GRID MODELING OF LONG-DURATION ENERGY STORAGE FOR DEEP DECARBONIZATION

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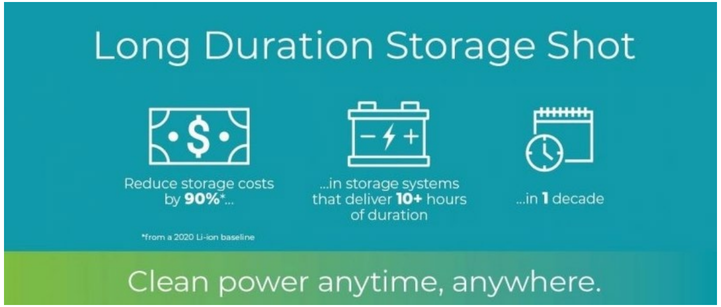
A POWER SYSTEM IN TRANSITION

- Ambitious decarbonization goals in the United States and globally
- Rapid increase in variable renewable energy (wind and solar)
- Increasing interest in energy storage to enable more renewable energy on the grid
- Extensive research on improving energy storage technologies
  – Research goals focus on technology cost

Energy Storage
Office of Electricity

ENERGY STORAGE GRAND CHALLENGE
U.S. DEPARTMENT OF ENERGY



RESOURCES IN ZERO-CARBON ELECTRICITY SYSTEMS

	Zero Fuel Cost	Non-Zero Fuel Cost
Non-Zero Marginal Cost	(Opportunity Cost) Reservoir hydro Pumped storage hydro Batteries Other Storage Demand Response	(Variable Fuel Cost) Bioenergy Hydrogen Gas w/CCS Coal w/CCS
Zero Marginal Cost	(No Opportunity Cost) Wind Solar Run-of-river Hydro Geothermal	(Fixed Fuel Cost) Nuclear

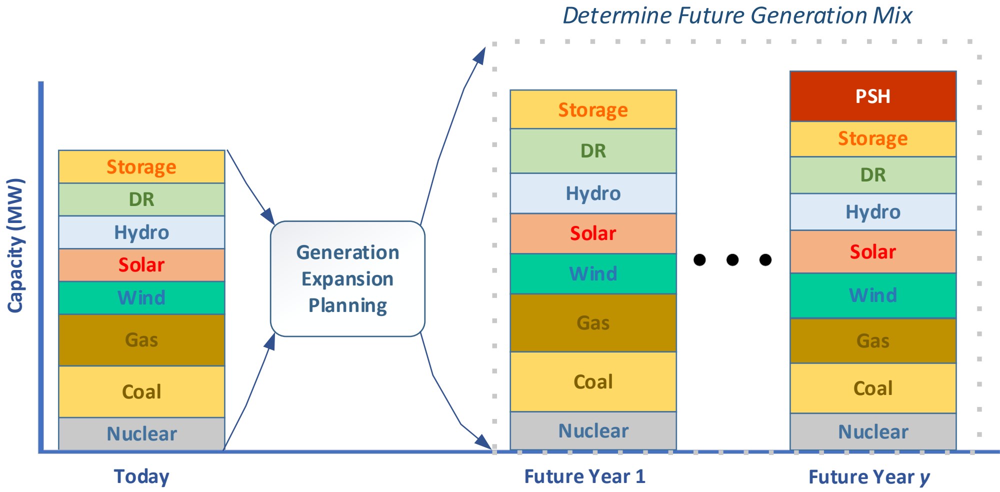
Zhou, Botterud, Levin, ANL-22/31.

- What will planning, operations and market prices look like in a zero-carbon system?
- How will energy storage be operated? What is the role of long-duration energy storage?

CAPACITY EXPANSION MODELING FOR ENERGY STORAGE AND DECARBONIZATION ANALYSIS

CAPACITY EXPANSION PLANNING

- For conducting long-term system studies
  - Generation capacity investments and retirements
  - The role of transmission and energy storage
  - Future load patters
- Minimize total expected supply cost
  - Determine the time, location, and size of new assets
  - Generation, transmission, storage, demand response
- Subject to
  - System reliability constraints
  - Technology constraints
  - Financial constraints
  - Environmental constraints



MODELING TOOLS USED IN THE RECENT DECARBONIZATION STUDIES

- Classification of generation expansion planning (GEP) models

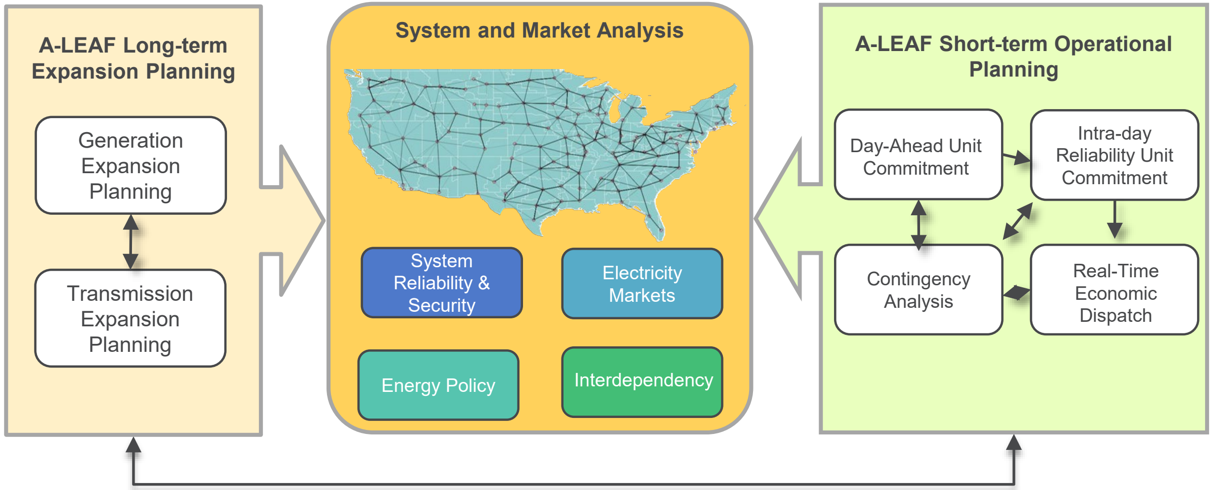
Category	Key Features	Modeling Options Increased robustness, increased complexity →				
Planning	Planning Horizon	static	milestone-years	rolling horizon		path optimization
	Type of decisions	investment		+ retirement		+ transmission expansion
Short-term System Operations	Temporal time resolution	hourly				sub-hourly
	Representative days	time slices	days	weeks	months	full
	Modeling detail	power balance		economic dispatch (ED)		unit commitment (UC)
Network	Geographical Scope	regional				national
	Spatial Resolution	single zone	multi zone	hybrid		nodal
	Transmission constraints	none	inter-zonal	+selected intra-zonal		full
	Power flow model	none	transport	DC		AC

