# The Future of Energy Storage

An Interdisciplinary MIT Study

# 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.**

**Deep decarbonization of the electricity sector combined with electrification of other parts of the economy means that the electric power sector must be deeply decarbonized 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 economic and reliability reasons.**

**What kinds of electricity storage technologies and policies would make this most likely? How do these choices vary regionally?**

# Technologies Studied

Electrochemical storage

- Li-ion
- Redox flow batteries
- Metal-air batteries

Mechanical storage

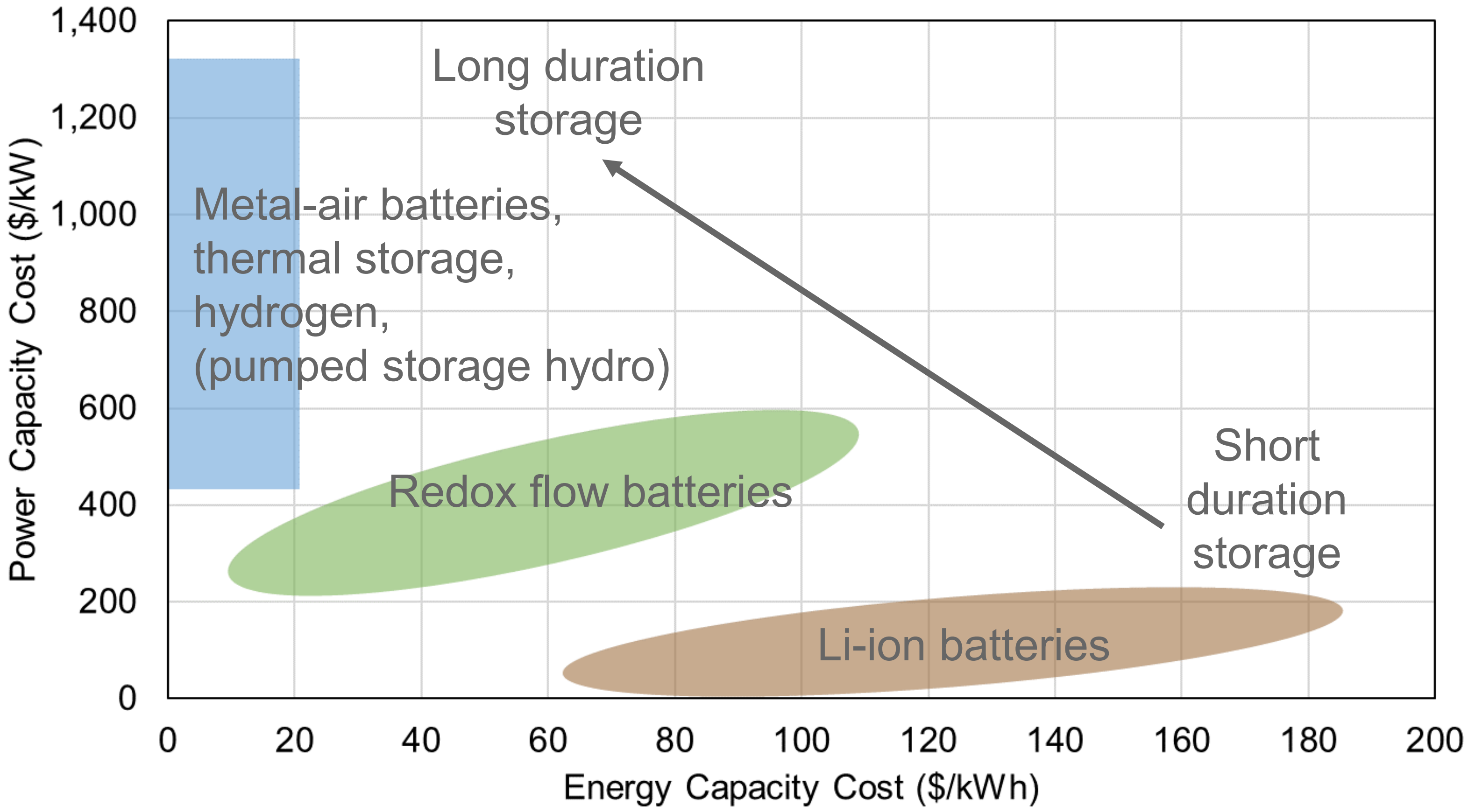
- Pumped storage hydro
- Compressed air storage

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

## What needs to be done now to enable electricity storage to play a major role in limiting climate change?

Our three main messages:

1. Federal R&D policy should focus on long-duration storage technologies to support affordable, reliable future electricity systems.
2. Storage can make regionally-tailored, net-zero electricity systems affordable.
3. Market designs and regulatory policies need to be reformed to enable equitable & efficient decarbonization.

