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Multi-hazard risk mitigation for electric power systems using investment optimization

KA Jones, B Arguello, LK Nozick

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Outline

- Problem description
- System description
- Interdiction model
- Flood and wind scenarios
- Metrics and proposed investments
- Results

Defining resilience

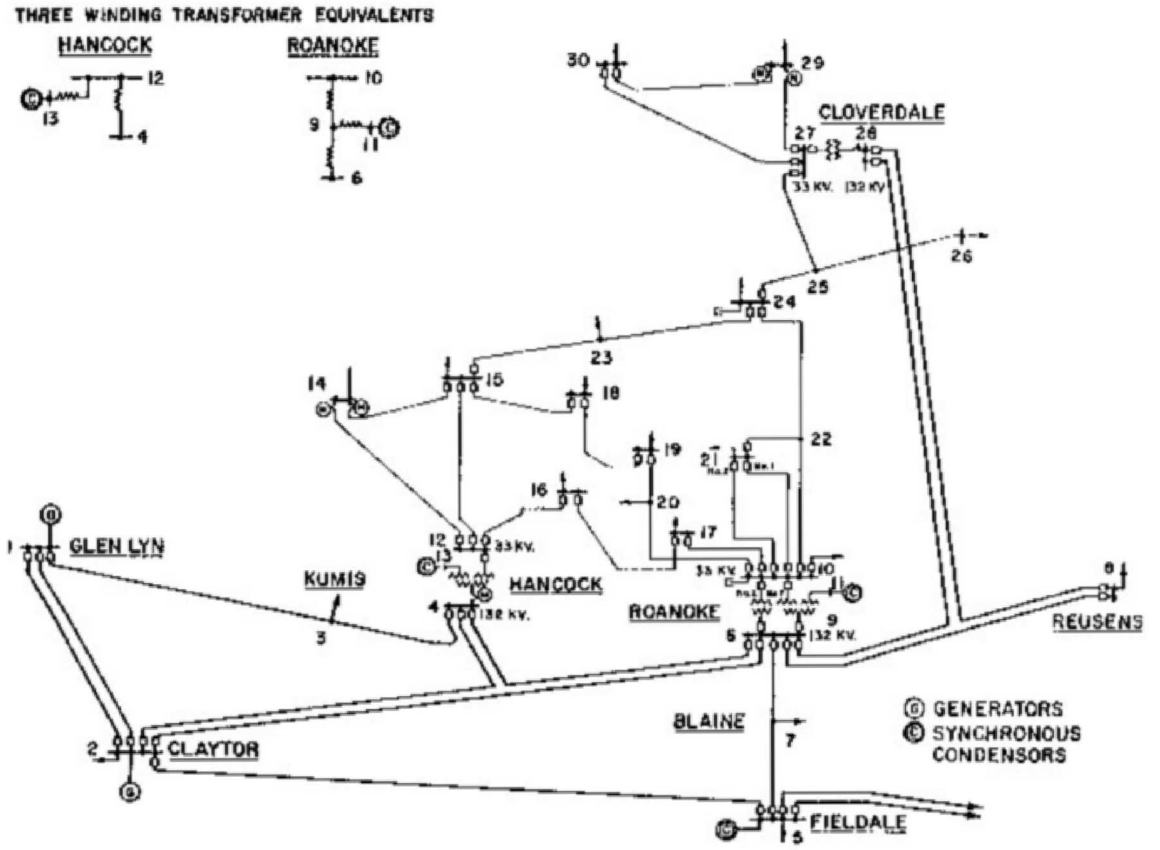
- Presidential Policy Directive (PPD)-21 definition of resilience
  - “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.”
- Consider acute disruption events such as the Design Basis Threat (DBT)
  - Differs from traditional reliability analysis
  - Include low probability, high consequence events
  - Incorporate uncertainty

Problem description and approach

- Develop a single investment strategy to improve resilience of the grid against multiple hazards
- Metrics can be qualitative, and the anticipated improvement from investments can be uncertain
- Optimize investments in hardening measures against multiple threats (in this case study, physical attack and flood), incorporating:
  - Subjective and qualitative metric evaluation via the Analytic Hierarchy Process (AHP)
  - Potential downstream impacts on other infrastructures
  - Recovery over time, using repair stages
  - Initial and recurring costs

System description

- Examples used:
  - IEEE 30 bus system (below)
  - IEEE 24 bus system (backup slides)

