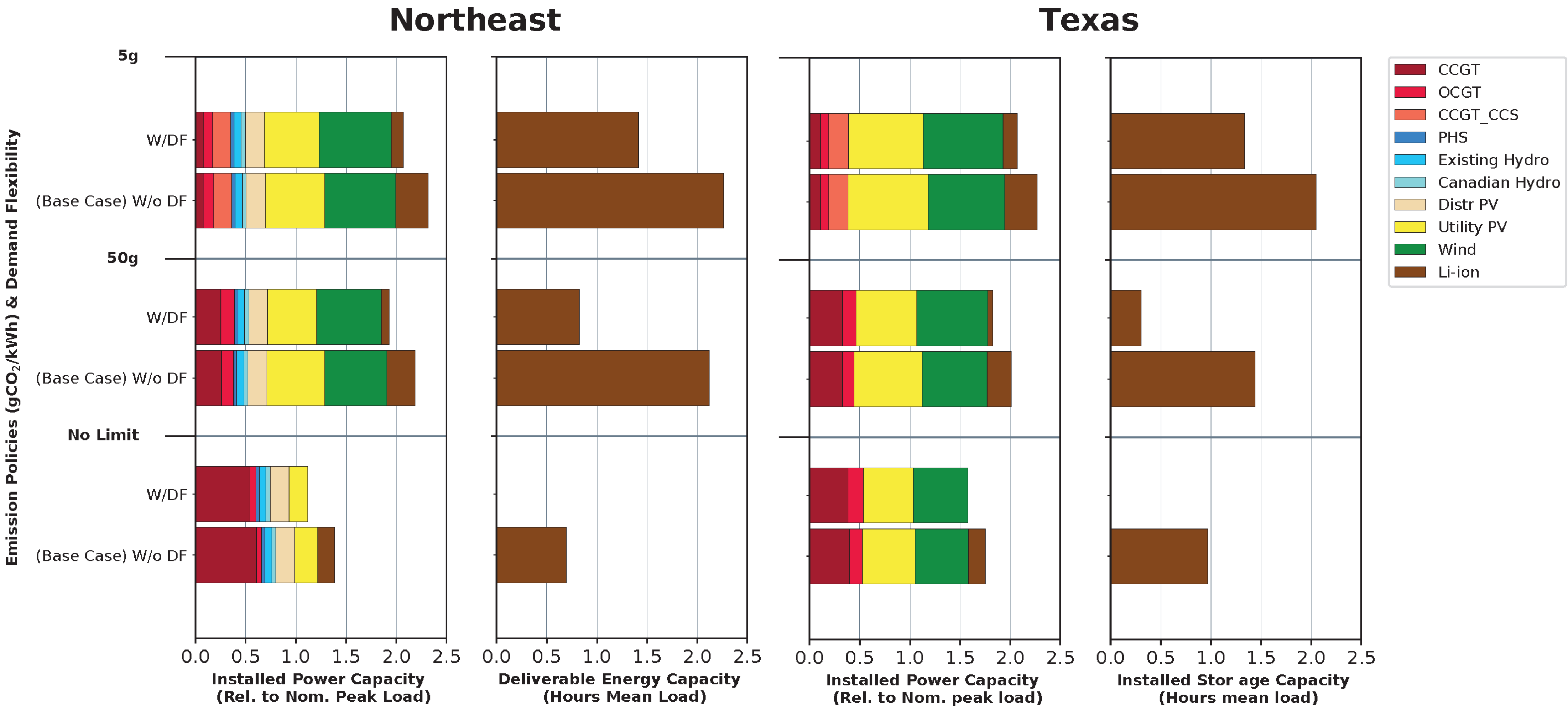
Small-scale BTM generation & storage can have important grid-level effects – already a reality in some systems (e.g., CA, HI)

Frequency Distribution of Spot Prices



With proper incentives, intra-day demand shifting from applications like EV charging reduces costs and the need for short-duration (Li-ion) storage

