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Sandia National Laboratories

Resilience for Energy Infrastructure

Singapore NRF

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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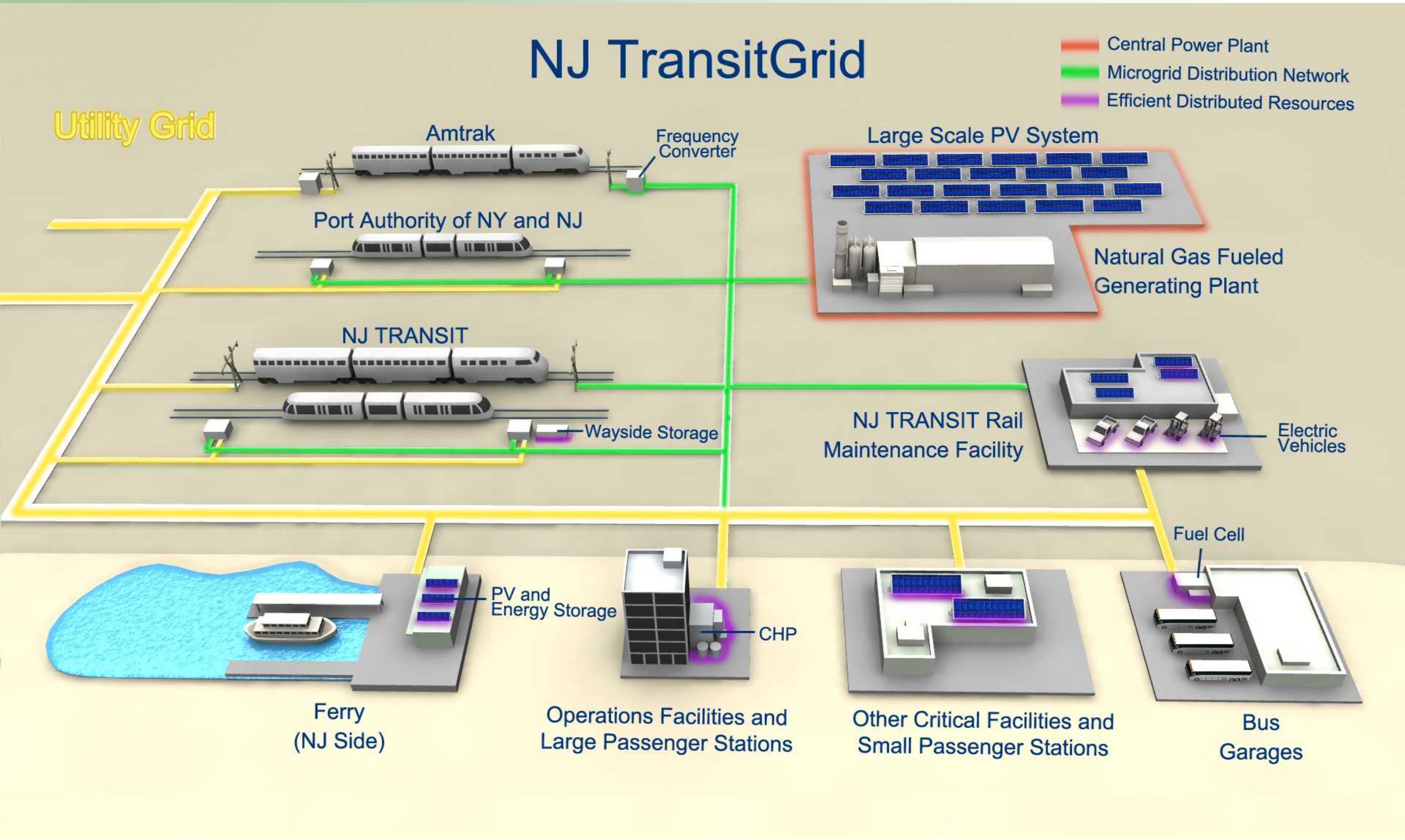