MODELING TOOLS USED IN THE RECENT DECARBONIZATION STUDIES

- Comparison of modeling tools

Category	Key Features	Net Zero America (Princeton)	LA 100 (NREL)	openENTRANCE (Europe)	US Inter-Regional (MIT)
GEP Model		RIO	RPM	GENESYS-MOD	ZEPHYR
Planning	Planning Horizon	Milestone-years (2020-2050, every 5y)	Milestone-years (2020-2045, every 5y)	Milestone-years (2015-2050, every 5y)	Milestone year (2040)
	Type of decisions	Inv. + Ret. + Trans.	Inv. + Trans.	Inv. + Ret.	Inv. + Trans.
Short-term System Operations	Temporal time resolution	Hourly, 24hr per day	Hourly, 24hr per day	Hourly, time slices	Hourly
	Representative days	41 days	5 days	4 days	Full
	Modeling detail	ED	ED	ED	ED
Network	Geographical Scope	National (US)	WECC	EU	National (US)
	Spatial Resolution	Multi-zone (16 U.S. regions)	Hybrid (36 balancing areas, focus area)	Multi-zone (30 EU regions)	Multi-zone (11 planning areas)
	Transmission constraints	Inter-regional	Inter-regional	Inter-regional	Inter- & Intra-regional
	Power flow model		transport model	transport model	transport model

ARGONNE LOW-CARBON ELECTRICITY ANALYSIS FRAMEWORK (A-LEAF)



- Integrated ***national-scale*** power system simulation framework developed at ANL that has been applied to analyze different issues related to power system evolution.
- Suite of least-cost generation & transmission expansion, unit commitment, and economic dispatch models
- Determine system optimal generation portfolio and hourly or sub-hourly unit dispatch under a range of user-defined input assumptions for technology characteristics and system/market requirements

A-LEAF: KEY MODELING FEATURES

Policy / Market Design

- Carbon pricing
- Clean energy standards
- Production/investment tax credits
- Short-term markets for energy and ancillary services
- Capacity markets/payments, clean energy markets

Temporal Resolution

- Hourly or 5-minute dispatch
- Representative day groups
  - Using a backward scenario reduction algorithm
  - Multi-day optimization
  - Enforce inter-temporal constraints within day groups

Spatial Resolution

- National-scale geographical scope
  - National dataset
  - Network data: NREL's ReEDS, EIA
  - Timeseries data: NREL's Cambium
- Configurable network representation
- Power flow / transmission expansion
  - Inter-tie lines
  - Transportation model with losses (0.01% per mile)

Storage Representation

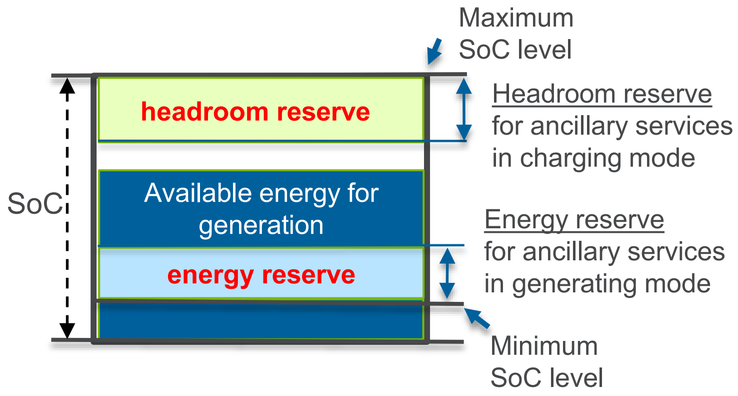
Endogenous Investment Decisions	Grid Services	Tracking of SOC	Energy Throughput Constraint
• Location, capacity, duration • Separate power and energy costs	• Energy • Reserves • Capacity	• Hourly • Multiple consecutive days	• Limits annual use of storage • Charging, discharging, regulation deployment

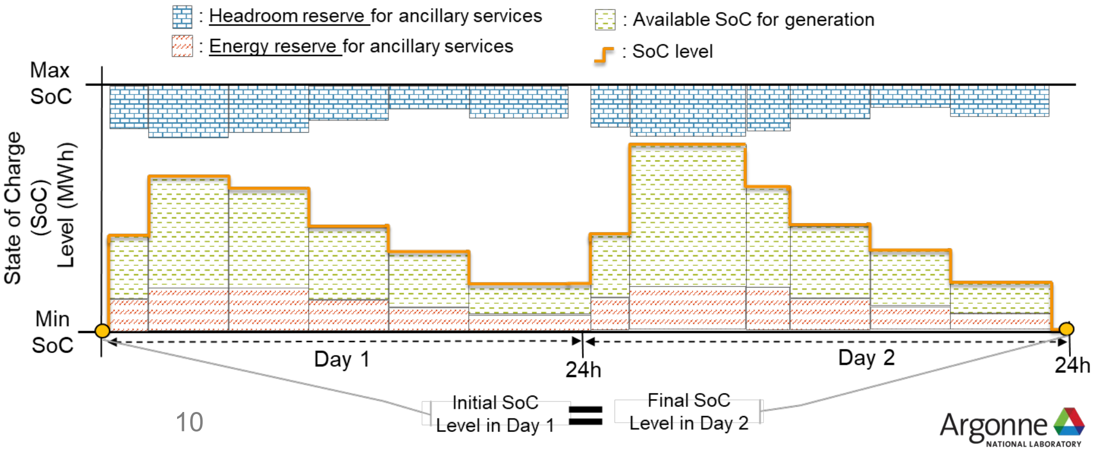
Material

- Raw material consumption from assets in the power grid
- Ongoing collaboration with the GCMaT (Global critical materials agent-based model) team at ANL

A-LEAF: ENERGY STORAGE REPRESENTATION

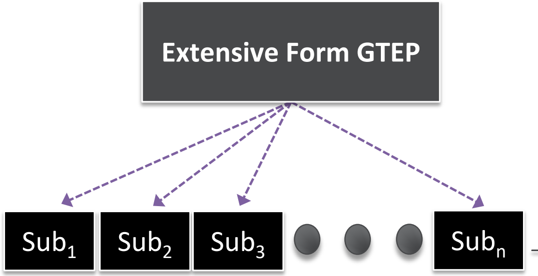
- Multiple energy storage technologies
  - Batteries, CAES, PSH
- Endogenous investment decisions
  - Location, capacity, duration
  - Separate power and energy costs
- Grid services
  - Energy, reserves, capacity
- Tracking of SOC level
  - Hourly
  - Multiple consecutive days
- Degradation
  - Energy throughput constraint
  - Limits annual use of storage (charging, discharging, reserve deployment)

