Future of Energy Storage

Storage in the electricity system: Key modeling results through 2050

Presented by:
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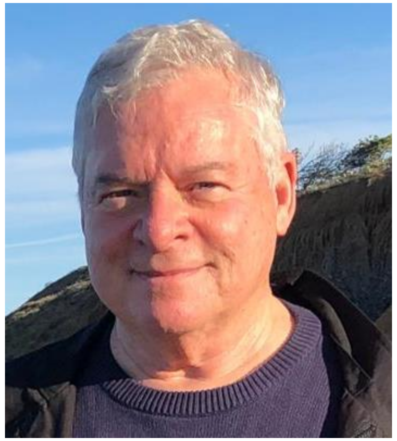
Modeling storage in high variable renewable energy power systems (Chapter 6)

Contributing authors



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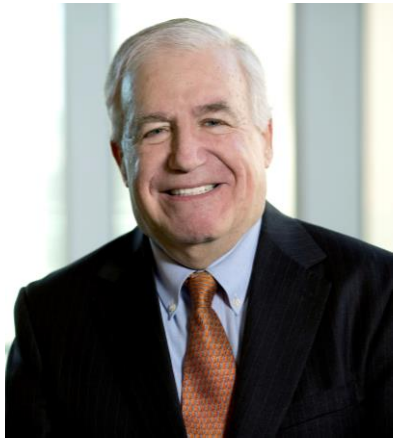

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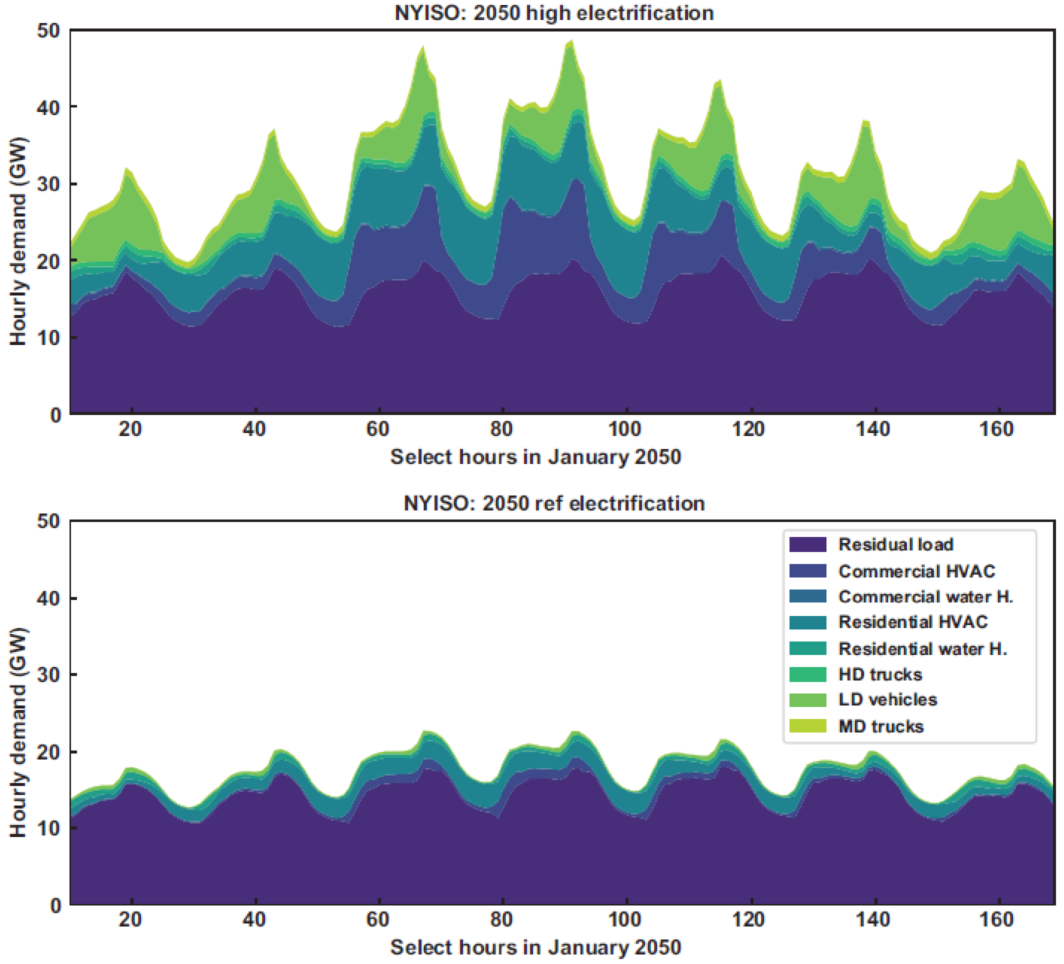
The electricity grid in "2050" will look very different from the one today

1. What does "zero" carbon mean for the grid?

	2018	
Electricity generation		
	TWh	**% 2050**
U.S. total	4,178	62%
Northeast	238	52%
Southeast	834	117%
Texas	477	33%
Electricity-related CO_2 emissions		
	MMT	**gCO_2/kWh**
U.S. total	1,874	449
Northeast	55	232
Southeast	327	392
Texas	230	482

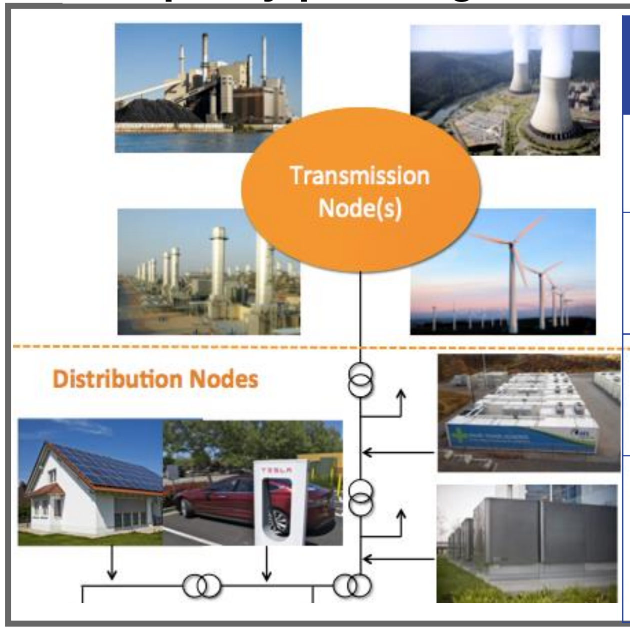
All 3 regions have experienced significant emissions reductions between 2005 and 2018, but much remains to be done to get to a near-zero carbon future by 2050.

2. How will electrification of other sectors affect load?



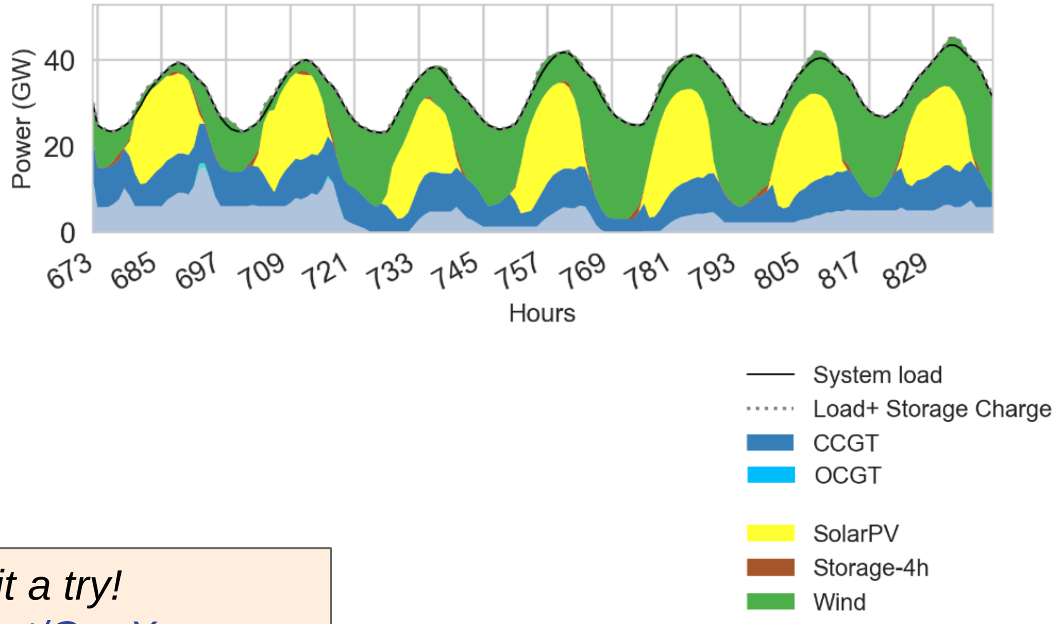
Analysis used the GenX model, an integrated electricity system planning model to study decarbonization of electricity systems

Capacity planning for the bulk power system (GenX)



Unique features
Operational detail
Temporal resolution (hourly)
Demand and supply side resources
Configurable network & market representation (energy, operating reserves)

