Coordinating Storage and Renewable Growth Under Uncertainty to Manage Grid Risk

Elnaz Kabir
Assistant Professor ,
Engineering Technology and Industrial Distribution

Collaborators: *Seyed Ehsan Ahmadi, Mohammad Fattahi*

TEXAS A&M UNIVERSITY
Engineering

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Future & Generation Mix

Increased Renewable generation and storage share

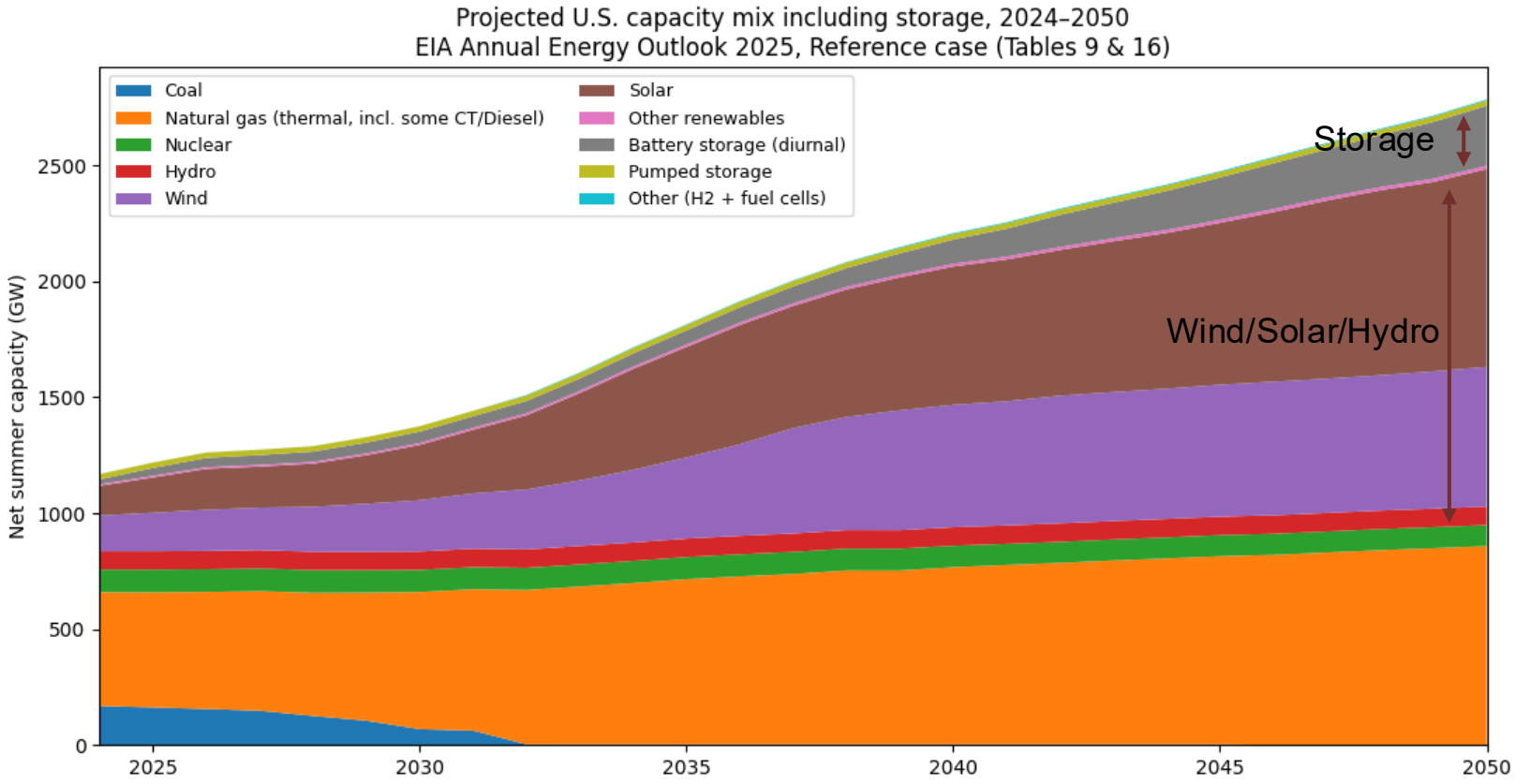


Fig1.

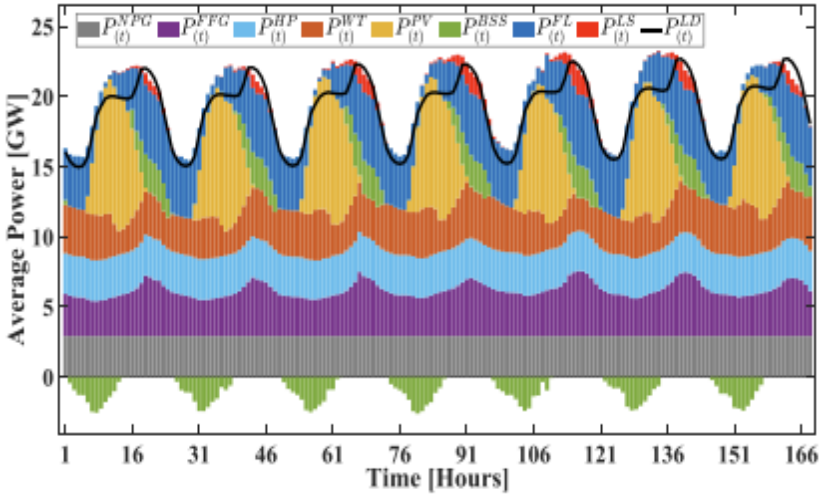
Motivation

Spatial-temporal variability and Covariability of wind-, solar-, and hydro-power and load.

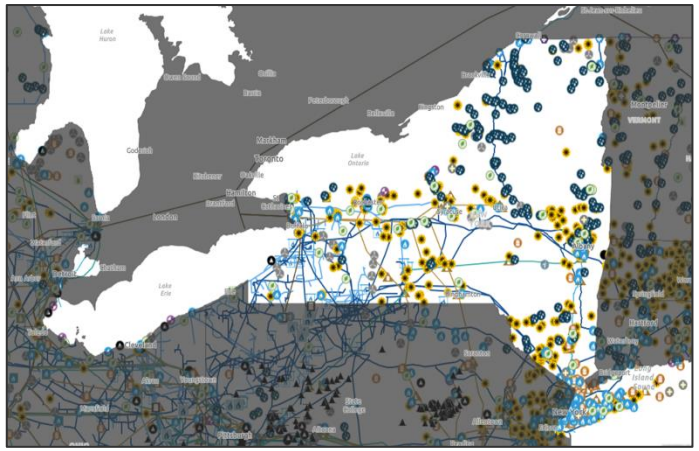
Power grid constraints: topology, transmission limits, spatial load and generation distribution

Storage features: technology, duration, degradation, life-cycle, life time, self-charge/discharge, rated power, etc.

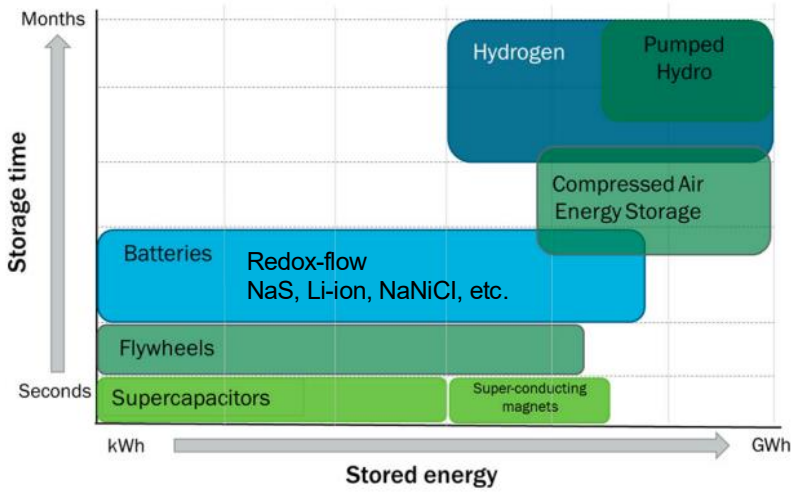
Intermittency/variability/covariability



congestion, curtailment, load shedding



where/how much/which technology



Kabir, Elnaz, et al. "Quantifying the impact of multi-scale climate variability on electricity prices in a renewable-dominated power grid." *Renewable Energy* 223 (2024): 120013.