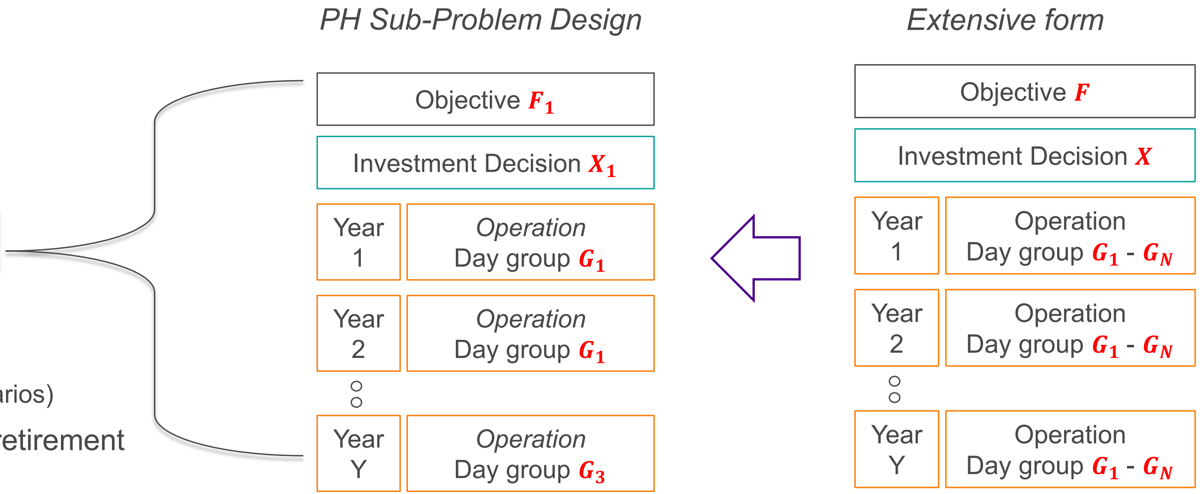




A-LEAF: COMPUTATIONAL EFFICIENCY

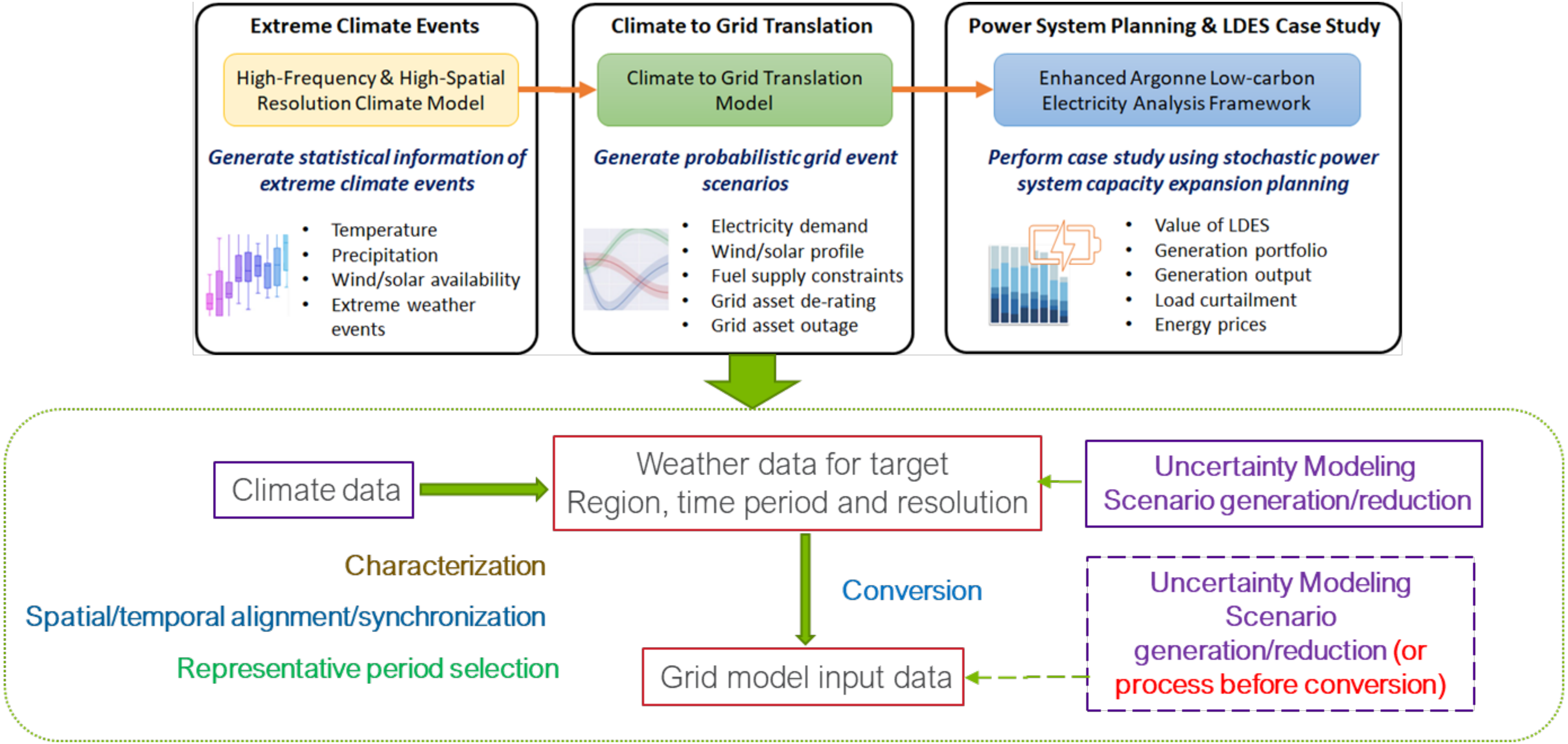
- Decomposition using Progressive Hedging (PH)





