Future Energy Systems Center

April 2, 2024

Interim Project Update:

Uncertainty-Aware Power-Natural Gas System Planning under Deep Decarbonization Scenarios

System impacts of decarbonization pathways for space heating in cold climates



Project Team

Principal Investigators



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MITEI

Senior Postdoctoral Associate

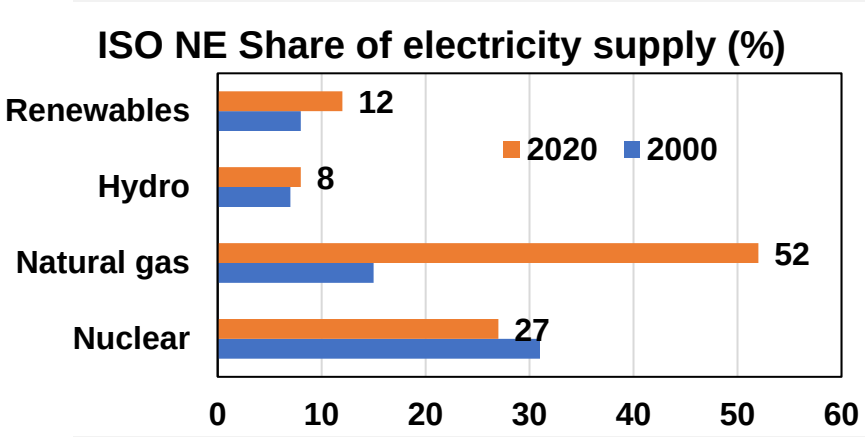


Rahman Khorramfar
MITEI and LIDS

Project motivation and objectives

Motivation

- Since 2005 to 2021, share of NG-based power generation in the electricity generation mix doubled to 38%[1] [EIA energy facts]
- Increasing variable renewable energy (VRE) generation changing role of natural gas power generation on the grid
- Planning of electricity and NG infrastructure is becoming more coupled owing to the growing policy interest in electrification for achieving economy-wide decarbonization by mid-century




WINTER STORM 2021

Texas largely relies on natural gas for power. It wasn't ready for the extreme cold.

BY ERIN DOUGLAS FEB. 16, 2021 3 PM CENTRAL

Objectives

1. Evaluate impact of joint power-gas planning on the infrastructure outcomes
2. Impact of inter-annual weather variation on supply and demand under different electrification and carbon constraints
3. Explore role for emerging supply (e.g. long-term storage) and demand-side technologies (e.g. envelope improvements)
4. What is the role uncertainty in the joint power-gas planning?
5. What are the resiliency implications of alternative decarbonization pathways?

1. U.S Energy Information administration
2. Data sourced from https://www.iso-ne.com/static-assets/documents/2021/08/neppa_gvw_aug_2021_final.pdf

Joint Power-NG Expansion Model under Decarbonization Scenarios (JPoNG)

Minimize CAPEX and OPEX (Power + NG)

Residential demand Model + NREL EFS demand data for other sectors[1]

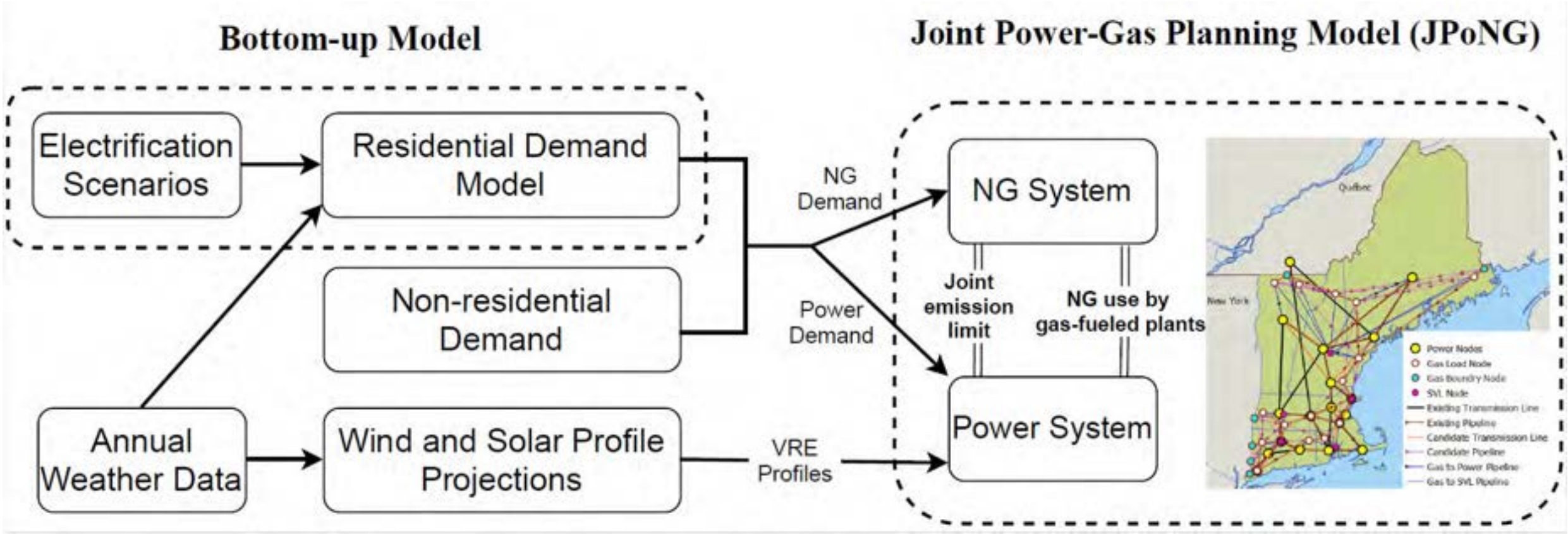
Power System (hourly, over rep. days):
- **Investment** (new plants and transmission lines), **operational**
- **Policy**: RPS, resource availability,
- **Other**: CCS with dedicated pipelines
- Li-ion + **Long-duration** energy storage (**LDES**)

NG System (daily, over rep. days):
- **Investment** (new pipelines), **operational**
- Biogas
- Other: **Storage/Vaporization/Liquefaction** facilities
- Strategic decommissioning of pipelines