Objectives

- **Main Goals**

❖ systematic assessment of **BSS capacity required for target RES penetration**

❖ Incorporate **full techno-economic attributes** of multiple BSS types.

❖ Capture **spatio-temporal variability** in RES and demand (uncertainty).

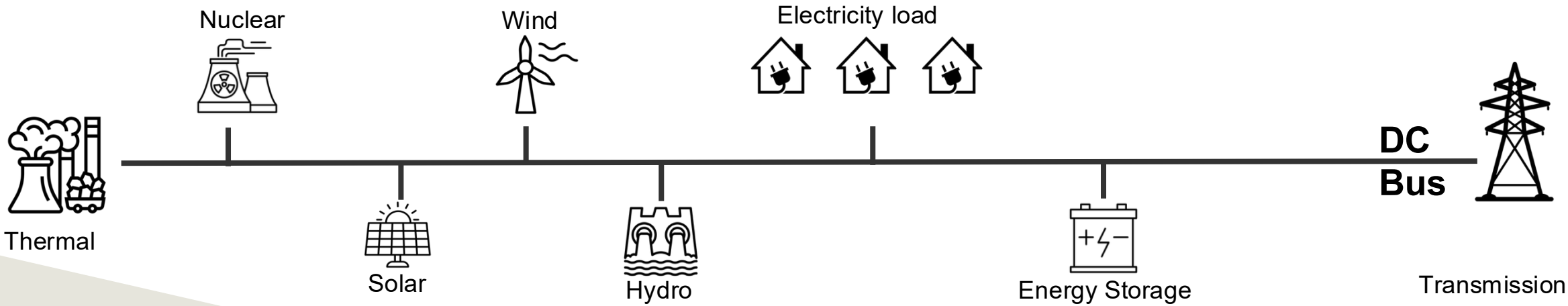
❖ Introduce **cost-effectiveness metrics** for BESS planning

- **Key Contributions**

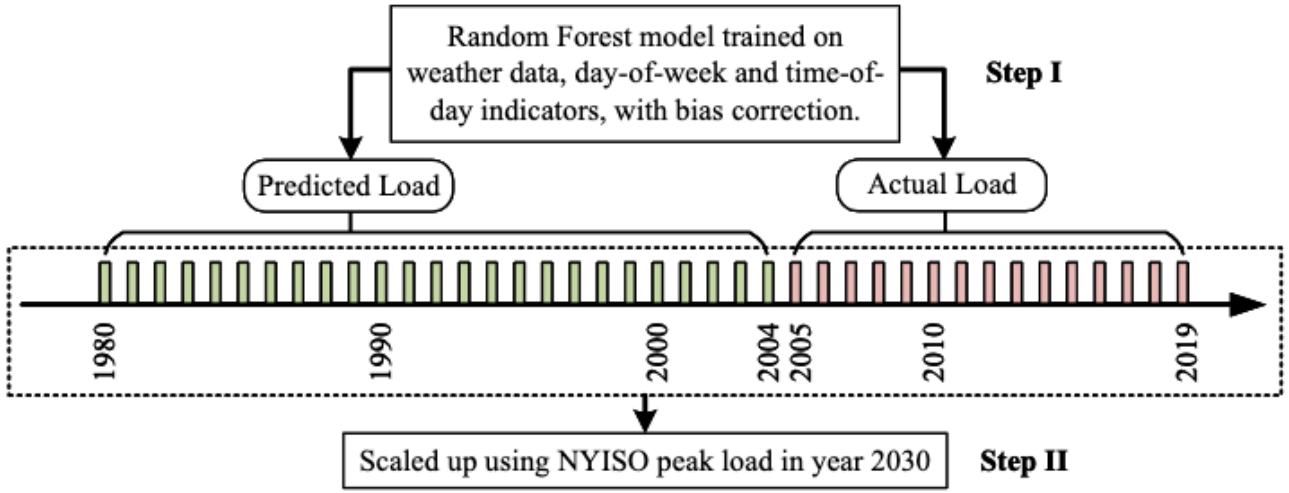
❖ Two-stage stochastic model to account for uncertainty in DC-OPF problem.

❖ Novel metrics for cost effectiveness

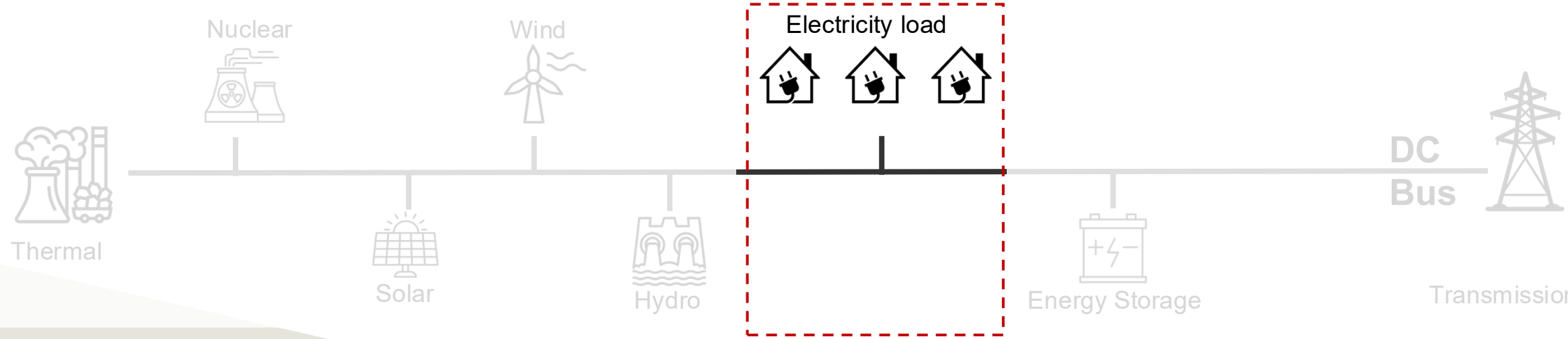
Modeling Framework



Renewable and Load Modeling



Flowchart of the load modelling process.



Renewable and Load Modeling

Temperature
Solar radiation
Solar site features

$$F_{l,t,s}^{pv} = \frac{G_{l,t,s}^{eff}}{G^*} \times \frac{\eta_{l,t,s}}{\eta_l^*}$$

Solar generation (cap)

Wind speed
Wind Farm features

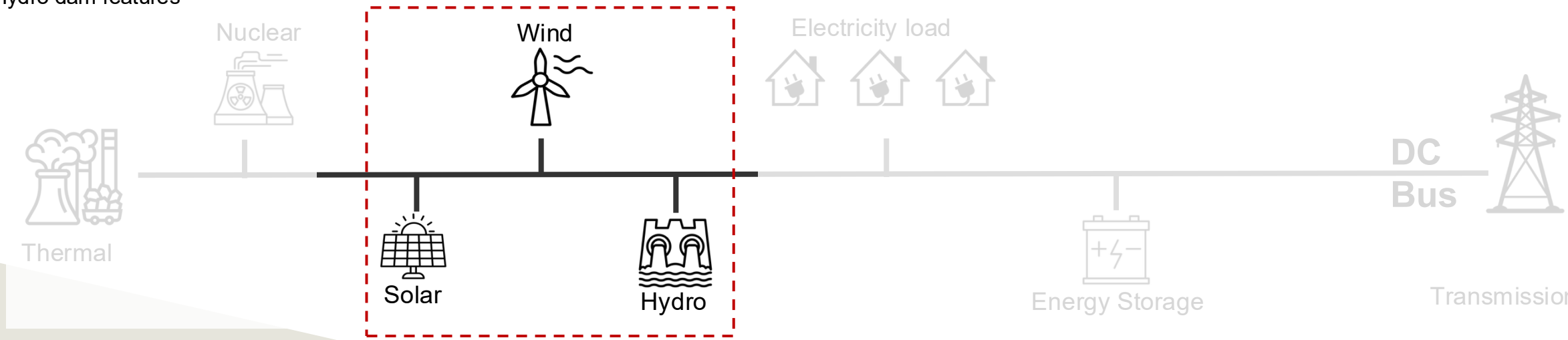
$$F_{l,t,s}^{wt} = \begin{cases} 0, & \text{if } v_{l,t,s} < v_{cut-in} \text{ or } v_{l,t,s} > v_{cut-out} \\ \dfrac{v_{l,t,s}^3 - v_{cut-in}^3}{v_{rated}^3 - v_{cut-in}^3}, & \text{if } v_{cut-in} \le v_{l,t,s} < v_{rated} \\ 1, & \text{if } v_{rated} \le v_{l,t,s} \le v_{cut-out} \end{cases}$$