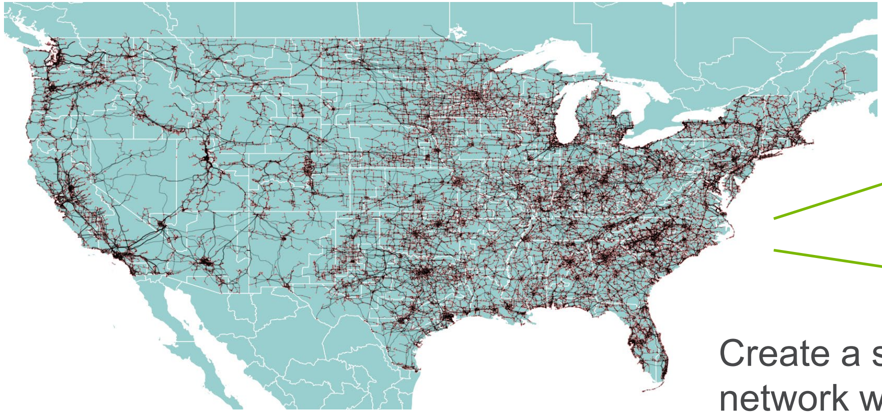
- Horizontal decomposition
  - Day groups
  - Potential extension (e.g., renewable scenarios)
- Ensure agreement between investment/retirement solutions from each sub-problem
  - Non-anticipativity constraint (i.e., $X_1 = X_2 = \ldots = X_N$) is introduced and then relaxed
- Parallel computing

FROM CLIMATE SCIENCE TO CAPACITY EXPANSION

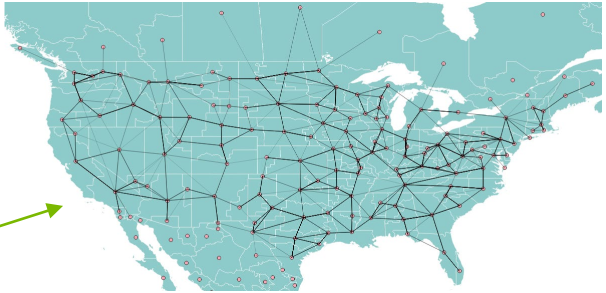


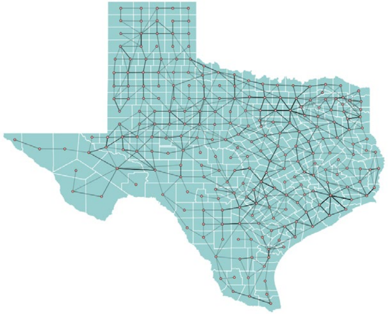
FLEXIBLE TRANSMISSION NETWORK REPRESENTATION

~90,000 US Transmission Lines
in HIFLD Data



Bus
Transmission Line



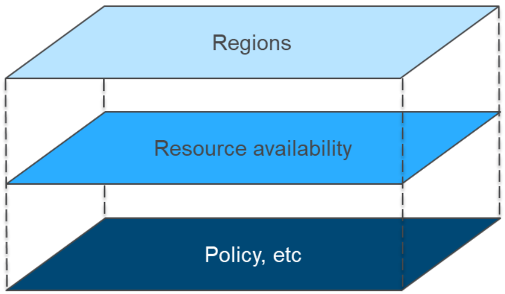


Create a simplified synthetic network with tunable level of detail

ILLUSTRATIVE EXAMPLES

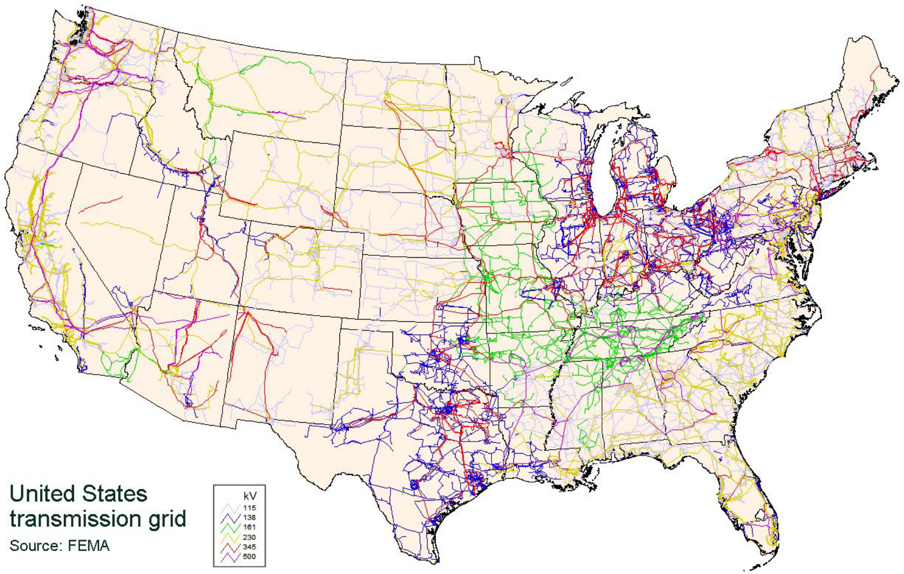
NATIONAL DATASET

- US electric system representation
  - Multiple layers



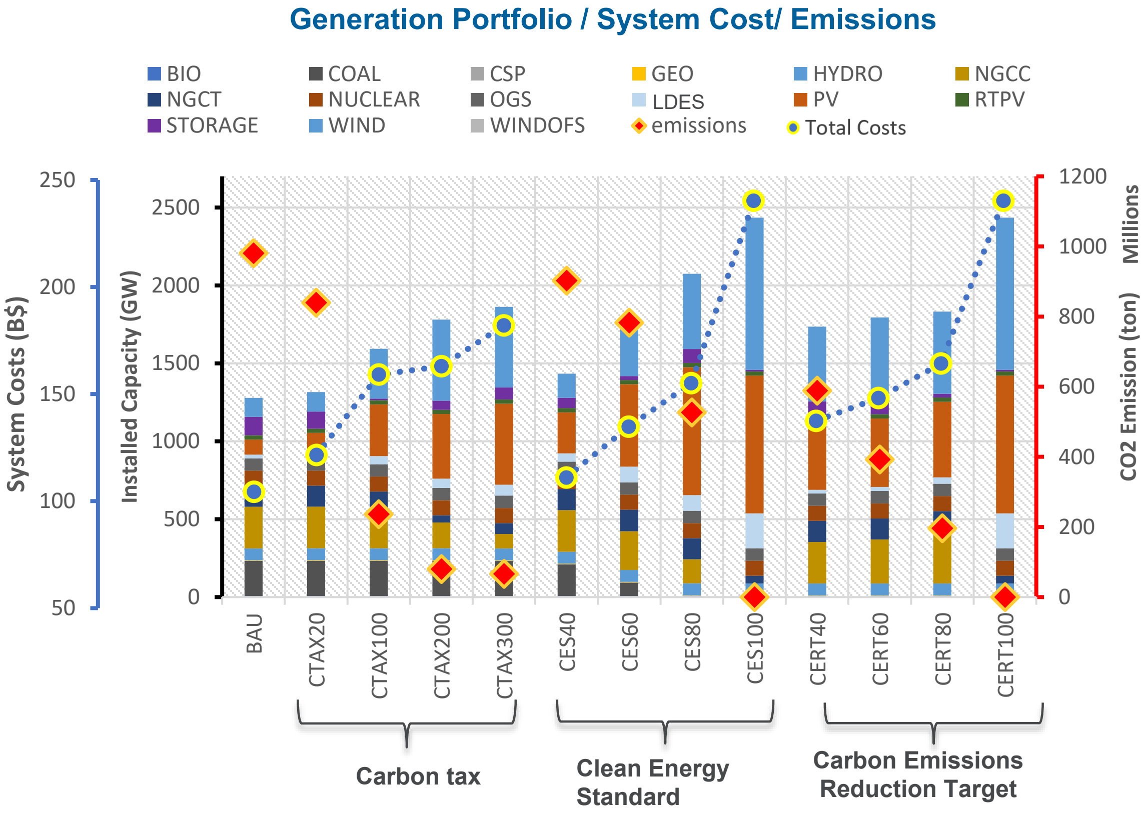
- Spatial resolution options (*configurable*)
  - 134 balancing authorities
  - **48 states**
  - 18 regional system operators
  - 3 interconnections

