PIE Project, Report 6. **Integrating resilience (for extreme events) into an expansion planning framework: Formulation and Next Steps**

Task G6-3: Enhance resilience modeling

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Contents

Co-optimized Expansion Planning (CEP): Concept

Exploratory,
not predictive.

TODAY

2024

2029

2034

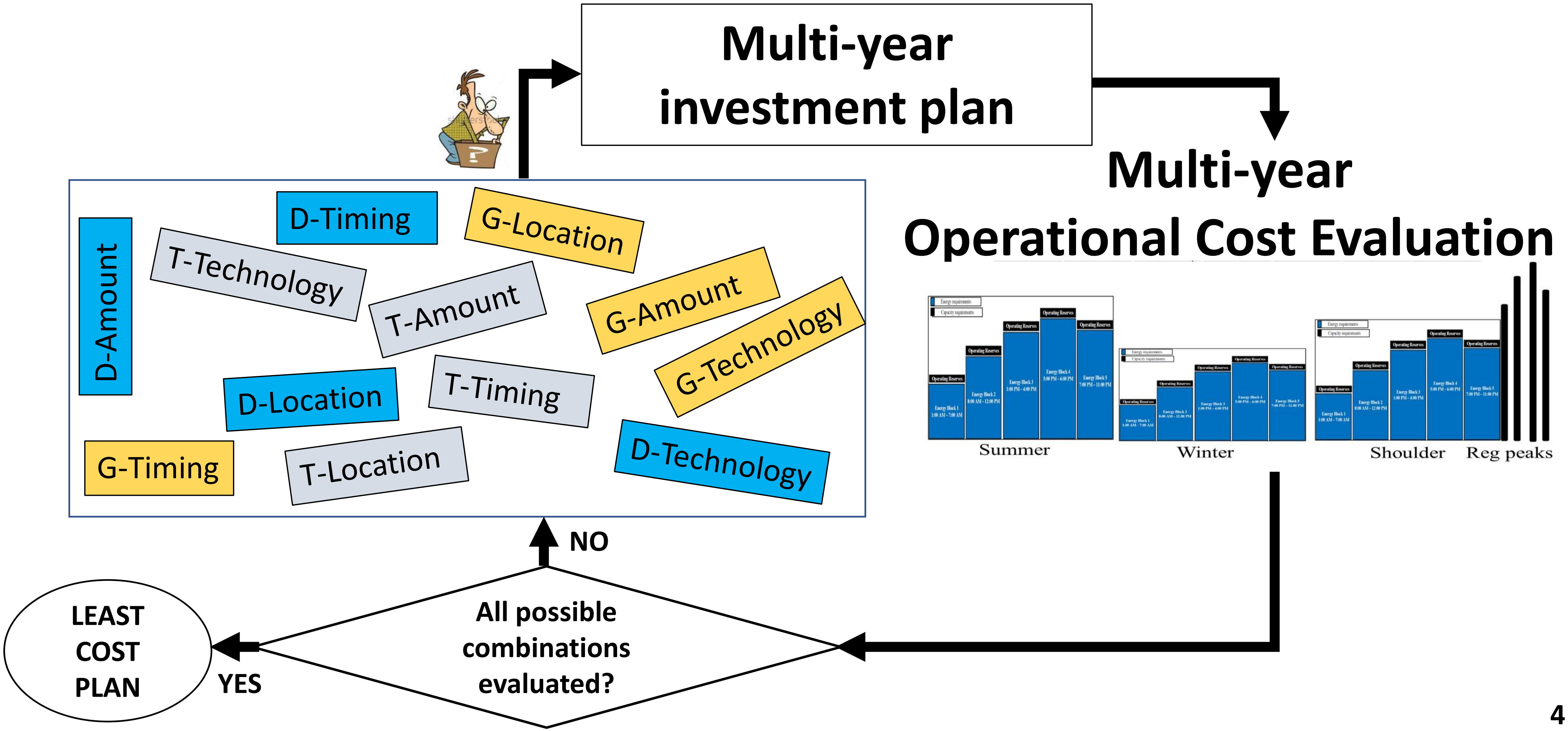
2039

Identifies transmission & generation investments over time period (~5-35yrs) to minimize net present worth of