Wind generation (cap)

Temperature
Precipitation
Ice condition
Hydro dam features

$$P_t = \rho g \eta Q_t H_t, \qquad E_t = P_t \Delta t$$

Hydro generation (cap)



Grid and non-renewable generation

$$\min \sum_z \sum_{i \in G_z} \left[\left(\delta^{dg}_{z,g,i,t} + \pi^{em} \cdot \delta^{em}_{z,g,i} \right) \cdot \sum_t p^{dg}_{z,g,i,t,s} \right]$$
$$+ \sum_z \sum_{i \in G_z} \left[\pi^{pf} \cdot u^{dg}_{z,g,i,s} \cdot \left(\tau \cdot \overline{P}^{dg}_{z,g,i} - \sum_t p^{dg}_{z,g,i,t,s} \right) \right]$$
$$+ \sum_z \sum_{i \in I_z} \left[O \cdot \sum_t p^{ls}_{z,i,t,s} \right]; \quad \forall s \in S$$

Ahmadi, Seyed Ehsan, et al. "Generator Retirement Optimization for New York State Energy Transition: Balancing Cost, Reliability, and Emissions." *2025 IEEE Texas Power and Energy Conference (TPEC)*. IEEE, 2025.

$$p^{re}_{z,r,i,t,s} \le \overline{P}^{re}_{z,r,i,t,s}; \qquad \forall z \in Z, r \in R, i \in R_z, t \in T$$

$$\underline{P}^{dg}_{z,g,i} \le p^{dg}_{z,g,i,t,s} \le \overline{P}^{dg}_{z,g,i}; \qquad \forall z \in Z, g \in G, i \in G_z, t \in T$$

$$p^{dg}_{z,g,i,t,s} - p^{dg}_{z,g,i,t-1,s} \le P^{rd}_{z,g,i}; \qquad \forall z \in Z, g \in G, i \in G_z, t \in T$$

$$p^{dg}_{z,g,i,t-1,s} - p^{dg}_{z,g,i,t,s} \le P^{ru}_{z,g,i}; \qquad \forall z \in Z, g \in G, i \in G_z, t \in T$$

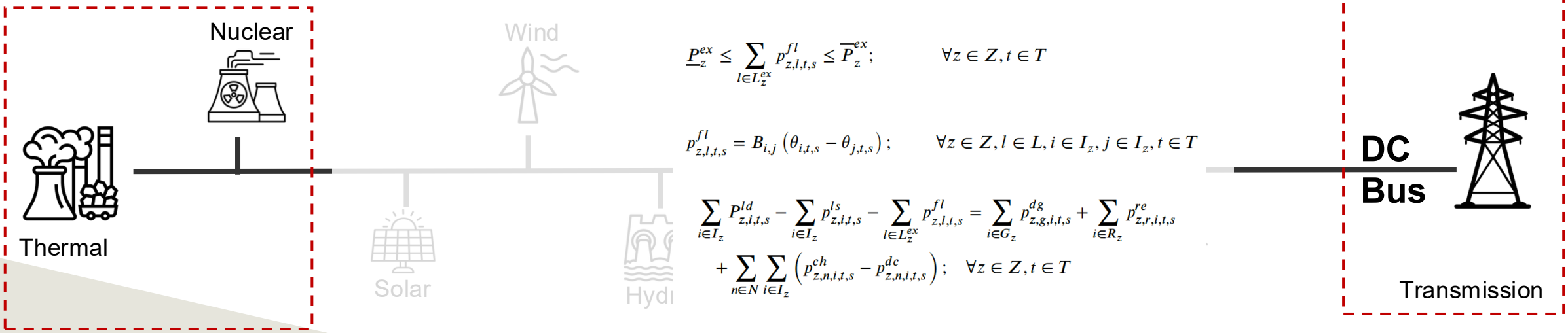
$$p^{ls}_{z,i,t,s} \le P^{ld}_{z,i,t,s}; \qquad \forall z \in Z, i \in I_z, t \in T$$

$$\underline{P}^{fl}_{z,l} \le p^{fl}_{z,l,t,s} \le \overline{P}^{fl}_{z,l}; \qquad \forall z \in Z, l \in L^{in}_z, t \in T$$

$$\underline{P}^{ex}_{z} \le \sum_{l \in L^{ex}_z} p^{fl}_{z,l,t,s} \le \overline{P}^{ex}_{z}; \qquad \forall z \in Z, t \in T$$

$$p^{fl}_{z,l,t,s} = B_{i,j} \left(\theta_{i,t,s} - \theta_{j,t,s} \right); \qquad \forall z \in Z, l \in L, i \in I_z, j \in I_z, t \in T$$

$$\sum_{i \in I_z} P^{ld}_{z,i,t,s} - \sum_{i \in I_z} p^{ls}_{z,i,t,s} - \sum_{l \in L^{ex}_z} p^{fl}_{z,l,t,s} = \sum_{i \in G_z} p^{dg}_{z,g,i,t,s} + \sum_{i \in R_z} p^{re}_{z,r,i,t,s}$$
$$+ \sum_{n \in N} \sum_{i \in I_z} \left(p^{ch}_{z,n,i,t,s} - p^{dc}_{z,n,i,t,s} \right); \quad \forall z \in Z, t \in T$$



Mathematical Modeling

- **Energy Balance and Charging/Discharging:**

$$e^{bs}_{z,n,i,t,s} = e^{bs}_{z,n,i,t-1,s} + \left(\eta^{ch}_{n} \cdot p^{ch}_{z,n,i,t,s} - \frac{p^{dc}_{z,n,i,t,s}}{\eta^{dc}_{n}}\right) - \left(\frac{\eta^{sd}_{n}}{24} \cdot e^{bs}_{z,n,i,t-1,s}\right); \quad \text{Battery Energy (SOC) Balance}$$

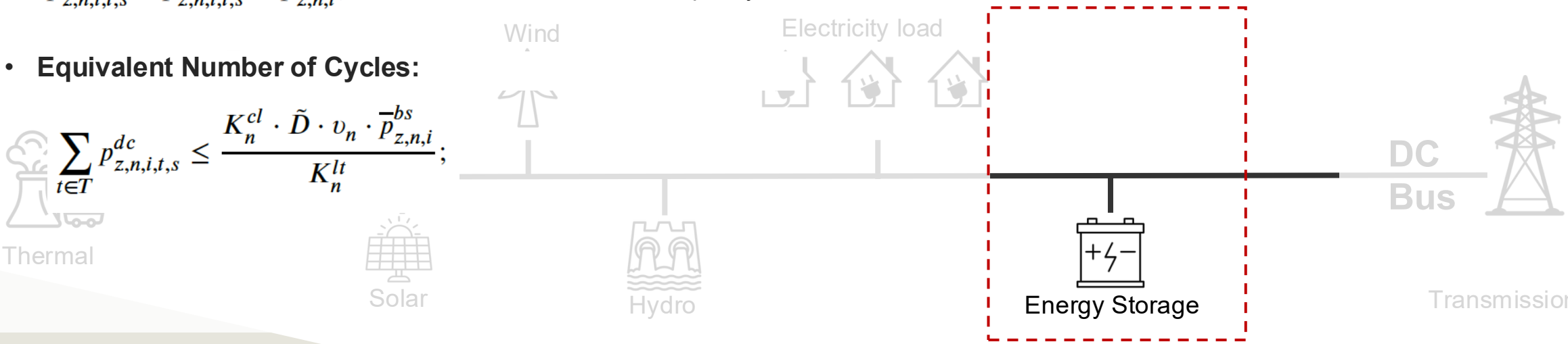
$$(1 - \overline{D}_{n}) \cdot \upsilon_{n} \cdot \overline{p}^{bs}_{z,n,i} \leq e^{bs}_{z,n,i,t,s} \leq \upsilon_{n} \cdot \overline{p}^{bs}_{z,n,i}; \quad \text{Battery Energy Capacity}$$

$$e^{bs}_{z,n,i,0,s} = e^{bs}_{z,n,i,T,s}; \quad \text{Energy level at the first and last period}$$

$$p^{ch}_{z,n,i,t,s} + p^{dc}_{z,n,i,t,s} \leq \overline{p}^{bs}_{z,n,i}; \quad \text{Rated Power Capacity}$$

- **Equivalent Number of Cycles:**

$$\sum_{t \in T} p^{dc}_{z,n,i,t,s} \leq \frac{K^{cl}_{n} \cdot \tilde{D} \cdot \upsilon_{n} \cdot \overline{p}^{bs}_{z,n,i}}{K^{lt}_{n}};$$