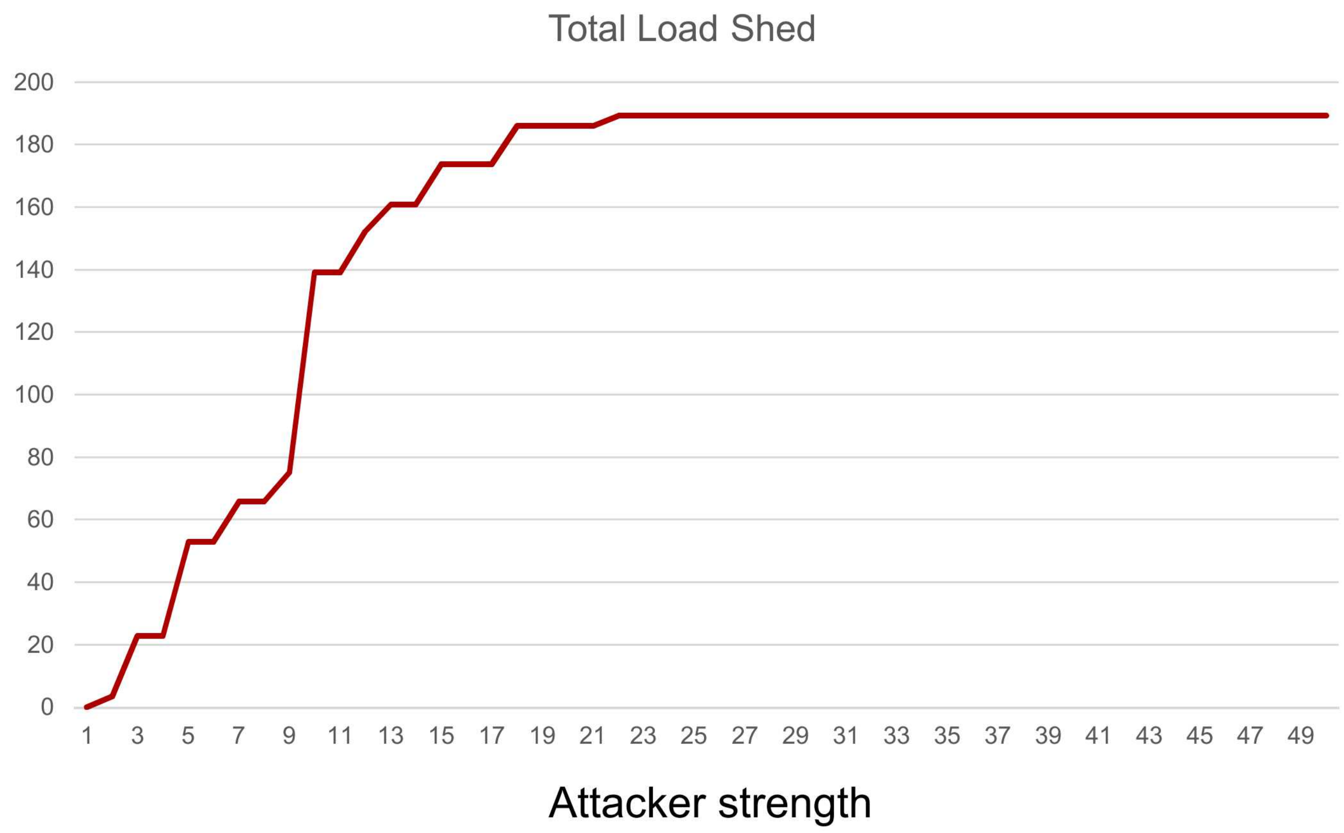


http://www2.ee.washington.edu/research/pstca/pf30/pg_tca30fig.htm

Physical attack interdiction model

- The attacker has a limited capability to attack the system
- Units of strength represent how hard it is to interdict (attack) a bus or a line/branch
  - In the baseline for this example, a bus costs 6 units of strength to attack and a branch costs 1
  - Represents real-world limitations like size of group, equipment available, or skill level of attacker
- Modified version of model described in Motto et al, IEEE Transactions on Power Systems (2005)

Interdiction – load shed



Steep increase in load shed until attacker strength of 11

Interdiction – Design Basis Threat

- Consider a design basis threat that assumes an attacker strength ("budget" for attacks) of 5
- Attacker chooses the following branches, resulting in load shed of 52.8 MW:
  - '2_to_4', '2_to_5', '6_to_7', '6_to_8', '8_to_28'
- Run the analysis again, with each of those branches hardened to a level of 2, 4, or not at all (stay at "cost" 1) to see next best attack and load shed under those measures
- Based on that analysis, also add in 5 more branch hardening options for a final list of 10 and examine impact to load shed of hardening at different levels:
  - '25_to_26', '2_to_4', '28_to_27', '2_to_5', '2_to_6', '8_to_28', '6_to_7', '6_to_8', '5_to_7', '15_to_18'

Investment options – interdiction

- Buses and lines can prioritized for investment consideration based on the number of attacker budget scenarios they appear in or regression analysis
- Based on the hardening analysis for Design Basis Threat of 5 for interdiction, investment options identified:

Investment Option	Hardening	Load Shed Reduction (MW)	Cost of Investment
A	**6_to_8** hardened to level 4	21.4	$38,000
B	**6_to_8** hardened to level 4 and **15_to_18** hardened to level 2	23.5	$40,000 Yr 1 $5,000 Yr 2 Recurring cost of $5K
C	**25_to_26** and **2_to_4** hardened to level 2	0 (for attacker "budget" of 5) – listed for later consideration	$30,000

Investment options – flood/wind

- Based solely on weather scenarios. Concern with lines/branches is primarily wind but also unstable ground from flooding. For buses the concern is primarily flooding.