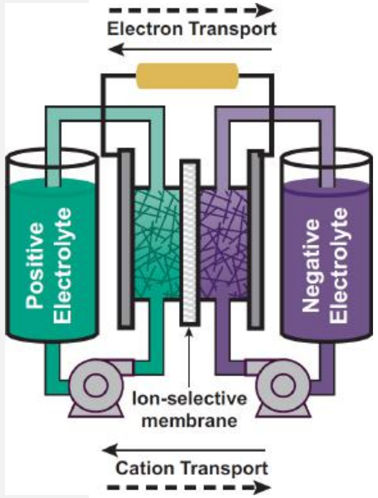
# Message #1

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

# Long-duration energy storage options are developing

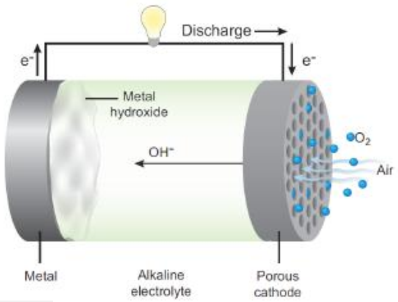
## Redox Flow Batteries

- 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



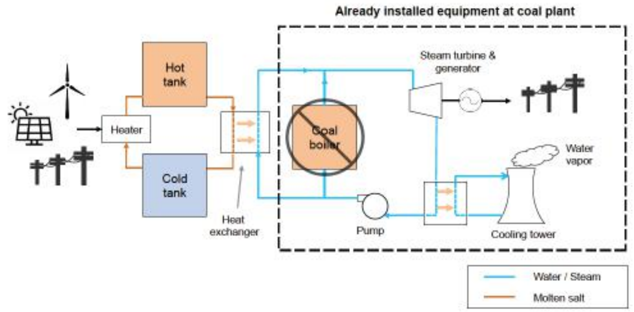

## Metal-Air Batteries

- 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



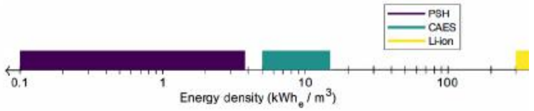

## Thermal Energy Storage

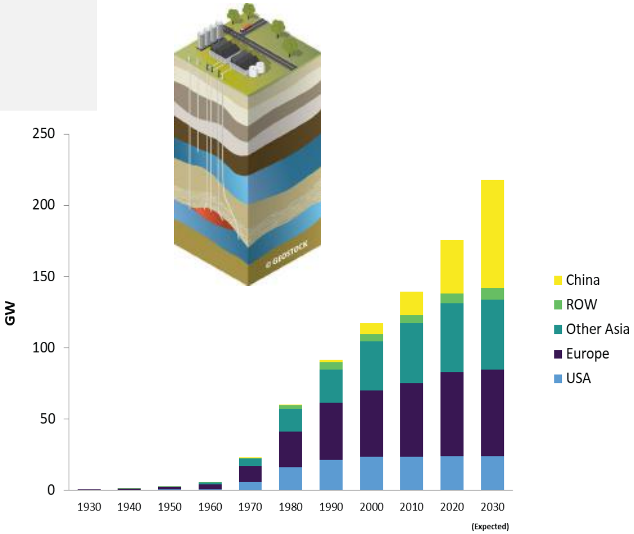
- Key challenge: conversion of heat to electricity
- Identified a new low-cost option: Steam turbine retrofit with TES at existing coal plants




## Mechanical Energy Storage

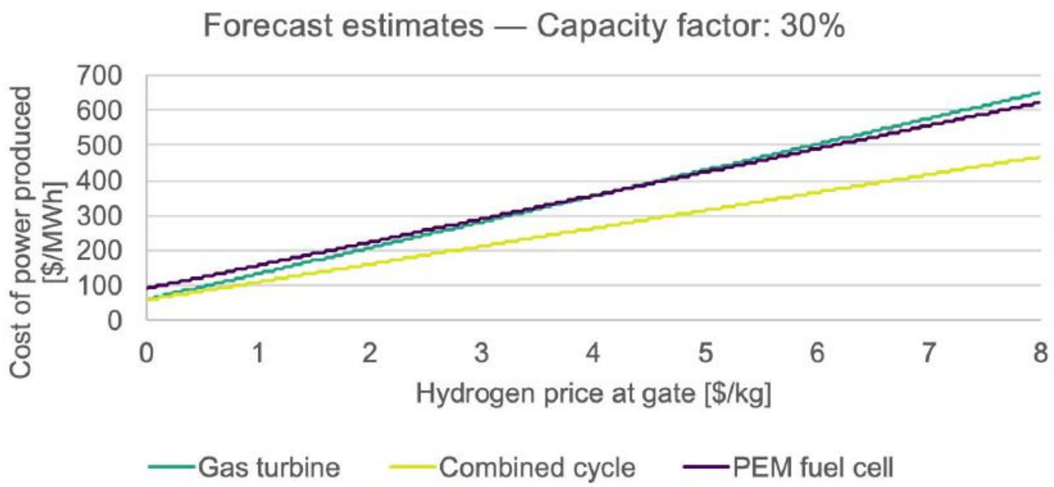
- Constrained by low energy density, geology
- Pumped storage hydropower is expanding rapidly in China but not U.S.

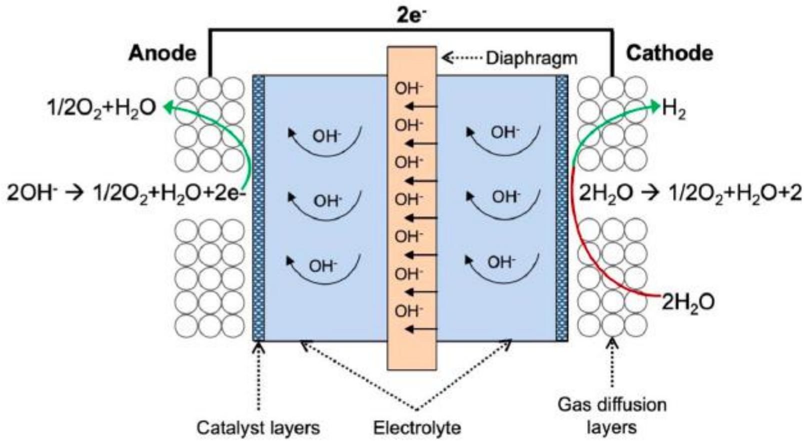


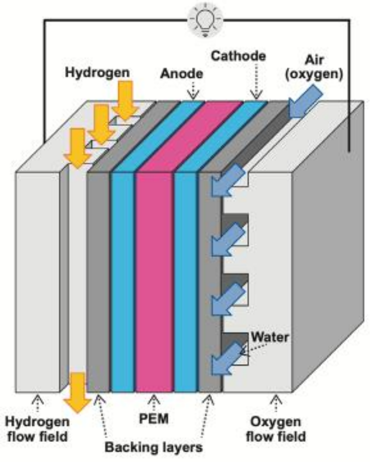



# Chemical energy storage (hydrogen)

- 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.