Mathematical Modeling

- **Annualized Capital and Replacement Cost:**

$$C^{cc}_{z,n,i} = \left(\delta^{ec}_{n} \cdot \upsilon_{n} + \delta^{pc}_{n} + \delta^{bp}_{n} + \delta^{cc}_{n} \cdot \upsilon_{n}\right) \cdot \left[\frac{in \cdot (in+1)^{K^{pt}}}{(in+1)^{K^{pt}} - 1}\right] \cdot \overline{p}^{bs}_{z,n,i};$$

$$C^{rc}_{z,n,i} = \delta^{br}_{n} \cdot \upsilon_{n} \cdot \left[\frac{in}{(in+1)^{K^{lt}_{n}} - 1}\right] \cdot \overline{p}^{bs}_{z,n,i};$$

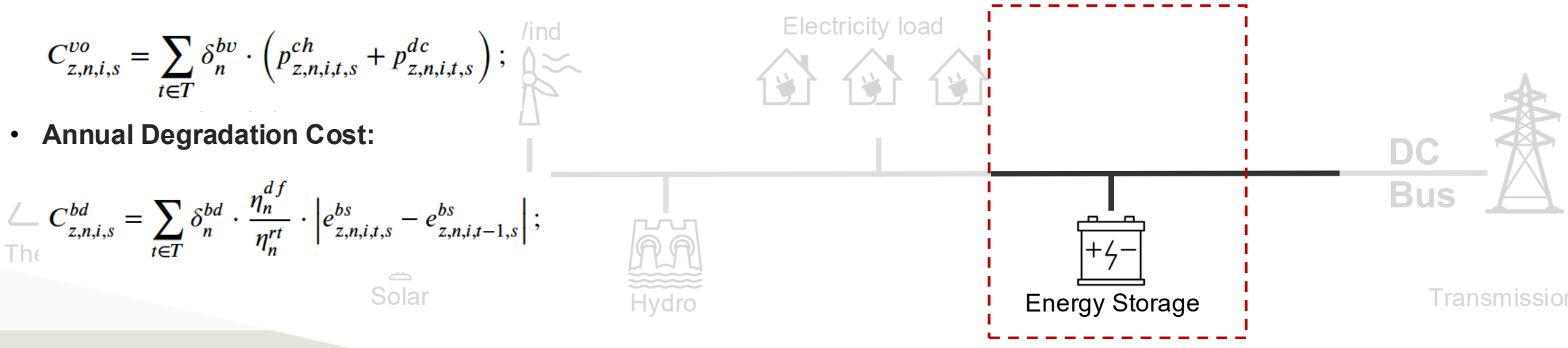
- **Annual Fixed and Variable O&M Cost:**

$$C^{fo}_{z,n,i} = \delta^{bf}_{n} \cdot \overline{p}^{bs}_{z,n,i};$$

$$C^{vo}_{z,n,i,s} = \sum_{t \in T} \delta^{bv}_{n} \cdot \left(p^{ch}_{z,n,i,t,s} + p^{dc}_{z,n,i,t,s}\right);$$

- **Annual Degradation Cost:**

$$C^{bd}_{z,n,i,s} = \sum_{t \in T} \delta^{bd}_{n} \cdot \frac{\eta^{df}_{n}}{\eta^{rt}_{n}} \cdot \left| e^{bs}_{z,n,i,t,s} - e^{bs}_{z,n,i,t-1,s} \right|;$$



Methodology Overview

- **Model Structure (BSS Capacity Expansion):**
  - **Stage 1 (Investment decisions)**: location, size, and technology of BSS.
  - **Stage 2 (Operational decisions)**: hourly dispatch optimization

$$\min \sum_{z\in Z}\sum_{n\in N}\sum_{i\in I_z}\left[C^{cc}_{z,n,i}+C^{rc}_{z,n,i}+C^{fo}_{z,n,i}\right]+\mathbb{E}\left[Q\left(\overline{p}^{bs},\xi\right)\right]$$

Subject to:

$$\sum_{z\in Z}\sum_{n\in N}\sum_{i\in I_z}\overline{p}^{bs}_{z,n,i}\le\varphi^{bs}$$

$$\overline{p}^{bs}\in\mathbb{R}^{+}$$

$$\min\ Q(\overline{p}^{bs},\xi^{s})=\sum_{z\in Z}\sum_{n\in N}\sum_{i\in I_z}\left[C^{vo}_{z,n,i,s}+C^{bd}_{z,n,i,s}\right]$$

$$+\sum_{z\in Z}\sum_{i\in G_z}\sum_{t\in T}\left[\left(\delta^{dg}_{z,g,i,t}+\delta^{co}\cdot\delta^{em}_{z,g,i}\right)\cdot p^{dg}_{z,g,i,t,s}\right]$$

$$+\sum_{z\in Z}\sum_{i\in I_z}\sum_{t\in T}\left[O\cdot p^{ls}_{z,i,t,s}\right]$$

Methodology Overview

- **Stochastic Approach:**
  - **Uncertain inputs**: RES generation and demand.
  - **Sample Average Approximation:** Balances computational tractability and solution accuracy.

Algorithm 1 The SAA method.

Step 1: Selecting random Scenarios
for $w = 1, 2, \ldots, W$ **do**
Select randomly M' scenarios from the set of M scenarios.
Solve the two-stage stochastic program with selected M' scenarios.
Achieve optimal objective h^w and first-stage decisions x^w.
for scenarios $s = 1, 2, \ldots, M$ **do**
Fix the first-stage solution x^w and solve the problem for scenario s.
Achieve the optimal objective for solution x^w and scenario s as $f^{w,s}$.
end for
Calculate the simulation response r^w as $\frac{\sum_{s=1}^{M} f^{w,s}}{M}$.
end for
Step 2: Calculate the mean and variance for the lower bound of the true objective value:

$$\mu_L = \frac{\sum_{w=1}^{W} h^w}{W}, \quad \sigma_L^2 = \frac{1}{W-1} \sum_{w=1}^{W} \left(h^w - \mu_L\right)^2$$

The $(1-\alpha)\%$ CI for the lower bound is:

$$\left[\mu_L - t_{\alpha/2,W-1} \frac{\sigma_L}{\sqrt{W}}, \mu_L + t_{\alpha/2,W-1} \frac{\sigma_L}{\sqrt{W}}\right]$$

Step 3: Calculate the mean and variance for the upper bound of the true objective value:

$$\mu_U = \min_{w=1,2,\ldots,W} \left(r^w\right)$$

$\hat{w}$ is the index related to $\min_{w=1,2,\ldots,W} \left(r^w\right)$, and

$$\sigma_U^2 = \frac{1}{M-1} \sum_{s=1}^{M} \left(f^{\hat{w},s} - \mu_U\right)^2$$

The $(1-\alpha)\%$ CI for the upper bound is:

$$\left[\mu_U - z_{\alpha/2} \frac{\sigma_U}{\sqrt{M}}, \mu_U + z_{\alpha/2} \frac{\sigma_U}{\sqrt{M}}\right]$$

Step 4: Return the final solution $x^{\hat{w}}$ for the first-stage decisions.

Cost-effectiveness metrics

Summary of cost-effectiveness metrics.

Metric	Units	Meaning
RCRCE (π^{rc})	MWh-year/$	How much renewable curtailment is avoided per $1 of BSS cost. Higher values indicate greater cost-effectiveness, reflecting more efficient utilization of RES and higher returns on investment.
LSRCE (π^{ls})	MWh-year/$	How much load shedding is avoided per $1 of BSS cost. Higher values indicate greater cost-effectiveness, reflecting more efficient supply of load and higher returns on investment.