Illustration of operational and temporal detail in GenX model

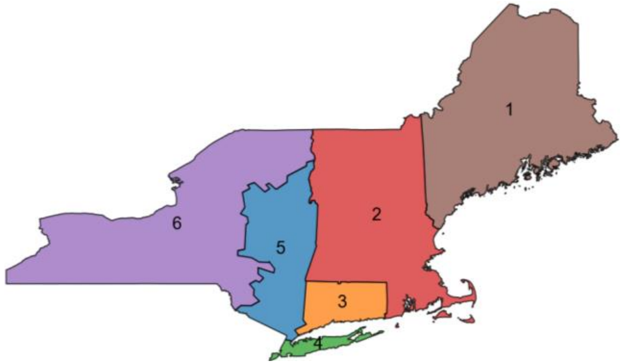


GenX is open-source, give it a try!
https://github.com/GenXProject/GenX

Powered by: julia + JUMP

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

U.S. Regions

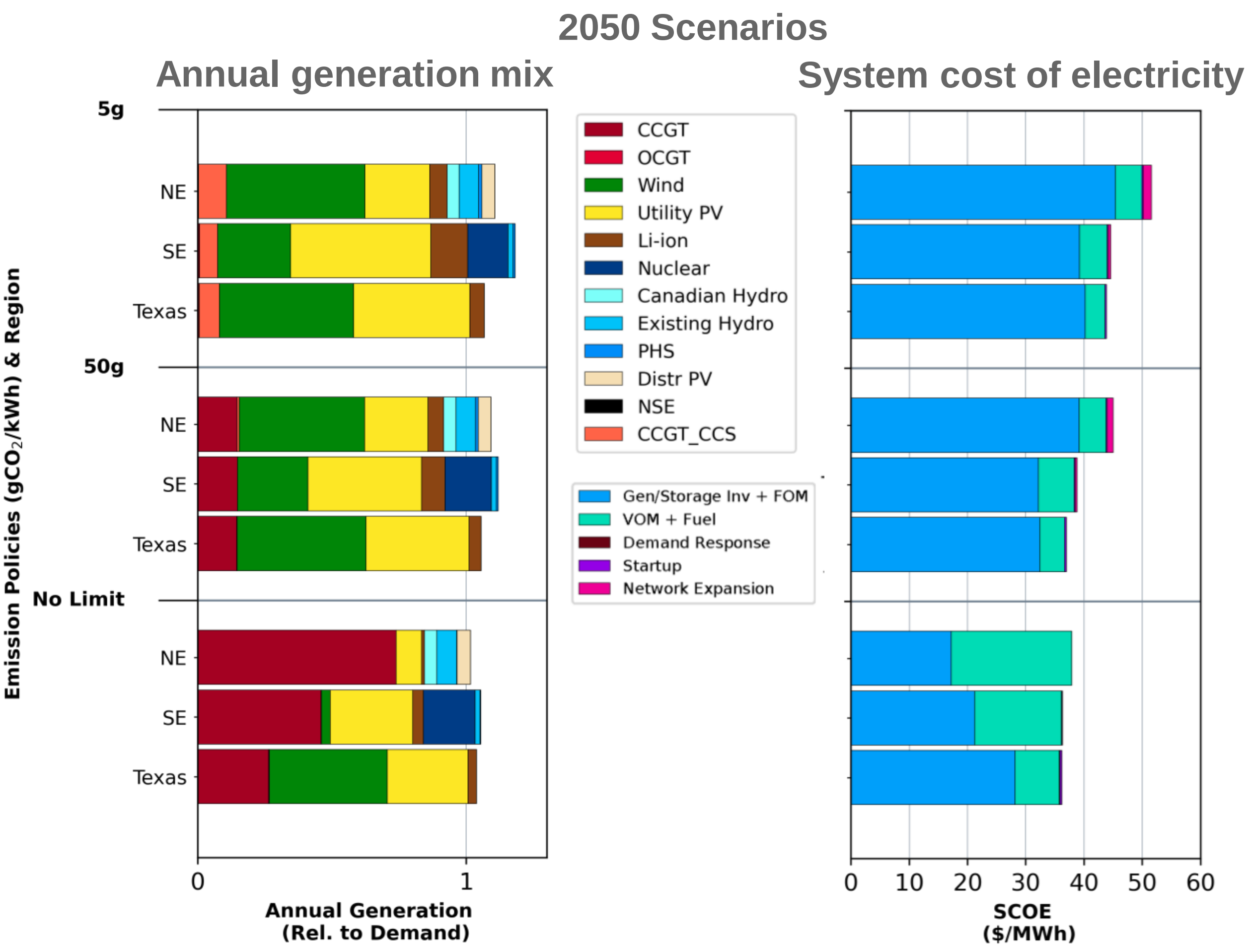
	U.S. Northeast	U.S. Southeast	Texas
			
Grid CO_2 emissions intensity (2018)[1]:	232 gCO_2/kWh	392 gCO_2/kWh	482 gCO_2/kWh

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
- Simulated hourly solar PV and wind capacity factors for 7 weather years
- **Continued cost reductions for VRE and Li-ion storage** by 2050
- Sparing use of natural gas generation with carbon capture and sequestration (CCS)
- Continued availability of existing zero-carbon supply (e.g. nuclear in Southeast, hydro in Northeast)

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 and sparing use of gas



Near-complete decarbonization of electricity systems appears feasible from an hourly energy supply and demand balance perspective, using renewables, natural gas, and Li-ion alone

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

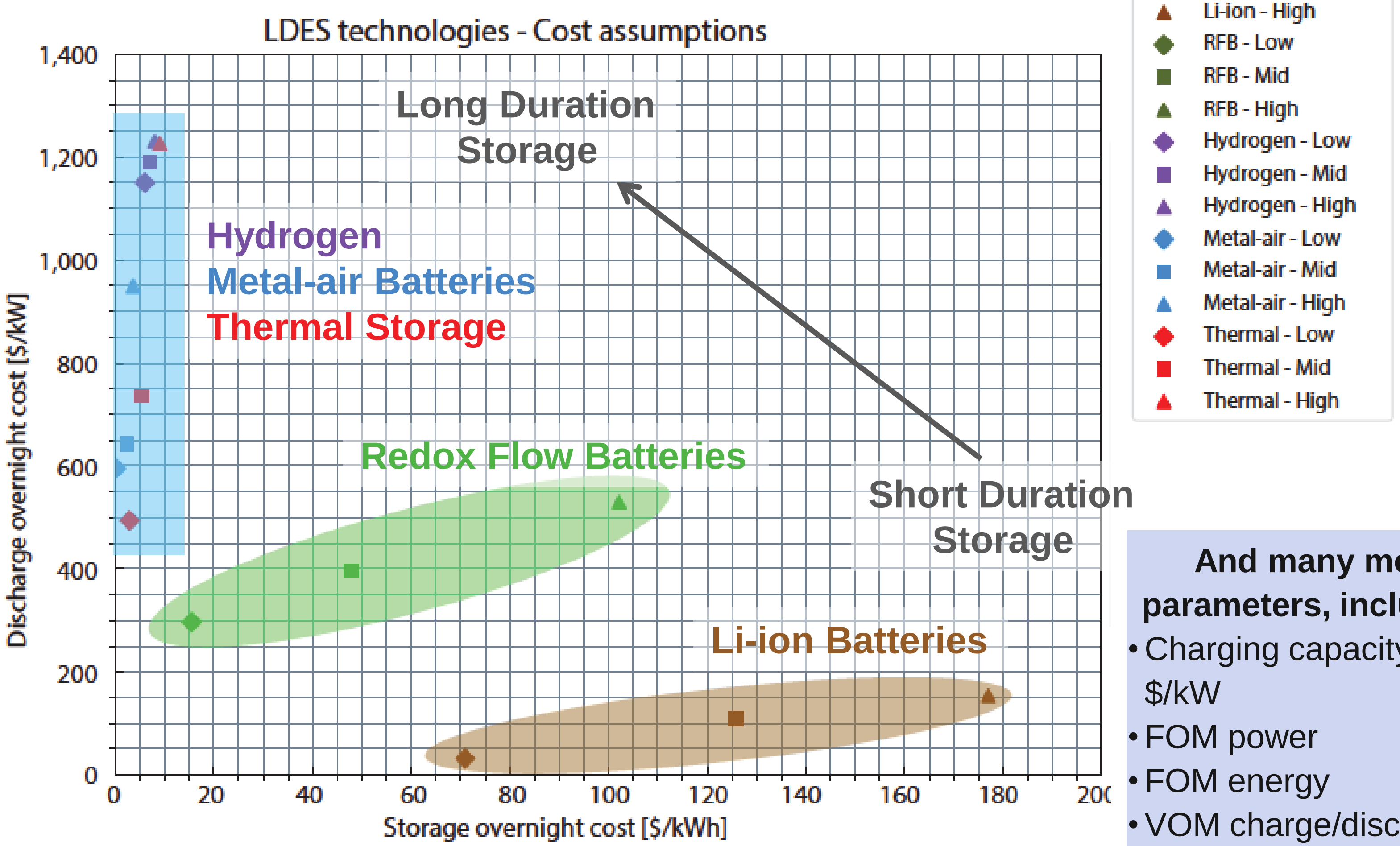
Study covered existing and emerging electricity storage technologies