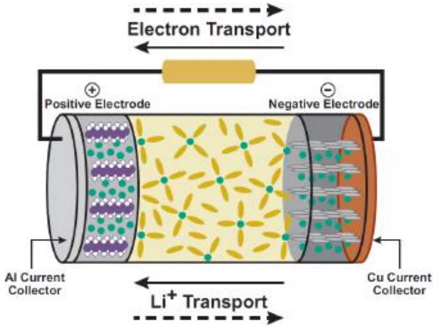



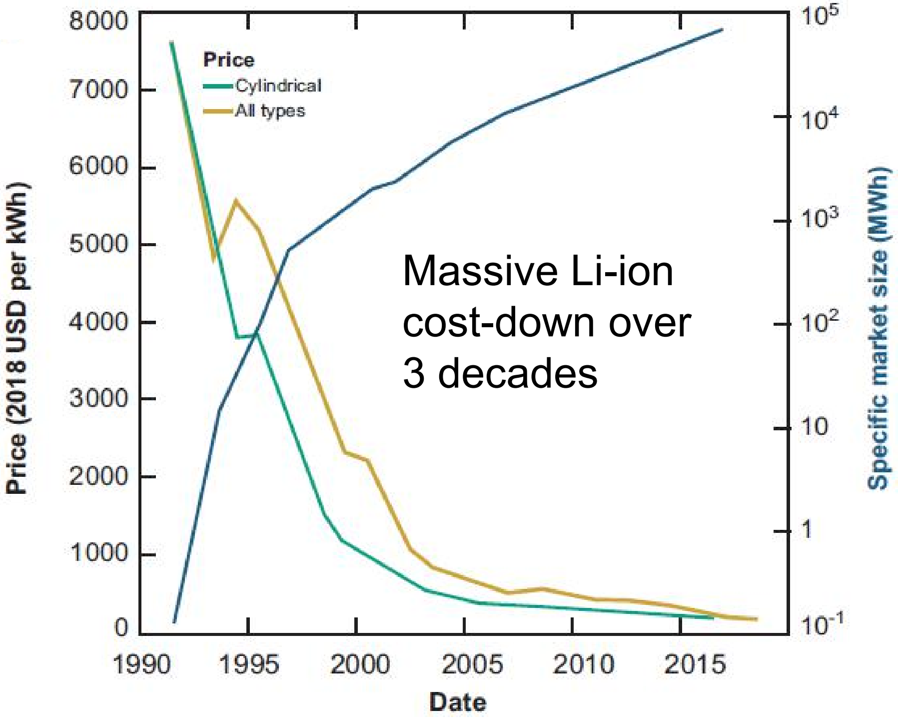



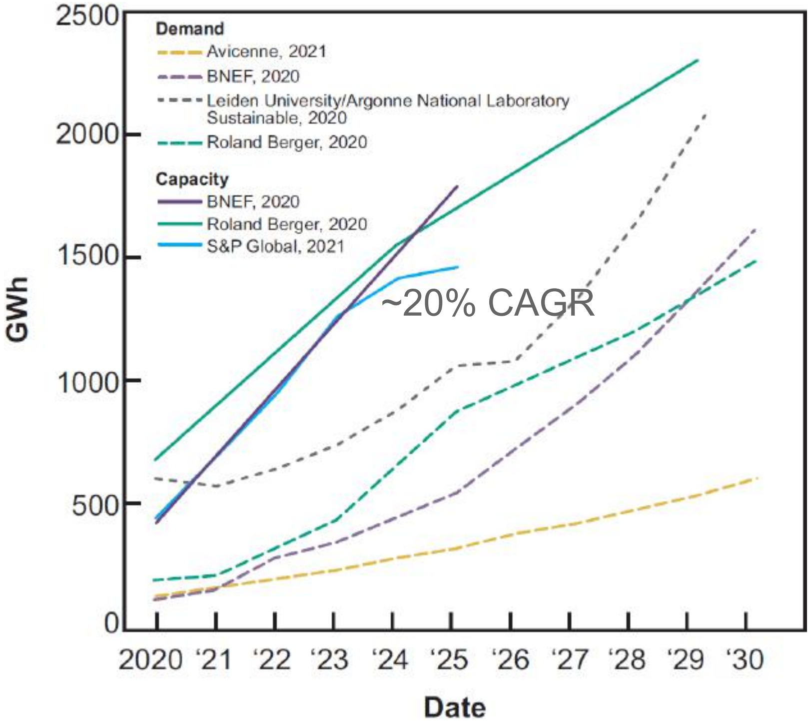

- While low costs to store hydrogen make hydrogen an appealing energy storage medium for long-duration applications, using hydrogen as a fuel to produce power is very expensive relative to similarly positioned thermal power generation assets.
- Long-duration energy storage will likely not be the main 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.

# Outlook for Li-ion

- Li-ion will likely remain a preferred technology for short-duration energy storage (<12h).
- EV market is driving Li-ion growth. Availability for grid-scale use will be determined by this growth.
- Recycling will not alleviate supply challenges in a rapidly growing deployment of technology.



