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# Co-optimizing Power Grid Reliability and Resiliency

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NNSA National Nuclear Security Administration

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# The U.S. Electric Grid

- Aging: 70% of transmission lines and transformers are over 25 years old [1].
- Vulnerable to
  - **Weather**
  - Equipment failure
  - Overgrown vegetation
  - Wildlife [2]
- American Recovery and Reinvestment Act (2009) allocated $4.5 billion to improve reliability and resiliency of power grid.

# Impact of Weather

- From 2003-2012, weather events caused 679 power outages, each affecting at least 50,000 customers [1, 2].
- Outages caused by severe weather estimated to cost the U.S. between $18 and $33 billion per year [1].

# Utilities' Motives

- Resiliency: ability to recover from low-probability, high-frequency disruptions:
  - Hurricanes
  - Floods
  - Ice storms
  - Cyber attack
- Reliability: ability to recover from high-probability, low-impact disruptions
  - Squirrels
  - Birds
  - Tree falls on distribution line

# Example Investments

| Reliability | Resiliency |
|---|---|
| • Squirrel guards<br>• Bird spikes<br>• Burying distribution line<br>• Add additional fuses [3] | • Bury transmission line<br>• Upgrade poles<br>• Add redundancy into system<br>• Elevate substation above flood level<br>• Move facility out of flood zone [4] |

# SAIDI and SAIFI Metrics

- System Average Interruption Duration Index (SAIDI):
  - Measures duration of outages:

$$SAIDI = \frac{\sum_{outages} (\text{num customers effected})(\text{outage duration})}{\text{total num customers}}$$

- System Average Interruption Frequency Index (SAIFI):
  - Measures frequency of outages:

$$SAIFI = \frac{\sum_{outages} (\text{num customers effected})}{\text{total num customers}}$$

# Justifying Investments

| Reliability | Resiliency |
| --- | --- |
| • Measured by SAIDI and SAIFI<br>• Less-expensive investments<br>• Evidence of immediate customer benefit | • Not captured by SAIDI and SAIFI<br>• Expensive investments<br>• Uncertain return on investment [5] |

# The Problem

- Utilities need to invest in both resiliency and reliability and be able to justify these investments to regulatory commissions
- We plan to co-optimize a model for choosing reliability investments and a model for choosing resiliency investments
  - Two models coupled by budget constraint
- Challenges:
  - Distributions of both reliability disruptions and resiliency disruptions uncertain
  - Choosing investments in either is a combinatorial problem
  - Is the budget constraint the only link between the two?
  - Want to scale to realistically sized power grids

# Current Model: Reliability

$$\text{minimize} \quad \frac{SAIDI_{\mathrm{up}}}{SAIDI_{\mathrm{syn}}} + \frac{SAIFI_{\mathrm{up}}}{SAIFI_{\mathrm{syn}}} \tag{1}$$

$$\text{subject to} \quad \sum_{i,d,u \in U_{i,d}} c_u \, y_{i,d,u} \leq B \tag{2}$$

$$SAIDI_{\mathrm{up}} = \frac{1}{N} \sum_{o \in O} CO_o \, TO_o \tag{3}$$

$$SAIFI_{\mathrm{up}} = \frac{1}{N} \sum_{o \in O} CO_o \tag{4}$$

$$CO_o = \min_{u \in U_o} \{ C_{o,u} \, y_{i_o,d_o,u} + C_o \, (1 - y_{i_o,d_o,u}) \} \quad \forall o \in O \tag{5}$$

$$TO_o = \min_{u \in V_o} \{ T_{o,u} \, y_{i_o,d_o,u} + T_o \, (1 - y_{i_o,d_o,u}) \} \quad \forall o \in O \tag{6}$$