Coupled by:
1. **Gas consumption in power system**
2. **Emission limit**

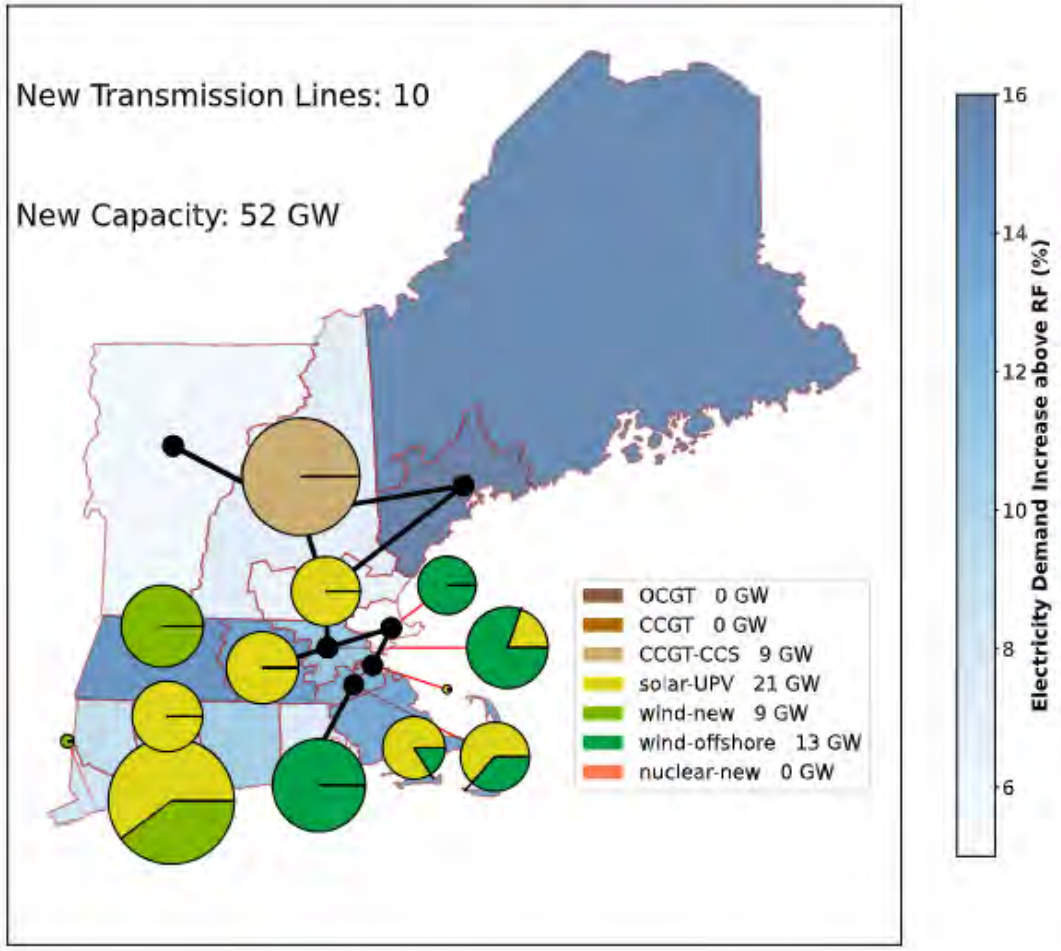
Key Model Parameters:
- Import gas price: **5.25$**/MMBtu
- Shedding cost: **10k$**/MWh-MMBtu
- WACC: **7.1%**
- Biogas cost: **20 $**/MMBtu

Overview of the modeling framework

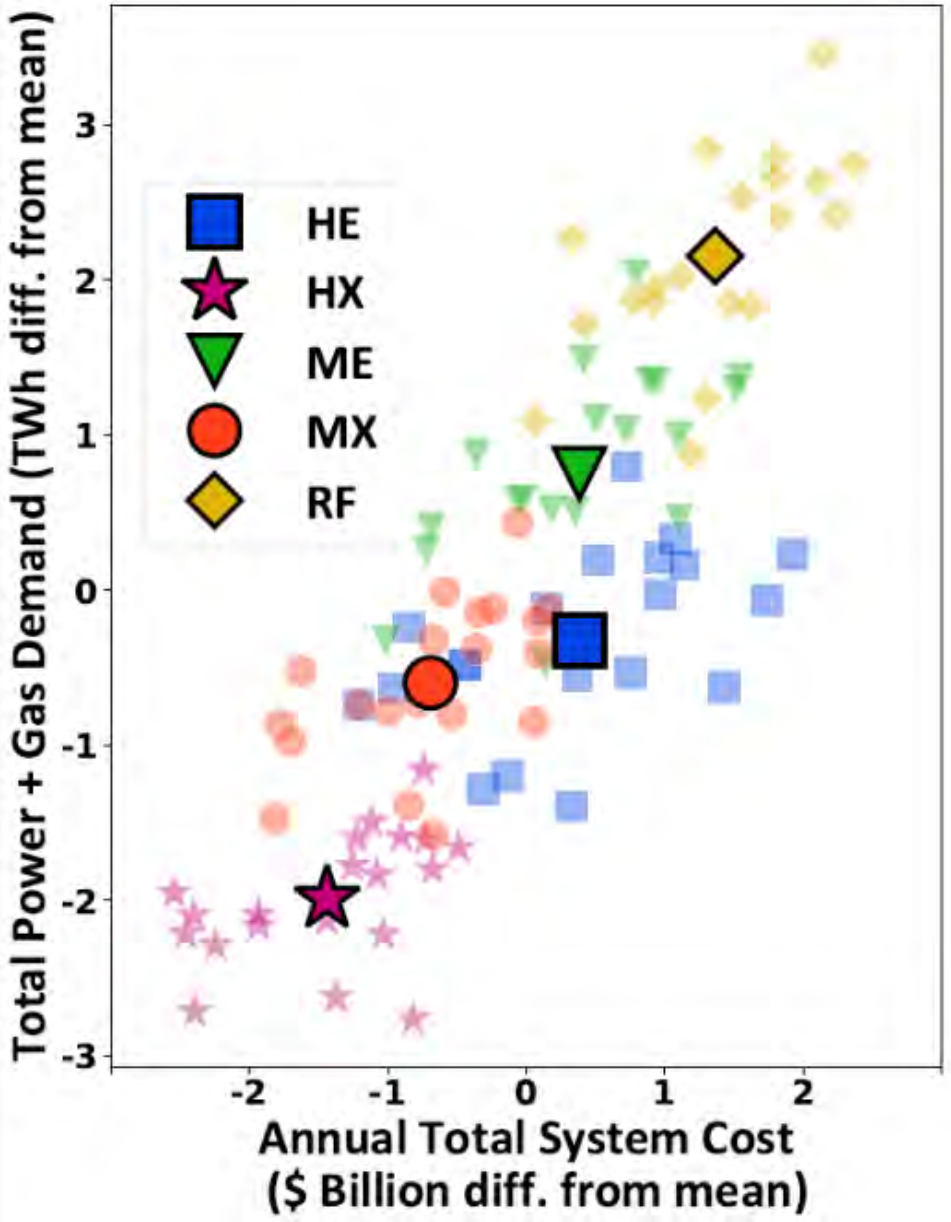


5 electrification levels, 20 different projections of power/gas load and capacity factors for the year 2050, New England

Impacts of Inter-annual variation (80% emissions reduction)



Installed capacity for WY=2003, HE scenario



Many More Results

- Total and peak load under each electrification level
- Capacity addition, generation mix, cost components, and import of fuel (biogas+NG)
- Length of peak load
- Sensitivity to CCS technology
- Renewable NG (low-carbon fuel) supply curve
- Impact of methane leakage
- Flexibility of light-duty vehicle

- Impact of long-duration battery storage

Cost-effective Planning of Decarbonized Power-Gas Infrastructure to Meet the Challenges of Heating Electrification

Rahman Khorramfar[1,2†], Morgan Santoni-Colvin[1†], Saurabh Amin[2,3], Leslie K. Norford[4], Audun Botterud[2] and Dharik Mallapragada[1*]



Applied Energy

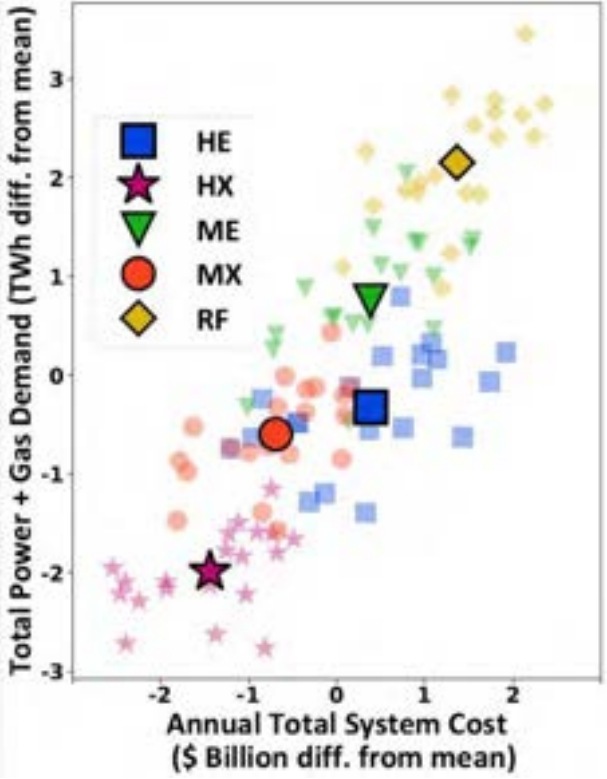
Volume 354, Part A, 15 January 2024, 122176



Electric-gas infrastructure planning for deep decarbonization of energy systems

Rahman Khorramfar [a], Dharik Mallapragada [b], Saurabh Amin [c]

Motivation



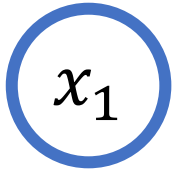
- Which planning outcome should be selected?
- How to model uncertainty in power-gas loads and renewable profiles?
- How to reflect the risk level of stakeholders?
- How to model extreme events/weather years?
- What are the resiliency implications of alternative decarbonization pathways?