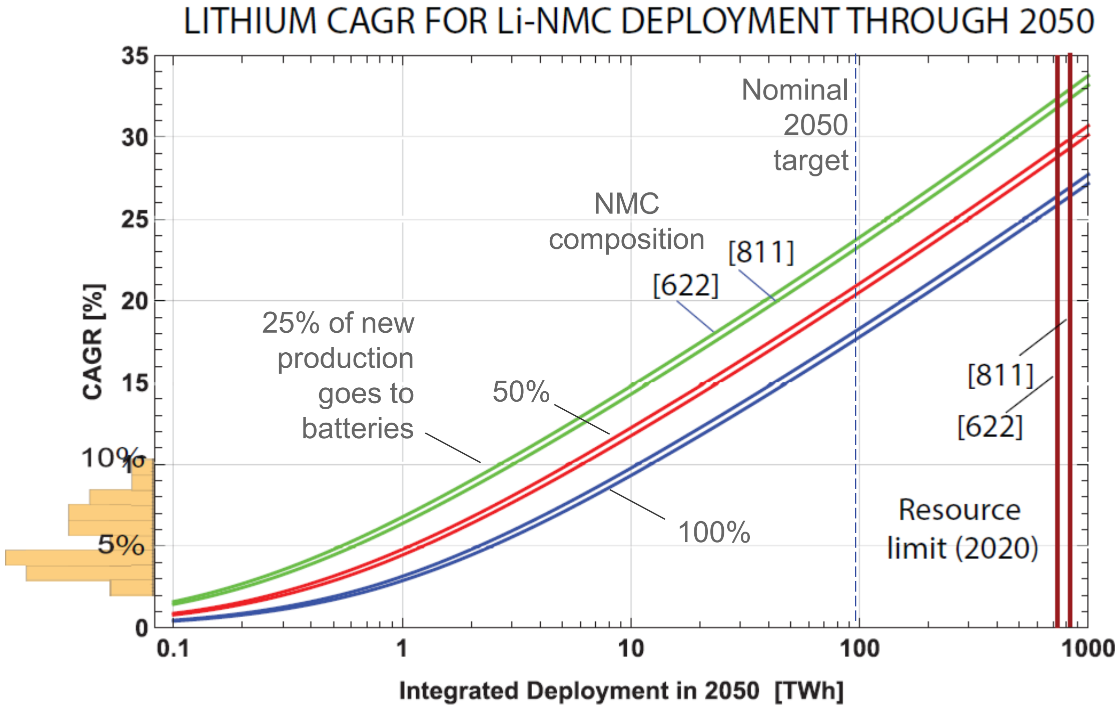

*80-140 TWh by 2040 (LDES Council/McKinsey & Company Nov. 2021.)

# Materials availability for electrochemical storage: Scaling production is the challenge

- Li-ion battery critical elements (Li, Co, Ni) are not resource limited but production limited.
- Vanadium production for redox flow batteries limited in the short term.
- Requires sustained CAGR of production over next 30 years at or above historical maxima.
- Typical time from prospecting to deployment of mineral resources is 5-15+ years.

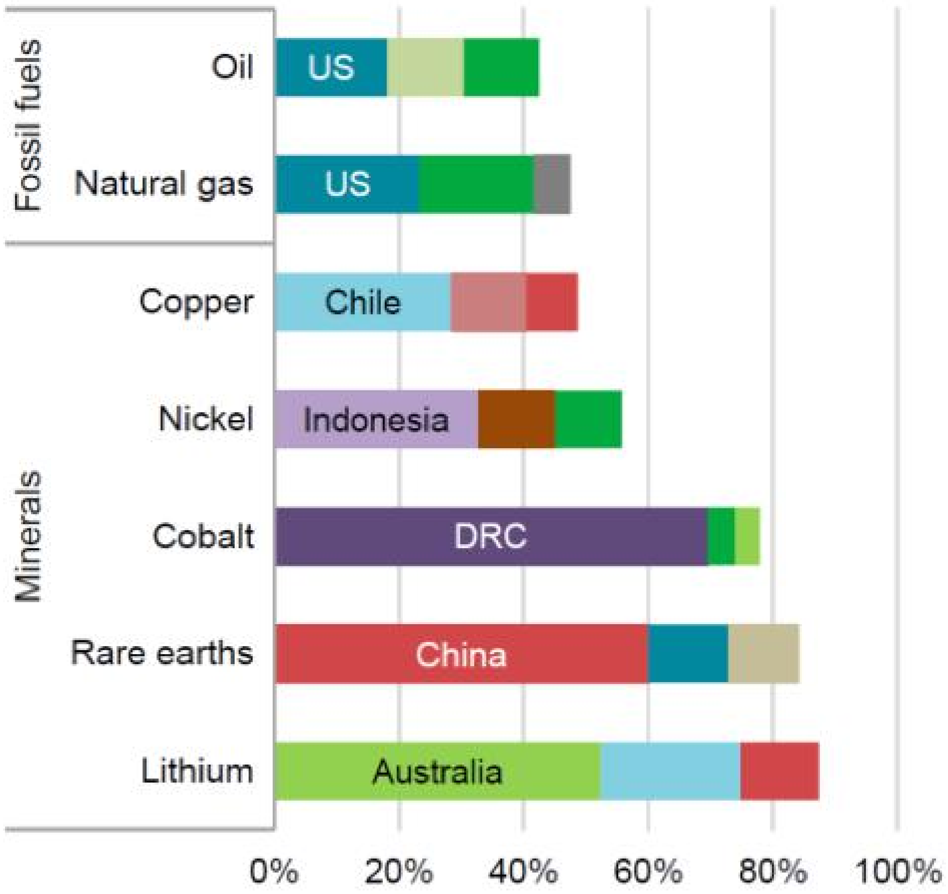
| | Historic CAGR | CAGR for 100 TWh through 2050 | Resource limit (2020) |
|---|---|---|---|
| Lithium | 3%-15% | 12% (50% mkt) | 700 TWh |
| Cobalt | -2%-10% | 6-15% (50% mkt) | 125-280 TWh |
| Nickel | 0%-5% | 10% (50% mkt) | 400 TWh |
| Vanadium | -5%-12% | 25% (50% mkt) | 70 TWh |

- Number in parentheses indicates % of deployment relevant for the materials market (mkt) in question
- CAGR = compound annual growth rate