Investment Option	Hardening	Load Shed Reduction (MW)	Cost of Investment
D	**28_to_27**, **27_to_29**, **27_to_30**, and **29_to_30** hardened to level 3	13	$22,000 Yr 1 $35,000 Yr 2 Recurring cost of $5K
E	**Bus 2** hardened to level 4	2.4	$18,000 Yr 1 $18,000 Yr 2

Metrics and evaluation

For investment optimization

- Buses and lines can prioritized for investment consideration based on the number of attacker budget scenarios they appear in or regression analysis
- Optimization evaluates the best investment plan given the priorities, potential impact, and budget available

Weights

Mission Name	Weight	Consistency Index (Target: 0.0-0.1) 0.00
Attack Hardening	0.33	
Flood/Wind Hardening	0.67	

Comparisons

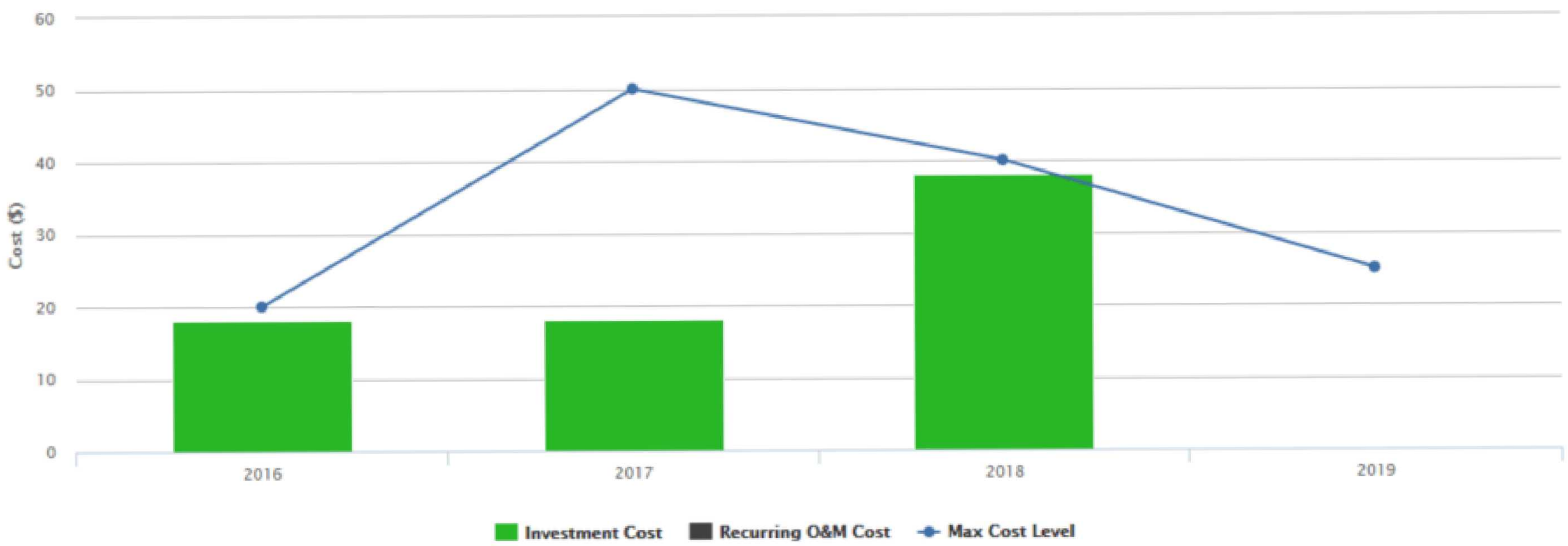
First Mission	Current Comparison Rating	
Attack Hardening	1/2 - between equal importance and somewhat less important than	Flood/Wind Hardening