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

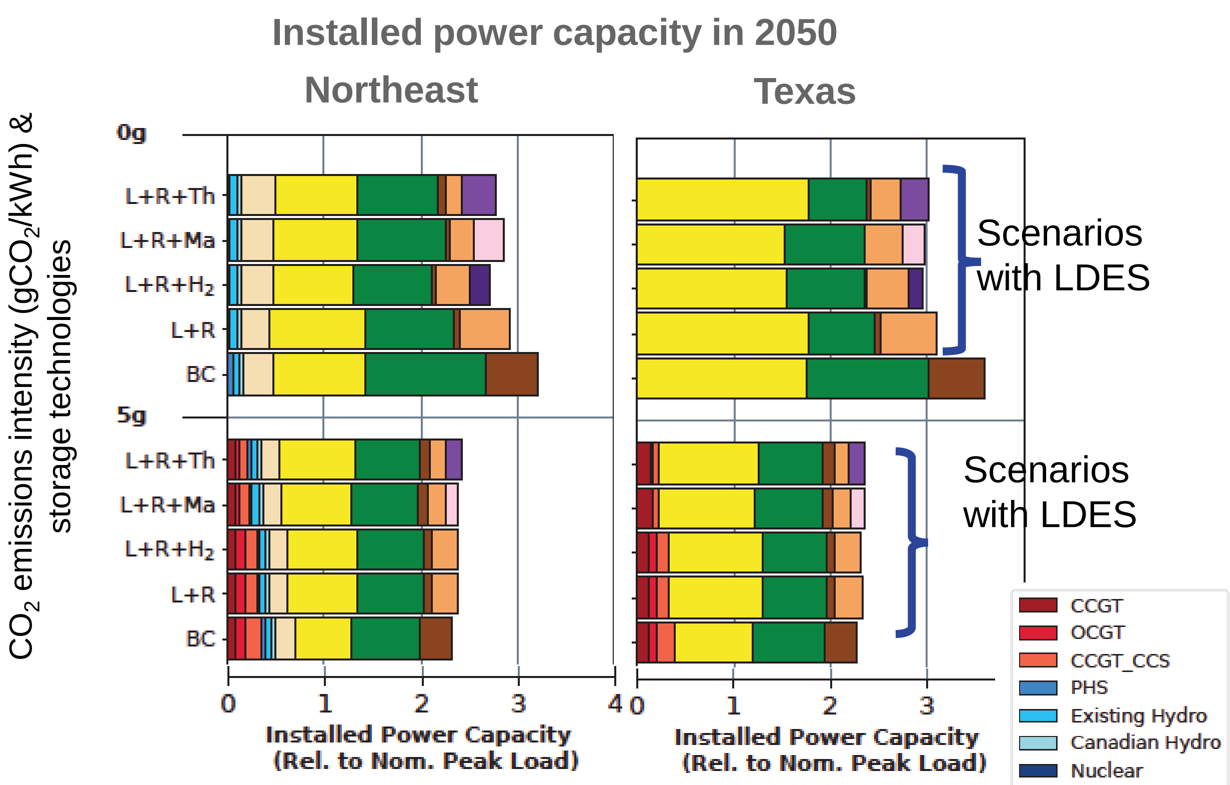
Chemical storage
- Hydrogen



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

And many more parameters, including:
- Charging capacity cost $/kW
- FOM power
- FOM energy
- VOM charge/discharge
- Efficiency charge %
- Efficiency discharge %

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



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

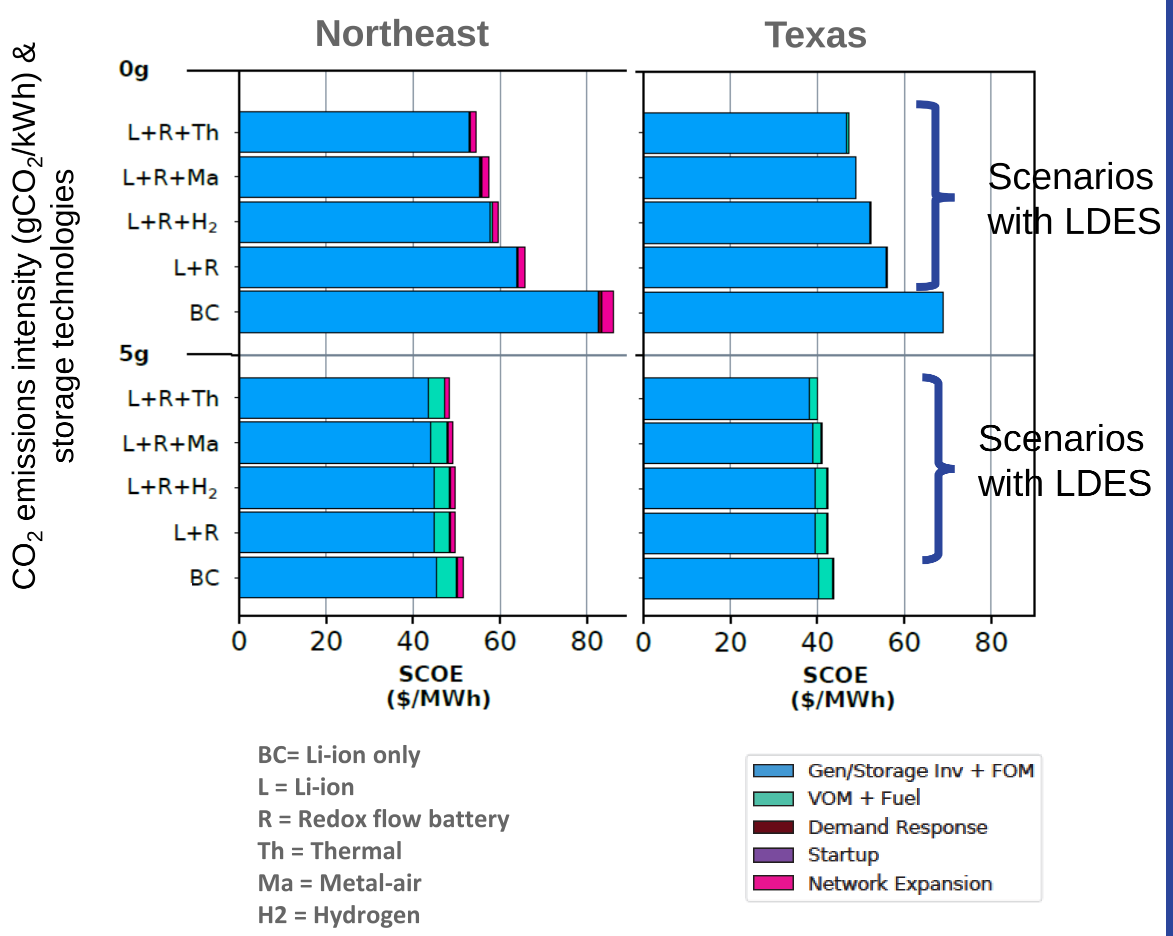
LDES substitutes for natural gas capacity, increases the value of variable renewable generation, and produces moderate reductions in system average electricity cost

LDES generally defined as >12 hours; days or weeks not on the economic horizon

At 5 gCO_2/kWh, the storage duration for LDES resources ranges between 39 and 59 hours (or 6-18 hours of mean system load), as compared to Li-ion storage duration of 1–2 hours

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

System cost of electricity (SCOE) in 2050



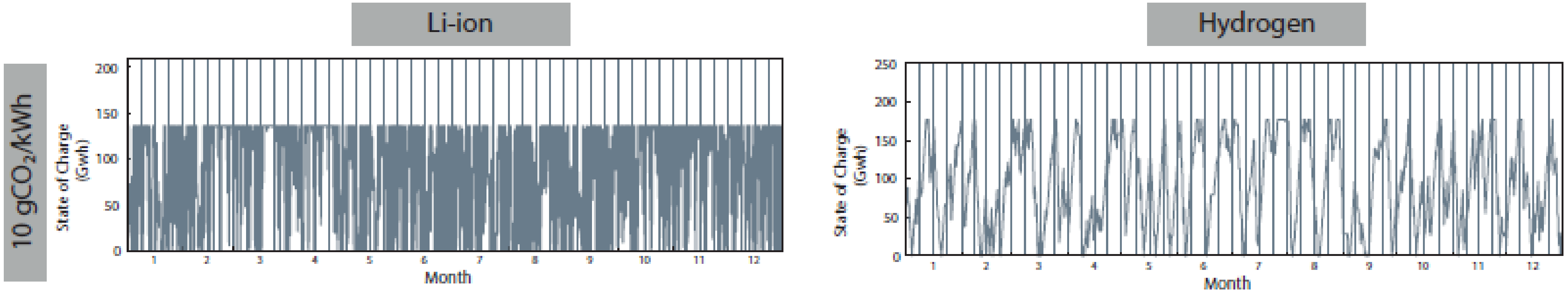
LDES generally defined as >12 hours; days or weeks not on the economic horizon

As long as some emissions are allowed ("net-zero"), it is optimal to have significant gas+CCS capacity that is run only during long periods of system stress – e.g. no wind for a week

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

It is too early to pick a winner among emerging LDES technologies, though in some areas, pumped hydro may become attractive again

Storage operations are complex, and do not follow simple cycling patterns



In the highly decarbonized Texas model, we see that, hydrogen storage is mostly used for longer-cycle operations

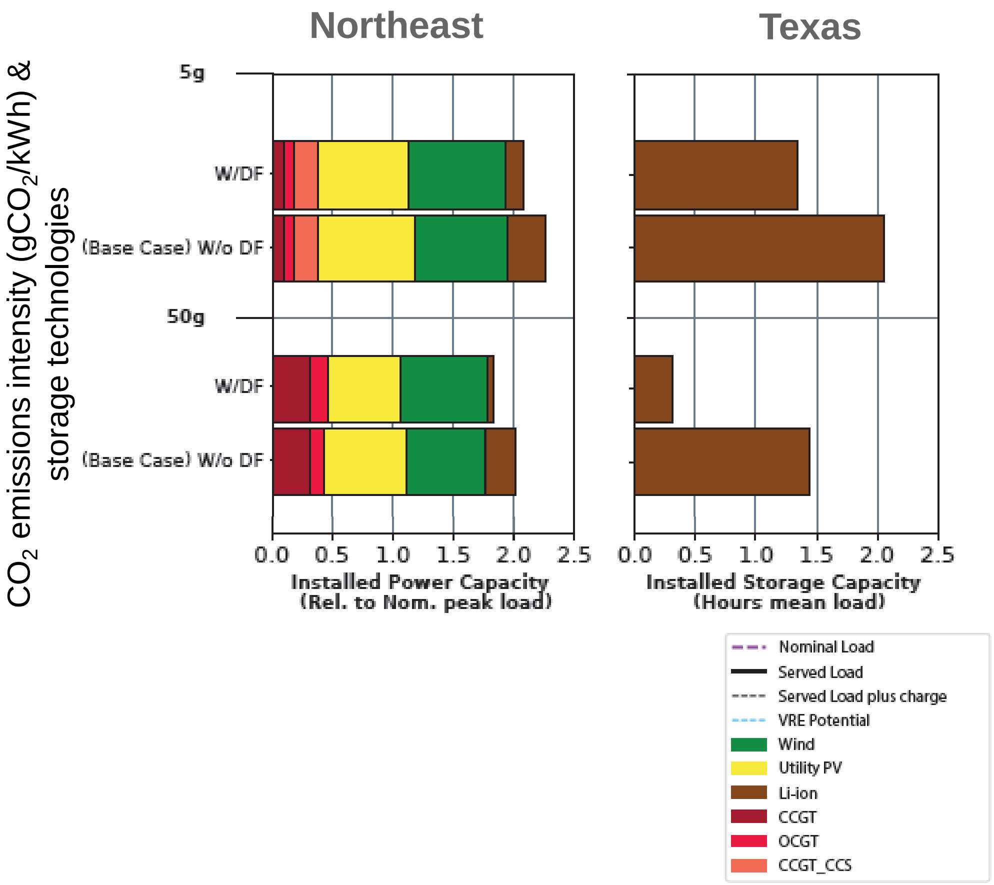
Frequency band	Mode of operation	10 gCO_2/kWh		1 gCO_2/kWh	
		Li-ion	H_2	Li-ion	H_2
Above 365 cycles/year	Daily	39%	1%	23%	0%
52 to 365 cycles/year	Weekly	34%	15%	29%	4%
12 to 52 cycles/year	Monthly	12%	59%	12%	32%
0 to 12 cycles/year	Seasonal	16%	25%	35%	64%