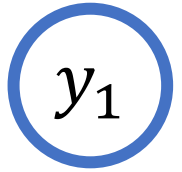
Different Paradigms to Characterize Uncertainty

Run each scenario independently and select the costliest realization

Investment decisions x

Operational decisions y





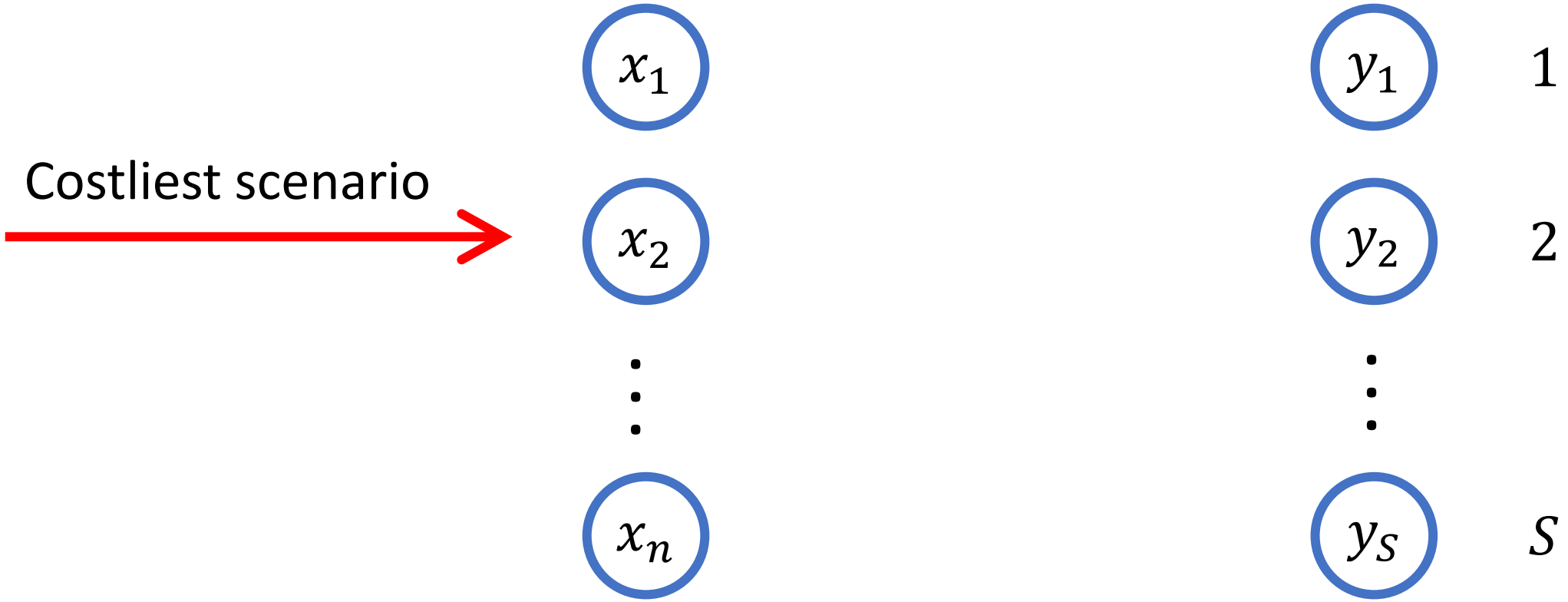
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Different Paradigms to Characterize Uncertainty

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Different Paradigms to Characterize Uncertainty

Investment decisions x

Operational decisions y

Stochastic Programming (SP):

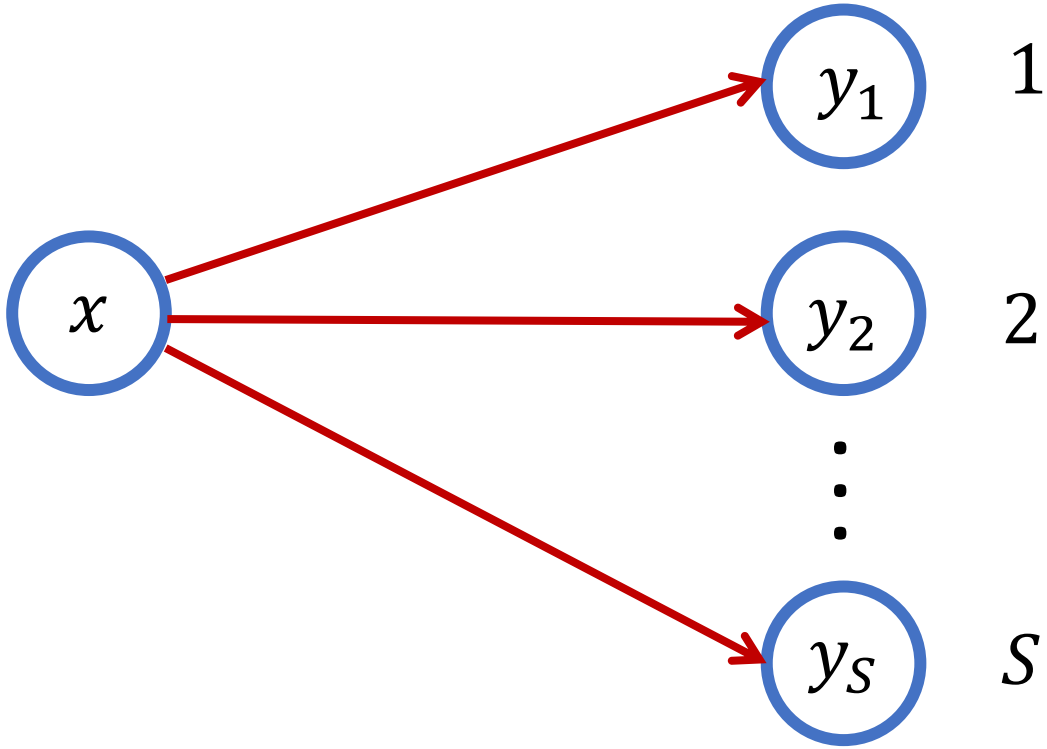
- The available scenarios fully characterize the underlying distribution
- The goal is to hedge against the expected realization of scenarios
- With discrete distribution:

$$\min_{x,y} c^1 x + \sum_{s \in S} p_s c_s^2 y_s$$

$$Ax = b$$

$$Tx + Wy = h$$

$$x \in Z \times R, \qquad y \in R$$



What about Risk-awareness

Varied risk-awareness

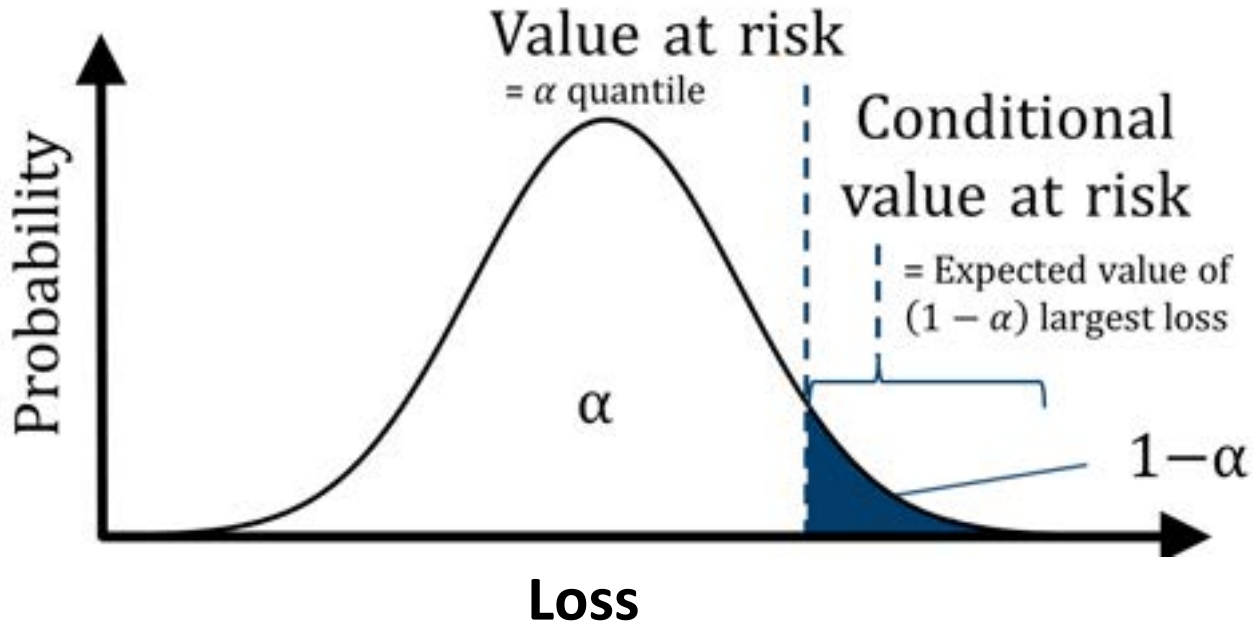
Higher emphasis on the worst $(1-\alpha)\%$ of outcomes (higher $\alpha \rightarrow$ risk-averseness)

$$\min_{x,y} c^1 x + \lambda \sum_{s \in S} p_s c_s^2 y_s + (1-\lambda) CVaR^{\alpha}$$

$$Ax = b$$

$$Tx + Wy = h$$

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What about Risk-awareness

Varied risk-awareness

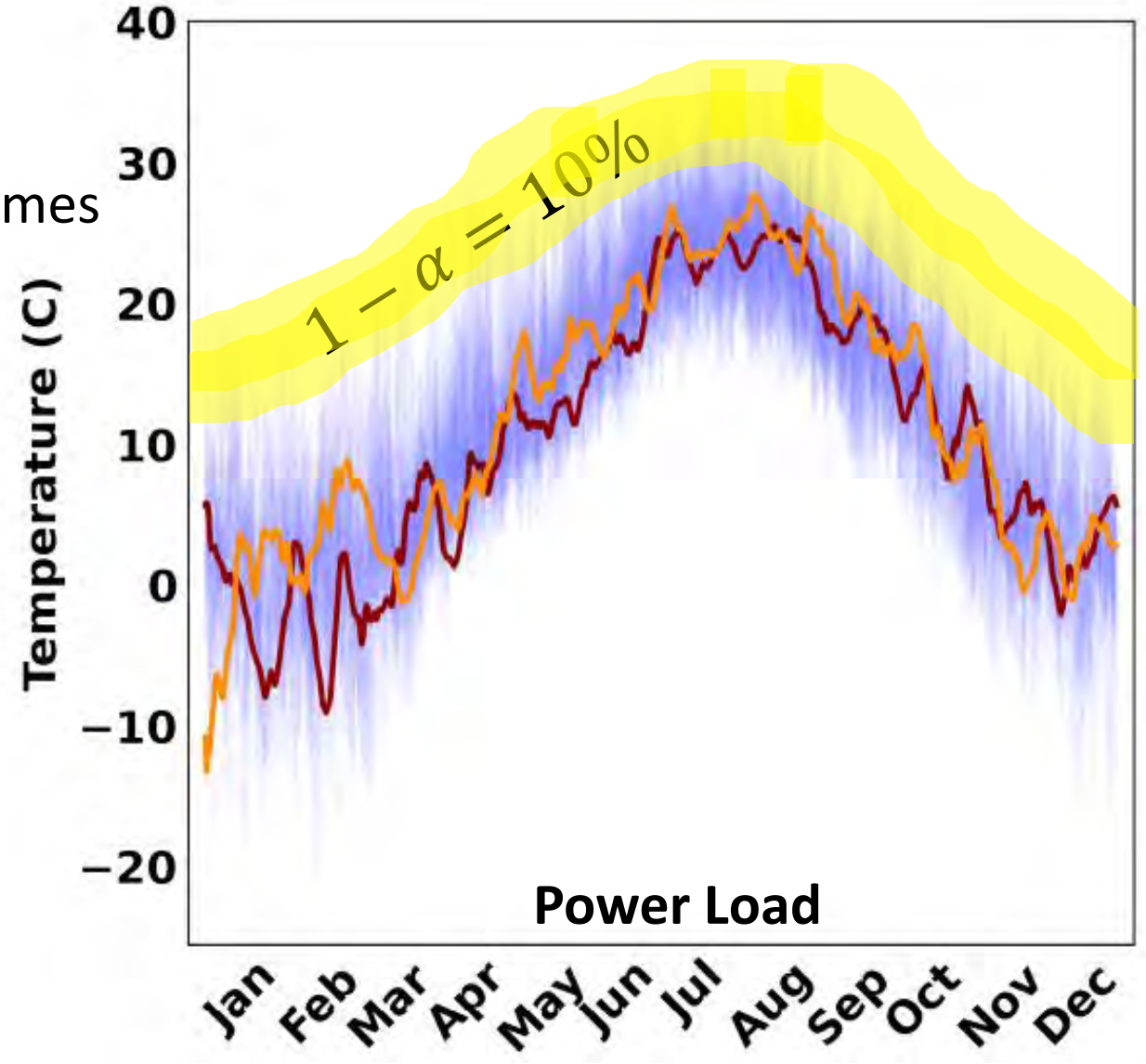
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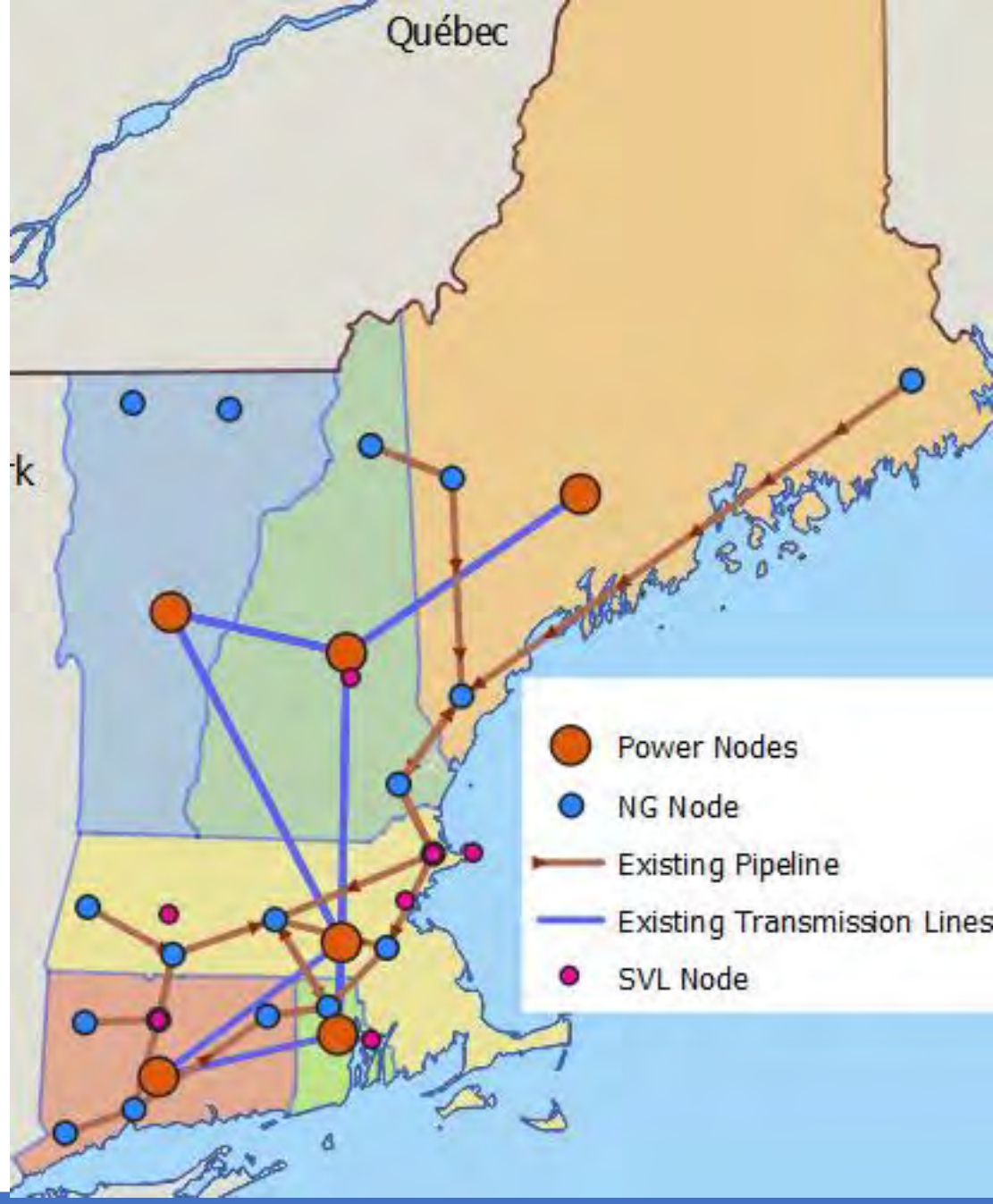
$$x \in Z \times R, \qquad y \in R$$