- investment costs plus
- operational costs

subject to assumed future conditions

Cooptimized Expansion planning (CEP): Implementation



Resilience-based CEP model (R-CEP): formulation

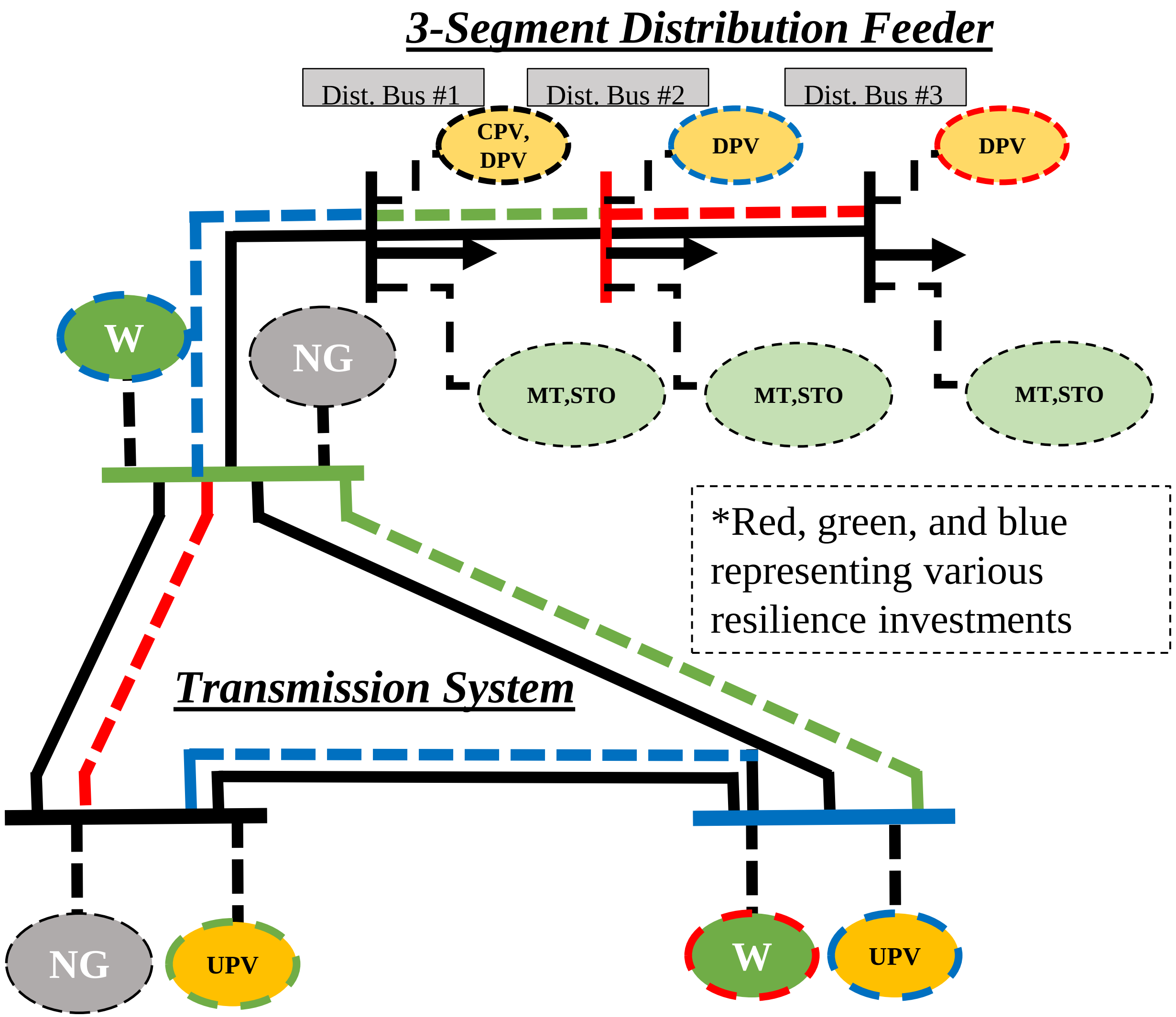
min

GTD Investment Costs
+ FOM, VOM, Fuel Costs
+ Operational Reserve Costs
+ Retirement costs
+ Load shedding costs
+ GTD resilience costs

Total Net Present Value

s.t.

- *DC power flow*
- *Power balance*
- *Regulation/Reserve Requirements*
- *Investment caps*
- *Renewable portfolio standards*
- *DER operational constraints*
- *Transmission thermal limits*
- *Line losses*
- Extreme event conditions (de-rating of component performance)
- Extreme event scenarios (geographic variation of extreme event & intensities)