A **frequency analysis** of the SoC of the storage technologies shows that optimal cycling operations are subject to CO_2 constrain

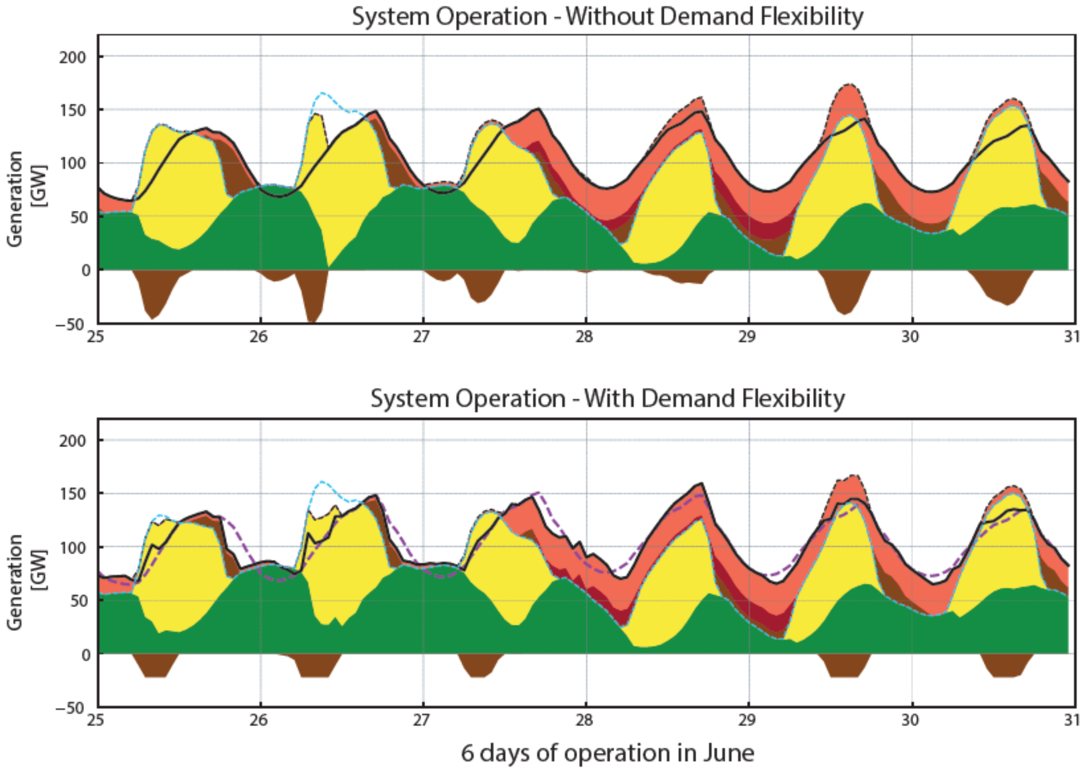
Need improved modeling and software tools to accurately represent the inter-temporal complexities of a deeply decarbonized power system

Demand flexibility from applications like EV charging generally compete with short-duration storage

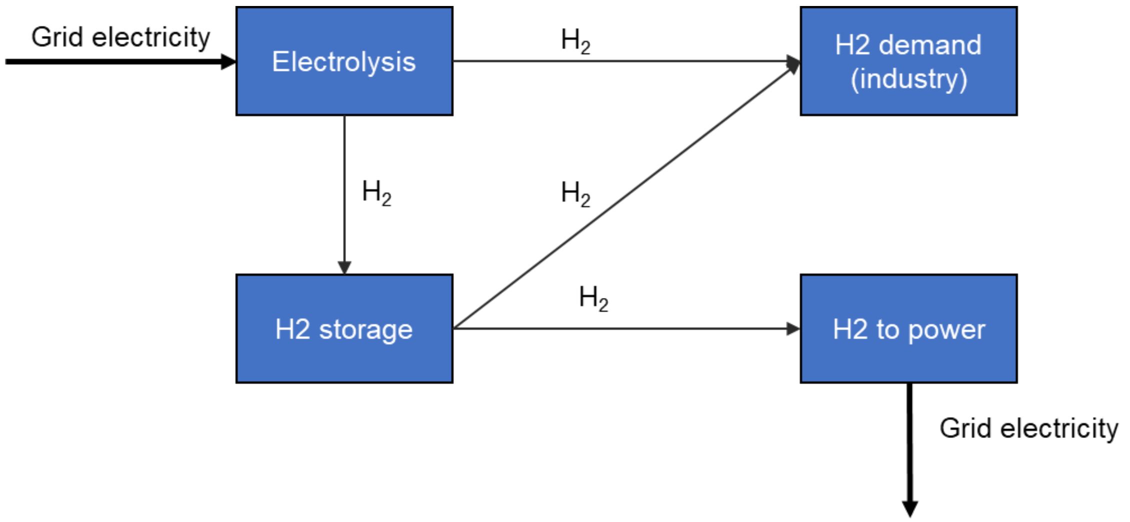
Power capacity impacts due to demand-side flexibility under various carbon constraints (2050)



When intra-day flexibility is assumed, Li-ion batteries' charge and discharge cycles become less frequent.

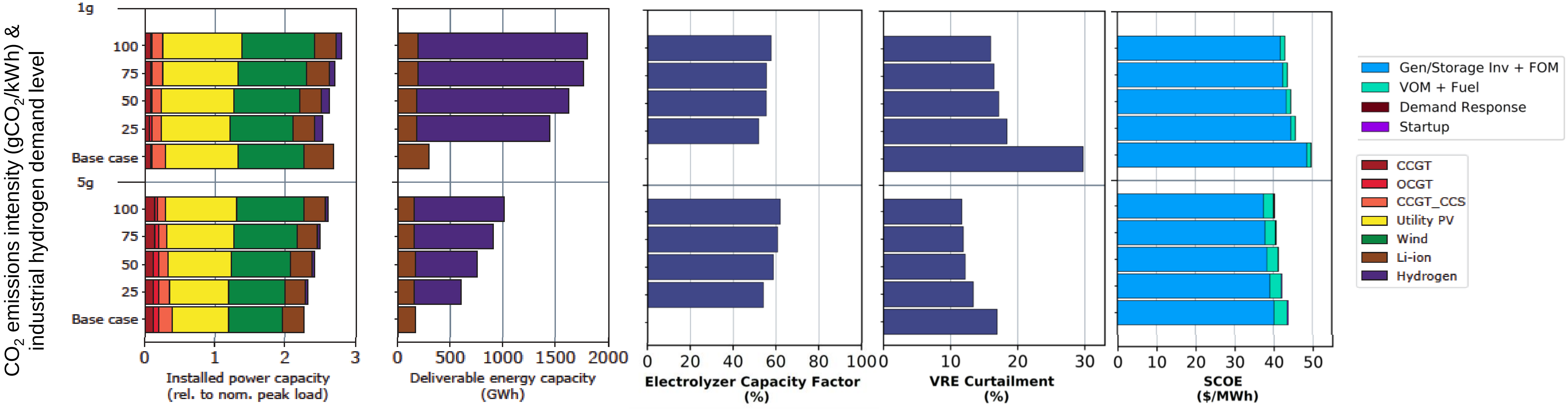


The role for hydrogen in grid decarbonization is differentiated from many other LDES