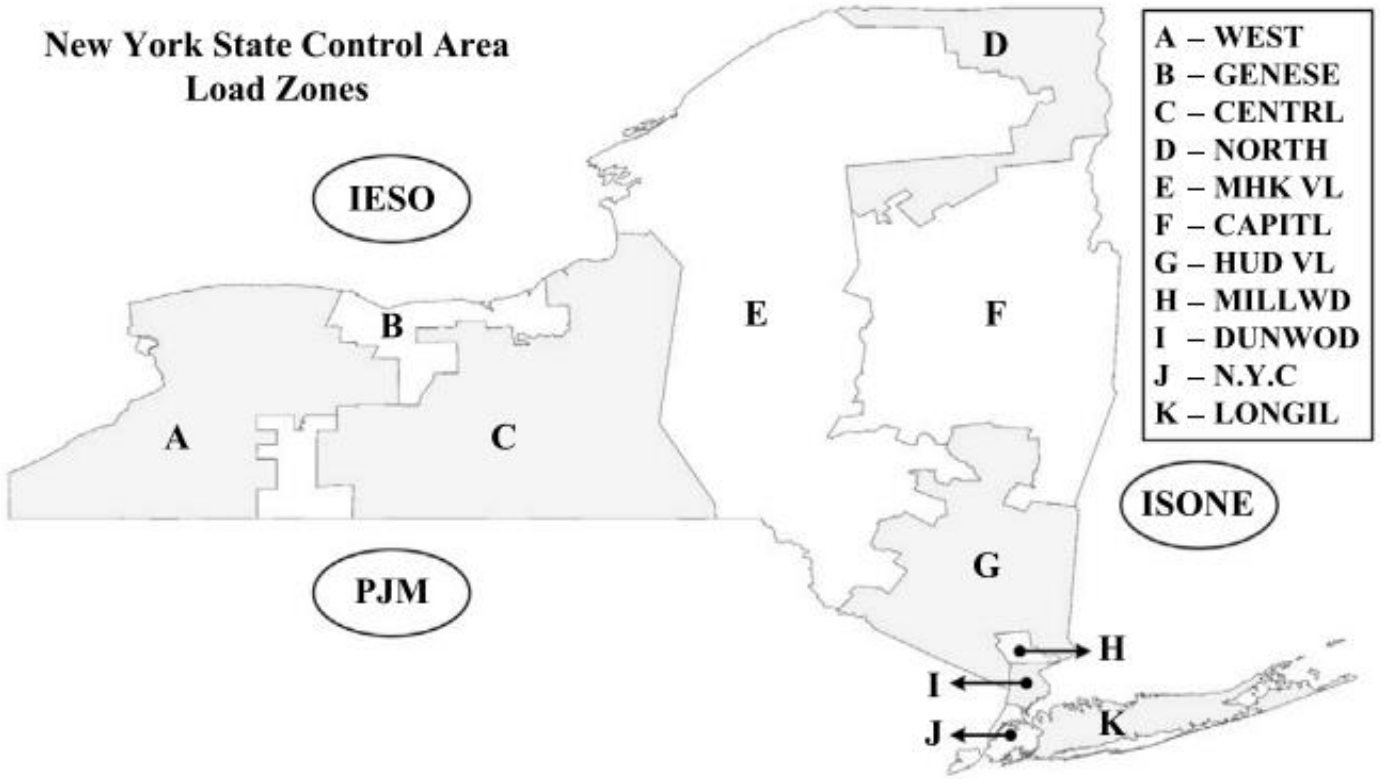
$$\pi^{rc} = \frac{1}{|S|} \cdot \sum_{s \in S} \frac{\phi_s^{rc}}{\lambda_s^{bs}}$$

$$\pi^{ls} = \frac{1}{|S|} \cdot \sum_{s \in S} \frac{\phi_s^{ls}}{\lambda_s^{bs}}$$

Case Study: 2030 NYS Grid

Case Study: 2030 NYS Grid

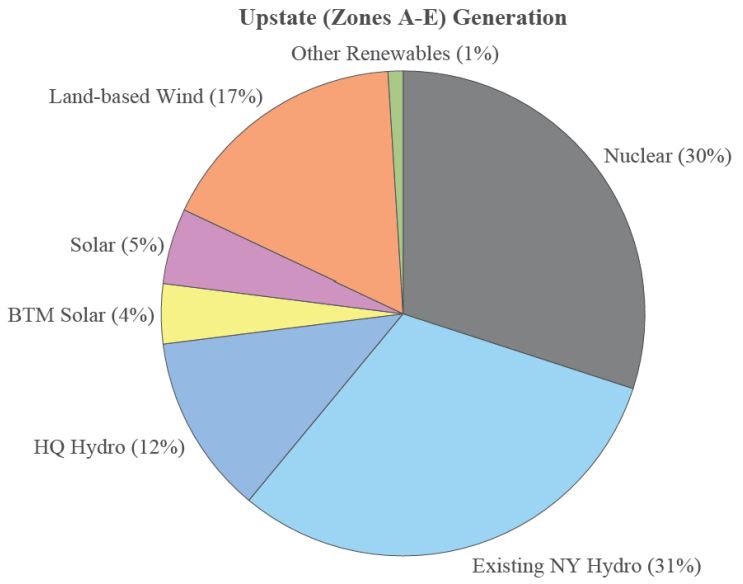
- 57-bus
- 94 transmission lines
- 6 nuclear plants



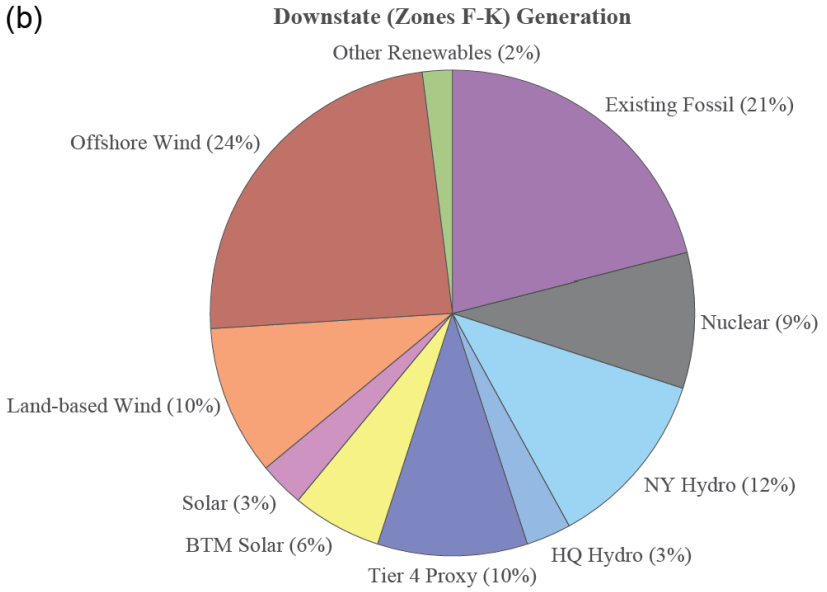
Case Study: 2030 NYS Grid

- CLCPA targets: **Upstate 100%** and **Downstate 80%** zero-emission.
- **Renewable Resources:** Onshore & Offshore Wind Power, Distributed & Utility-Scale Solar Power, Big and Small Hydro Power Plants.

(a)



(b)



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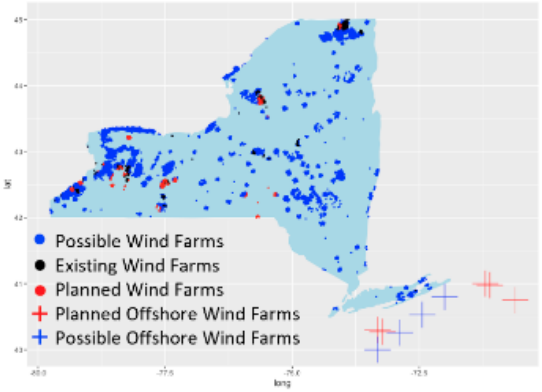
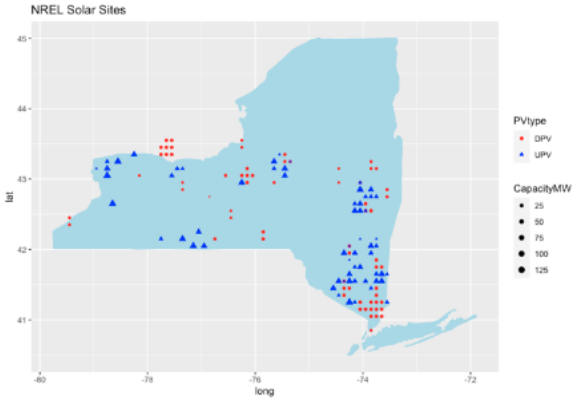
Zonal RES capacity.