Analysis and Results

- New England region for 2050
- Up to 20 load/CFs scenarios with equal probabilities
- Power System: 6 nodes, 33 high-voltage lines, 5 and 7 existing and new plant types
- NG: 23 gas nodes, 5 storage nodes, 83 lines

- 5 electrification scenarios
- Power system with hourly resolution
- NG system with daily resolution



Stochastic Programming vs. Deterministic Problem (capacity)

$$\min_{x,y} c^1 x + \lambda \sum_{s \in S} p_s c_s^2 y_s + (1-\lambda) CVaR^{\alpha}, \lambda = 1$$

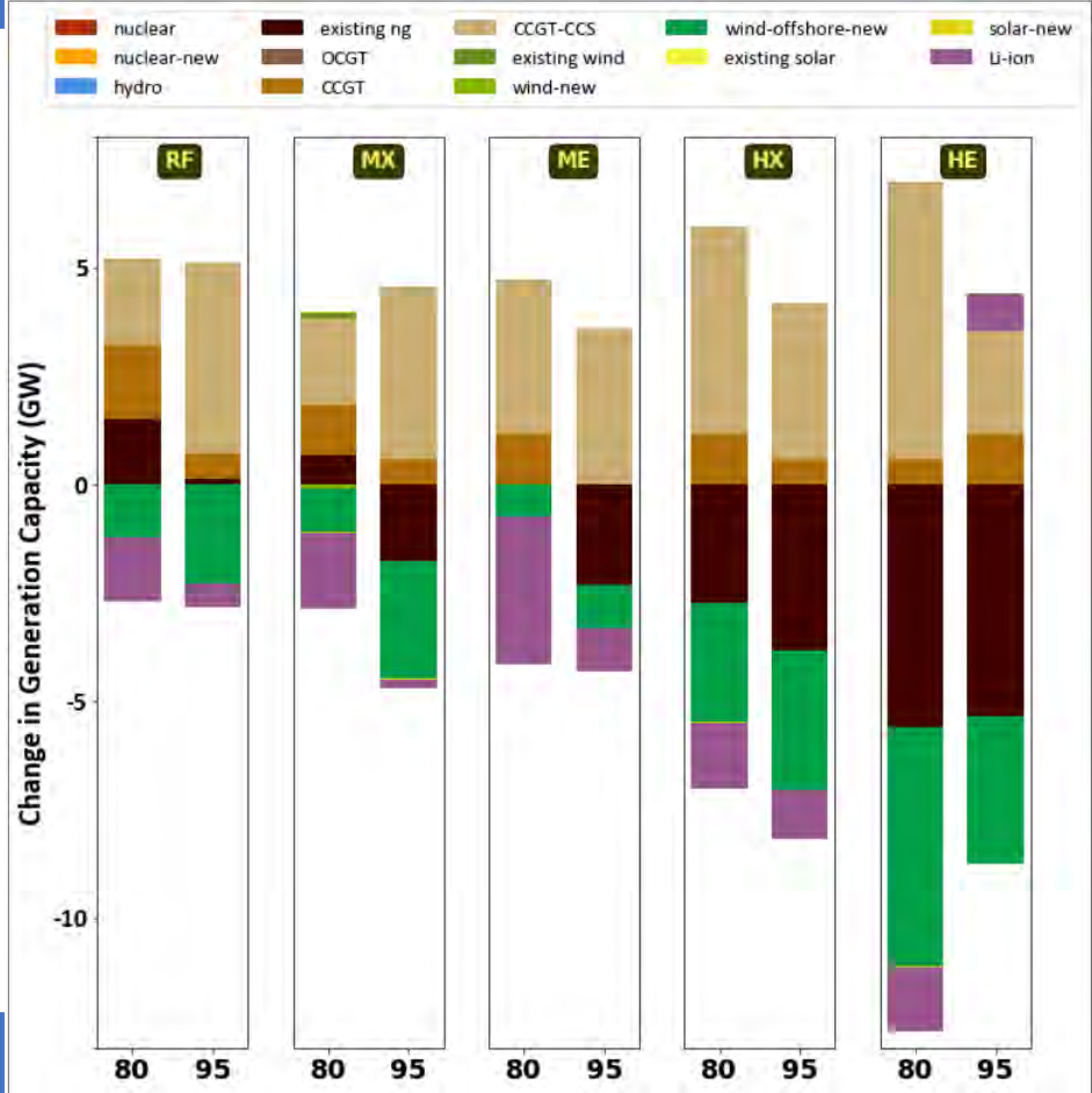
Deterministic problem is the scenario with the highest combined power-gas load

Going to SP:

- Existing gas capacity replaced by CCGT-CCS and CCGT
- Less offshore wind and generally less storage

Cost diff: (SP-Det)/Det

- ME **-1.5**% under 80% goal and -1% under 95%
- HX **2.2**% under 80% goal and 0.5% under 95%
- HE 0.5% under 80% goal and -0.5% under 95%