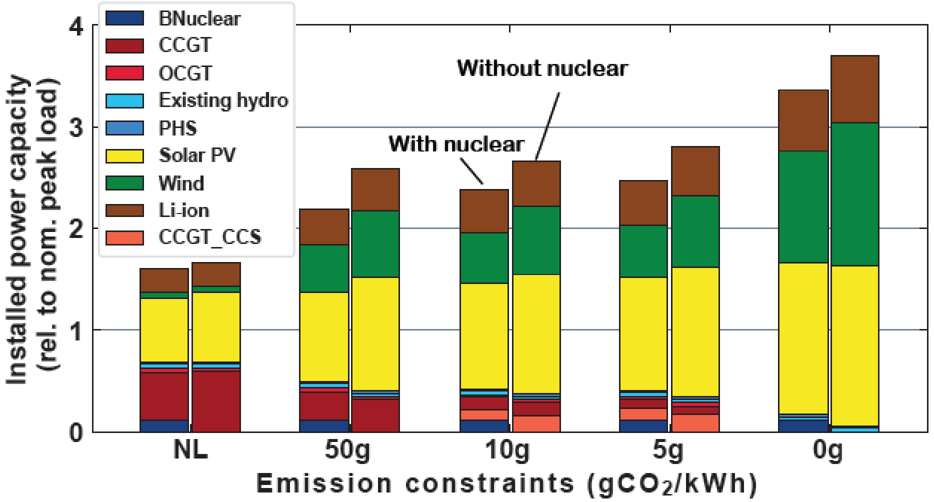


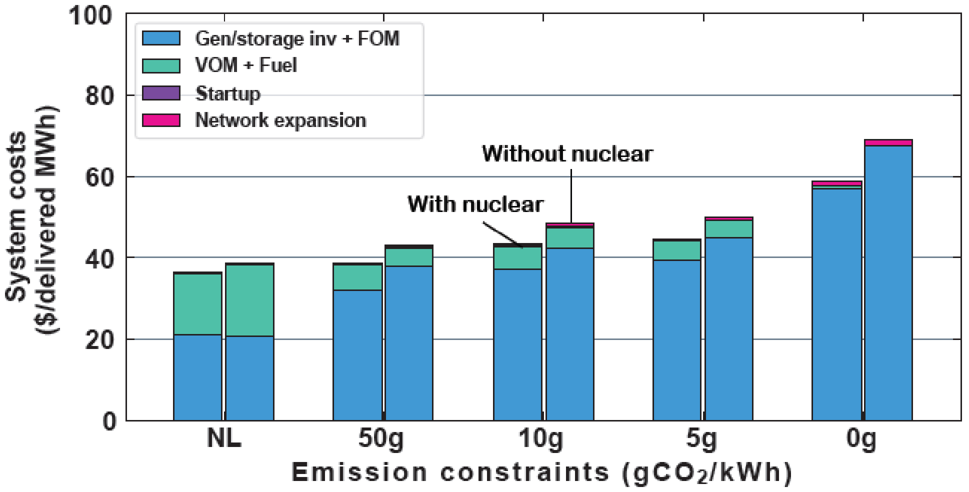
Flexible production of hydrogen for other sectors and relatively cheap hydrogen storage (vs. Li-ion storage) improve asset utilization, reduce VRE curtailment, and reduce system cost of decarbonization

We evaluated different levels of hydrogen substitution for natural gas as a heat source in industrial applications (100% corresponding to 19.7 GWh of hydrogen demand)



Availability of low-carbon dispatchable generation competes with VRE generation and storage





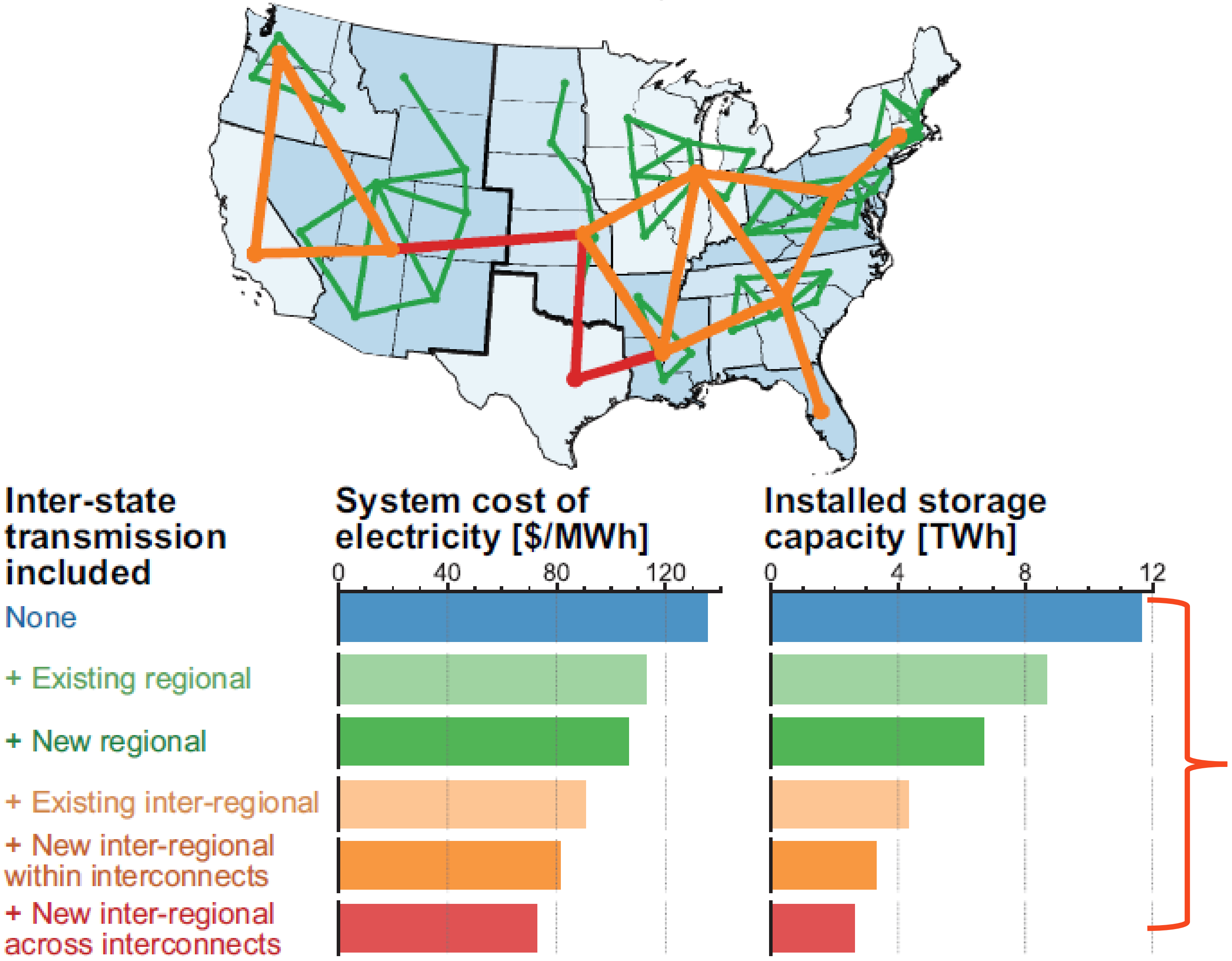
System cost increases 6-15% without availability of the existing nuclear fleet (U.S. Southeast)

When allowing the model to add new nuclear capacity:

- There's no economic deployment at current estimated completion costs ($6,048/kW[1])
- There are some deployments at assumed low cost ($4,202/kW) and ultra low cost ($2,818/kW) projections from the 2018 MIT Future of Nuclear study

1. Source: 2045 cost projection from NREL Annual Technology Baseline
2. https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf

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



Increased regional coordination of transmission planning has 2 main benefits[1]:

- It allows for increased VRE deployment in regions with higher-quality resources
- It improves VRE integration, by smoothing the effects of geographical differences

Read more at: Brown, Patrick R, and Audun Botterud. 2021. "The value of inter-regional coordination and transmission in decarbonizing the US electricity system." Joule 115–134. https://doi.org/10.1016/j. joule.2020.11.013.

Storage considerations for emerging markets and developing economies

Marc Barbar

Dharik Mallapragada

Robert Stoner

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

Demand-driven regions (e.g. India)

- Coal dominates bulk power supply
- Rapidly growing energy demand
- High quality solar resource

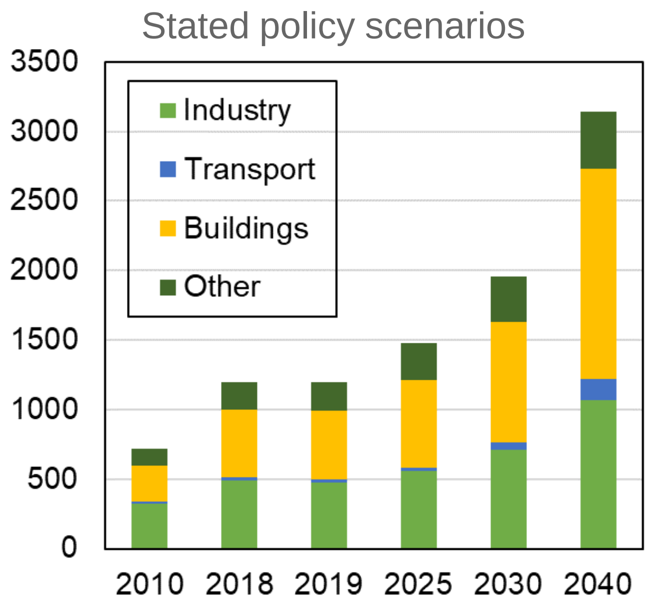
Supply-constrained regions (e.g. Nigeria)

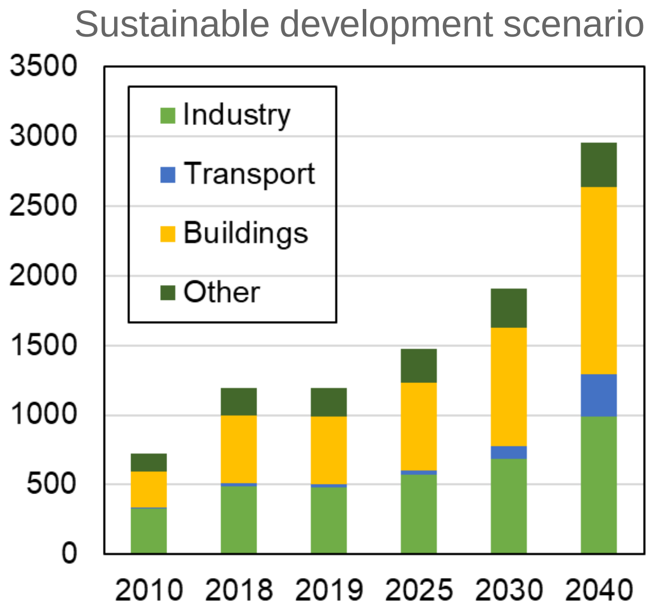
- Power supply (mostly gas) shortages and network issues[2,3]
- Reliance on off-grid supply (e.g. diesel)