Resource (MW)	Zones											Total
	A	B	C	D	E	F	G	H	I	J	K	
Land-Based Wind	2692	390	1923	1935	1821	–	–	–	–	–	–	8761
Offshore Wind	–	–	–	–	–	–	–	–	–	6391	2609	9000
UPV solar	5748	656	3585	–	2268	4661	2636	–	–	–	77	19631
DPV solar	704	218	596	69	673	827	684	61	90	672	846	5439
Hydro	2675	64	109	915	376	270	76	–	–	–	–	4485



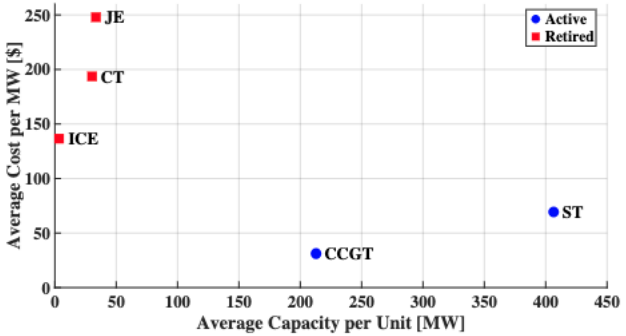
Wind farms

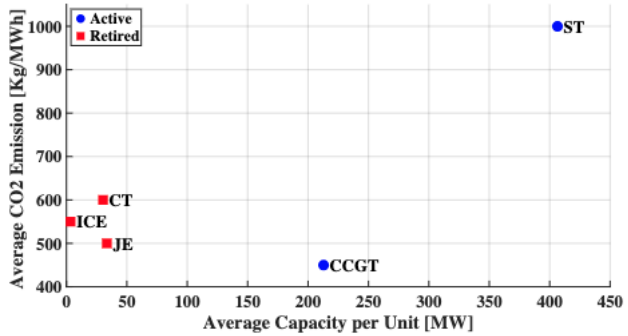


solar sites

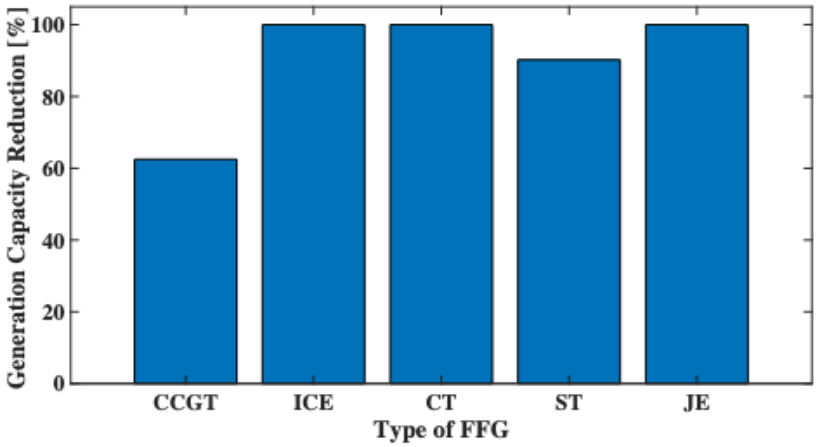
Case Study: 2030 NYS Grid

227 thermal generators (2019)
- Combined Cycle Gas Turbines (CCGTs)
- Steam Turbines (STs)
- Jet Engines (JEs)
- Combustion Turbines (CTs)
- Internal Combustion Engines (ICEs)





Optimal retirement of thermal generators (2030)



Generation capacity reduction from FFG retirements.

BSS Technologies

- **BSS Technologies:** Sodium-Sulfur, Lithium-ion, Lead-Acid, Zinc-Bromine, Vanadium Redox Flow, Sodium Metal Halide (ZEBRA).

Technical and economic characteristics of BSS technologies applied in this paper.

	BSS Technology		NaSB	LiB	LAB	ZEBRA	ZnBrB	VRFB
Economic Char.	*Capital Cost*	*Energy Capacity* ($/kWh)	465	189	220	482	192	393
		Power Conversion System ($/kW)	211	211	211	211	211	211
		Balance of Plant ($/kW)	95	95	95	95	95	95
		Construction and Commissioning ($/kWh)	127	96	167	110	164	180
	Replacement Cost ($/kWh)		199.8	409.59	190.92	202.02	216.45	144.3
	Fixed O&M Cost ($/kW-yr)		3.96	7.59	3.74	6.05	4.73	9.35
	Variable O&M Cost ($/MWh)		1.98	2.31	0.407	0.66	0.66	0.99
Technical Char.	*Storage Duration* (Hours)		2–8	2–8	2–8	2–8	2–10	2–12
	RTE		0.75	0.85	0.72	0.83	0.72	0.7
	Discharge Efficiency		0.85	0.85	0.85	0.85	0.78	0.7
	Maximum *DoD*		0.9	0.8	0.65	0.9	1	1
	Self-Discharge per Day (%)		0.05	0.2	0.08	0.3	0	0.15
	Annual RTE Degradation Factor (%)		0.34	0.5	5.4	0.35	1.5	0.4
	Cycling Limit at 80 % DoD		4000	3500	900	3500	3500	10000
	Operational Lifetime (Years)		13	10	3	12	10	15

Main Result and insights

Results & Insight - BSS Planning

- Sample Average Approximation

Statistical results for different values of M'. $\alpha = 0.05$, $M = 40$, and $W = 20$

M'	μ_U	σ_U	CI for LB	CI for UB	Gap (LB–UB) (%)
3	1.6191×10^{10}	0.2402×10^{10}	$(1.2935,\ 1.5578) \times 10^{10}$	$(1.5446,\ 1.6953) \times 10^{10}$	23.7 %
5	1.6169×10^{10}	0.2567×10^{10}	$(1.3814,\ 1.5831) \times 10^{10}$	$(1.5373,\ 1.6964) \times 10^{10}$	18.5 %
7	1.6166×10^{10}	0.2436×10^{10}	$(1.4986,\ 1.6889) \times 10^{10}$	$(1.5411,\ 1.6920) \times 10^{10}$	11.4 %

Results & Insight - BSS Planning

- **Impact of Stochasticity (weather variability)**

  Recourse Problem (RP),
  Wait-and-see (WS) Solution,
  Expected Value of Perfect Information (EVPI),
  Expected value of deterministic objectives across scenarios (EEV),
  Value of the Stochastic Solution (VSS)

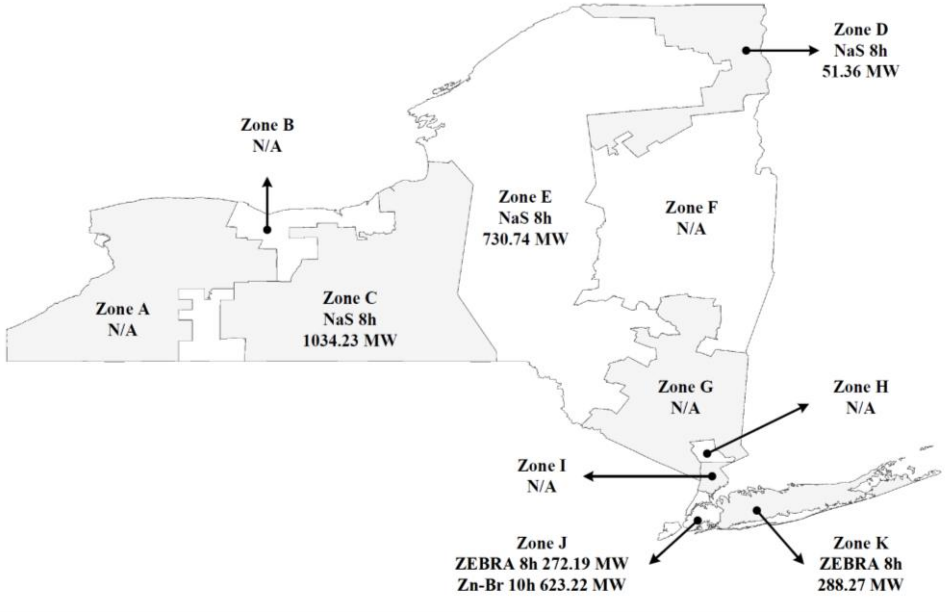
Values of RP, WS, EVPI, EEV, and VSS for the *Main Strategy* with 3000 MW *Rated Power capacity*.