Recommended investment plan

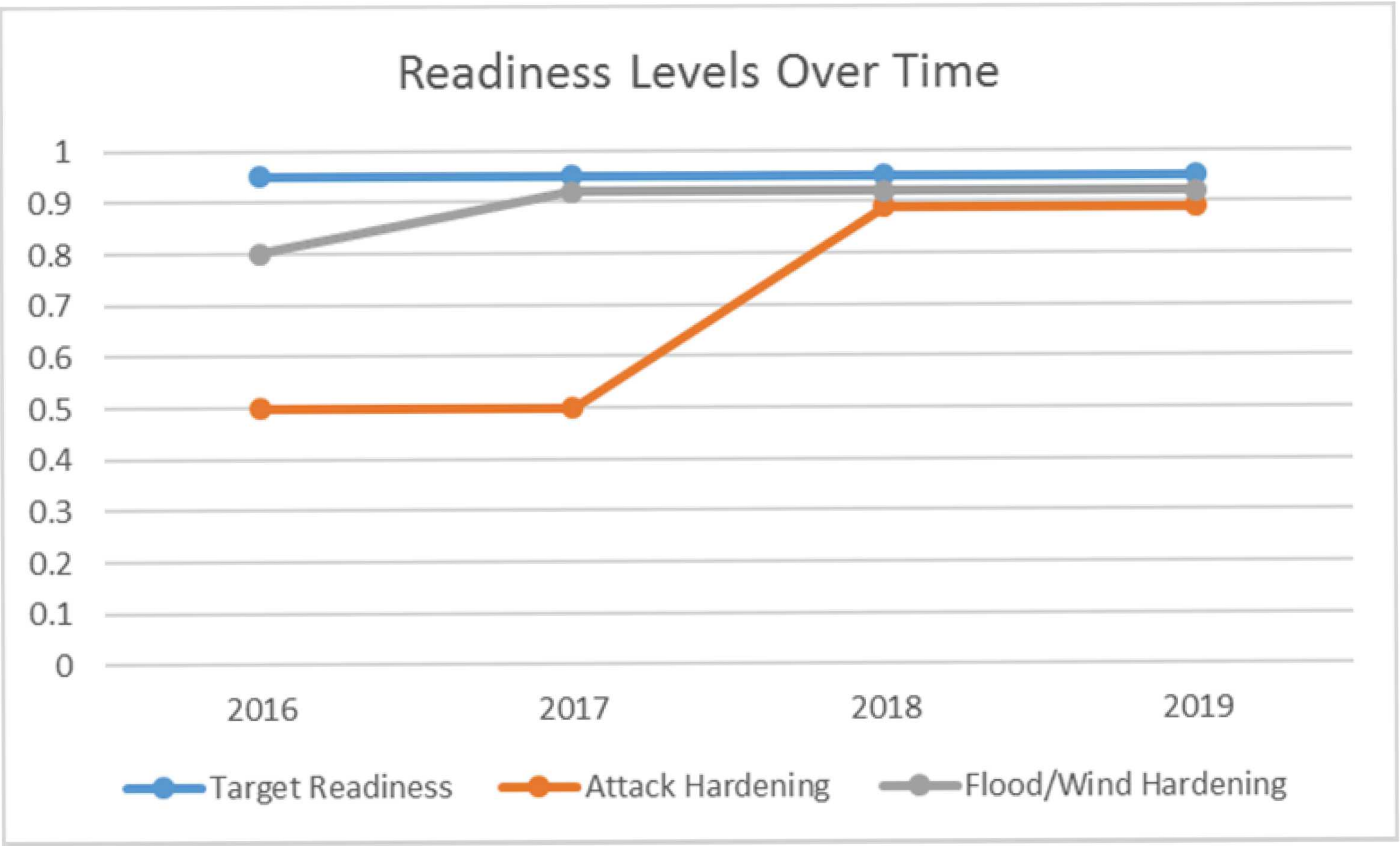
Selected Improvements by Fiscal Year						
Improvement	Investment Cost ($ Thousands)	Recurring O&M Cost ($ Thousands)	2016	2017	2018	2019
E	$36	$0	Acquired	Acquired		
A	$38	$0			Acquired	
B	$45	$5				
D	$57	$5				

- Budget caps: 20K available in 2016, 50K in 2017, 40K in 2018, and 25K in 2019
- Investment packages selected:
  - E (Bus 2) in 2016 and 2017
  - A (Branch 6_to_8) in 2018

