



# Task G6-3: Enhance Resilience Modeling

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# Overview

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- Objective and Motivation
- Challenges in Including Resilience in Coordinated Expansion Planning (R-CEP)
- Capturing Interdependencies between Resilience and Normal Investments
- Designer-specified Emphasis on Resilience Investments
  - Investment mix identified by the optimizers
  - Weighting resilience investments
  - Applying events with various severity levels
- Conclusions and Ongoing Work

# Objective & Motivation

## Objective:

Account for the extreme events in the long-term expansion planning to avoid billion-dollar costs in damages and outages.

Billion-dollar events to affect Iowa from 1980 to 2024 (CPI-Adjusted)

Disaster Type	Events	Events/Year	Percent Frequency	Total Costs	Percent of Total Costs
Drought	16	0.4	18.6%	\$10.0B-\$20.0B	25.5%
Flooding	8	0.2	9.3%	\$20.0B-\$50.0B	38.3%
Freeze	2	0.0	2.3%	\$5M-\$100M	0.1%
Severe Storm	57	1.3	66.3%	\$20.0B-\$50.0B	35.7%
Tropical Cyclone	--	--	--	--	--
Wildfire	--	--	--	--	--
Winter Storm	3	0.1	3.5%	\$100M-\$250M	0.4%
All Disasters	86	1.9	100.0%	\$50.0B-\$100.0B	100.0%

Extreme conditions like Cold/heat waves, very low wind, and overcast sky could be modeled by GE-MARS within ACEP scenarios.

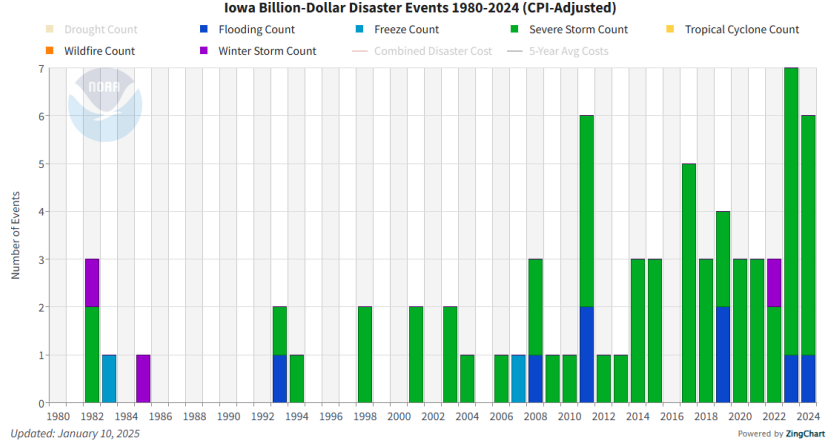
## Motivation:

Severe storms are the most frequent extreme events in Iowa, imposing significant damage to the power system.

We model two Derechos as the extreme events in our studies.

Hardening transmission structures reduces failure rates of transmission lines during high wind events.

The benefits of transmission line hardening can be evaluated by the resilience-based coordinated expansion planning tool.



# Challenges in Including Resilience in Coordinated Expansion Planning (R-CEP)

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- ❖ Hard to justify resilience investments:
  - Benefits are rare, uncertain, and hard to quantify
  - Benefit-cost ratios often look unsatisfactory compared to normal investments
  - Relies on designer judgment to balance resilience vs. normal investments
- ❖ Extreme events modeling
  - Sparse, biased histories: hard to build location-realistic normative events and capture geography
  - Requires modeling of spatial/temporal dependencies and correlated outages
  - Rare-event probabilities are difficult to estimate without scenario explosion in Monte Carlo simulations.
- ❖ Complexities in resilience modeling
  - Adding binary variables introduces mixed-integer complexity
  - Interdependencies between resilience and normal investments complicate optimization
  - Non-linearity emerges when modeling multiple investment options

# Interdependencies between Normal and Resilience Investments

- Coordinating line expansion and resilience investments enables better system performance during both normal and extreme conditions.

	Res-Candidate Lines		Non Res-Candidate Lines		Generation
	Line Capacity	Resilience level	Capacity	Resilience level	
Normal yrs	Yes	No	Yes	No	Yes
Derecho yrs	Yes	Yes – gets derated	Yes	No	Yes



**Normal line rating = Initial + expanded capacity**  

$$NR_l = NR_{l_0} + \Delta NR_l$$

**Initial resilience level      New resilience level**  

$$FP_{l,cum}^0 \rightarrow FP'_{l,cum}$$

Event Line rating for an expanded and hardened line:

*Non-linear form:*

**Variable**

$$ER_l = (1 - FP'_{l,cum}) * NR_l$$

*Linear approximation:*

$$ER_l = (1 - FP'_{l,cum}) * NR_{l_0} + (1 - FP_{l,cum}^0) \Delta NR_l$$

**Variable**

# Interdependencies between Normal and Resilience Investments

- ❖ In the base model, line ratings during derecho years were based on original thermal limits, ignoring capacity expansion to avoid non-linearity  $ER_l = (1 - FP'_{l,cum}) * NR_{l_0}$
- ❖ Expansion investments, however, also improve system resilience.
- ❖ To coordinate capacity and resilience, we add expansion variables to extreme years, allowing expanded capacity use during derecho events.  $ER_l = (1 - FP'_{l,cum}) * NR_{l_0} + (1 - FP^0_{l,cum})\Delta NR_l$
- ❖ Coupling resilience and expansion decisions helps identify investments that boost both normal and resilient operations, making them more attractive to policymakers.