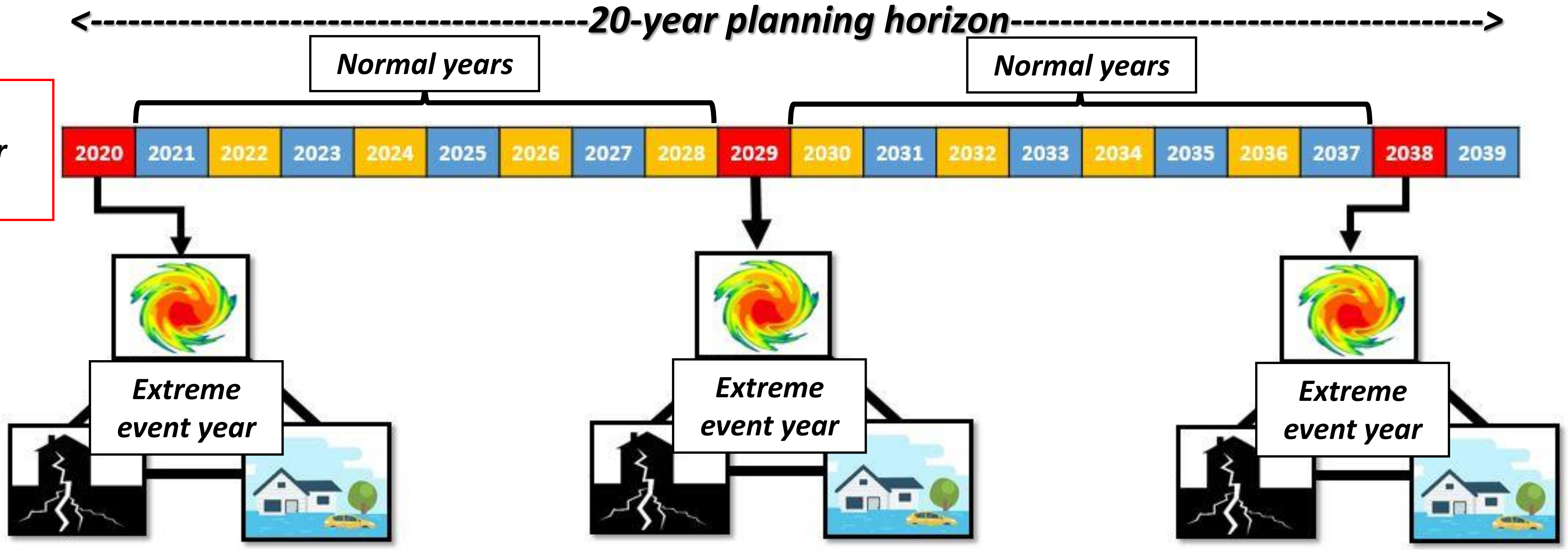
➔ Observe:

1. There is a cost to enhancing resilience.
2. Resilience is about extreme event severity/intensity and associated degraded system performance.
3. We reflect degraded system performance by de-rating component capability in the geo-region impacted by the event.
4. Central concept: Some “normal” investments enhance resilience; optimize on both normal & resilience investments.

Resilience-based CEP model (R-CEP): Types of years

Two types of meteorological years:
- ***EMY → Extreme Meteorological Year***
- ***TMY → Typical Meteorological Year***

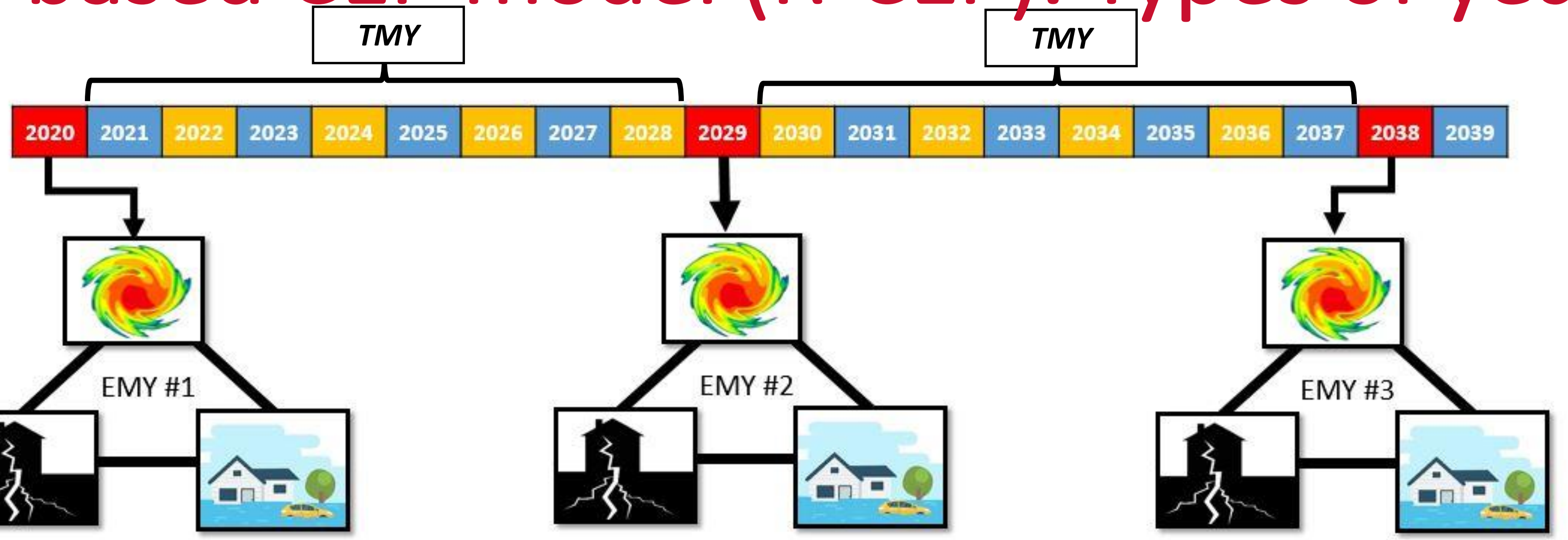
Three types of CEP years:
- ***Investment EMY (red)***
- ***Investment TMY (gold)***
- ***Operational TMY (blue)***