US electric system



http://www.geni.org/globalenergy/library/national_energy_grid/united-states-of-america/index.shtml

HOW DO POLICIES IMPACT FUTURE SYSTEM RESOURCE PORTFOLIOS AND EMISSION LEVELS?

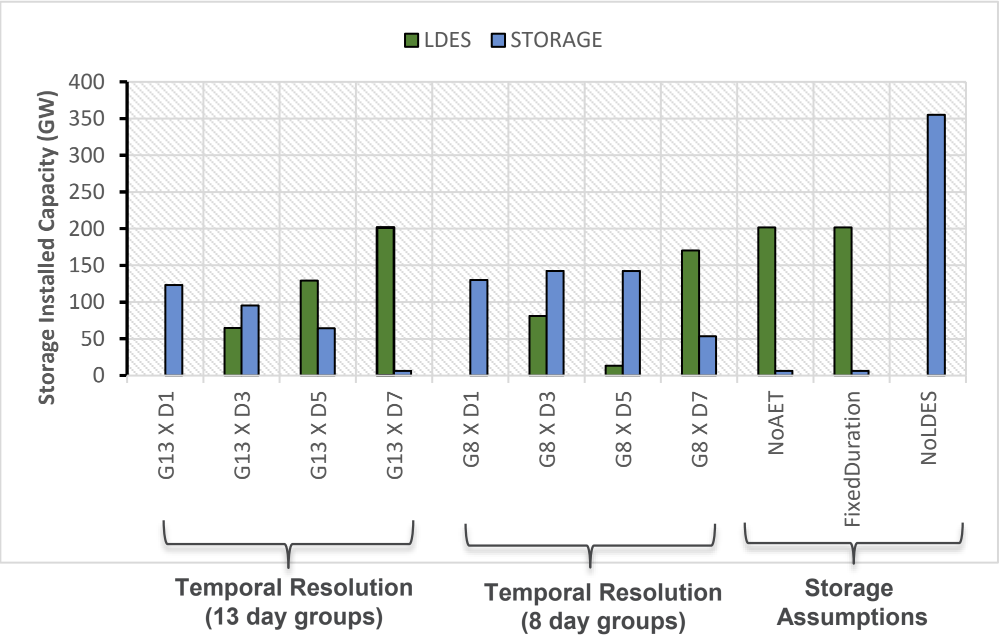


Policy Cases	Description
CTAX 20–300	Carbon Tax ($20-$300/ton)
CES 40–100	Clean energy standard (40-100%)
CERT 40–100	Carbon emissions reduction target (40-100%)

- Future **low-carbon** grid can be achieved through different policies and mechanisms
- Achieving a **zero-carbon** grid requires high investments in Wind, PV, and Storage at significant system costs
  - Higher capital costs, lower generation cost
- More investments in **Storage** (Li-ion battery parameters) and **LDES** (PSH parameters) with more Wind and PV resources

HOW DO MODELING ASSUMPTIONS IMPACT ENERGY STORAGE INVESTMENTS?

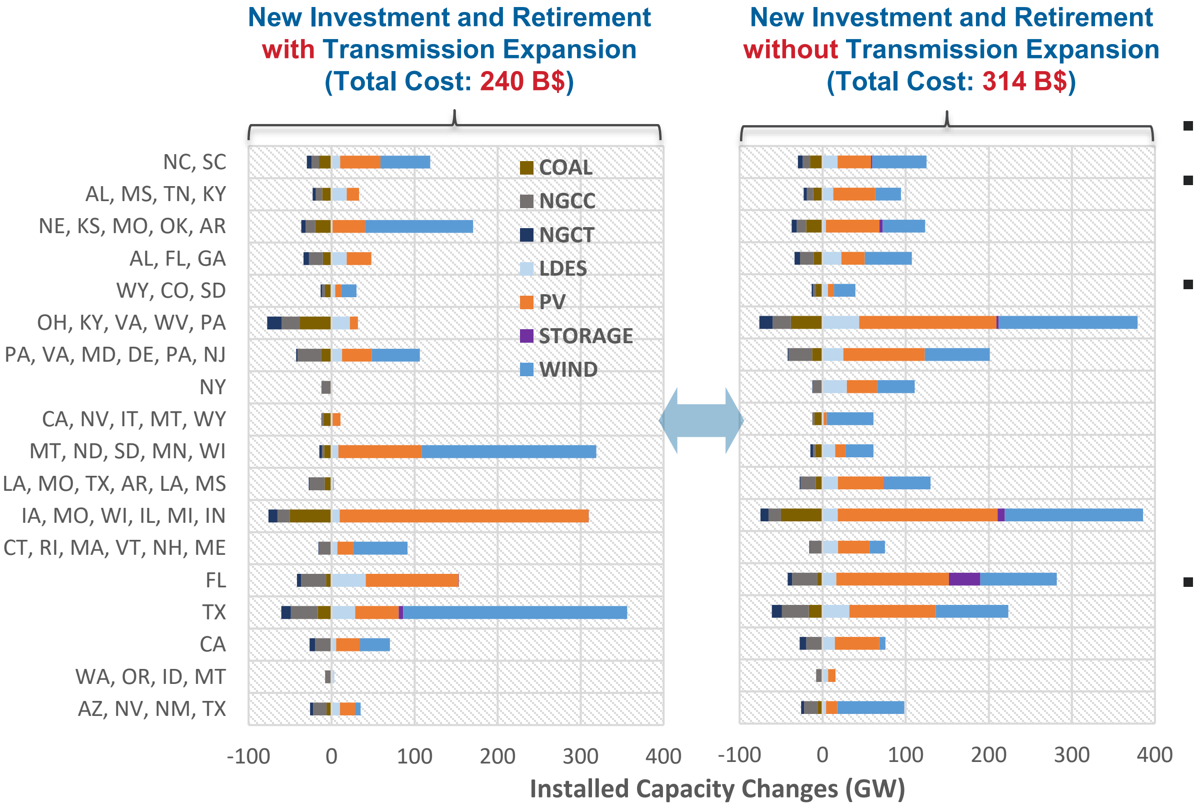
Energy Storage Investment (under CES 100%)