RP	WS	EVPI	EEV	VSS
1.6166×10^{10}	1.6147×10^{10}	1.8915×10^{7}	1.9728×10^{10}	3.5613×10^{9}

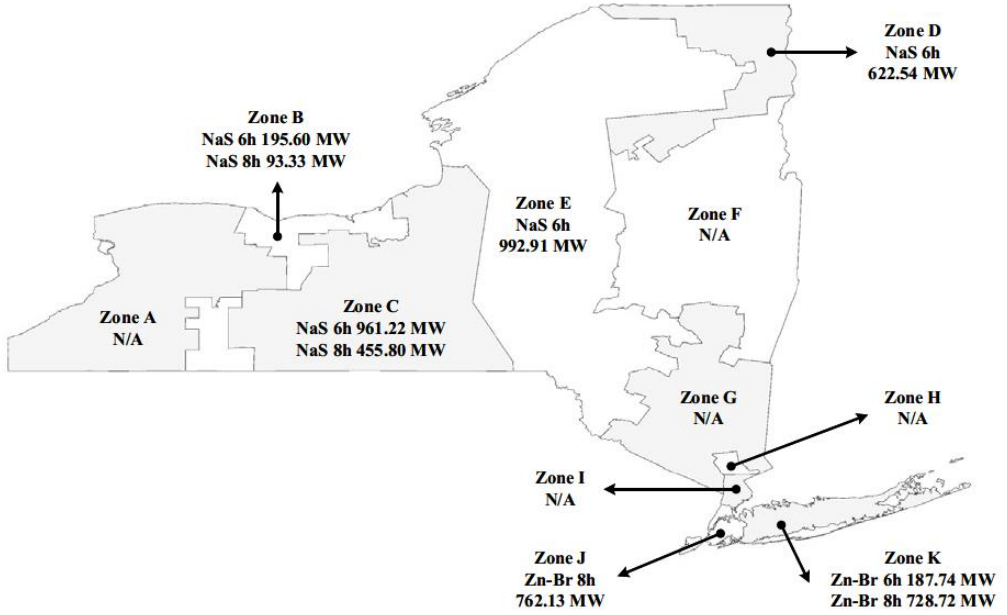
➢ A large VSS (≈22% of RP) shows that modeling load and renewable uncertainty is crucial for optimal BSS allocation.

Results & Insight - BSS Planning

- **Technology Deployment:**
  - ✓ BSS is most valuable where RES supply exceeds demand—especially when transmission to neighboring zones is limited.
  - ✓ **NaSB** (low cost, high duration) in Zones C–E (upstate).
  - ✓ **ZEBRA & ZnBrB** (high RTE) in Zones J–K (downstate with offshore wind).



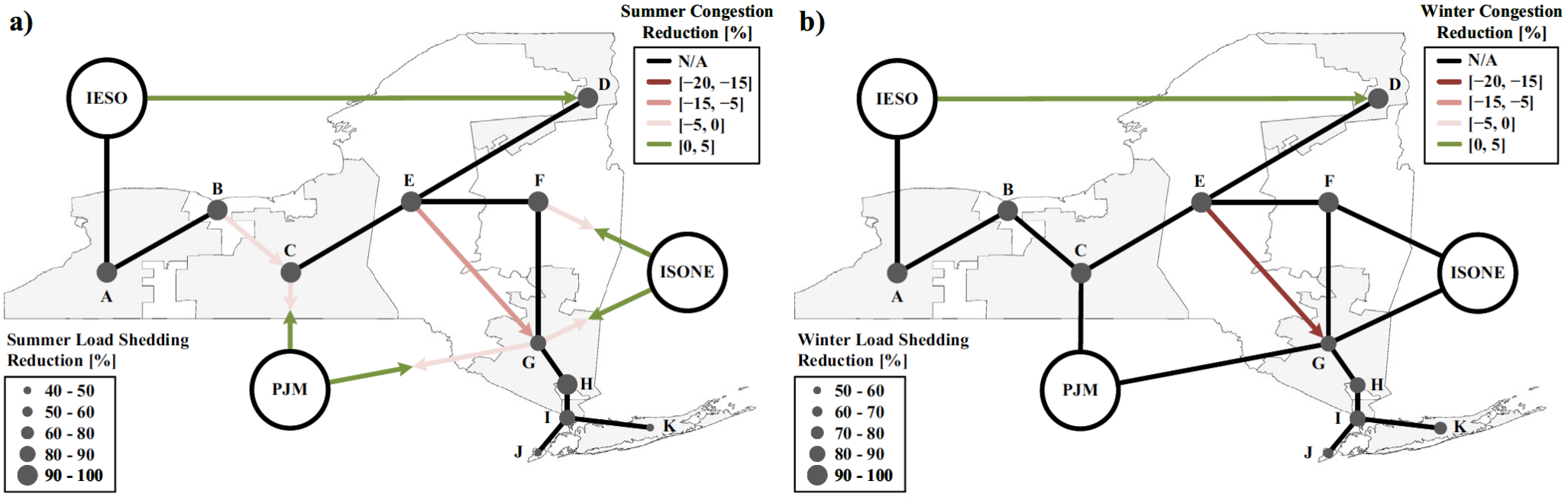
3000 MW rated power capacity.



5000 MW rated power capacity.

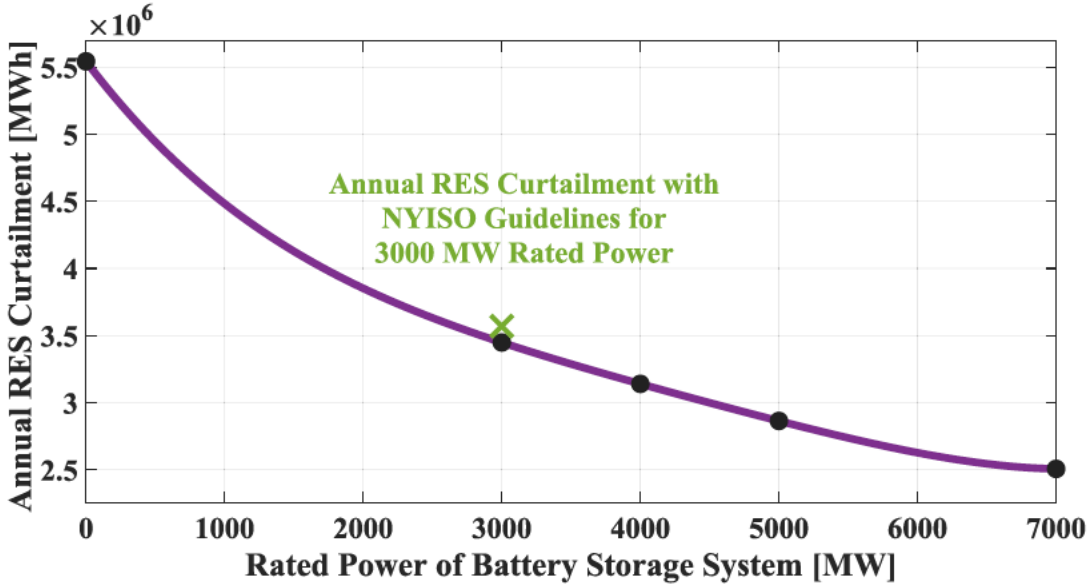
Results & Insight - BSS Planning

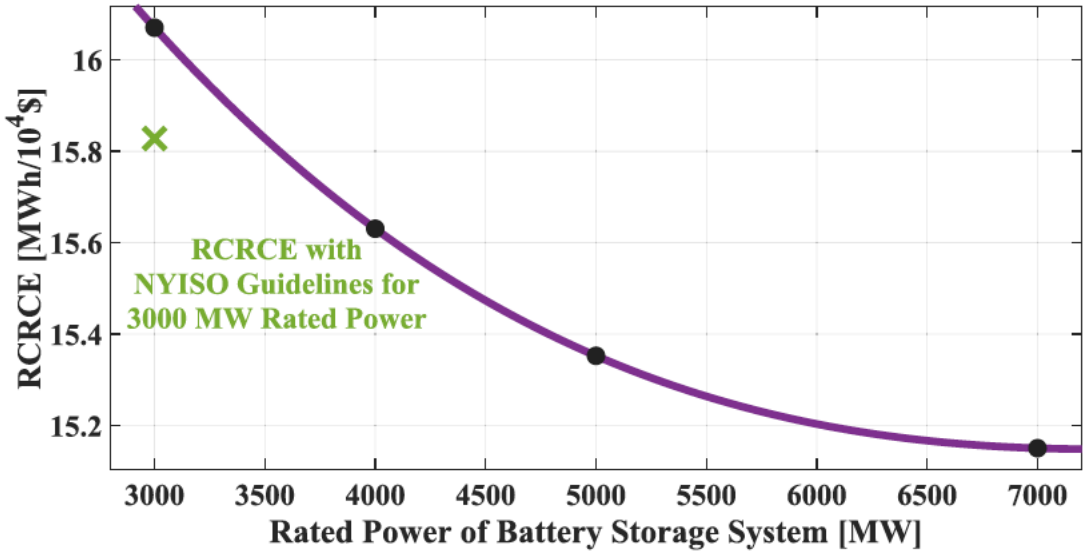
- Impact of BSS Integration (3000 MW)