Case	Objective (\$B)	Generation Inv.	Line Inv.	Resilience Inv.
Not capturing interdependencies	1286.29	286.18	3.84	16.57
Capturing interdependencies	1284.52	286.30	4.32	14.79

- ✓ Coupling resilience and expansion decisions results in capturing normal investment benefits to resilience performance.
- ✓ This helps identify investments that boost both normal and resilient operations, making them more attractive to policymakers.

# Designer-specified Emphasis on Resilience Investments

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- Resilience vs normal investments can be handled by the optimizer with different approaches:
  - a. Optimizing across technologies that improve one, the other, or both for the specified events
  - b. Adjusting resilience investments by a dial to identify investments that boost both normal and resilient conditions ( $\Gamma$ )
  - c. Controlling the frequency and severity of extreme events during the planning horizon (**transmission derates**) to reflect planners' tolerance for extreme event risk and explore how investment priorities shift accordingly

## Minimize costs of:

- Gen & Tran Capacity Investment
- +  $\Gamma$  \* Transmission Resilience Investment
- + Fixed and Variable
- + Reserve
- + Retirement
- + load shedding (normal + events)

## Subject to:

- Generation limits
- Transmission thermal limit
- Transmission derates (k)**
- Power flow (DC)
- Binary resilience levels

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Case	Objective (\$B)	Generation Inv.	Line Inv.	Resilience Inv.	Load-shed
Normal Condition (no event)	1271.94	282.93	3.89	0	0
No resilience investments	1282.51	282.93	3.89	-	7.46
With resilience investments	1278.17	284.25	4.16	5.89	0

- ✓ Ignoring extreme events in the long-term planning causes billion-dollar costs to the system
- ✓ Resilience investments and normal investments should be coordinated
- ✓ Normal investments can also benefit system resilience

# Designer-specified Emphasis on Resilience Investments

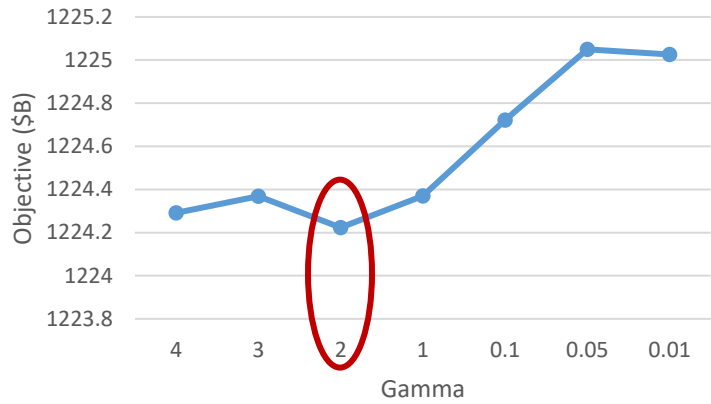
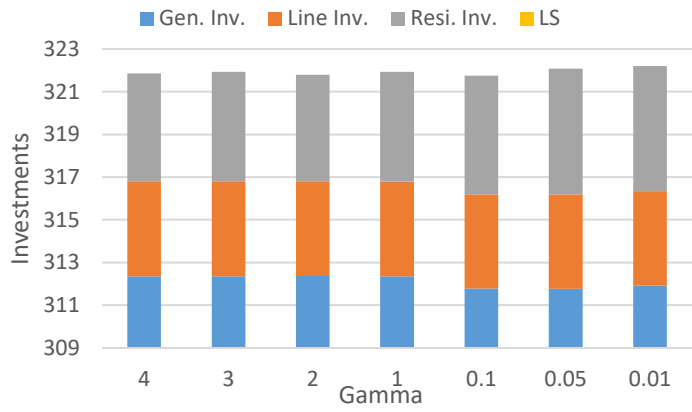
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- ✓ Increasing  $\Gamma$  reduces resilience investments which causes the optimizer to increase normal investments to compensate for extreme events
- ✓ Applying  $\Gamma$  as a dial reveals an inflection point where the marginal benefit of added resilience reduces, which we use as a marker for a justified resilience investment level

# Designer-specified Emphasis on Resilience Investments

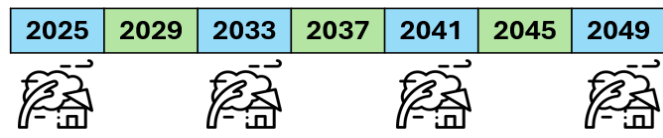
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- ✓ Initially, normal and event years were treated separately, with independent investment decisions
- ✓ With the interdependencies captured, all years can have events with different severities and have the option to invest in normal and resilience investments simultaneously
- ✓ Planners can shape the system's resilience performance by choosing the mix of events, i.e., the frequency, severity, location, and geographical expanse, used across the planning horizon

## Conclusions:

- a) With the increased frequency and severity of extreme events, it is important to plan for resilience investments to avoid outage costs.
- b) Resilience investments are hard to justify because of their uncertain and rare benefits.
- c) Resilience investments and normal long-term planning investments should be coordinated.
- d) Normal investments benefit resilience performance making it easier to justify resilience improvements.
- e) Using a dial for resilience investments helps planners to adjust relative emphasis on normal vs resilience investments.

## Ongoing work:

- Considering a HVDC ring around Iowa
- Study benefits of energy storage systems
- Include extreme conditions
- Event representation: normative vs Monte Carlo
- R-ACEP with RA