MITei

Risk-awareness

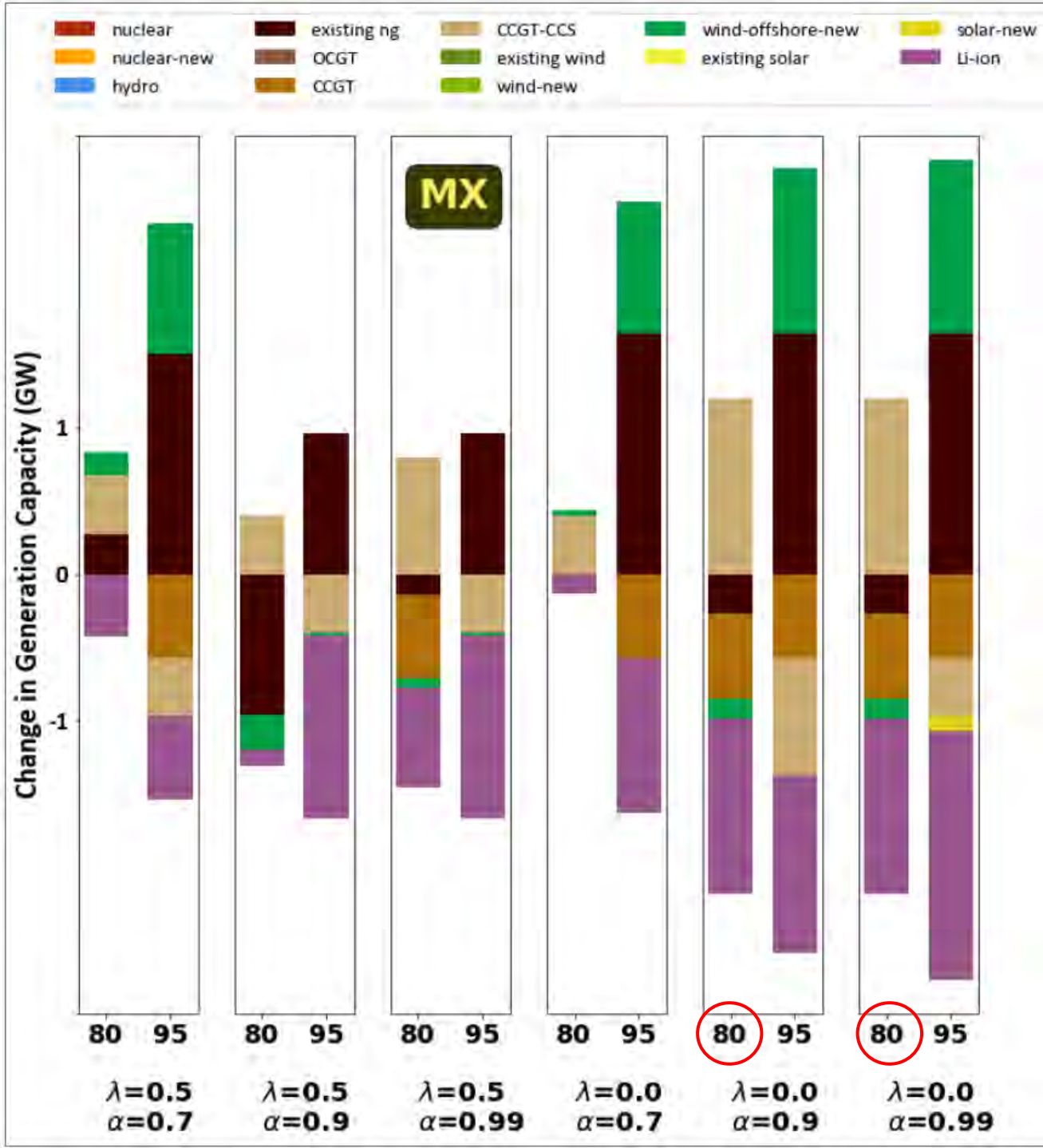
$$\min_{x,y} c^1 x + \lambda \sum_{s \in S} p_s c_s^2 y_s + (1-\lambda) CVaR^{\alpha}$$

Difference vs the case where $\lambda = 1$

- Risk awareness (low or high) increases the total system cost

- 80% decarbonization target:
  - More CCGT-CCS
  - Less storage and unabated gas capacity
- 95% decarbonization target:
  - More existing gas fleet and offshore wind
  - Less storage and new gas capacity

- Cost increase more sensitive under 80%
- Diminishing impact of increase in α
- Total system cost increase by up to **5%**



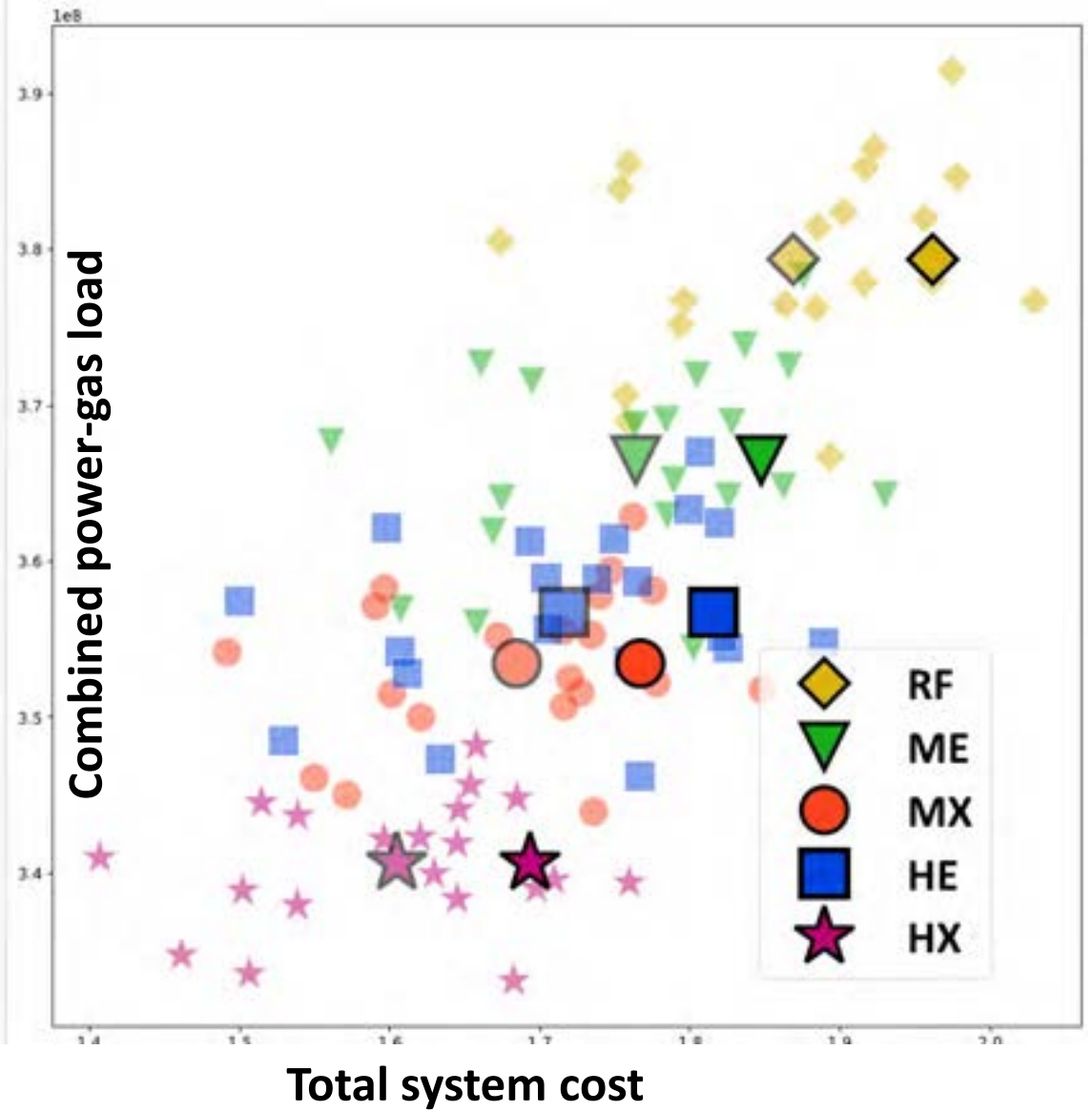
Value of planning under uncertainty

Cost diff: (SP-Det)/Det

- ME -1.5% under 80% goal and -1% under 95%
- HX 2.2% under 80% goal and 0.5% under 95%
- HE 0.5% under 80% goal and -0.5% under 95%