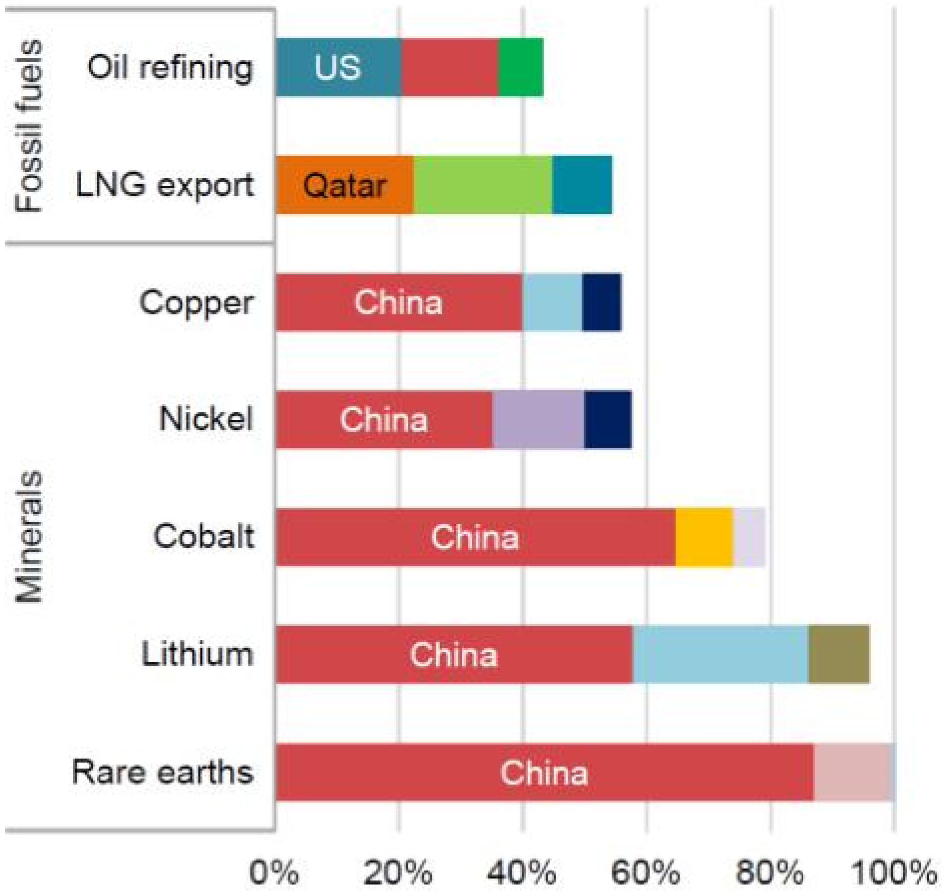


# Extraction and processing of energy transition minerals is more geographically concentrated than resources for today’s fossil fuel system

## Extraction




## Processing




Share of top three producing countries in production of fossil fuels and selected minerals

# Key Conclusions: Technology Development

- Lithium-ion batteries possess high energy density, high power density, and high roundtrip efficiency, facilitating their near-ubiquitous commercial use in electric vehicles and their widespread use in short-duration (today typically 4 hours or less) electricity system storage applications.

- To enable economical long-duration energy storage (> 12 hours), DOE should support research, development, and demonstration to advance alternative storage technologies that rely on earth-abundant materials.

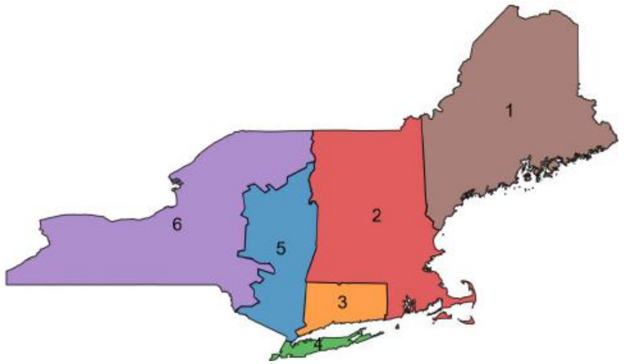
- Thermal storage retrofits of fossil energy power plants can provide near term benefits in providing electricity storage capacity while eliminating $CO_2$ emissions from these generators.

- Hydrogen's role as a form of energy storage for the electricity sector will likely depend on the extent to which hydrogen is used in the overall economy, which in turn will be driven by the future costs of hydrogen production, transportation, and storage, and by the pace of innovation in hydrogen end-use applications.

# Message #2

Storage can make regionally-tailored, net-zero electricity systems affordable

# We explored the role for storage technologies in power systems under alternative technology and carbon-constrained scenarios by mid-century for different regions

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

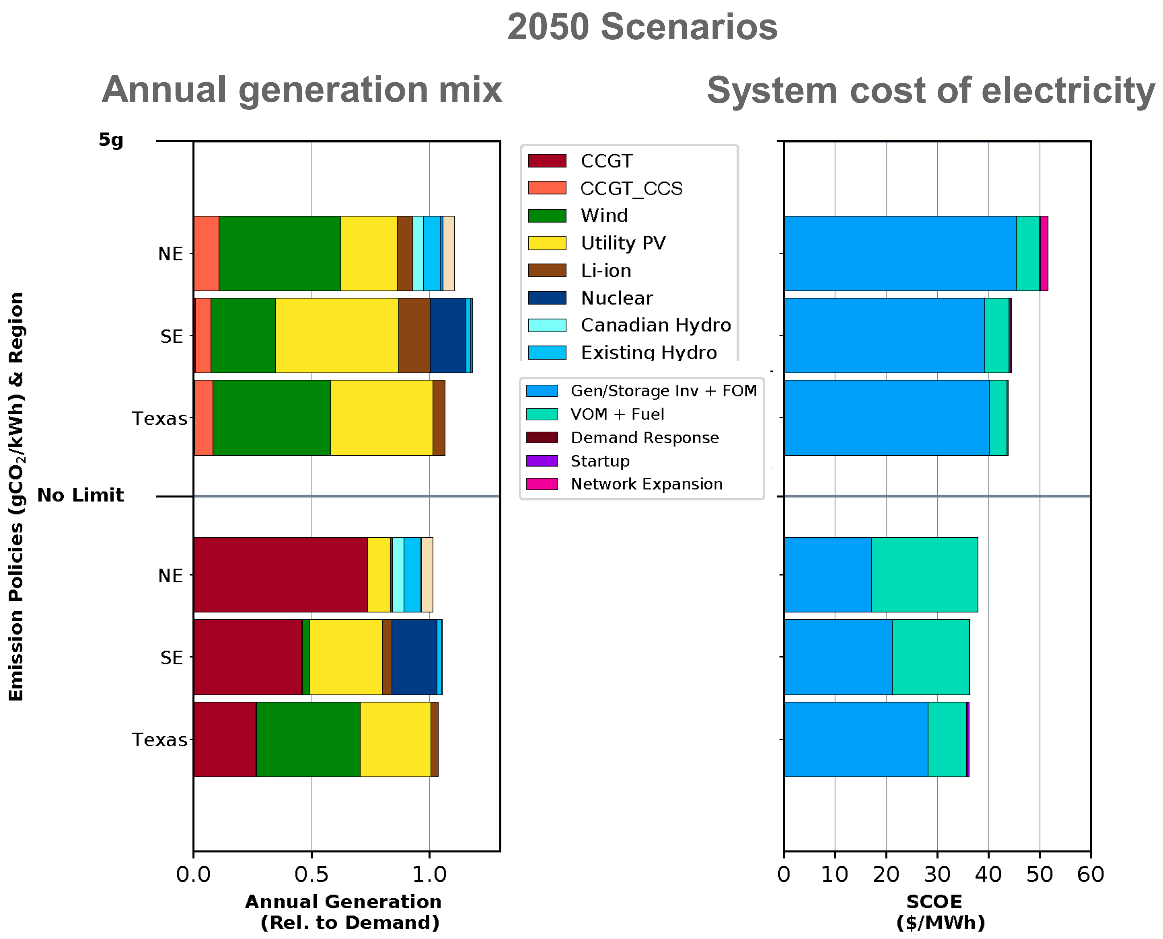
Findings are based on modeling **economically efficient net-zero emissions power systems** under a wide range of technological and policy assumptions, including