Cases	Description
Temporal Resolution	Varying the number of day groups and the number of days in each group
NoAET	Does not enforce the annual energy throughput cap
FixedDuration	Does not optimize storage duration
NoLDES	Dose not allow new investments of LDES (i.e., PSH)

- Temporal resolution and storage assumptions have substantial impacts on storage investment results
  - Optimizing across multiple consecutive days results in more LDES investments
- Substantial value of LDES
  - System needs higher Battery Storage investments to meet the clean energy target without LDES
- Relatively low impact of “NoAET” and “FixedDuration” cases due to the dominant LDES investments

HOW DOES TRANSMISSION EXPANSION IMPACT REGIONAL GENERATION PORTFOLIOS AND COSTS?



- Common policy: CES 100%
- Transmission expansion assumptions
  - 765 kV, 1666 $/MW-mile
- Higher Wind, PV, and Storage investments to meet the clean energy target without transmission expansion:
  - Wind: + 262 GW
  - PV: + 281 GW
  - **Storage: + 49 GW**
  - **LDES: + 105 GW**
- Coordinated transmission planning reduces cost of zero-carbon grid
  - **31% higher cost** without transmission expansion

CONCLUSIONS AND NEXT STEPS

CONCLUSIONS AND NEXT STEPS

- Importance of electricity planning models to guide policy decisions, electricity market design, and technology development
  - Policy decisions have substantial impacts on zero-carbon technology pathways
  - Value of individual technologies depend on system portfolio
- Modeling details may have substantial impacts on expansion results
  - Temporal resolution of particular importance for energy storage
  - Trade-off between modeling detail and computational effort
  - Efforts on improved capacity expansion modeling with energy storage
- Next steps
  - Complete current scenario-based decarbonization analysis
  - Combine with related efforts on climate and e extreme weather effects, materials/manufacturing challenges, battery degradation and lifetime effects
  - Conduct more detailed study on the value of LDES under future climate scenarios (regional or national level)

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- Z. Zhou, A. Botterud, T. Levin, “Price Formation in Zero-Carbon Electricity Markets: The Role of Hydropower,” Report ANL 22/31, July 2022.
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- T. Levin, J. Kwon, A. Botterud, “The long-term impacts of carbon and variable renewable energy policies on electricity markets,” Energy Policy, Vol. 131, pp. 53-71, 2019.
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- Argonne National Laboratory
- DOE OE Energy Storage Program

THANKS!

Project Team

Jonghwan Kwon, Neal Mann, Todd Levin, Zhi Zhou, Audun Botterud

BACKUP SLIDES

KEY QUESTIONS

- What is the **role of long-duration energy storage (LDES)** in decarbonizing the electric power system (e.g. through integrating VRE)?
- How do **climate change and changing weather patterns** affect the value proposition for LDES?
- How can LDES address the challenge of maintaining cost efficiency and reliability with **more frequent extreme weather events**?

Commentary

Extreme weather and electricity markets: Key lessons from the February 2021 Texas crisis

Todd Levin,[1,*] Audun Botterud,[1,2] W. Neal Mann,[1,3] Jonghwan Kwon,[1] and Zhi Zhou[1]

Joule

Joule 6, 1–15, January 19, 2022 © 2021 Elsevier Inc.

https://doi.org/10.1016/j.joule.2021.12.015

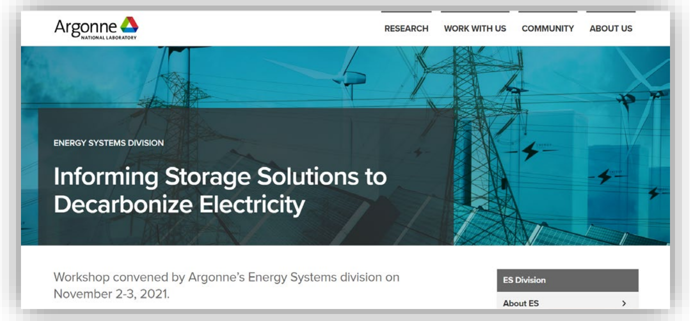
DECARBONIZATION AND ENERGY STORAGE ANALYSIS

Power System Planning and Operation Tools

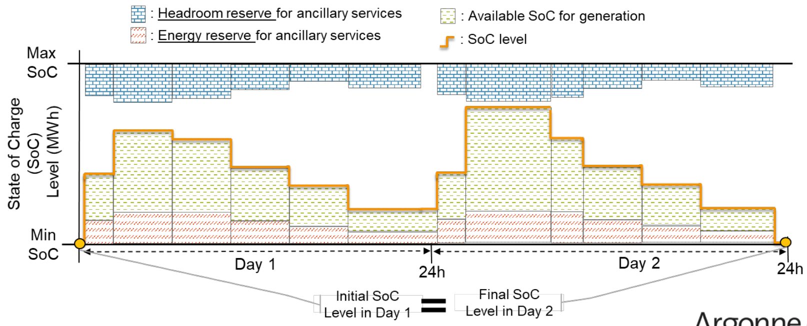
- **Multi-scale electric power systems modeling**
  - Argonne Low-Carbon Electricity Analysis Framework (A-LEAF)
  - National, regional, and local electric power markets
  - Long-term generation and transmission planning
  - Short-term unit commitment and economic dispatch
- **Suitable for large-scale energy storage analyses**
  - System level optimization model with chronological dispatch (energy storage is a price maker)
  - Multi-day optimization steps (day groups)
  - *Custom, flexible model formulations* including least-cost and game-theoretic objectives