NJ TransitGrid
Central Power Plant
Microgrid Distribution Network
Efficient Distributed Resources
Utility Grid
Amtrak
Frequency Converter
Large Scale PV System
Port Authority of NY and NJ
Natural Gas Fueled Generating Plant
NJ TRANSIT
NJ TRANSIT Rail Maintenance Facility
Wayside Storage
Electric Vehicles
Fuel Cell
PV and Energy Storage
CHP
Ferry (NJ Side)
Operations Facilities and Large Passenger Stations
Other Critical Facilities and Small Passenger Stations
Bus Garages

Hoboken, New Jersey

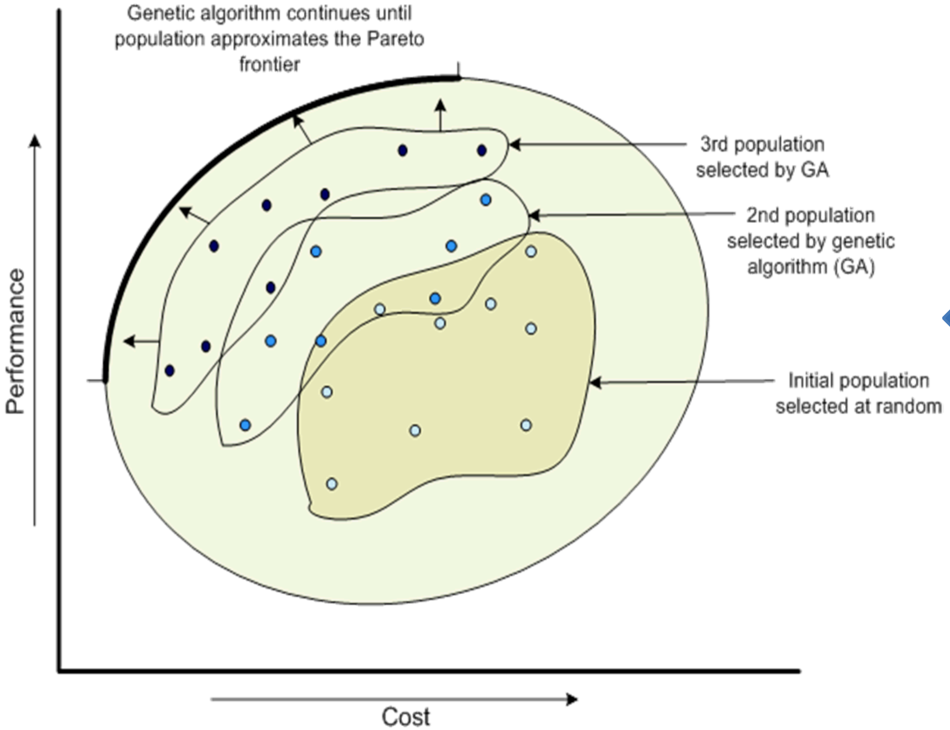
COOPR

Mixed Integer Optimization

Least Cost Topology for a Single Large Microgrid

Solution Subset:
Steiner Tree Problem

Pareto Optimality Using Genetic Algorithms



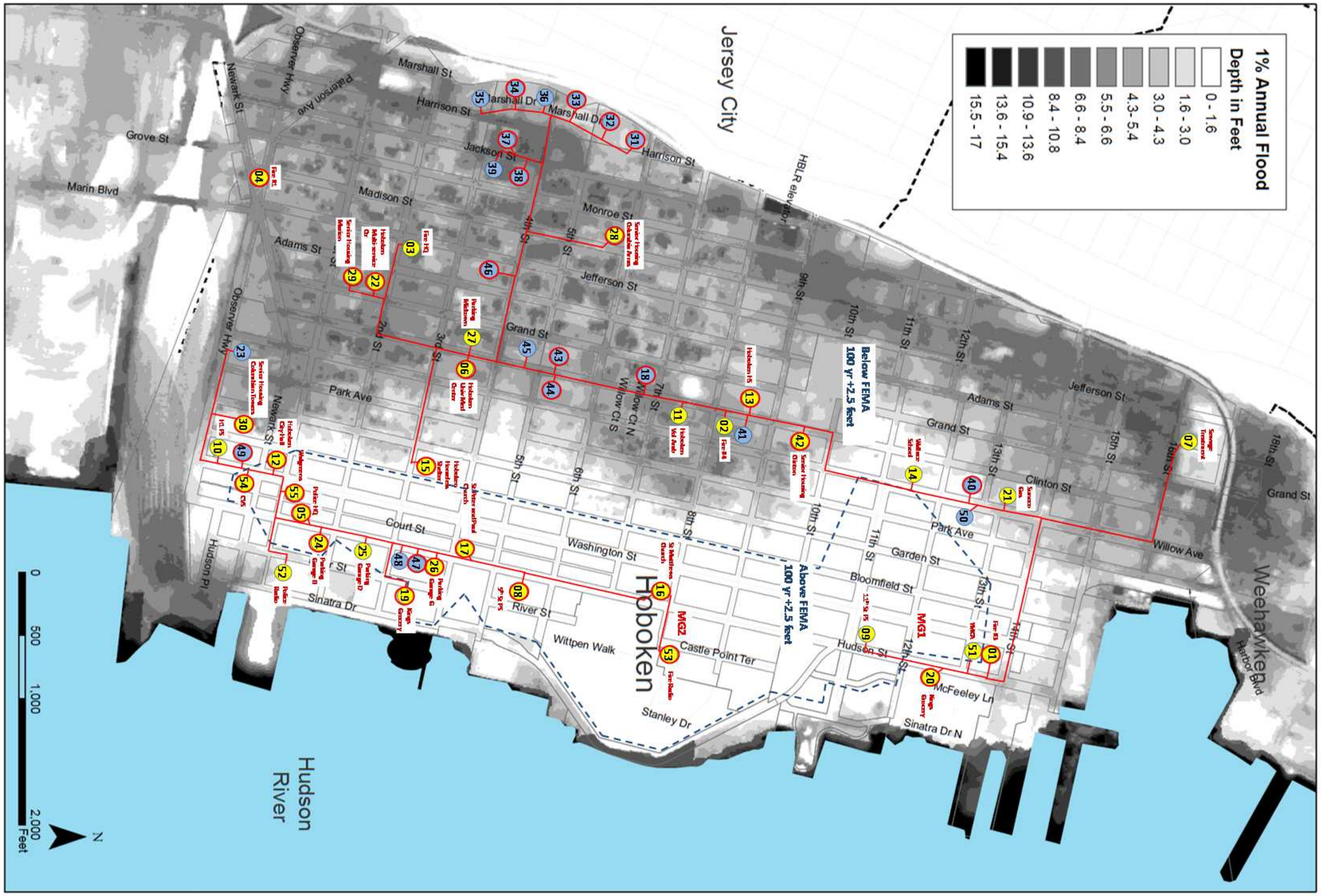