# Current Model: Resiliency

$$
\begin{aligned}
\text{minimize} \quad & \sum_{b\in\mathcal{B}} p_b^0 + \sum_{\omega\in\Omega} P_\omega \sum_{b\in\mathcal{B}} p_b^\omega && && (1)\\
\text{subject to} \quad & \sum_{b\in\mathcal{B}} C_b i_b + \sum_{l\in\mathcal{L}} C_l i_l + \sum_{g\in\mathcal{G}} C_g i_g \le T && && (2)\\
& \sum_{g\in\mathcal{G}_b} p_g^0 + \sum_{l\in\mathcal{L}_b^{\text{to}}} p_l^0 - \sum_{l\in\mathcal{L}_b^{\text{from}}} p_l^0 = D_b - p_b^0 && \forall b\in\mathcal{B} && (3)\\
& \sum_{g\in\mathcal{G}_b} p_g^\omega + \sum_{l\in\mathcal{L}_b^{\text{to}}} p_l^\omega - \sum_{l\in\mathcal{L}_b^{\text{from}}} p_l^\omega = D_b - p_b^\omega && \forall b\in\mathcal{B}, \forall\omega\in\Omega && (4)\\
& p_l^0 = Y_l^0 S_l(\theta^0_{B_l^{\text{to}}} - \theta^0_{B_l^{\text{from}}}) && \forall l\in\mathcal{L} && (5)\\
& p_l^\omega = y_l^\omega S_l(\theta^\omega_{B_l^{\text{to}}} - \theta^\omega_{B_l^{\text{from}}}) && \forall l\in\mathcal{L}, \forall\omega\in\Omega && (6)\\
& p_g^\omega \le p_g^0 + RU_g Y_g^0 + SU_g(y_g^\omega - Y_g^0) + \overline{P}_g(1 - y_g^\omega) && \forall g\in\mathcal{G}, \forall\omega\in\Omega && (7)\\
& p_g^0 \le \overline{P}_g y_g^\omega + SD_g(Y_g^0 - y_g^\omega) && \forall g\in\mathcal{G}, \forall\omega\in\Omega && (8)\\
& p_g^0 - p_g^\omega \le RD_g y_g^\omega + SD(Y_g^0 - y_g^\omega) + \overline{P}_g(1 - Y_g^0) && \forall g\in\mathcal{G}, \forall\omega\in\Omega && (9)\\
& -\frac{\pi}{3} \le \theta^0_{B_l^{\text{to}}} - \theta^0_{B_l^{\text{from}}} \le \frac{\pi}{3} && \forall l\in\mathrm{L} && (10)\\
& -\frac{\pi}{3} \le \theta^\omega_{B_l^{\text{to}}} - \theta_{B_l^{\text{from}}} \le \frac{\pi}{3} && \forall l\in\mathrm{L}, \omega\in\Omega && (11)
\end{aligned}
$$

# Current Model: Resiliency

$$-\overline{P}_l Y_l^0 \le p_l^0 \le \overline{P}_l Y_l^0 \qquad \forall l \in \mathcal{L} \qquad (12)$$

$$-\overline{P}_l y_l^\omega \le p_l^\omega \le \overline{P}_l y_l^\omega \qquad \forall l \in \mathcal{L}, \omega \in \Omega \qquad (13)$$

$$\underline{P}_g Y_g^0 \le p_g^0 \le \overline{P}_g Y_g^0 \qquad \forall g \in \mathcal{G} \qquad (14)$$

$$\underline{P}_g y_g^\omega \le p_g^\omega \le \overline{P}_g y_g^\omega \qquad \forall g \in \mathcal{G}, \omega \in \Omega \qquad (15)$$

$$0 \le p_b^0 \le D_b \qquad \forall b \in \mathcal{B} \qquad (16)$$

$$0 \le p_b^\omega \le D_b \qquad \forall b \in \mathcal{B}, \forall \omega \in \Omega \qquad (17)$$

$$y_l^\omega \le i_l \qquad \forall l \in \mathcal{L}, \forall \omega \in \Omega_l \qquad (18)$$

$$y_l^\omega \le i_{B_l^{\text{from}}} \qquad \forall l \in \mathcal{L}, \forall \omega \in \Omega_l \qquad (19)$$

$$y_l^\omega \le i_{B_l^{\text{to}}} \qquad \forall l \in \mathcal{L}, \forall \omega \in \Omega_l \qquad (20)$$

$$y_g^\omega \le i_g \qquad \forall g \in \mathcal{G}, \forall \omega \in \Omega_g \qquad (21)$$

$$y_g^\omega \le i_{B_g} \qquad \forall g \in \mathcal{G}, \forall \omega \in \Omega_g \qquad (22)$$

$$y_b^\omega \le i_b \qquad \forall b \in \mathcal{B}, \forall \omega \in \Omega_b \qquad (23)$$

$$y_l^\omega \le y_{B_l^{\text{from}}}^\omega \qquad \forall l \in \mathcal{L}, \forall \omega \in \Omega_l \qquad (24)$$

$$y_l^\omega \le y_{B_l^{\text{to}}}^\omega \qquad \forall l \in \mathcal{L}, \forall \omega \in \Omega_l \qquad (25)$$