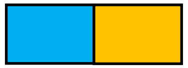
Model Feature	What model features are in each type of CEP year? Investment EMY	Investment TMY	Operational TMY
Capacity Investments		X	
Resilience Investments	X		
Retirements	X	X	
Operational costs	X	X	X

Observe:
- capacity investments only allowed in investment TMY
- resilience investments only allowed in investment EMY
- retirements allowed in any investment year (EMY or TMY)
- operational costs are incurred in all three types of years

Resilience-based CEP model (R-CEP): Types of years

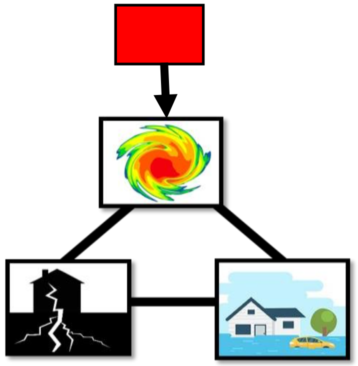


Typical meteorological years:



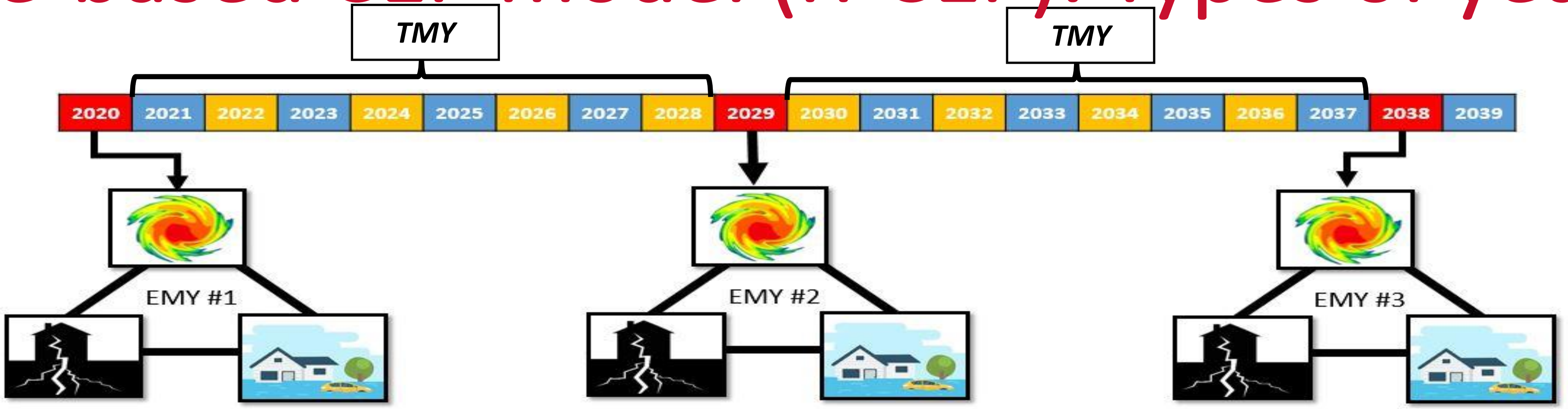
- → *Models normal conditions*
- → *Uses normal ratings on components*
- → *Investments driven by component rating & need to satisfy power demand*

Extreme meteorological years:

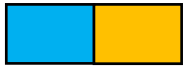


- → *Models extreme event scenarios:*
  - *Hurricanes*
  - *Tsunami/flooding*
  - *Earthquakes*
  - *Other: winter storms, wildfires, geomagnetic storms, etc.*
- → *Uses de-rated components based on event intensity and component resilience level to identify optimal resilience investments*
- → *Investments driven by component derating & need to satisfy power demand*

Resilience-based CEP model (R-CEP): Types of years



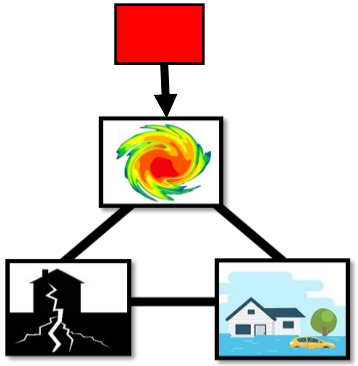
Typical meteorological years:



Block #	Season	Period of Day	Time (# hours)
1	Rainy	11PM-6AM	1712
2	Rainy	7AM-1PM	1498
3	Rainy	2PM - 6PM	1070
4	Rainy	7PM - 10 PM	816
5	Dry	11PM-6AM	1208
6	Dry	7AM-1PM	1057
7	Dry	2PM - 6PM	755
8	Dry	7PM - 10 PM	604
9	PEAK	Top 40 hours in block 7	40

9 total operating blocks per TMY

Extreme meteorological years:



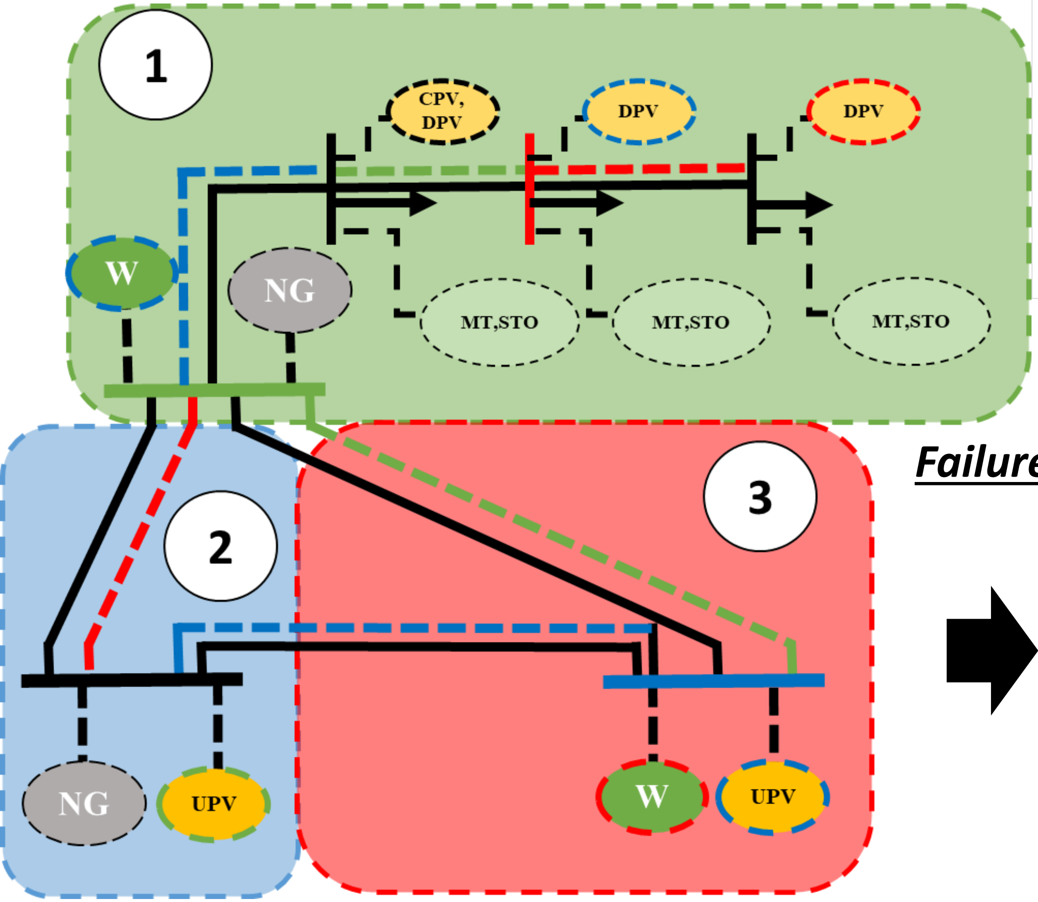
EMY Period	Time Duration (hours within year)	Corresponding Event
1	0-23	Extreme event occurring
2	24-192	Week after extreme event
3	193-912	Month after extreme event
4	913-4512	5 months after extreme event
5	4513-8760	Remaining 6 months of year