- $CO_2$ 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)



1. Data from Independent System operators and EIA State Electricity Profiles

# Near-complete decarbonization by mid-century is feasible without sacrificing reliability or incurring significant cost penalty using VRE and Li-ion storage




Results presume favorable cost reduction trends continue for Li-ion batteries and VRE capacity

Challenges of “getting to zero” vary across regions based on their resource endowments and demand patterns

Energy storage can substitute or complement all other elements of a power system (transmission, generation, demand management)

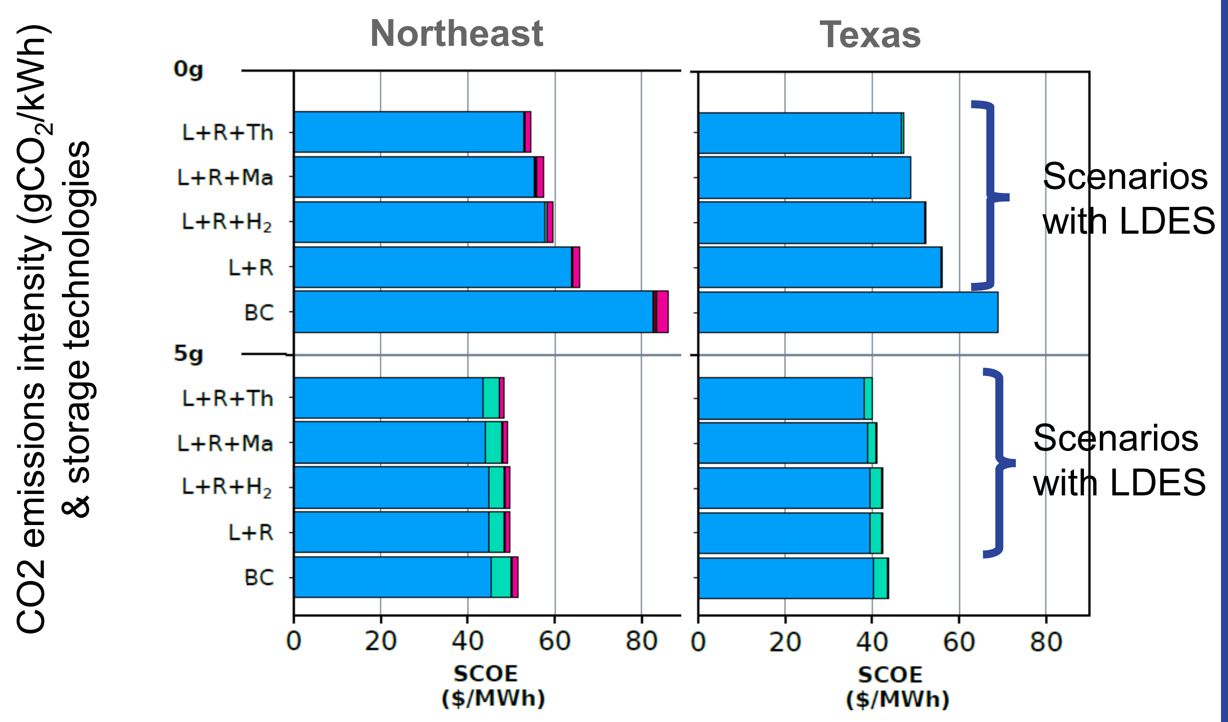
**→ More sophisticated analytical tools are needed to plan, operate, and regulate power systems**

Transmission expansion can play an important role in reducing grid decarbonization costs and directly competes with storage