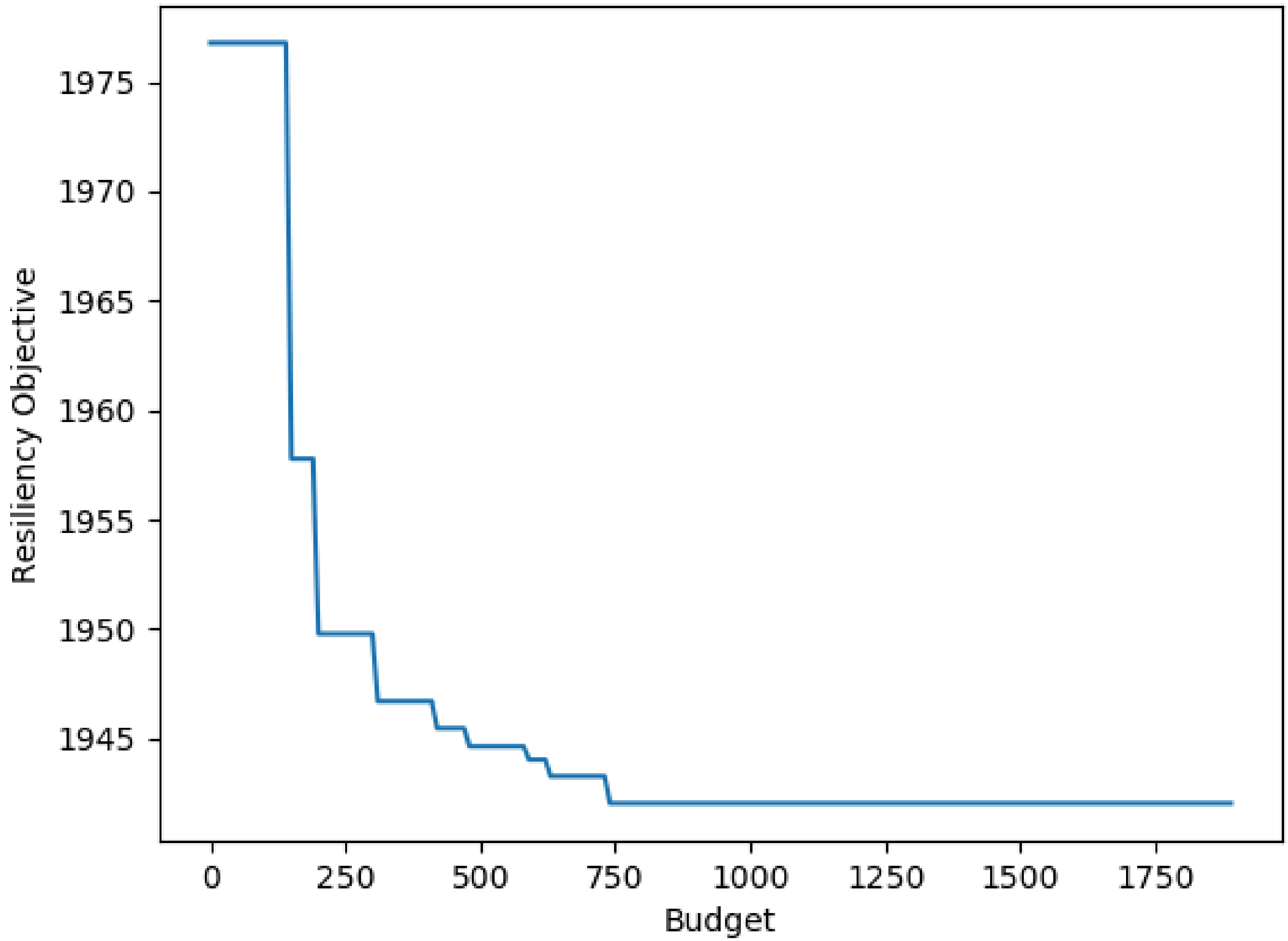
$$y_g^\omega \le y_{B_g}^\omega \qquad \forall g \in \mathcal{G}, \forall \omega \in \Omega_g \qquad (26)$$