EMY Block	Time of Day
1	11pm-6am
2	7am-1pm
3	2pm-6pm
4	7pm-10pm

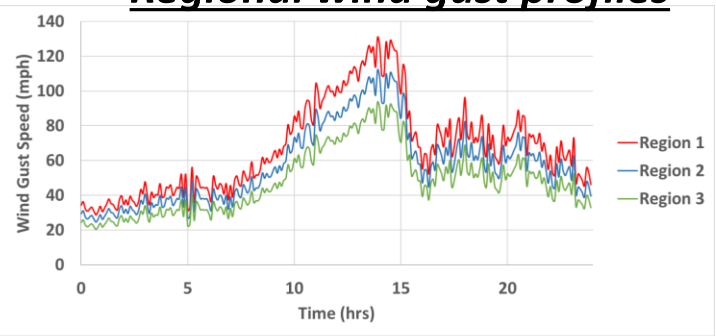
20 total operating blocks per EMY

Resilience modeling in the R-CEP model

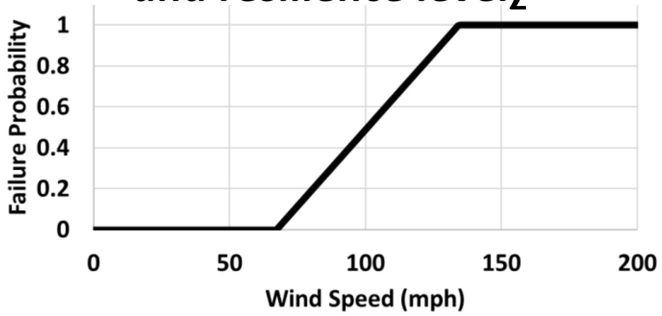
Meteorological regions



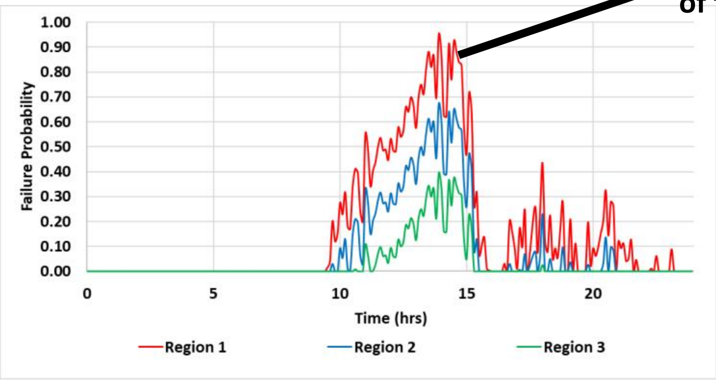
Regional wind gust profiles



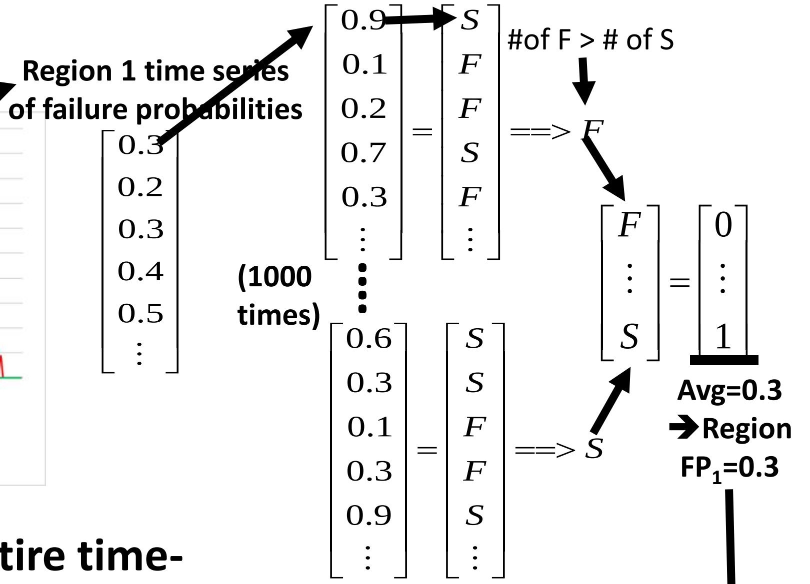
Fragility curves (one for each component type and resilience level)



Failure probs. as a function of time



For each element, MC Draw 0→1;
If ≤ failure prob, F. If > failure prob, S



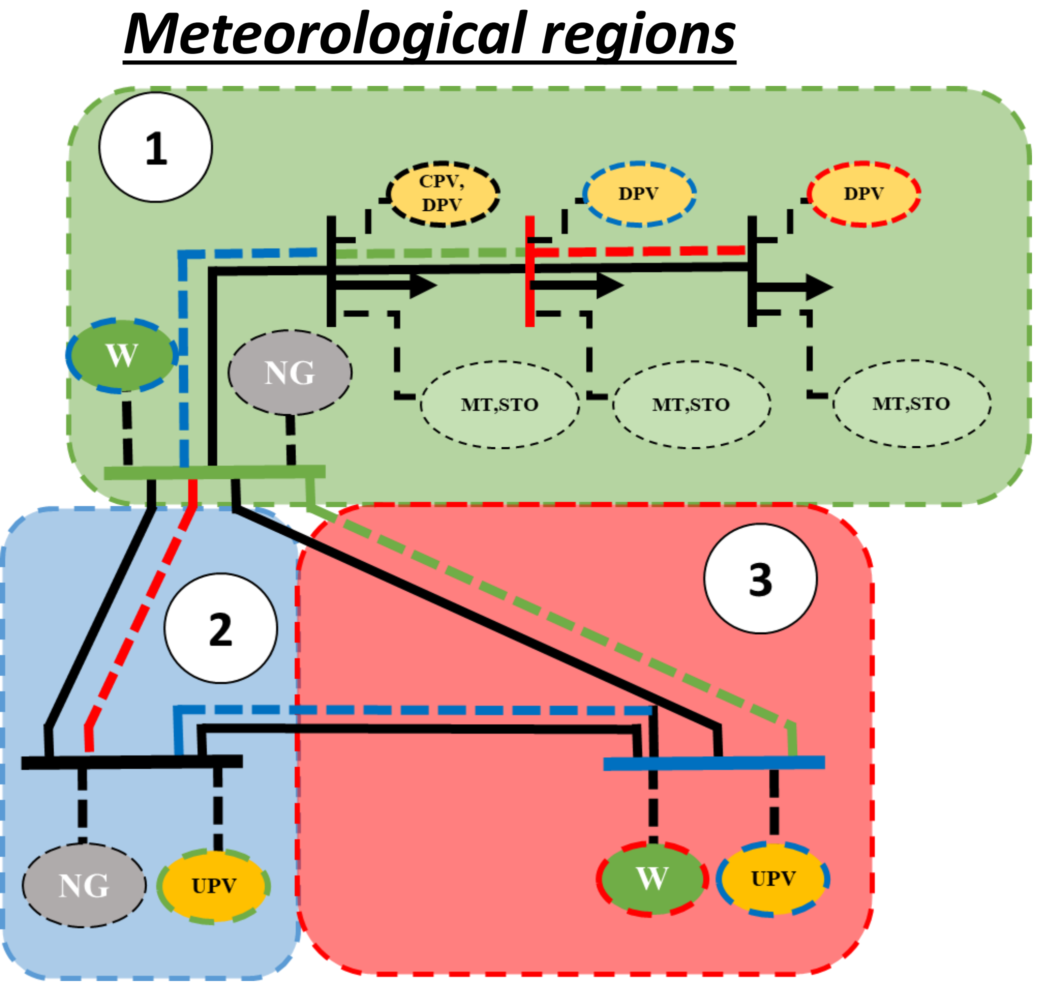
M. Panteli and P. Mancarella, "Modeling and evaluating the resilience of critical electric power infrastructure to extreme weather events,"IEEE Systems Journal, vol. 11, no. 3, pp. 1733–1742, 2017.