Results & Insight - BSS Planning

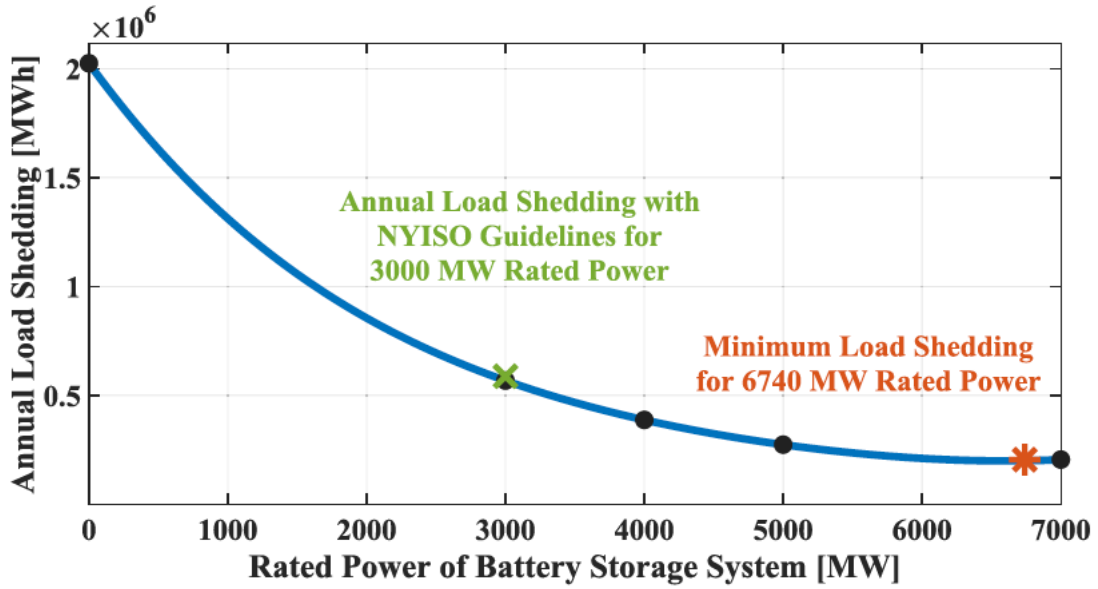
- **Impact of BSS capacity on RES Curtailment:**
  - ✓ **Further** reduction in curtailment (3000 MW → 7000MW).
  - ✓ **Non-linear cost relationship**: higher capacity vs. returns in efficiency.

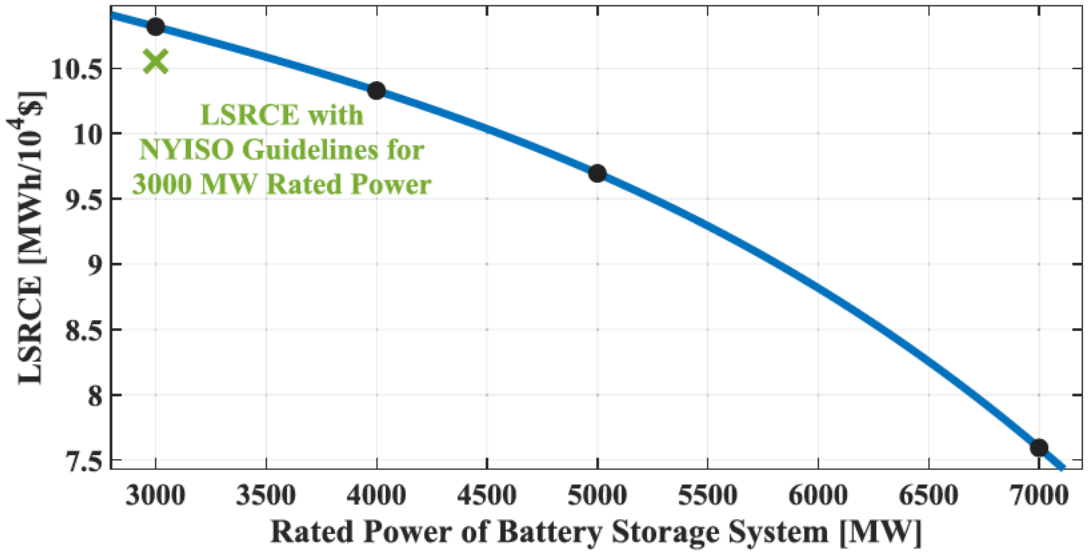




Results & Insight - BSS Planning

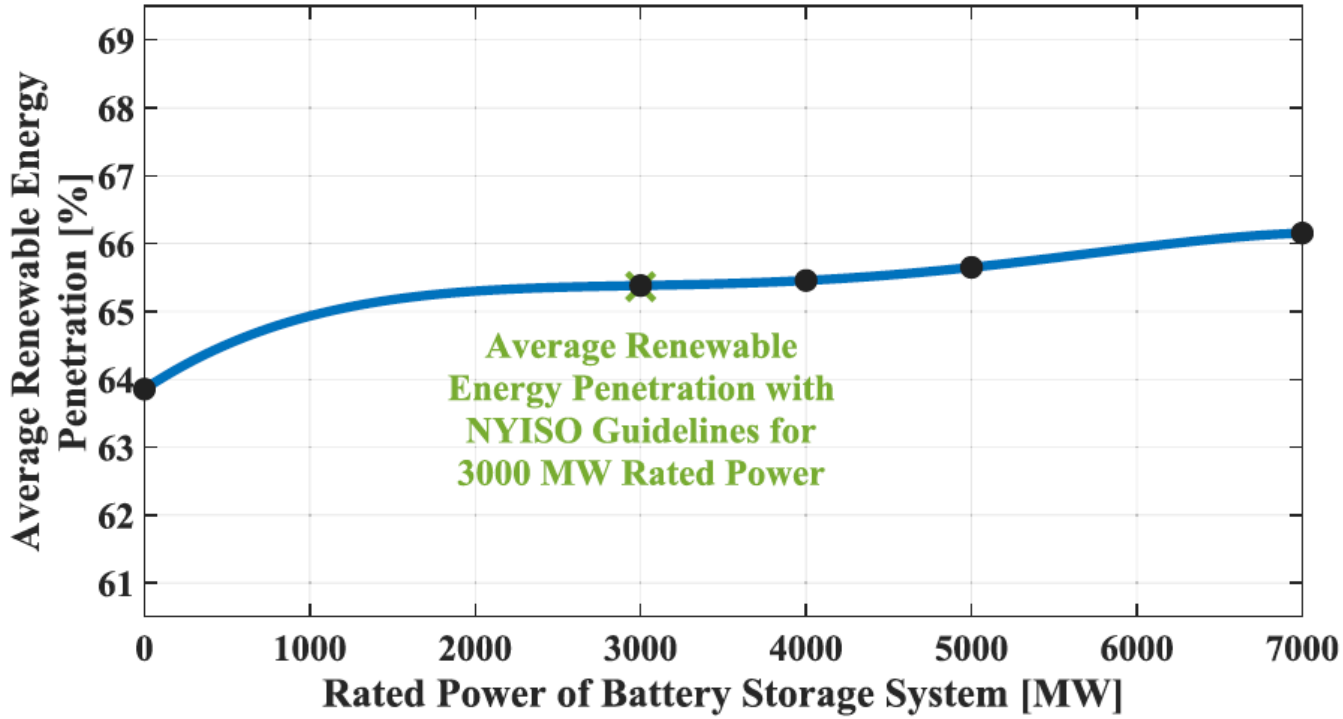
- **Impact of BSS capacity on Load Shedding:**
  - ✓ **Further** reduction in load shedding (3000 MW → 7000MW).
  - ✓ **Non-linear cost relationship**: higher capacity vs. returns in efficiency.





Results & Insight - BSS Planning

- Impact of BSS capacity on RES Penetration Level:



Average renewable energy penetration for different rated power capacities of BSS.

Summary & Concluding Remarks

- **Cost-Effectiveness Trends:**
  - **LSRCE & RCRCE decline with larger BSS capacity.**
  - Efficiency gains plateau due to **grid bottlenecks and diminishing returns**.
- **Limits of BSS-Only Strategy:**
  - BSS alone cannot meet 70% RES target.
  - Transmission upgrades or hybrid solutions are required.
- **Actionable Recommendations:**
  - **Targeted BSS siting** in congested, high-curtailment areas.
  - Combine BSS with **infrastructure upgrades** and **grid-side innovation**.

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THANK YOU

Kabir Research Group