Energy Storage Modeling

- **Multiple energy storage technologies**
  - E.g. various batteries, CAES, PSH
- **Multiple grid services**
  - Energy, reserves, capacity
- **Tracking of SOC level**
  - Hourly (or sub-hourly)
  - Multiple consecutive days
- **Lifetime and capacity degradation**
  - Calendar and cycle degradation
  - Limits on annual use of storage
- **Manufacturing and materials constraints**



https://www.anl.gov/es/informing-storage-solutions-to-decarbonize-electricity

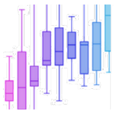


PROPOSED RESEARCH

Future Climate Scenarios

High-Frequency & High-Spatial Resolution Climate Model

Generate statistical information of likely future weather patterns

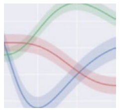


- Temperature
- Precipitation
- Wind speed
- Solar irradiance
- Extreme events

Climate to Grid Translation

Climate to Grid Translation Model

Generate probabilistic grid event scenarios

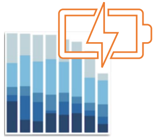


- Electricity demand
- Wind/solar profiles
- Fuel supply constraints
- Grid asset de-rating
- Grid asset outages

Power System Planning with LDES

Argonne Low-carbon Electricity Analysis Framework (A-LEAF)

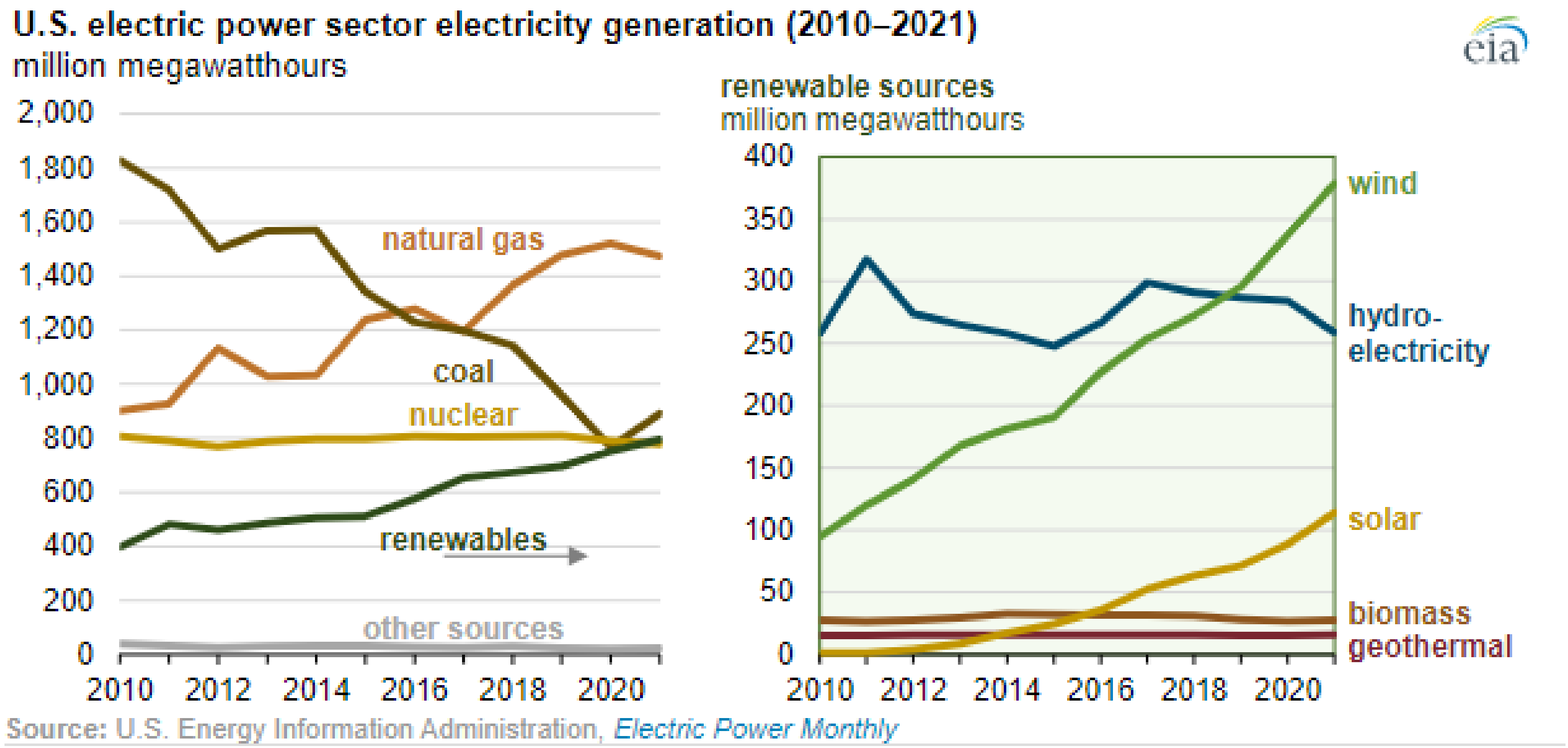
Power system capacity expansion planning and production cost simulations



- **Value of LDES**
- Generation portfolio
- System scheduling
- Demand response
- Energy prices

- **Study:** The value of LDES under future climate scenarios (national, regional, local)
- **Deliverables**: Enhanced model capabilities (future climate, degradation, LDES), comprehensive climate-LDES analysis for selected regions/locations, document results in report/journal paper
- **Team**: ANL Energy Systems Division, ANL Environmental Science Division, Form Energy