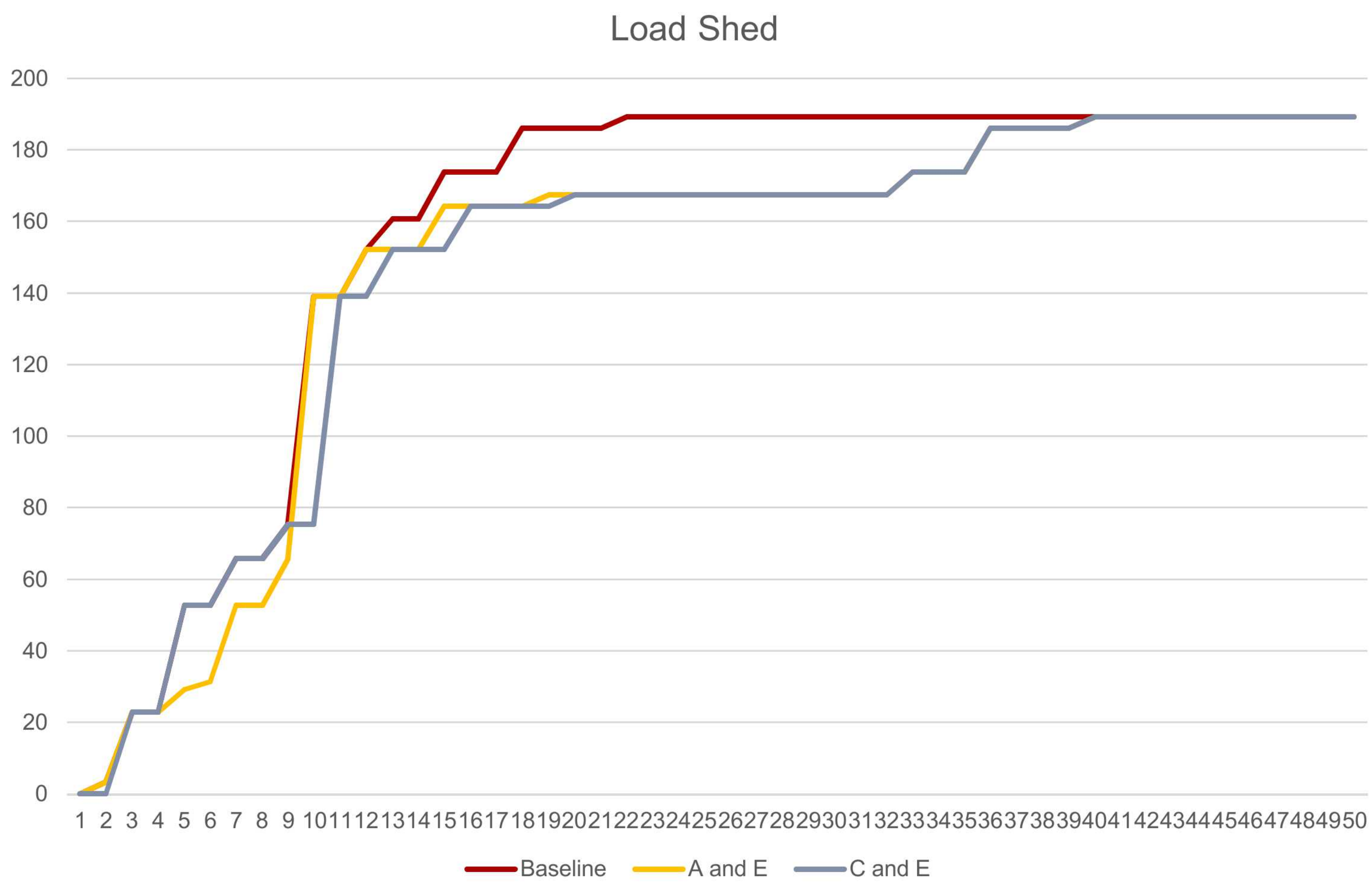
Cost per year



Readiness Over Time

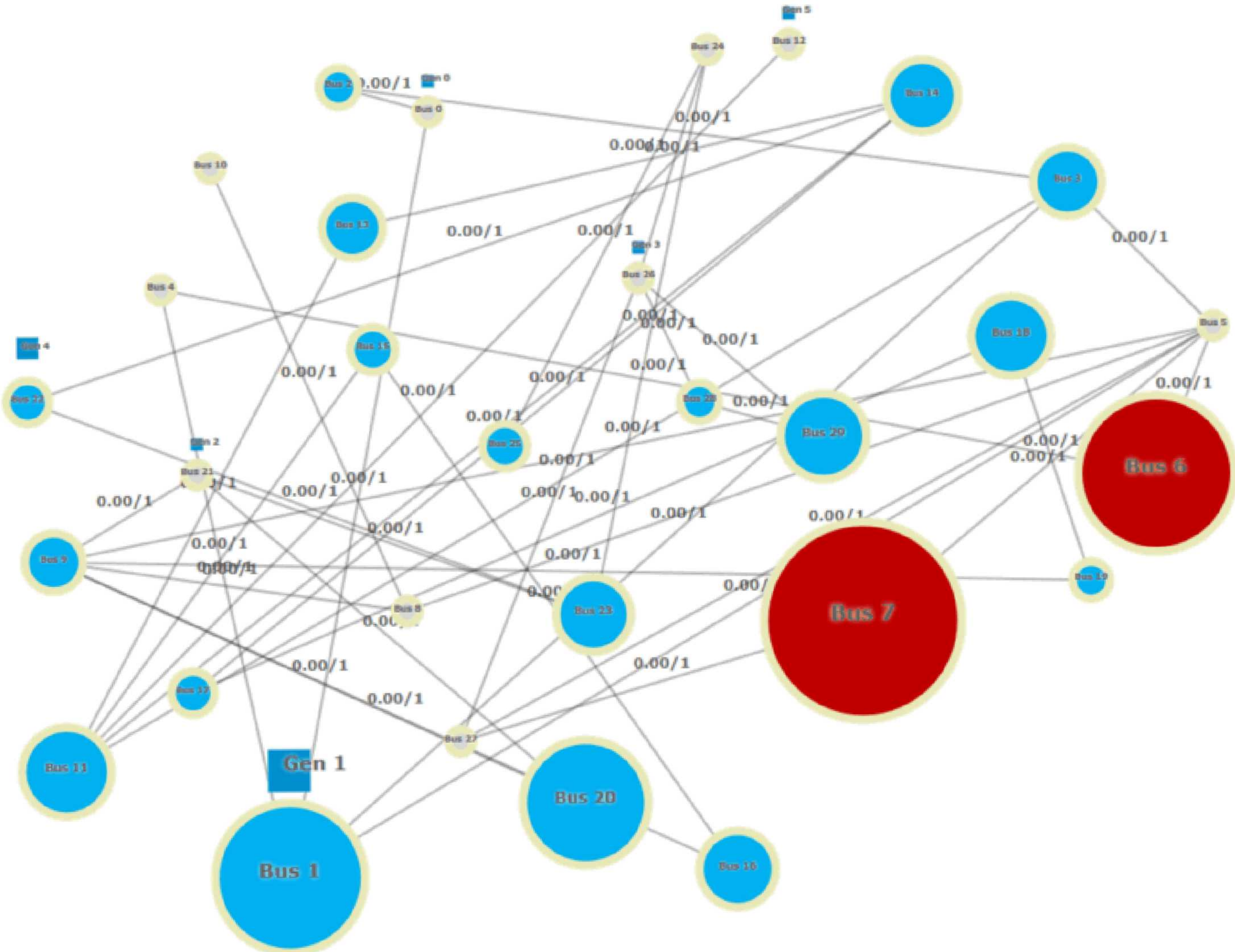


Load Shed Curve After Investment

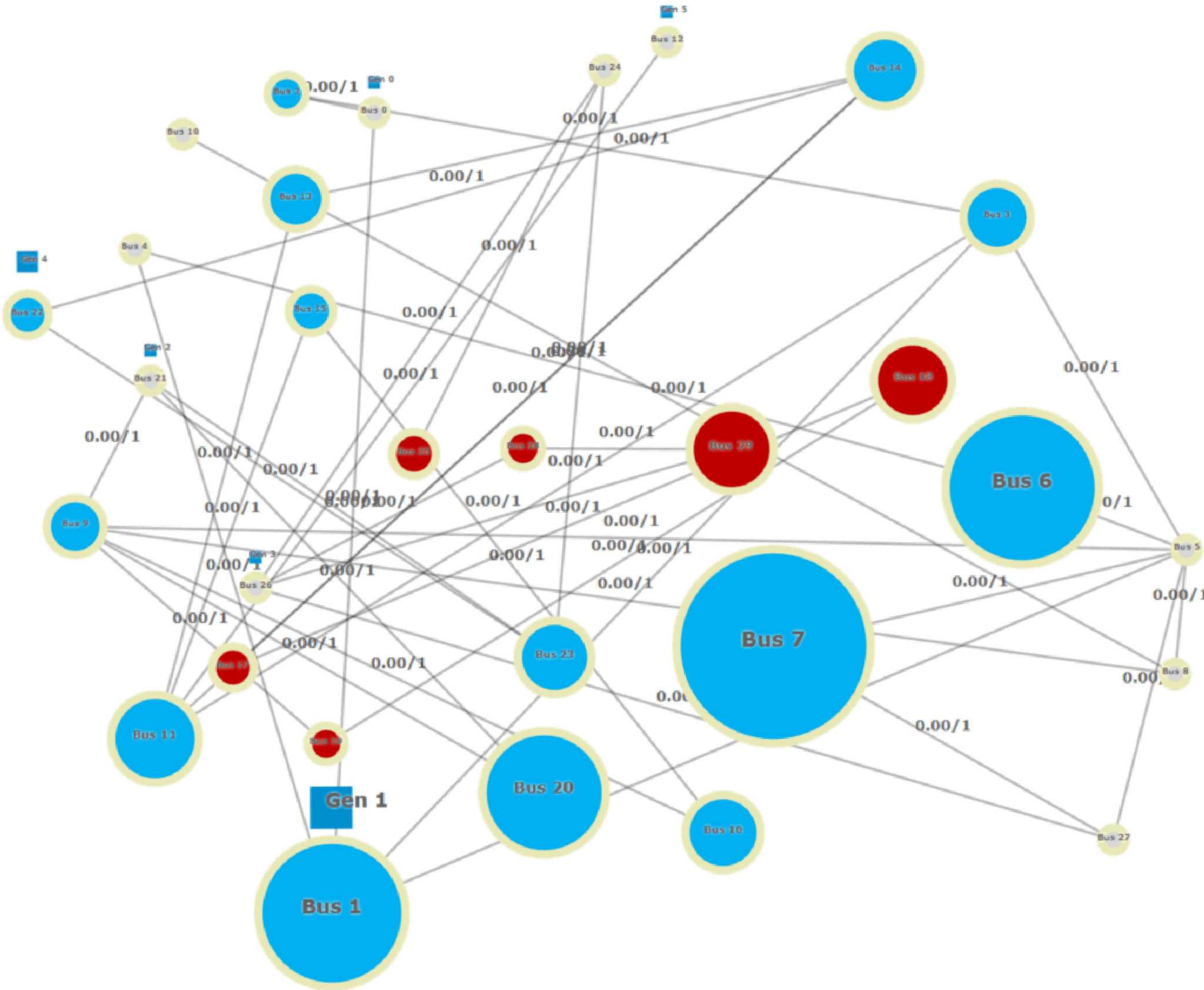