Topology →

← Performance

Event Driven Simulation

Monte Carlo Analysis

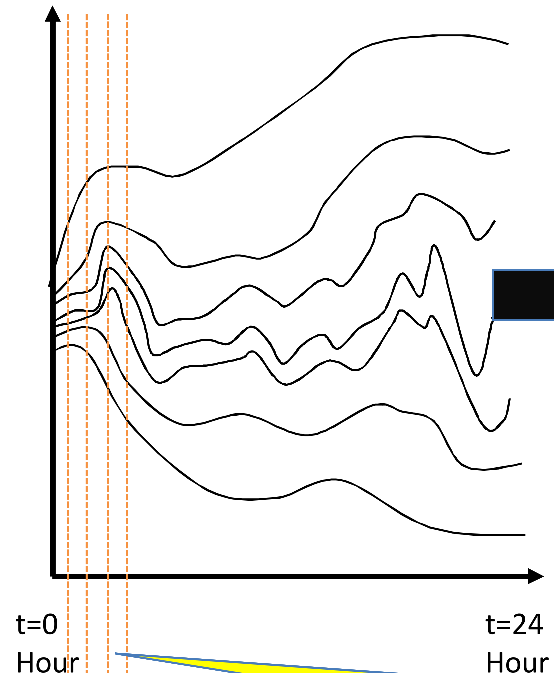
A Hoboken Microgrid Solution



UBS solution A clusters

Getting a Commitment from the Stochastic Scenarios

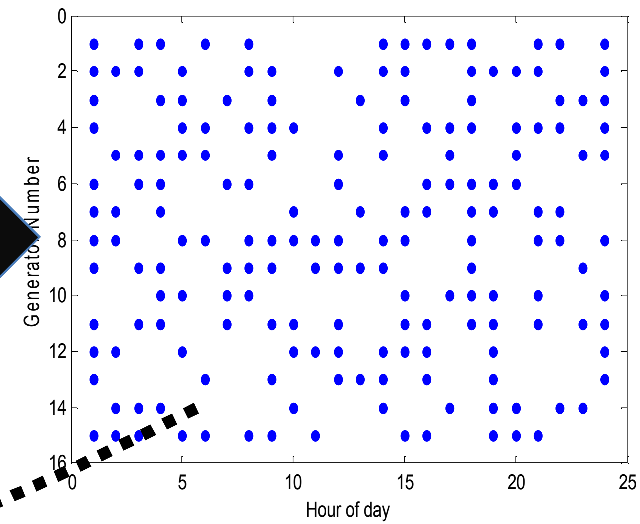
Scenarios

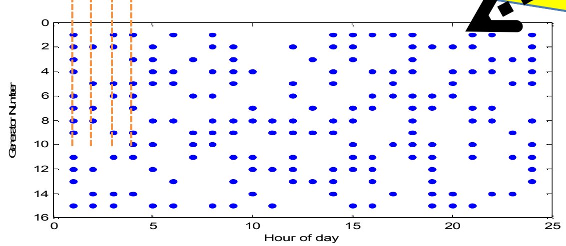


Find a singe UC that has the lowest expected cost across all scenarios

Progressive Hedging used to minimize expected cost and CVAR

Generator Commitment





Each hour has a commitment that yields the lowest probability weighted cost across all scenarios

$$\min \sum P_j LMP_j$$

How Do We Design for Resilience?

- Engage stakeholders
- **Establish a design basis (design basis threat doc)**
- Define performance metrics
- Define system boundaries
- Collect system and operations info and data
- Generate feasible designs
  - **measure performance against the design basis**
  - improve the design
  - repeat

What Are Gaps for Resilience Metrics?

- Attribute based metrics are primarily used today (e.g. number of critical spare transformers)
  - They don't quantify resilience
  - They don't indicate certainty about effectiveness
- Performance based metrics:
  - Are quantitative and denote uncertainty
  - Allow optimal allocation of resources in system planning and operations
  - Provide an ability to differentiate resilience among systems
  - Inform development of policy goals and the assessment of their effectiveness
  - Achieve **utility** in exchange for **complexity**