1. http://www.geni.org/globalenergy/library/national_energy_grid/nigeria/nigeriannationalelectricitygrid.shtml
2. Emodi et al. Energy policy for low carbon development in Nigeria: A LEAP model application, Renewable and Sustainable Energy Reviews, 68, 2017
3. https://theconversation.com/why-nigerias-electricity-grid-collapses-and-how-to-shore-it-up-179705#:~:text=What%20is%20the%20national%20electricity,to%20generate%20and%20distribute%20electricity

Electricity demand in India projected to more than double by 2050, driven mainly by air conditioning

India electricity consumption projections (IEA WEO 2020[1])





Role of space cooling in electricity demand[2]

Region	% of total demand	% of peak demand
India – 2016	10%	10%
India – 2050	30%	45%
US – 2016	25%	30%
China – 2016	8%	20%
China – 2050	8%	20%

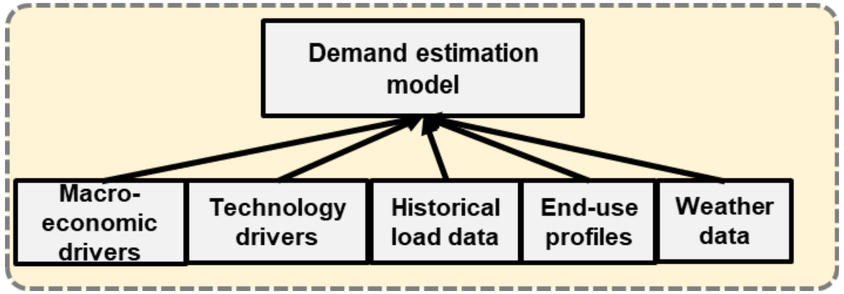
Key Questions of interest

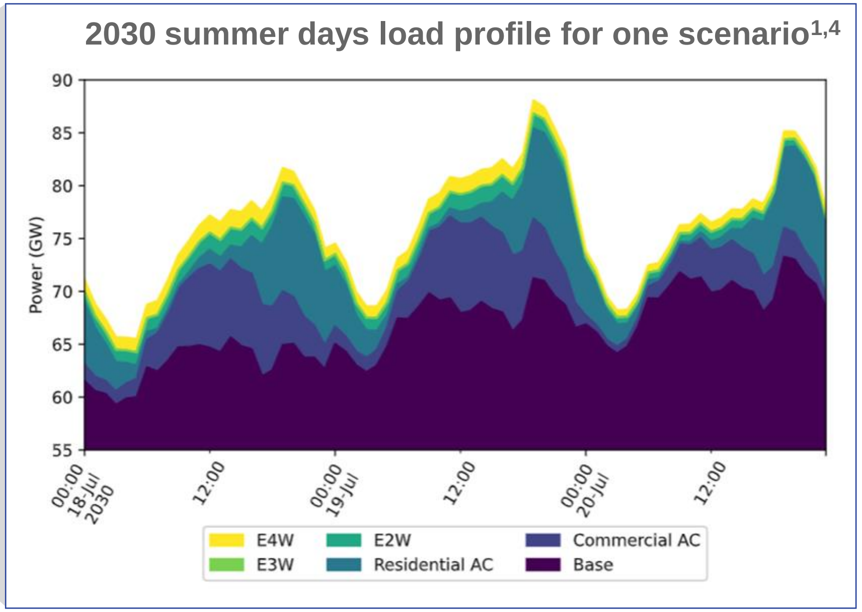
- How does AC load growth impact investments in energy storage at the transmission and distribution level?
- How do technological factors impact long-term prospects for grid decarbonization under no and moderate carbon policy constraints?
  - Availability of low-cost energy storage, gas availability and prices, renewables capital costs and growth limits

1. IEA World Energy Outlook 2020
2. IEA Future of cooling report, 2018 (Figure 3.9 and Figure 3.10); Data rounded to nearest 10 value as shown in plots.

We use multi-stage investment planning analysis + bottom-up demand estimation to study long-term role of energy storage in the Indian power system

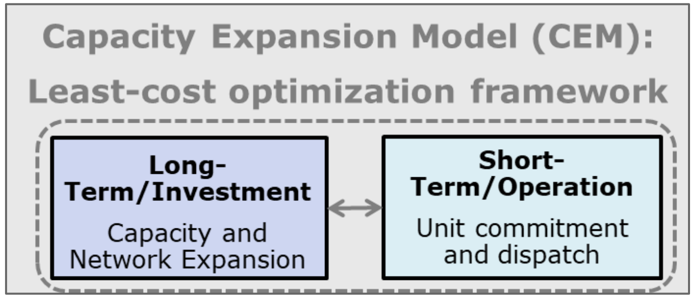
Bottom-up demand characterization[1]





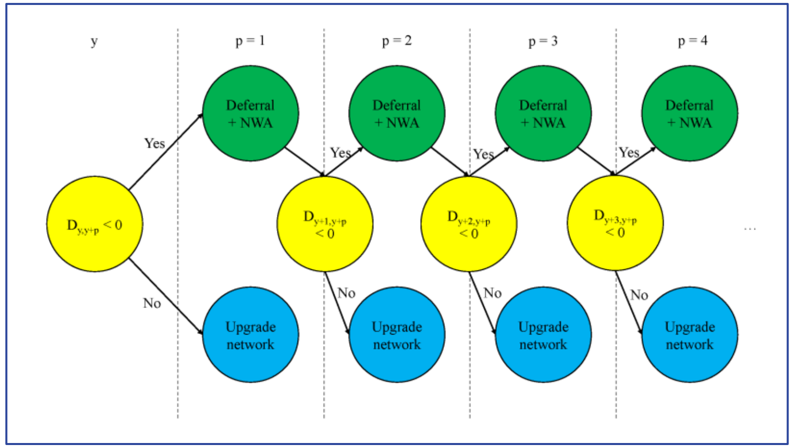
Bulk power system analysis

(GenX[2])



Distribution network analysis

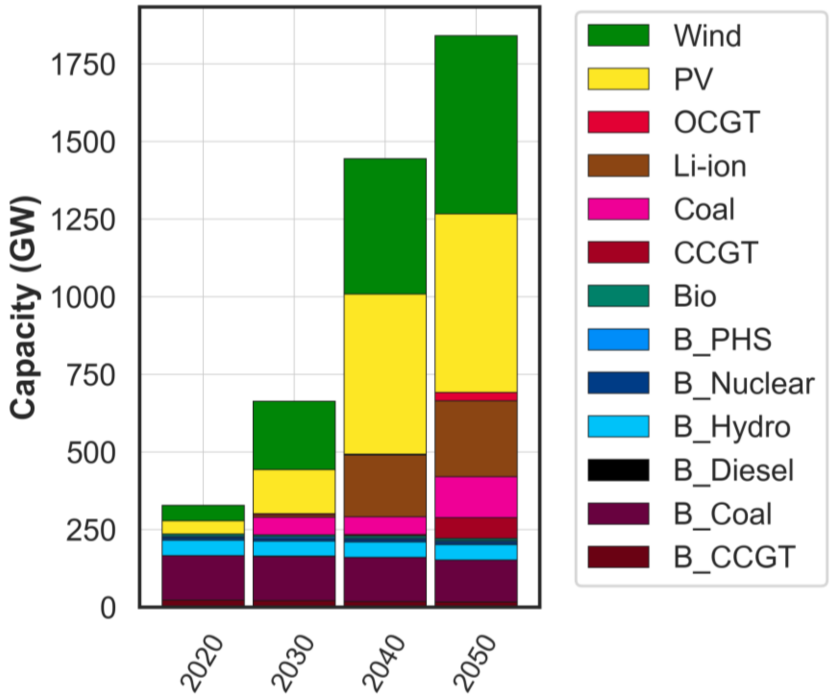
(real-options based approach[3])



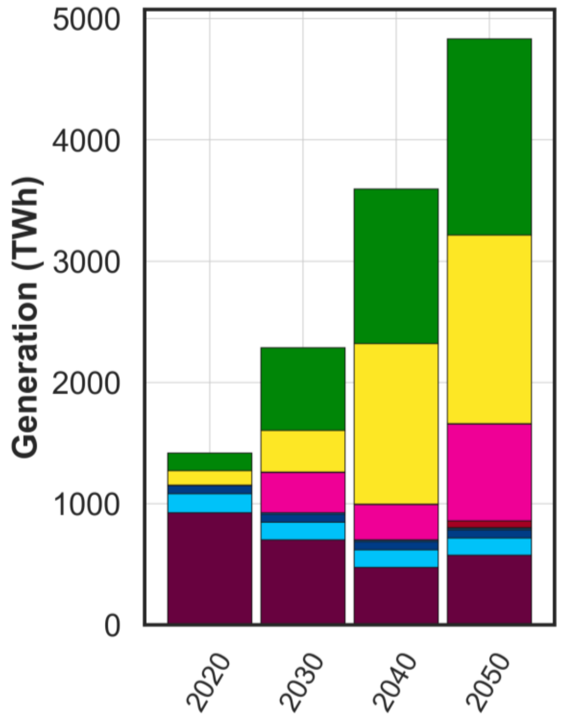
1. Barbar, Mallapragada, Alsup, Stoner. *Scientific Data* 8, 1-11, 2022.
2. https://github.com/GenXProject/GenX 3. Barbar, Mallapragada and Stoner. Energy Strategy Reviews, 41, 100862, 2022. 4. Results correspond to stable GDP growth, baseline AC efficiency, home EV charging

Reference scenario: renewables dominate new investments with storage, gas, and coal in later periods as demand grows - renewables growth rate much faster than historical trends