While investment C provided no benefit at budget 5, for others it performs better

No Hardening at DBT



Hardened System at DBT



Extensions

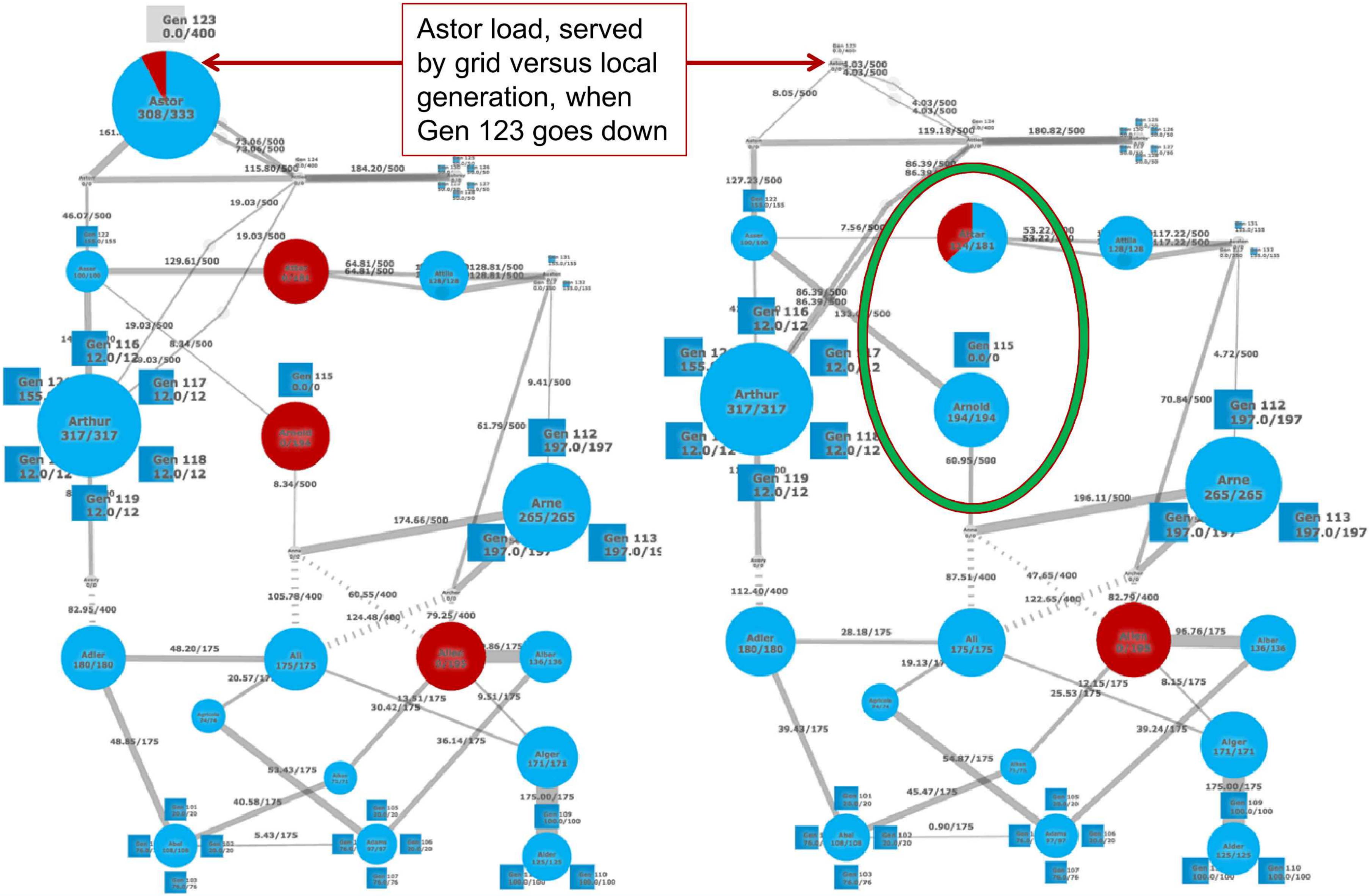
- Minimize criticality-weighted load shed over time
  - Use this to incorporate downstream impacts more explicitly
  - Can use customer type, people served, economic consequences of each MW of load shed, etc. to develop the weights