# Reliability and Resiliency Value Functions

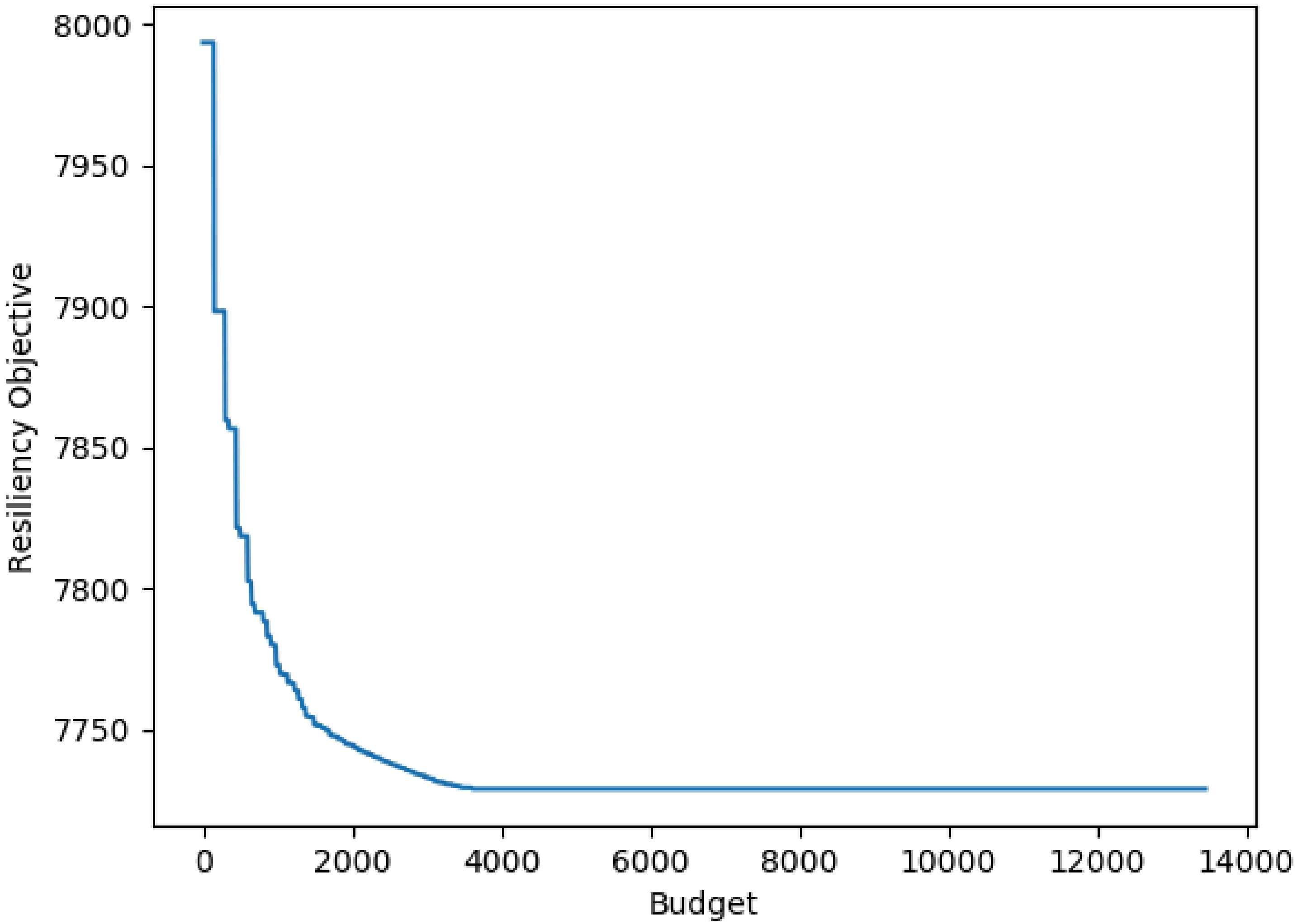
1. Solve with budget = 0.
2. Calculate minimum cost of set of investments not chosen in current solution. Call this cost $\delta$.
3. Solve the model with $\text{budget} = \text{budget} + \delta$.
4. Repeat steps 2 and 3 until budget is equal to cost of choosing all investments

Do this with both reliability and resiliency models, use results to create Pareto frontier.