Total cost in **SP** vs. the **mean cost** across all scenarios
RF: 4%, ME: 4.7%, MX: 4.9%, HE: **5.8%,** HX: 5.52%

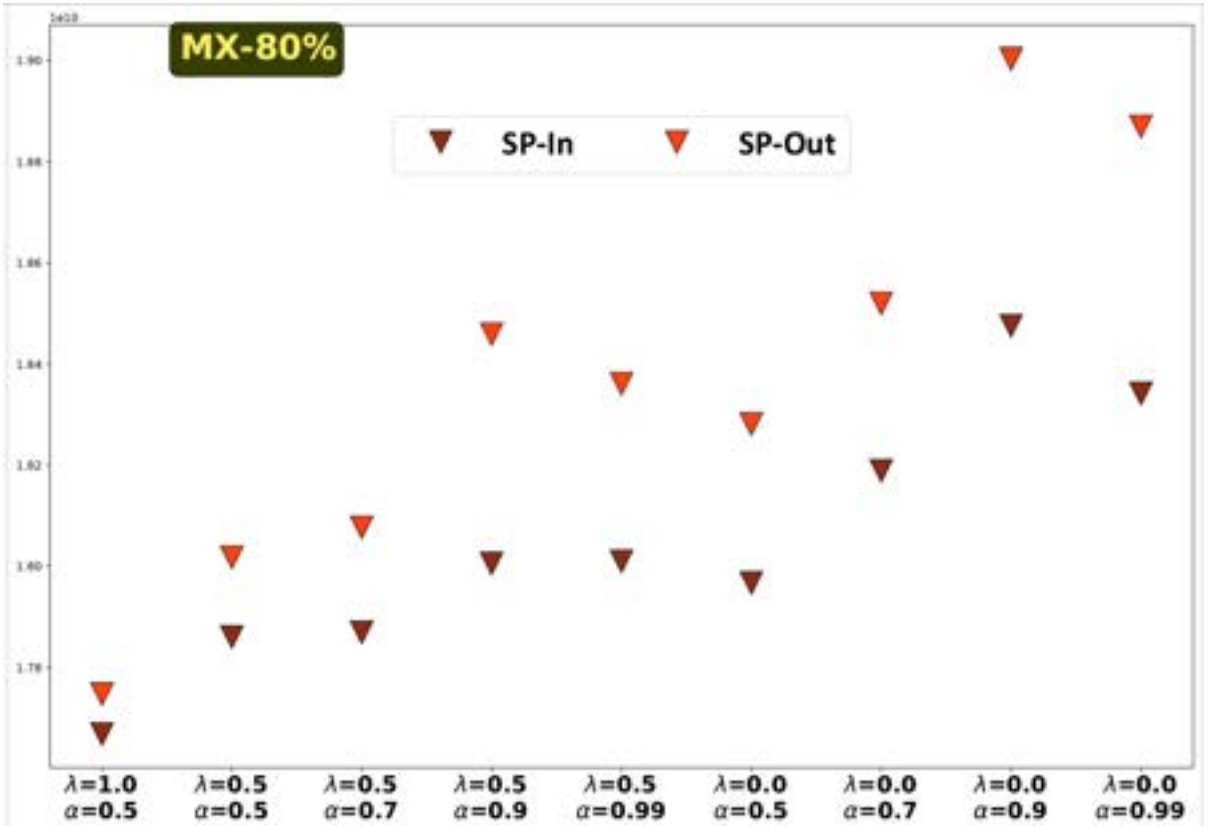
Value of Stochastic Solution (**VSS**): 60-100%
Expected Value of Perfect Information (**EVPI**): 2-5%