Resilience versus Reliability

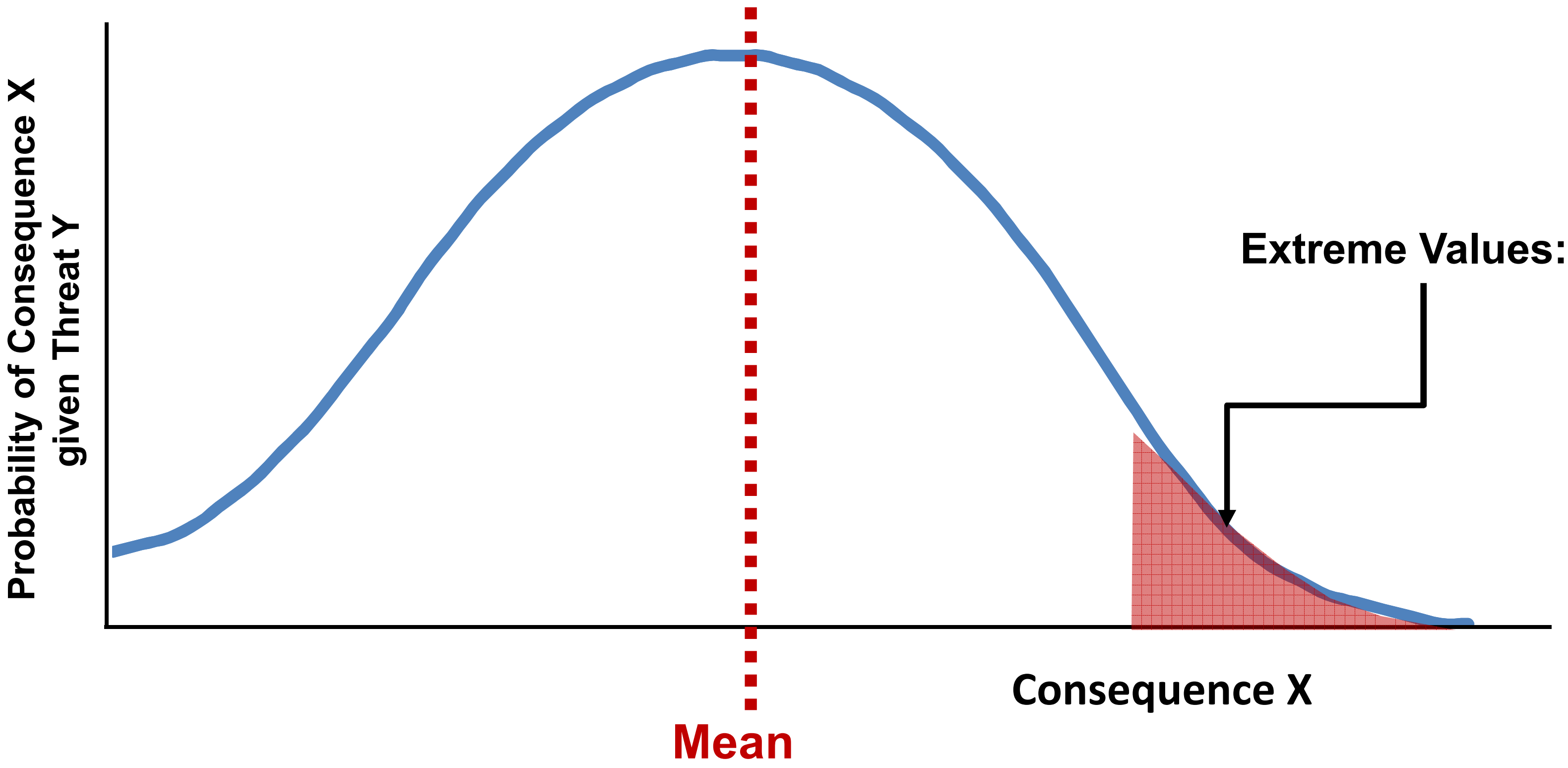
Separating reliability and resilience is important

- Reliability is compulsory
- Reliability is related to rate recovery
- Adoption of resilience metrics will be easier if reliability definitions remain as-is

Reliability	Resilience
High Probability, Low Consequence (SAIDI/SAIFI exclude storm data)	Low Probability, High Consequence
Not risk based	Risk Based, includes: Threat (you are resilient to something) System Vulnerability (~reliability) Consequence (beyond the system)
Operationally, You are reliable, or you are not [0 1]. Confidence is unspecified	Resilience is a continuum, confidence is specified
Focus is on the measuring impact to the system	Focus is on measuring impact to humans