**→ Need for statutory and regulatory changes to reduce barriers to transmission expansion**

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

System cost of electricity (SCOE) in 2050

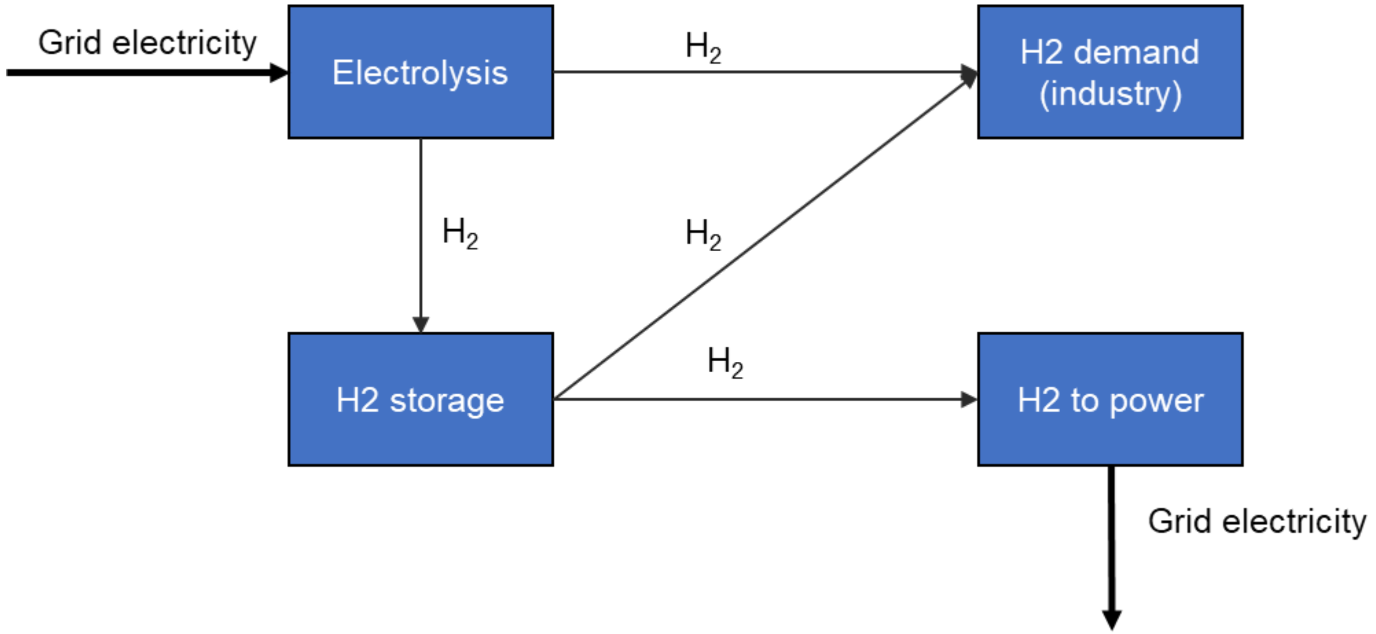



BC= Li-ion only
L = Li-ion
R = Redox flow battery
Th = Thermal
Ma = Metal-air
H2 = Hydrogen

Cost impacts of long-duration storage are greatest when natural gas generation is not an option (i.e. 0 $gCO_2$/kWh)

**→Focus Public and Private RD&D on improving cost and performance attributes of emerging LDES**

# The role for hydrogen in grid decarbonization is differentiated from many other LDES technologies due to its potential use in economy-wide decarbonization




**Efforts to promote adoption of hydrogen outside the power sector would make its use in the electric power system more attractive by creating a large flexible electric demand**

# Storage plays a distinctive and important role in high-growth developing countries. We looked closely at *well-supplied* India, and *under-supplied* Nigeria.


Grid $CO_2$ emissions intensity (2019)[2]: **725 $gCO_2$/kWh**

**Important features:**

- **High coal intensity** in existing generation fleet
- **Low natural gas** supply and little existing infrastructure
- **Low cost labor** and correspondingly **lower VRE and storage costs**
- **High projected overall growth** from economic development
- High growth in use of **air-conditioning (AC) and EV's**
- **Excellent wind and solar** resources
- **Significant seasonal variability** in VRE generation

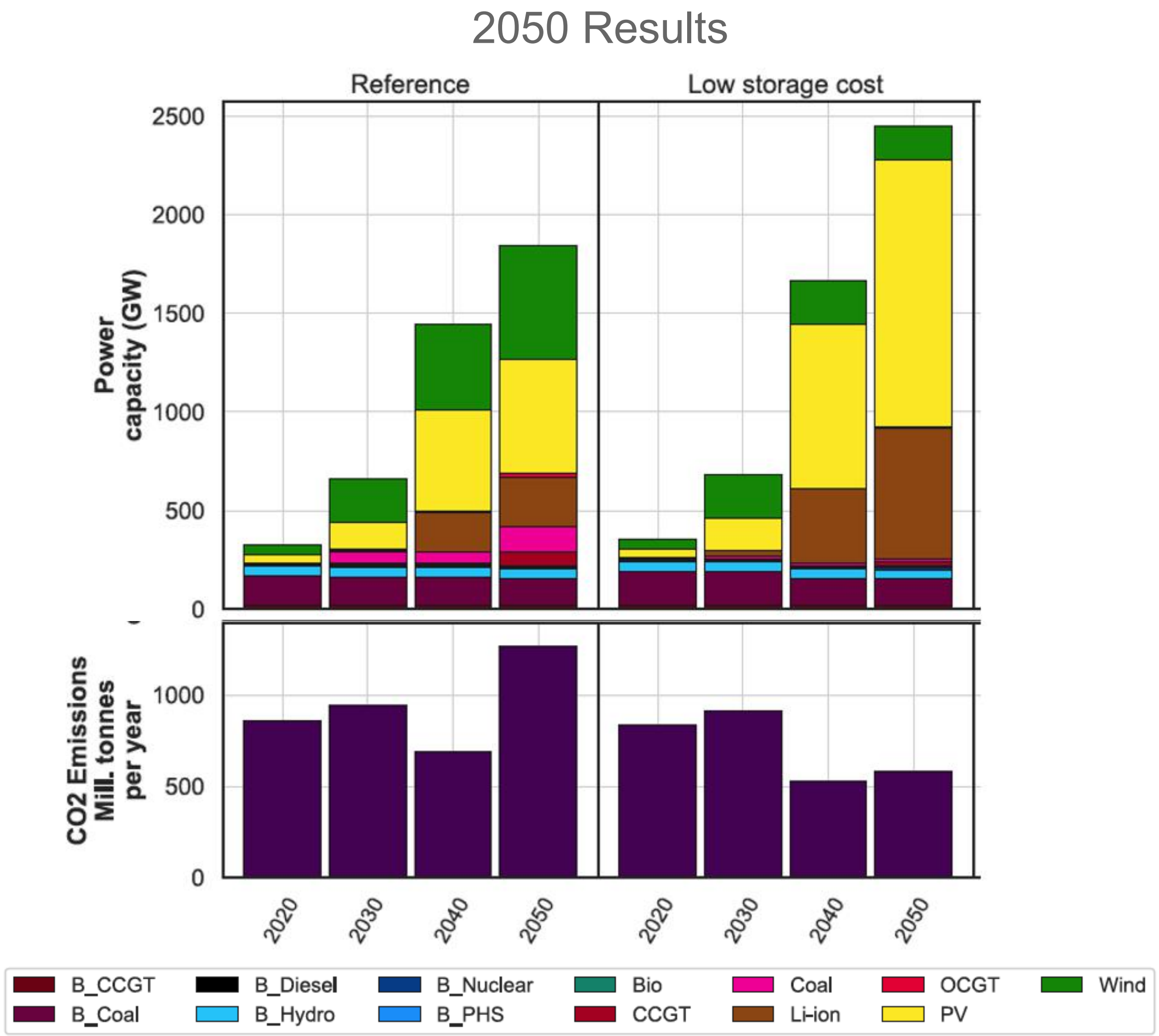
**Modelling Impact:**

- **Low cost storage trajectory**
- **Low cost solar and wind**
- **Expensive gas**



1. Generation and emissions data for 2019 from IEA World Energy Outlook 2020

# Storage enables wind and solar, and helps to reduce urban distribution costs.




**INDIA: Using LDES or lithium ion batteries with a low cost trajectory results in approximately a 50% reduction in 2050 $CO_2$ emissions relative to our baseline scenario - *without policy.***

- ❑ Coal is displaced mainly by solar and storage.
- ❑ New coal generation is largely avoided, but older plants linger.
- ❑ Air conditioner efficiency has a significant impact on the storage and generation mix.
- ❑ Urban distribution network upgrade costs are significantly reduced with distributed batteries.
- ❑ In under-supplied (Abuja) grids, storage is less helpful in reducing costs and emissions.