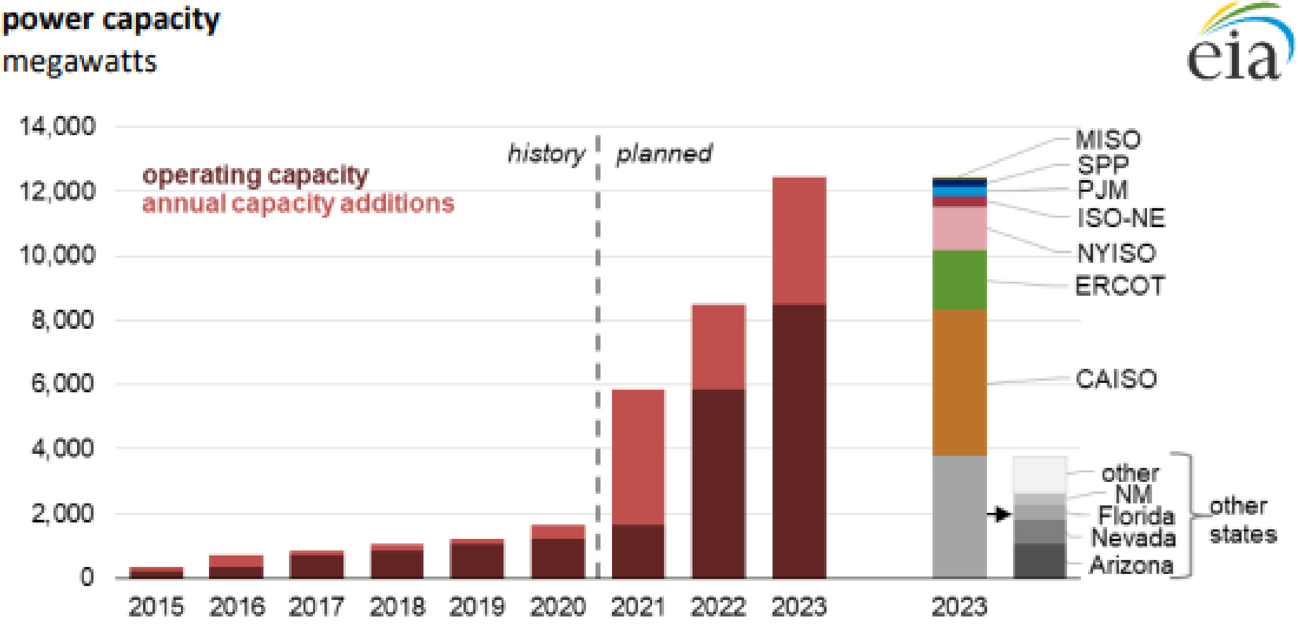
GROWTH IN RENEWABLE ELECTRICITY GENERATION



Ambitious U.S. decarbonization goals: Carbon-free electricity by 2035, net-zero economy by 2050

INCREASING INTEREST IN ENERGY STORAGE

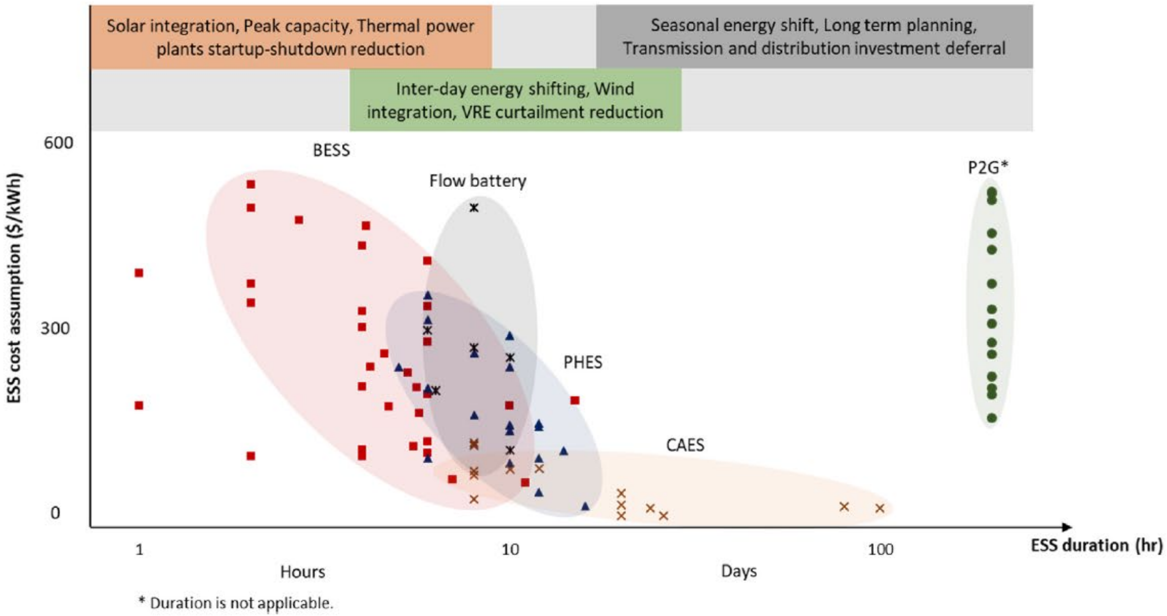
Figure ES4. Large-scale battery storage cumulative power capacity, 2015–2023



Source: U.S. Energy Information Administration, Dec 2020 Form EIA-860M, *Preliminary Monthly Electric Generator Inventory*

ENERGY STORAGE TECHNOLOGIES AND APPLICATIONS

Technology		Efficiency (%)	Storage duration (hour)	Lifetime (year)	Cost ($)	References
Electrochemical	Conventional battery	70–90	1–15	5–15	500-650/kW 175-200/kWh	[71–74]
	Flow battery	up to 85	4 and longer	15–20	700-2500/kWh	[44,75,76]
Mechanical	PHES	70–75	5–20	30–50	600-2000/kW	[7,77]
	CAES	85	up to 100	30	1000-2000/kW	[74,78,79]
Chemical	P2G	50-70 (one-way)	Not applicable	20	900-2200/kW	[80–82]



Jafari, Botterud, Sakti, RSER 158 (2022).

A-LEAF: KEY FEATURES

Category	Key Features	Modeling Options (Increased robustness, increased complexity →)				
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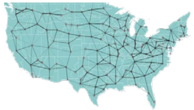
	Spatial Resolution	single zone	**multi zone**		hybrid	nodal
	Transmission constraints	none	**inter-zonal**		+selected intra-zonal	full
	Power flow model	none	**transport**		DC	AC

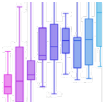
ONGOING A-LEAF ENHANCEMENTS TO STUDY THE FUTURE OF THE U.S. ELECTRICITY SYSTEM

Modeling of the U.S. Electric Power Grid



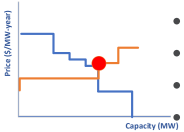
- Configurable network
- Transmission network
- Resource potentials

Climate and Weather Data Analysis



- Wind/solar availability
- Wind /solar forecasting
- Extreme weather events

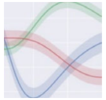
Wholesale Market Designs / Policies / Regulations



- Forward and spot markets
- State and national policies
- Price formation
- Capacity and A.S.

Decarbonization
Reliability
Resiliency

Translation of the Climate Data into Grid Model Inputs



- Electricity demand
- Wind/solar profile
- Grid asset de-rating
- Grid asset outage

Interdependency

- Material & Manufacturing
- Transportation
- Natural gas
- Water

Advanced Operations & Planning Tools

- Generation portfolio
- Generation scheduling
- Energy prices
- Value of LDES

CONTACT INFORMATION

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