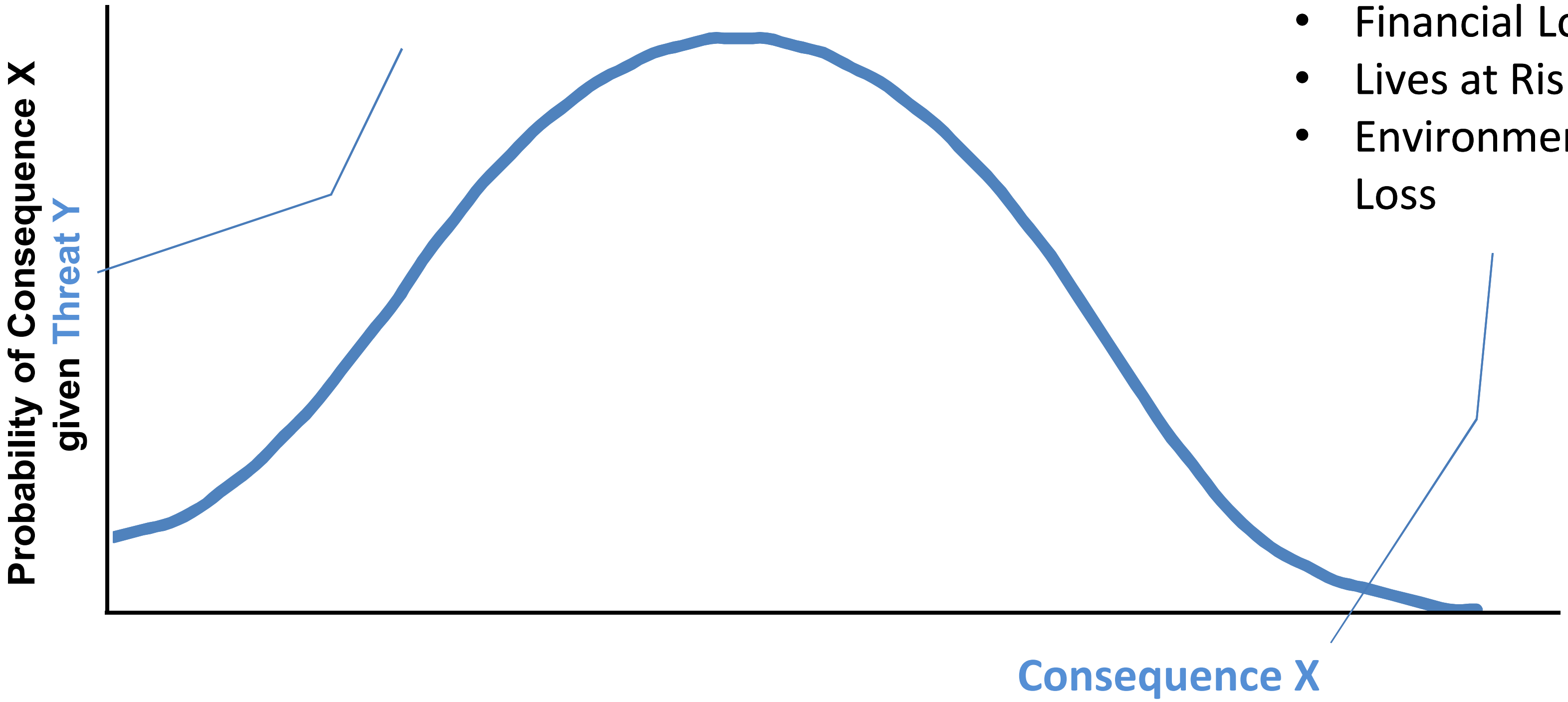
Energy System Resilience Metric Framework

(Metrics have X and Y defined)