Capacity (GW)
Reference scenario

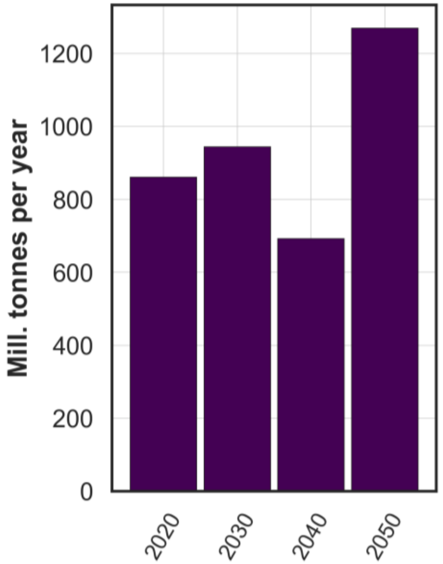


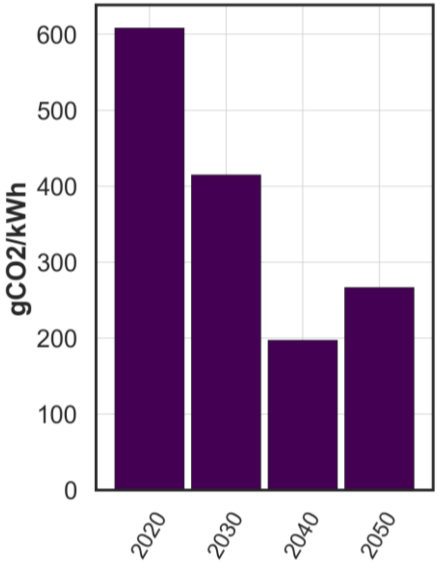
Generation (TWh)
Reference scenario



Reference scenario
AC efficiency: baseline
Gas price: $11/MMBtu

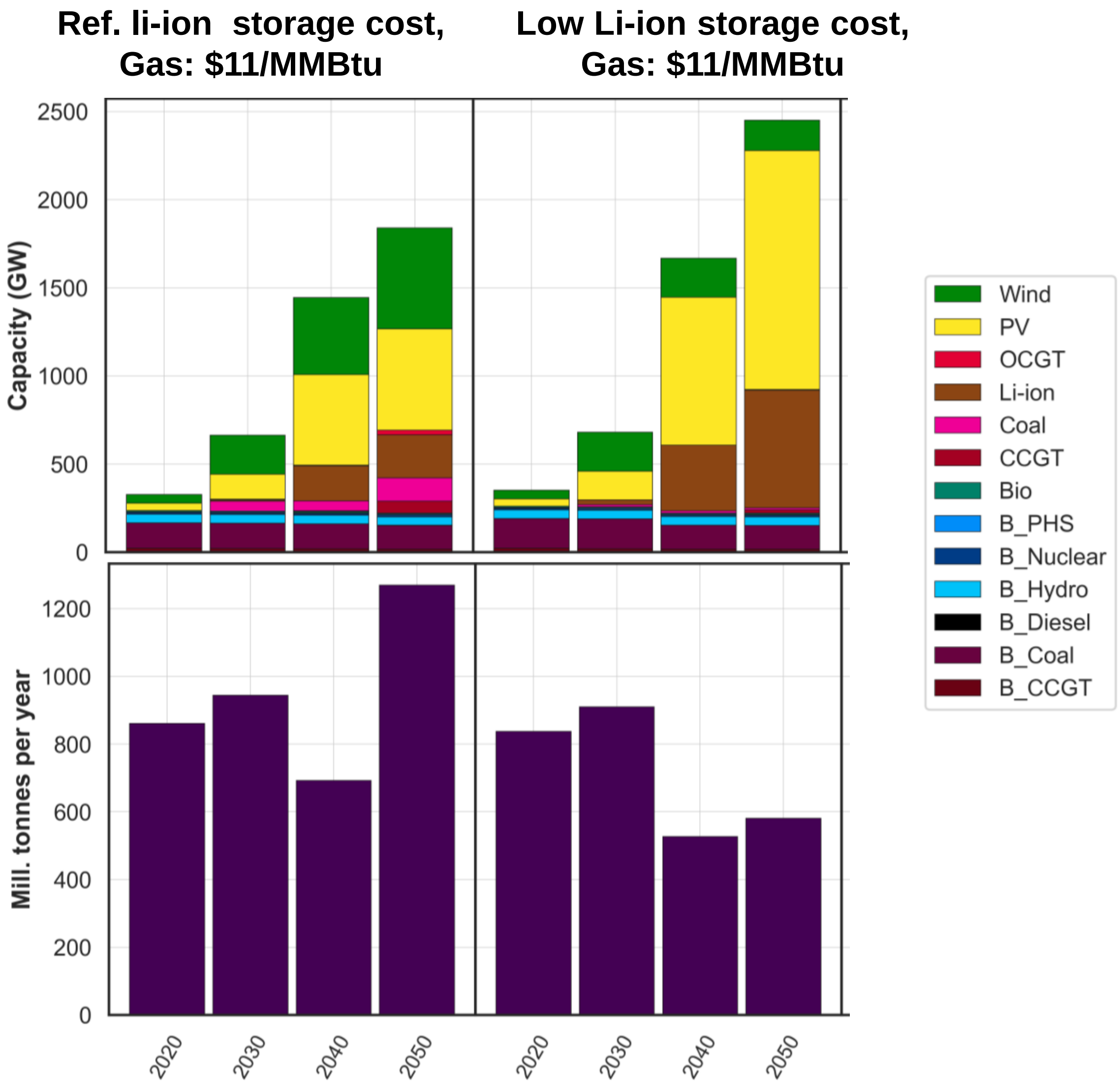
Power sector CO_2 emissions
Reference scenario





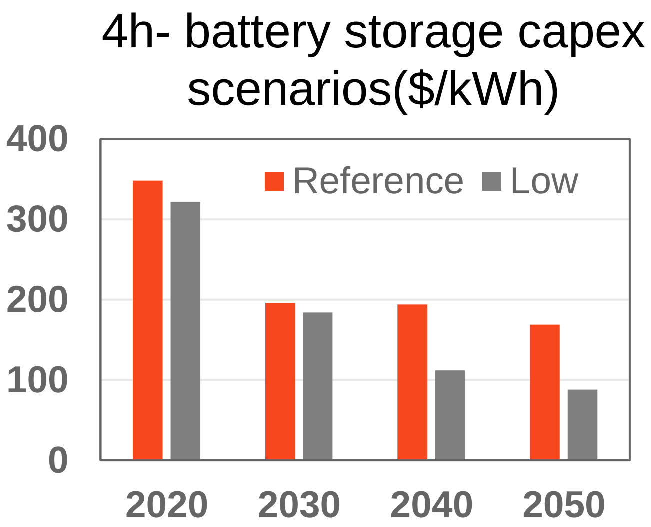
- Annual generation: 1,418 TWh in 2020 vs. 4,833 TWh in 2050
- Peak Load: 202 GW in 2020 vs. 901 GW in 2050
- Annual average renewables additions: 2019
    - Wind: 3 GW, Solar: 10 GW

Low energy storage costs could significantly reduce new coal capacity additions even without a carbon price, leading to > 50% lower emissions in 2050



Global vs. India (model) estimated battery storage capacity (GWh)

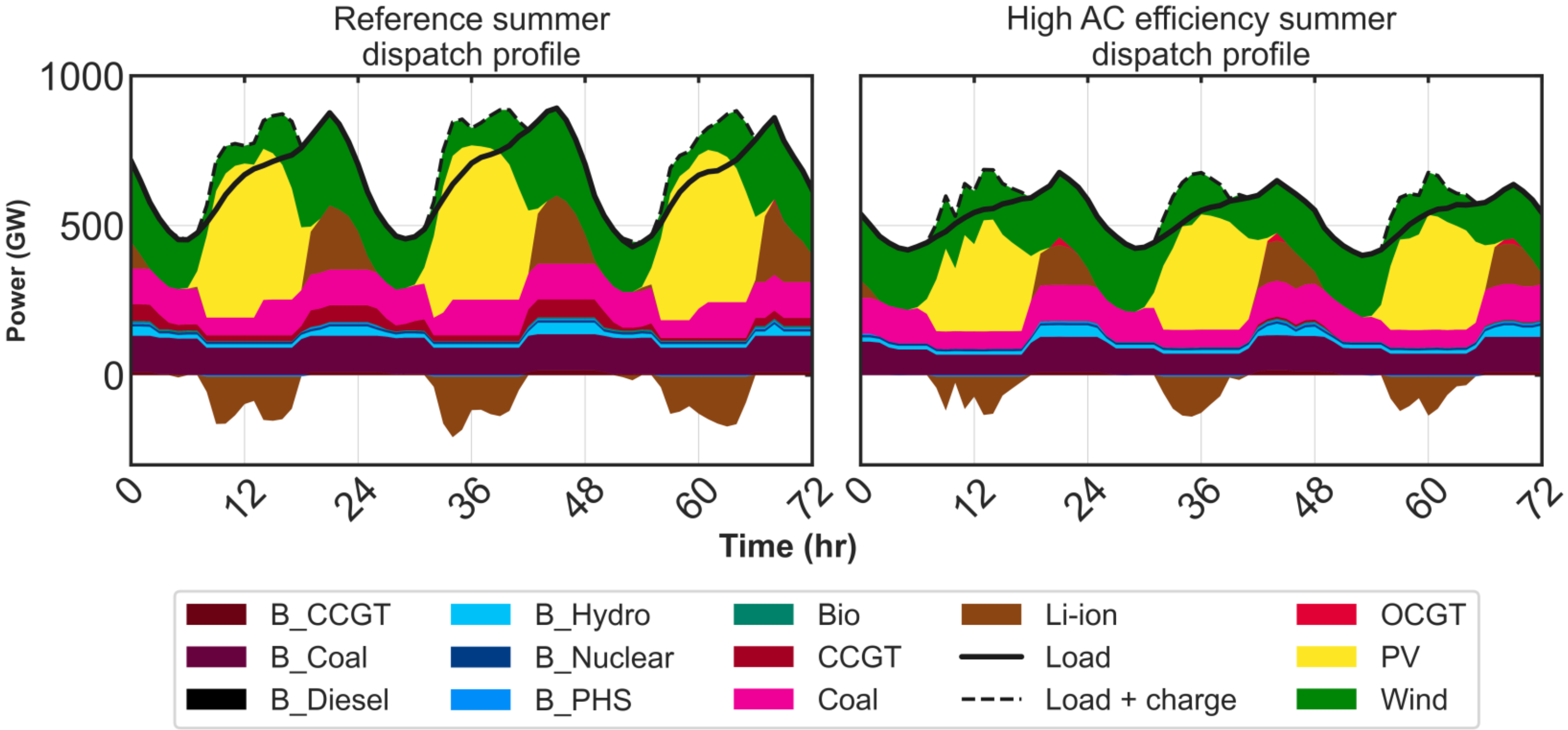
Global capacity 2018[1]	17
BNEF **global** projection: 2040[1]	2850
Model - **India** (2040)	649-4716