Resilience metric, in this case minimized

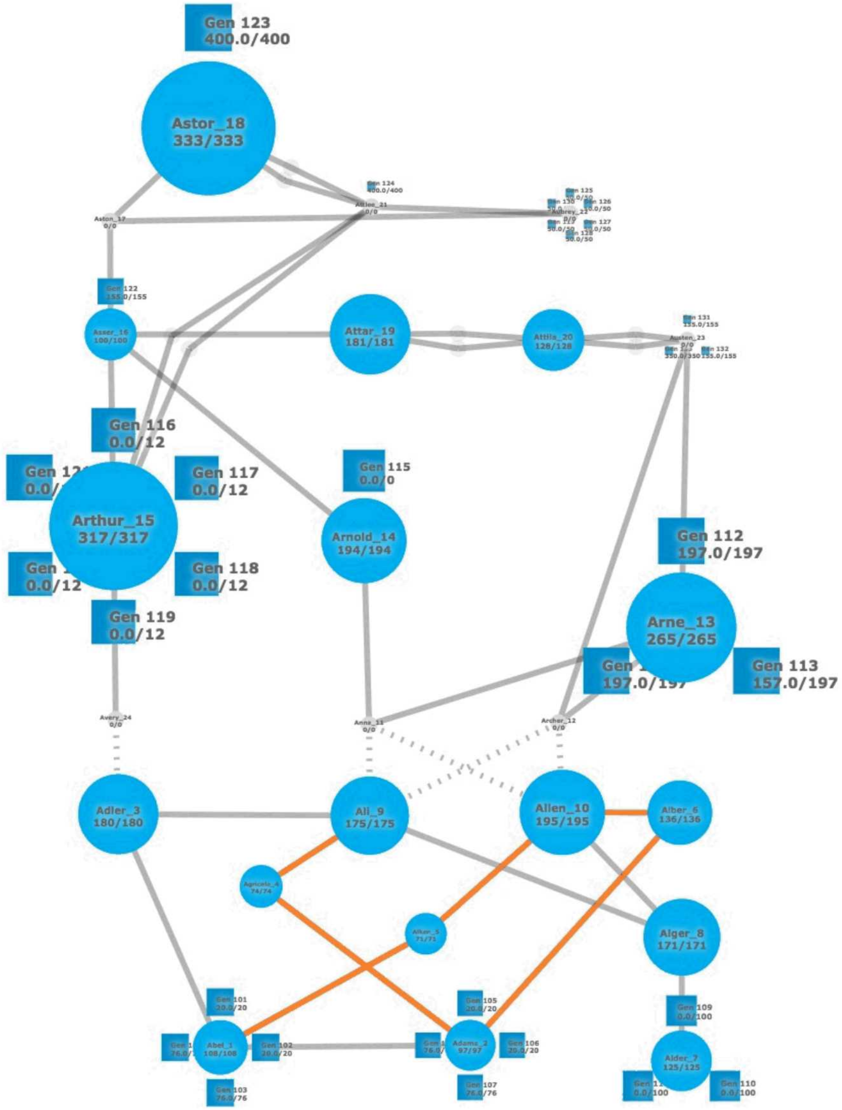
- Include repair stages
  - Repair time of components varies depending on the type of component and severity of the damage. From a modeling perspective, this can be included by identifying repair stages that will be presented as time periods, t^1, t^2, t^3 …
  - Redefine all variables by including an identifier to the repair stage, *n*. Define repair costs by the incremental costs corresponding to each repair stage.
  - Ensure that load shed is non-increasing by bus as repair stage increases - no demand location gets worse off as repairs happen
  - Represents expected operator behavior due to downstream impacts

BACKUP SLIDES

24 Bus - Backup generation at Astor



IEEE 24 Bus Link analysis example



- Let 2, 3, 4, and 5 links go down in random combinations
- Regression analysis to determine the links with the largest statistically significant coefficient when part of the disabled link set
- In this case, “top 6” links consistently show greatest impact on objective value
- One factor in determining where to harden or add redundancy