B. Li, R. Roche, and A. Miraouri, "A temproal-spatial natural disaster model for power system resilience improvement using DG and line hardening," IEEE Manchester PowerTech, pp. 1–6, 2017.

This MC process compresses entire time-series into a single failure probability and then a component derate.

➔Use failure probabilities (FP_l) to de-rate the system component's performance: $\boldsymbol{P_l = (1 - FP_l) * TL_l}$ where P_l is the line flow and TL_l is the thermal limit of line *l*

Resilience modeling in the R-CEP model



- Generation (solar & wind) is de-rated via ***bus multipliers*** that range from (0 to 1)
- Bus multipliers are a function of geographic location and resilience level
- Use bus multipliers ($\boldsymbol{\Omega_b}$) to de-rate the system component's performance

$$\boldsymbol{P_{g,b}} = (\boldsymbol{\Omega_b}) * \boldsymbol{C_g}$$

  - Where $P_{g,b}$ is the generator's derated capacity and $\boldsymbol{C_g}$ is the installed capacity of generator g
- For certain events (such as earthquakes and flooding) resilience investments at the bus level are introduced by outaging all generation at affected buses

Resilience modeling in the R-CEP model

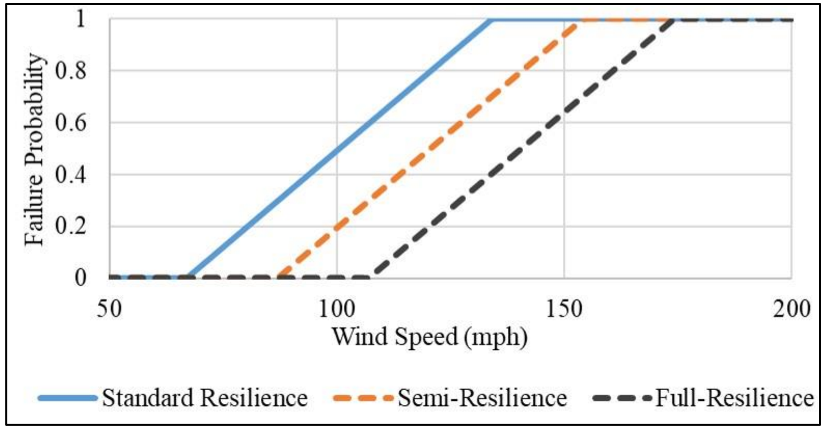
Extreme Event & Resilience Modeling

- Resilience levels (***Standard***, ***Semi***, & ***Full***) introduced for wind, solar, transmission lines, and distribution segments

→ This is a MILP!!!

- Fragility curves shifted for lines; bus multipliers are increased by resilience level
- **Central concept**: Resilience levels are used to locate specific components where grid hardening investments should occur via upgrading from one resilience level to another.
- Resilience levels have **temporal components**