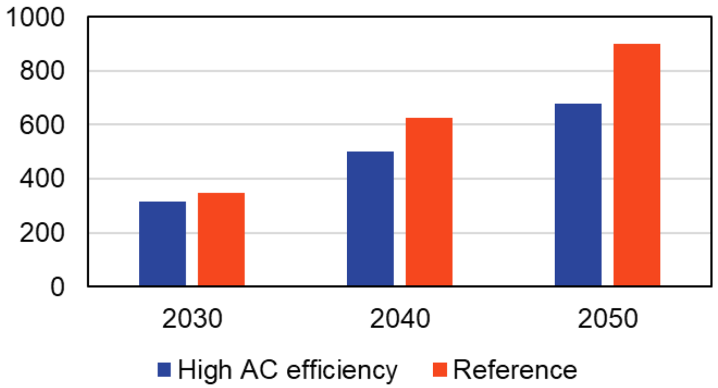
Reference scenario load assumptions: baseline AC efficiency, EV charging during the day time; discount rate = 9%; results based on modeling annual grid operations using 16 representative weeks; battery storage modeled with costs for Li-ion and 85% RTE; 1. https://about.bnef.com/blog/energy-storage-investments-boom-battery-costs-halve-next-decade/

Improved air conditioning efficiency directly impacts midnight peak load and reduces need for energy storage, but also flattens demand which favors coal over solar generation

System dispatch in 2050 for reference and high AC efficiency scenarios



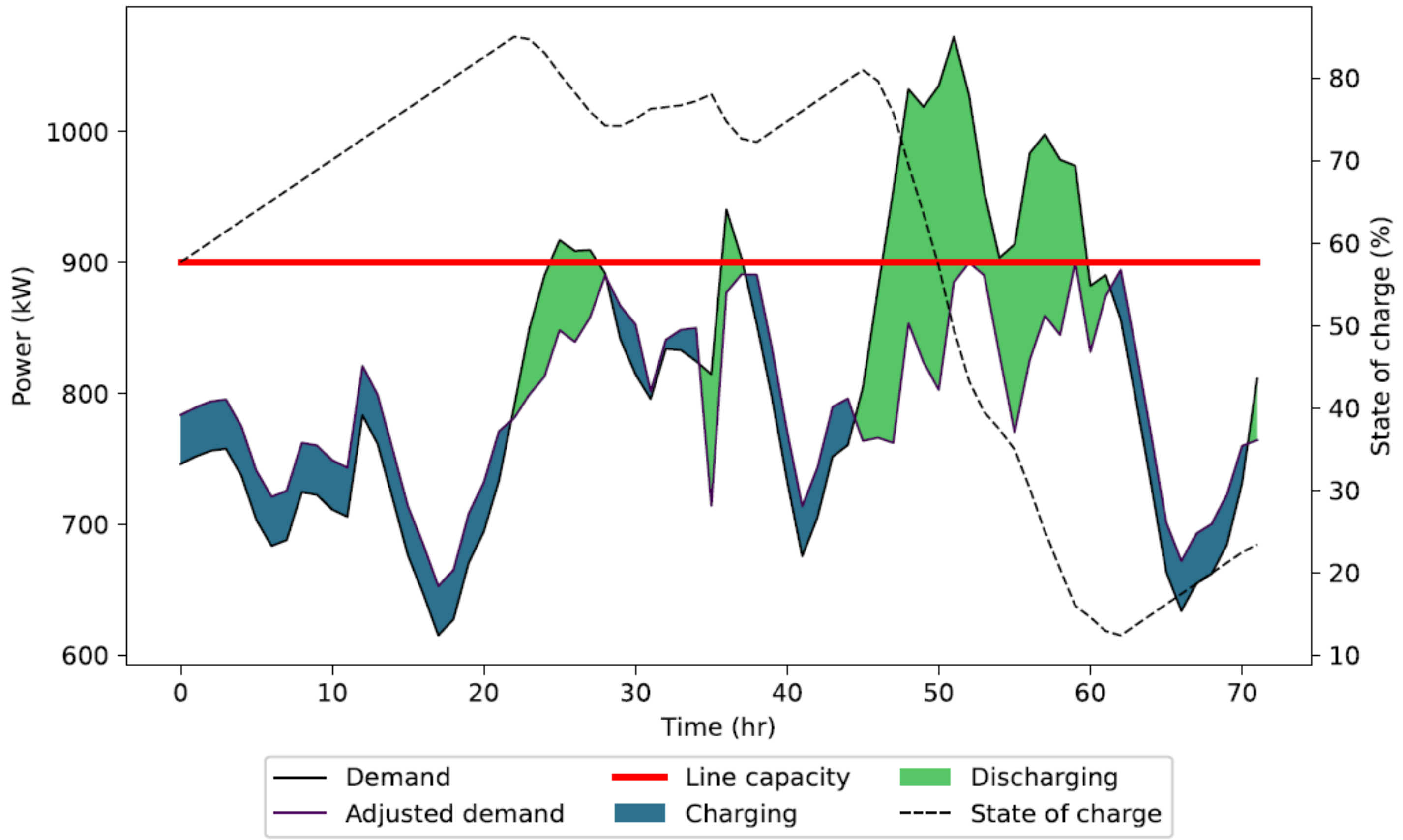
Estimated peak demand (GW)[3]



- Increased need for peaking generation and storage to serve AC load during nights
- Grid emissions intensity in 2050 with high AC efficiency > reference case (316 vs. 267 gCO_2/kWh)

Potential for cost-effective storage deployments to defer upgrading urban distribution networks in response to growing peak demand

Hourly dispatch simulation of NWA battery storage for one summer week load profile from Delhi (2030)[1]



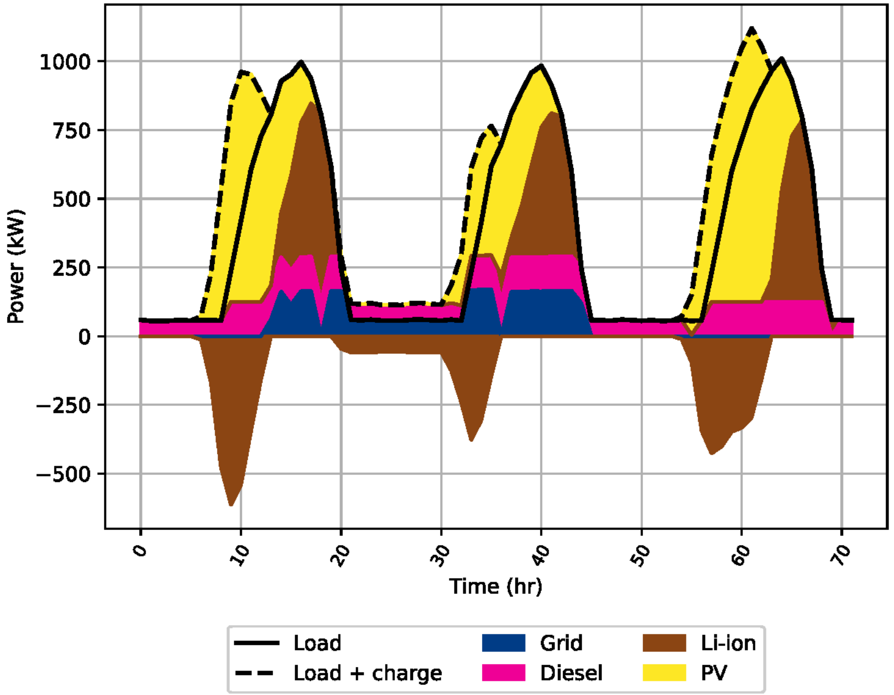
- Estimated potential of 140 GWh of storage across 4 major Indian megacities
- Drivers of distribution-level storage value in Indian context:
  - Congested urban feeders
  - High financing costs
  - Rapidly growing peak consumption

1.Barbar, Mallapragada and Stoner. Energy Strategy Reviews, 41, 100862, 2022.

In under-supplied Nigeria, we studied storage use as part of mini-grids that could potentially improve reliability and cost of power supply and reduce emissions from diesel

Aerial view of Wuse market, Nigeria[1]

Simulated minigrid dispatch without any simulated grid outages



- Storage role determined by **predictability and duration of grid outages**
  - Unpredictable and long duration outages (as it is today) makes storage less attractive vs. diesel

1. Figure source: Rockefellar foundation, Grid connected minigrid in an urban market, 2020: https://www.rockefellerfoundation.org/wp-content/uploads/2020/10/EE-Download-Solutions-CaseStudies-Urban-grid-connected-system.pdf