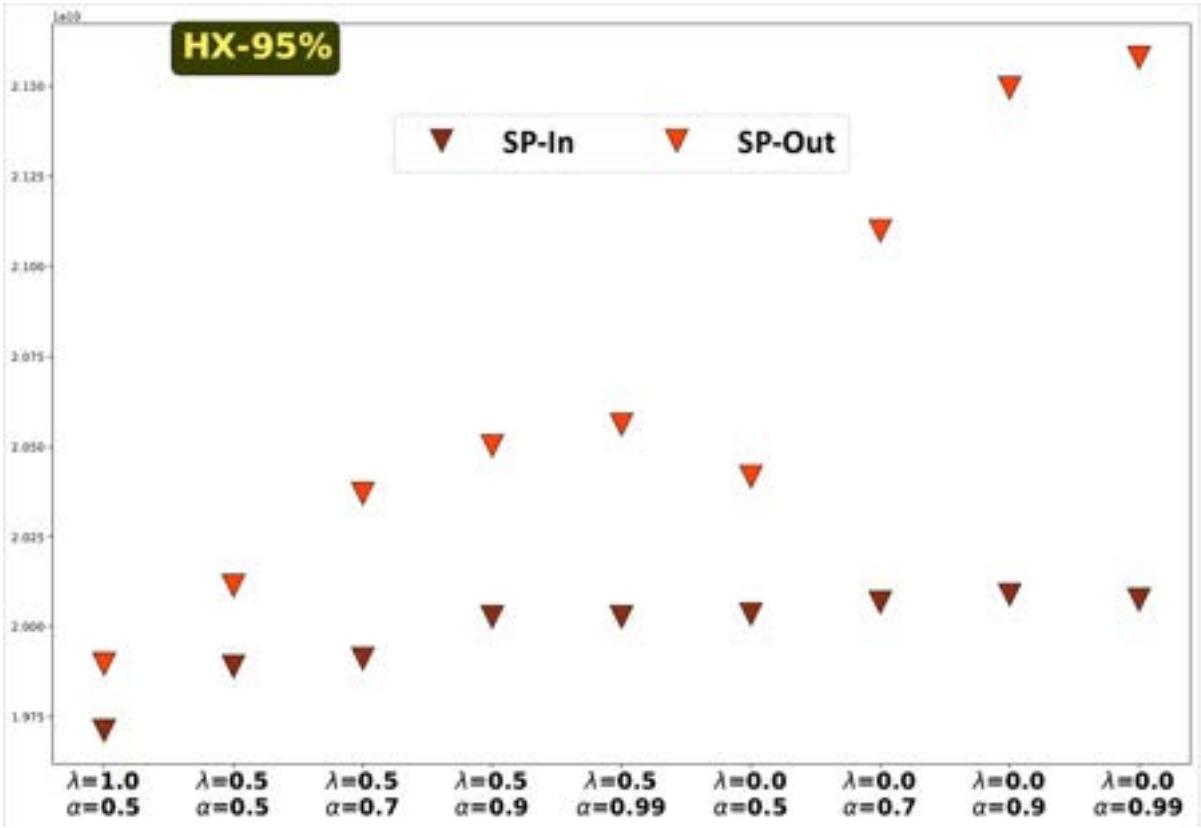


Out of Sample Performance

In sample: solve SP for the first 10 scenarios

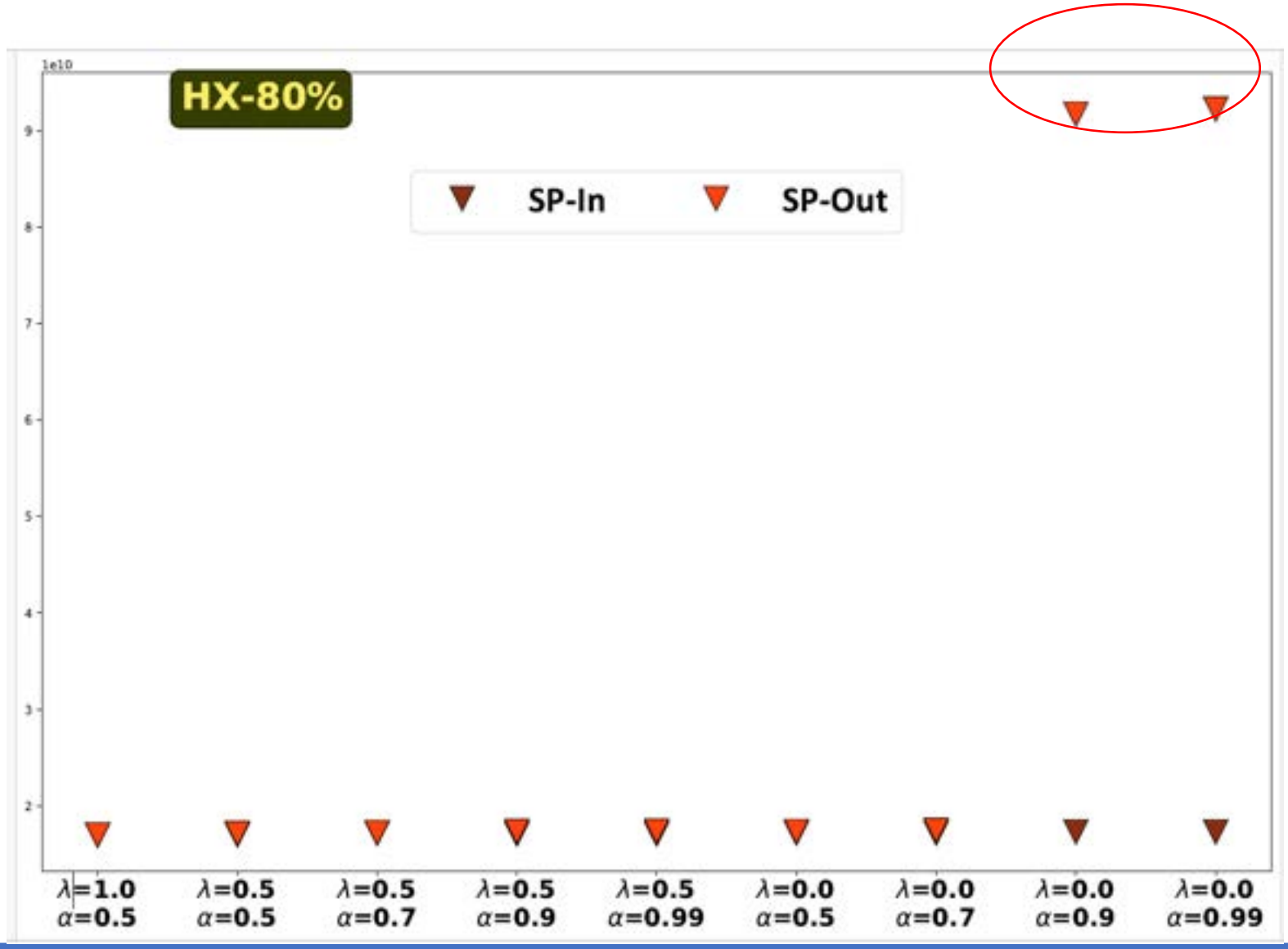
Out-of-sample: Given the investment decisions from in-sample instance, solve the SP for the next 10 scenarios





Out of Sample Performance

Poor out-of-sample performance due to extreme scenarios or higher risk-averseness

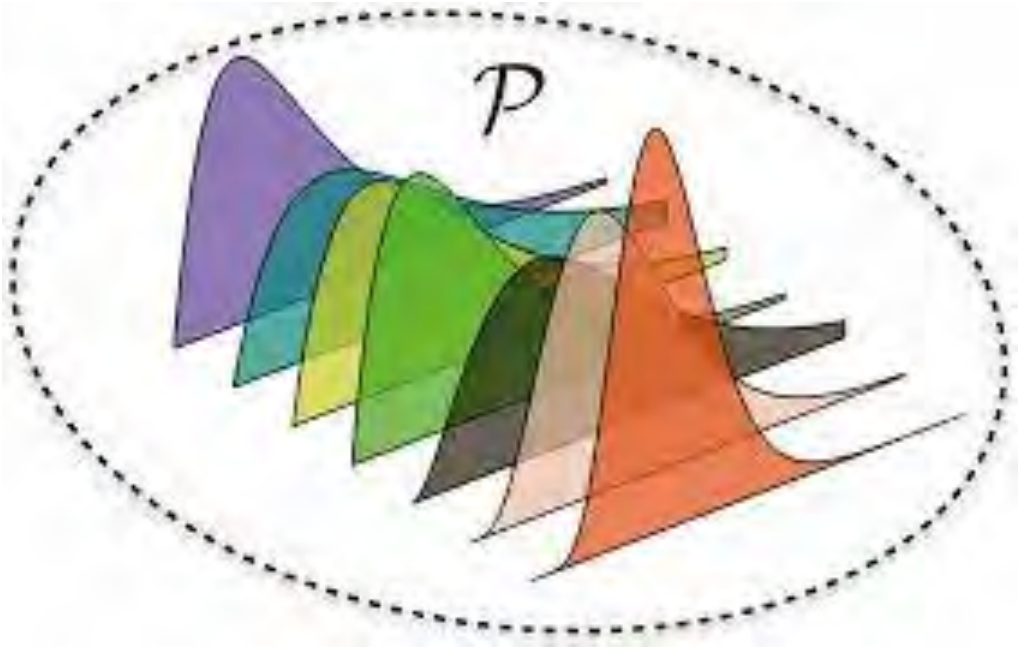


Different Paradigms to Characterize Uncertainty

distributionally robust optimization (DRO):

- The available scenarios only provide partial information about the possible distribution
- The goal is to hedge against the **worst** realization among potential distributions
- Ambiguity set can be defined to incorporate variety of extreme events

$$\min_{x} c^1 x + \max_{p \in P} (\lambda c_s^2 y + (1-\lambda) CVaR^{\alpha})$$



Takeaways

- Overlooking uncertainty in energy supply and demand can be **misleading**
- Risk awareness of energy planners can considerably impact energy outcomes, especially the share of dispatchable resources
- SP approach can yield significantly different outcomes, with usually higher system cost

Next Steps:

- Enhance scalability of problems (a decomposition algorithm with good performance is developed for SP)
- Other criteria than least system cost (resiliency, robustness, reliability)
- Generative ML methods to synthesize extreme scenarios

Acknowledgment: This work is supported by

- MITEI Future Energy System Center
- MIT Climate Grand Challenge “Preparing for a new world of weather and climate extremes”

Thank You!

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Results:

1. Importance of uncertainty
   - Value of stochastic solution
   - Value of DRO solution (pending)
   - Expected value of perfect information for SP
   - Expected value of perfect information for DRO (pending)
2. Robustness
   - In sample and out-of-sample performance
   - Misplaced performance
3. SP vs DRO (outcomes of the model, what asset are importance in DRO etc.)
4. Impact of risk measure and uncertainty
   - Total bulk system cost
   - Which assets hedge more against uncertainty/risk-awareness (pending)