**The 2050 EMDE storage market is very large.**

# Key Findings: Planning for deployment of storage as part of regionally-tailored, net-zero electricity systems

- **The complex role played by storage and its impact on system costs and greenhouse gas emissions means that more sophisticated analytical tools are needed to plan, operate, and regulate the power systems of the future, and to ensure that these systems are reliable and efficient.**
  - This effort should be led by DOE in cooperation with independent system operators and regional transmission organizations (ISOs/RTOs).
  - The available scope for load flexibility and demand response to reduce grid storage needs and associated costs must be included.
  - The current likelihood that cost-effective transmission projects to bring generation from areas with high-quality VRE resources to major load centers will face extended delays or possible rejection suggests the need for statutory and regulatory changes to reduce barriers to transmission expansion.
- **Coal-dependent emerging market and developing economy countries that lack access to abundant low-cost gas or gas infrastructure, such as India, represent a very large and important future market for electricity-system applications of energy storage technologies.**
  - These countries should aggressively deploy storage and VREs now starting with Li ion.

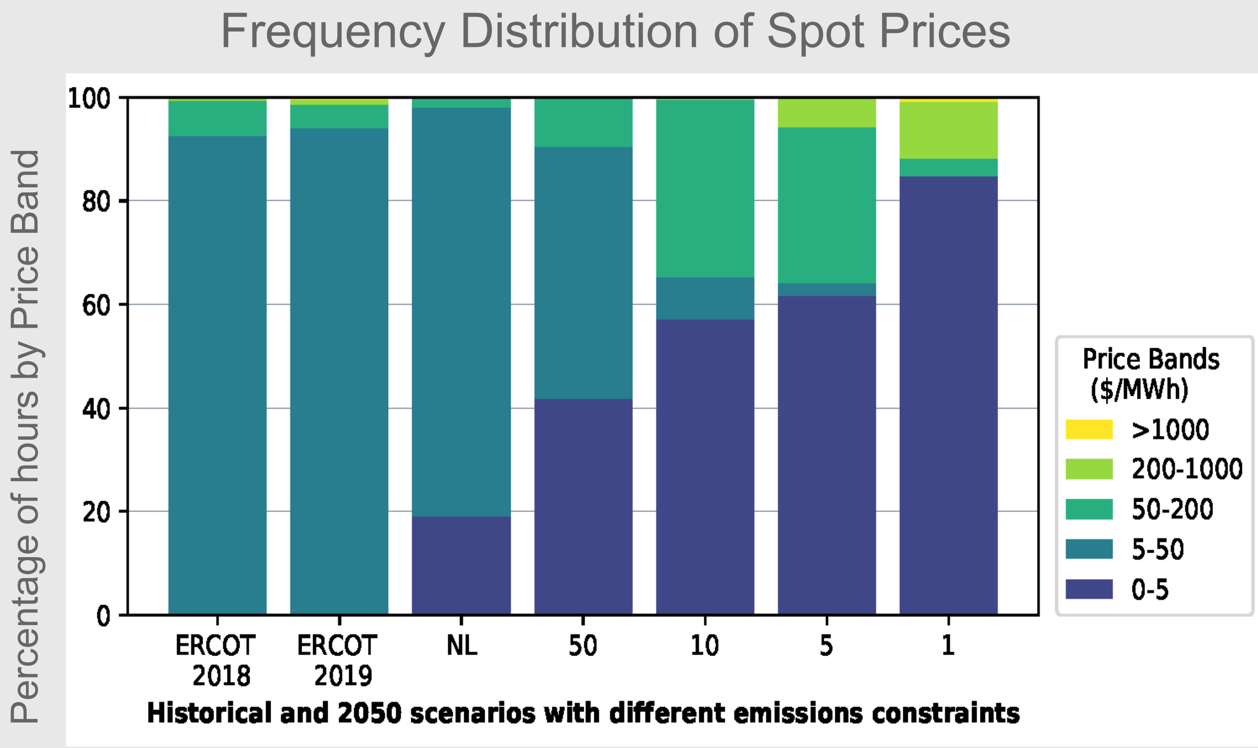
# Message #3

Market Designs and Regulatory Policies Need to be Reformed to Enable Equitable & Efficient Decarbonization

# Two Important Features of Future Efficient Decarbonized Electric Power Systems:

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

Small-scale generation & storage can have important grid-level effects – already a reality in some systems



## Necessary Wholesale-Level Reforms (FERC, ISOs, States) for Efficient Production

Increased spot market volatility will make market designs without price caps & capacity markets even less attractive than at present

Need to redesign capacity markets to value wind/solar generation ***and storage*** properly

Payments for capacity, subsidies need to be lump-sum to avoid distorting dispatch

Customer premises generation & storage need to see wholesale prices *on the margin* (perhaps via aggregators) to avoid distorting wholesale energy & other markets

# Necessary Retail-Level Reforms (States) for Efficient Consumption

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 cut demand when wholesale prices are high, but charging per-kWh retail rates equal to wholesale prices would involve intolerable risk

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
- Will need to devise & use insurance schemes, load management contracts, other devices

# Our Main Messages

1. Federal R&D policy should focus on long-duration storage technologies to support affordable, reliable future electricity systems.
2. Storage can make regionally-tailored, net-zero electricity systems affordable.
3. Market designs and regulatory policies need to be reformed to enable equitable & efficient decarbonization.

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