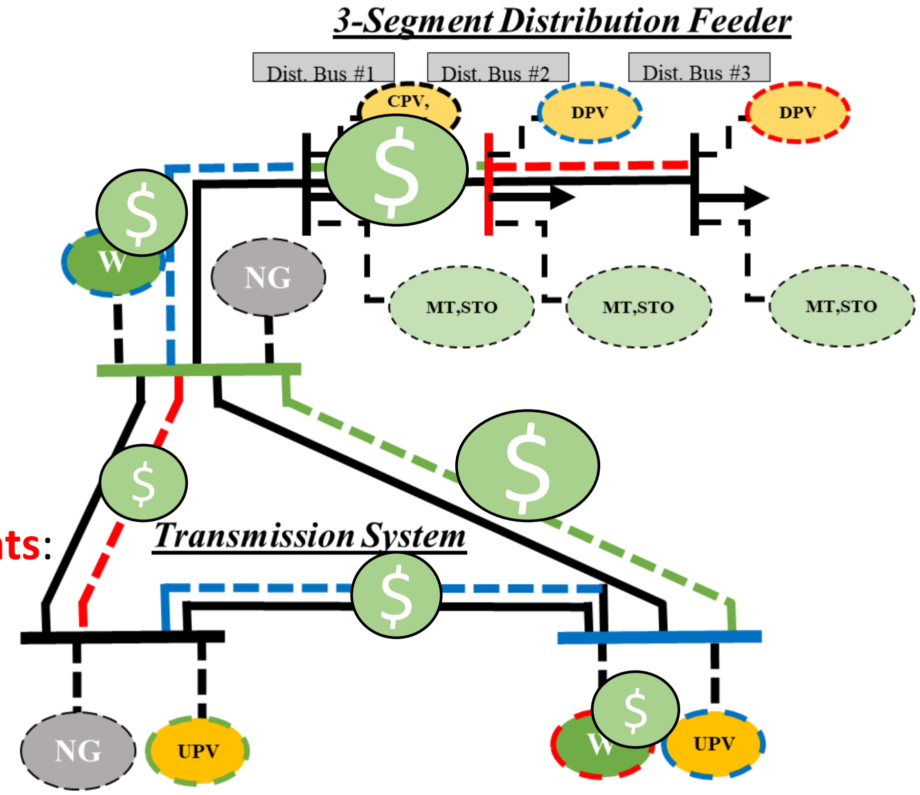
EMY Period	Period	Standard	Semi	Full
1	Hurricane occurring	***De-rated***	***De-rated***	***De-rated***
2	Week after hurricane	***De-rated***	***De-rated***	*Normal*
3	Month after hurricane	***De-rated***	***De-rated***	*Normal*
4	5 months after hurricane	***De-rated***	*Normal*	*Normal*
5	Remaining 6 months of year	*Normal*	*Normal*	*Normal*



Resilience levels have cost components:

- Standard → No cost
- Semi → 1.5 * Expansion cost
- Full → 2.0 * Expansion cost

→ ***Higher resilience = higher cost***



Resilience Investments

	Standard	Semi	Full
Transmission & Distribution Lines	❖ Basic repairs made ❖ Susceptible to future failures ❖ Basic repairs made	❖ Annual vegetation management ❖ Replacing wood poles with steel ❖ Pre-event preparation (crews, pre-stage materials)	❖ Semi-annual vegetation management ❖ Replacing wood poles with steel/concrete ❖ Pre-event preparation (crews, pre-stage materials) ❖ Underground lines where feasible
Wind & Solar Technologies	❖ Basic repairs made ❖ Susceptible to future failures ❖ Basic repairs made	❖ Annual maintenance schedules ❖ Enhanced foundation design ❖ Enhanced site-selections ❖ Strengthening support towers	❖ Semi-annual maintenance schedules ❖ Enhanced foundation design (larger and deeper foundation designs) ❖ Enhanced site-selections ❖ Underground connections where feasible
Substations	❖ Basic repairs made ❖ Susceptible to future failures ❖ Basic repairs made	❖ Specialized site-selection studies ❖ Annual maintenance of structures ❖ Elevated platforms when appropriate ❖ Construction of water/wind barriers	❖ Enhanced studies for site selection ❖ Semi-annual maintenance of structures ❖ Elevated platforms when appropriate - ❖ Construction of barriers/control room protected
Expected Recovery Time	***6 months***	***1 month***	***24 hours***

R-CEP Optimization problem

Minimize: $Objective = Fuel\_Costs + FOM\_Costs + VOM\_Costs + Gen\_Inv\_Costs +$

$$Retirement\_Costs + Line\_Cap\_Costs + LS\_Costs + Loss\_Costs + Reserve\_Costs$$

$$+ Line\_Resiliency\_Costs + Bus\_Resiliency\_Costs$$

Subject to:

- Cumulative generation capacity
- Retirement criteria
- Max load shed
- Max gen dispatch for peak load blocks
- Max gen dispatch for non-peak load blocks
- Gen min stable level
- Ramping constraints
- System wide planning reserve margin
- Energy efficiency modeling
- Energy storage modeling
- Cumulative line capacity
- Line flow modeling constraints
- Line loss modeling constraint
- Power balance constraint
- DC power flow constraint
- Derated line flows in EMY
- Reslnce line invstmnt constraints
- Reslnce bus invstmnt constraints

Note: The analytic problem expression is given in,
C. Newlun, “Co-optimized expansion planning for power system resilience and adaptation”, Ph. D. Dissertation, Iowa State University, 2022.

Next steps

We have already developed basic code to perform R-CEP. Initial testing using non-MISO data indicates it performs reasonably.

1. Identify an Iowa-centric extreme event (2020 Derecho?)
2. Replace initial testing data with MISO data.
3. Obtain results with MISO data. Assess/evaluate.
4. Complete report.