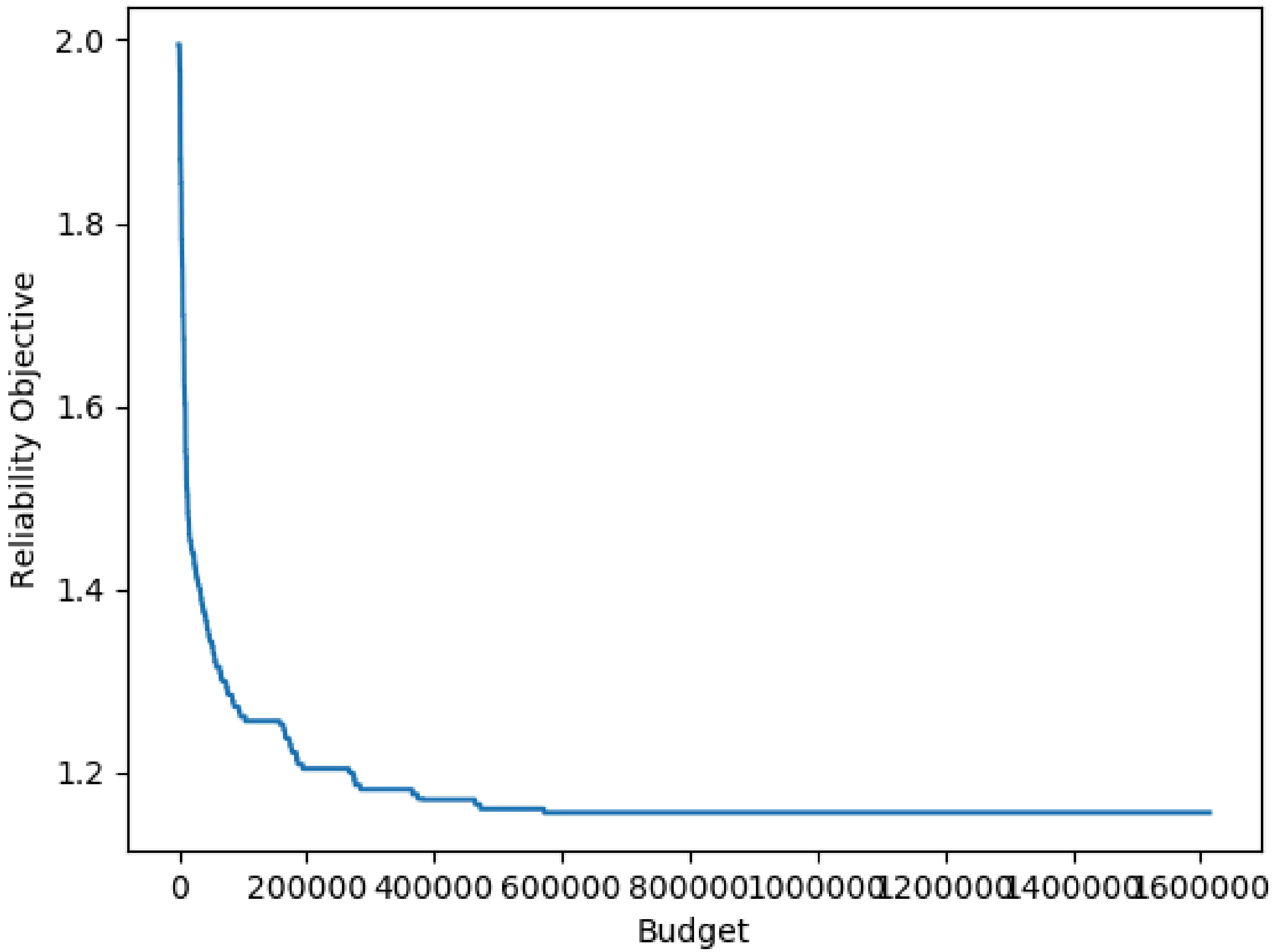
# Resiliency (11 bus Example)



# Resiliency (73 bus example)



# Reliability



# Continuing…

- Both models will be distributionally robust
- Develop parametric stochastic programming techniques for repeated solves of the models
- Depending on performance, also develop different co-optimization strategy.
  - Could expand auction-type algorithms from Ezgi Karabulut's dissertation [6]

# References

[1] President's Council of Economic Advisors, U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability, "Economic Benefit of Increasing Electric Grid Resilience to Weather Outages," August 2013.

[2] Larsen, Peter H., Kristina H. La Commare, Joseph H. Eto, and James L. Sweeny, "Recent trends in power system reliability and implications for evaluating future investments in resiliency," *Energy* 117 (2016): 29-46.

[3] Pierre, Brian, "Investment Optimization to Improve Power System Reliability Metrics," Sandia National Labs

[4] Lin, Yanling, and Zhaohong Bie, "Study on the Resilience of the Integrated Energy System," *Energy Procedia* 103 (2016) 171-176.

[5] Mukhopadhyay, Sayanti, and Makarand Hastack, "Public Utility Commissions to Foster Resilience Investment in Power Grid Infrastructure," *Procedia – Social and Behavioral Sciences* 218 (2016): 5-12.

[6] Karabulut, Ezgi, "Distributed Integer Programming," Doctoral dissertation, December 2017.

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