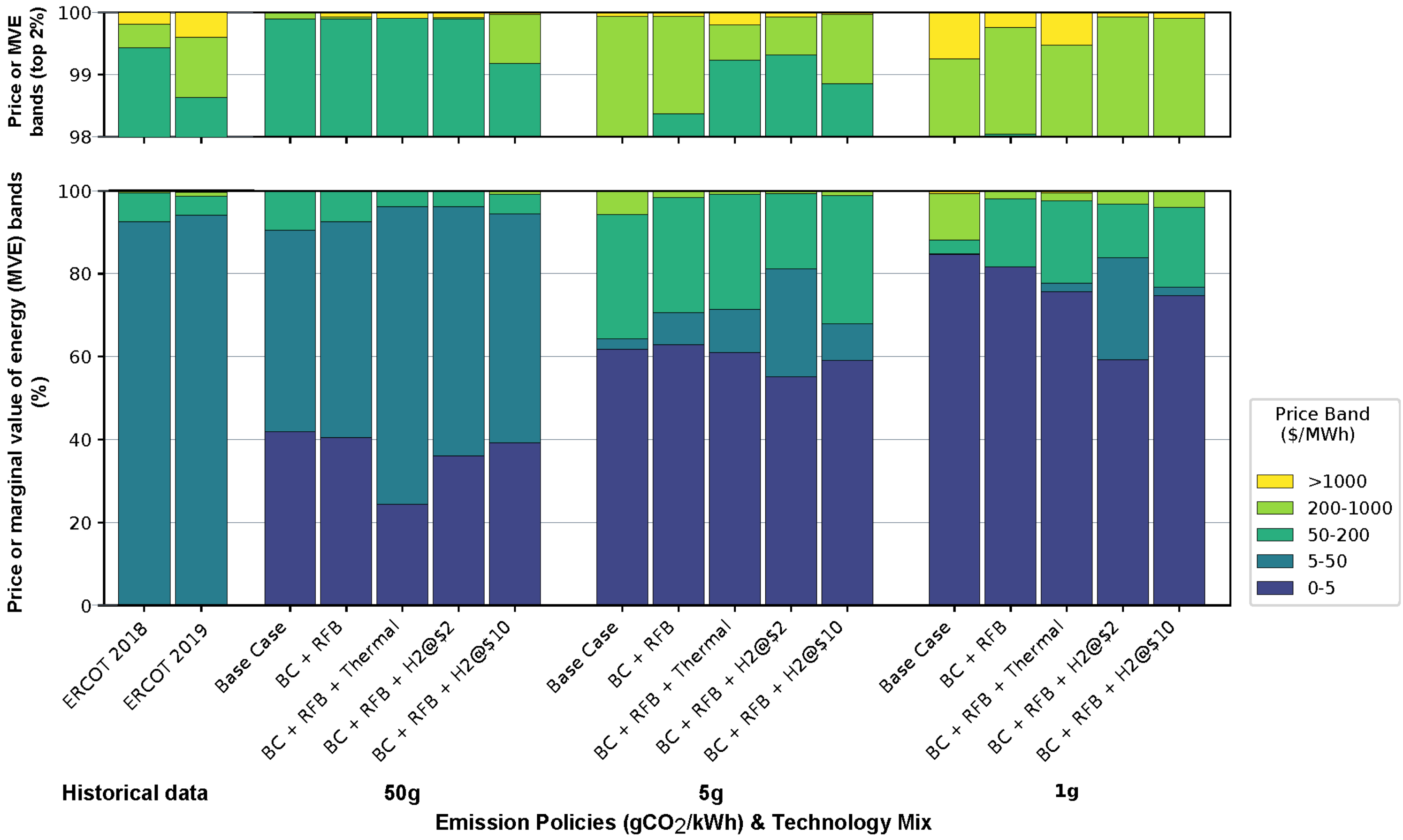
Power and energy capacity impacts due to demand-side flexibility under various carbon constraints (2050)



High Volatility Is Only Modestly Reduced by the Availability of Long-Duration Storage

More results for Texas, now including mid- and long-duration storage technologies (MLDES) shows:

- Availability of MLDES technologies significantly reduces likelihood of highest spot prices (yellow) in highly decarbonized (1 gram) case
- Still significant increase relative to history in very low (purple) spot prices



Policy and Regulatory Implications

Necessary Wholesale-Level Reforms (FERC, ISOs, States)

Energy Markets: For efficient operation, storage must be able to pay spot energy prices (day-ahead and real-time) for charging and be paid spot energy prices for discharging.

- Spot market prices need to be able to reach the Value of Lost Load (VOLL) to enable demand response

Capacity Markets: If supplemental capacity support payments are necessary, storage should be paid fixed annual technology specific- and system-dependent prices for capacity (MW) and duration (MWH/MW)

- Will need ELCC or ELCC-like measures of contributions to reliability, which will depend on stochastic demand and supply characteristics, charge/discharge profiles, interactions with system conditions, …
- Competitive procurement mechanisms should be used to determine market-clearing prices for supplemental capacity remuneration
- Design of LT contracts is important to provide efficient charge and discharge incentives based on short-term market prices and operating conditions

Wires: When storage provides wires-related benefits (e.g., to defer transmission/distribution investment), it should be compensated for those benefits

- But treating storage as only “transmission” (or as only “generation”) leads to inefficient outcomes

Necessary Retail-Level Reforms (States)

More volatile wholesale markets implies much higher social cost of today's time-invariant rates

Efficient economy-wide decarbonization requires retail rates to be very low *at the margin* when wholesale spot prices are low to encourage electrification

Also need incentives to reduce demand when wholesale prices are high, but simply using per-kWh retail rates equal to wholesale prices would involve imposing intolerable risk on customers

- The core challenge is to enable consumers to see marginal energy prices that vary with spot wholesale prices, while keeping variation in their average per-kwh cost at acceptable levels

Research/experimentation needed on reducing consumer risk while preserving incentives

- Will need higher, *equitably differentiated* fixed charges to cover the system's higher fixed costs while still sending proper marginal-cost based price signals for marginal consumption
- Will need to devise & use hedging/insurance schemes, load management contracts, other behind-the-meter devices

The Main Messages

1. Federal R&D policy should focus on long-duration storage technologies to support affordable, reliable, deeply decarbonized future electricity systems.

2. Optimal investments in Renewables+Storage+Transmission need to be facilitated to make regionally-tailored, net-zero electricity systems affordable.

3. Market designs, retail rates, and regulatory policies need to be reformed to enable equitable & efficient decarbonization.

Questions, Comments?