Prototype Metrics
Probability of Consequence X, Given Threat Y

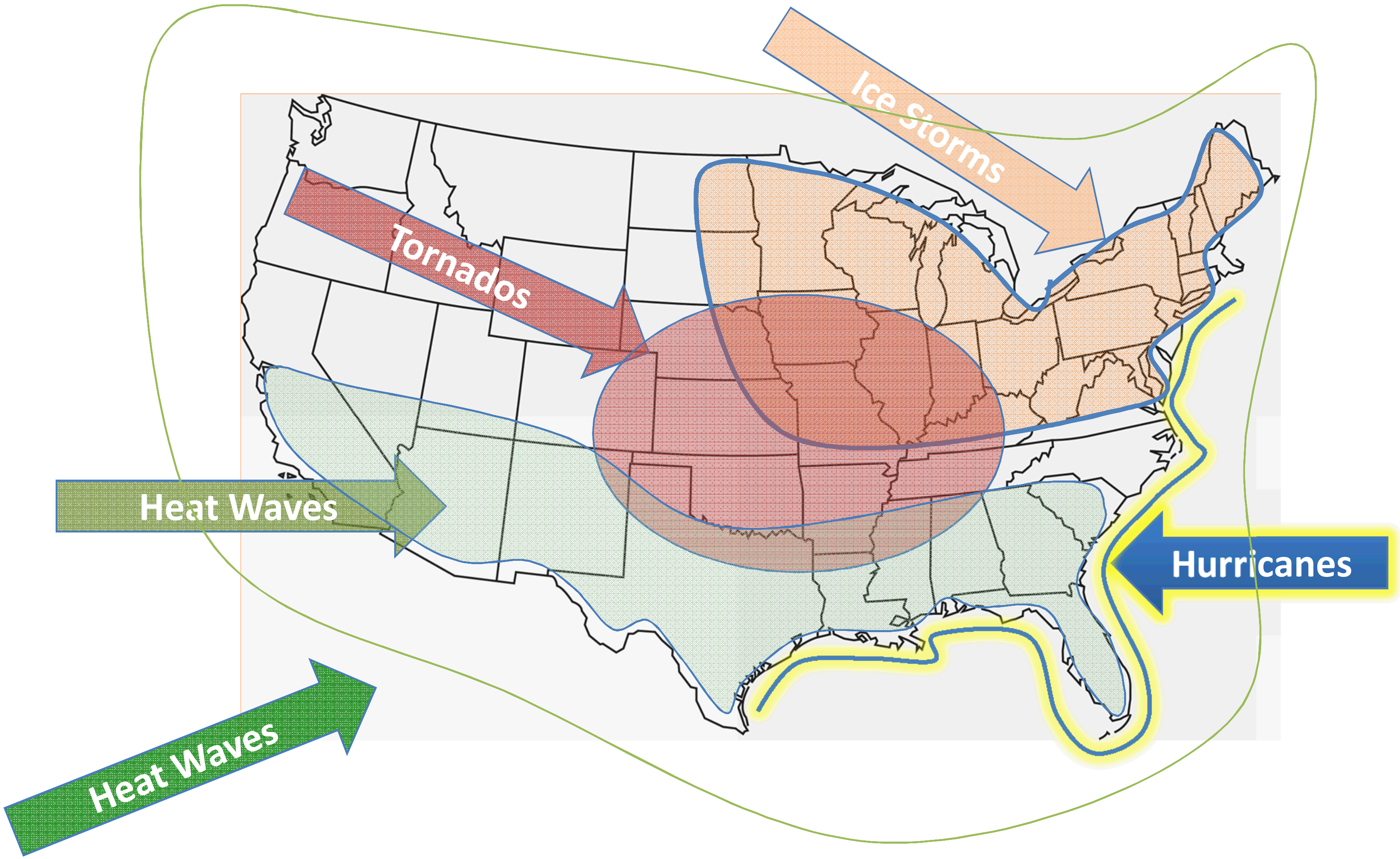
- Category 5 Hurricane
- Flood
- Ice Storm
- Combined Physical/Cyber Attack
- Probability weighted Threat Vector



- Financial Loss
- Lives at Risk
- Environmental Loss

Regional and Demographic Differences

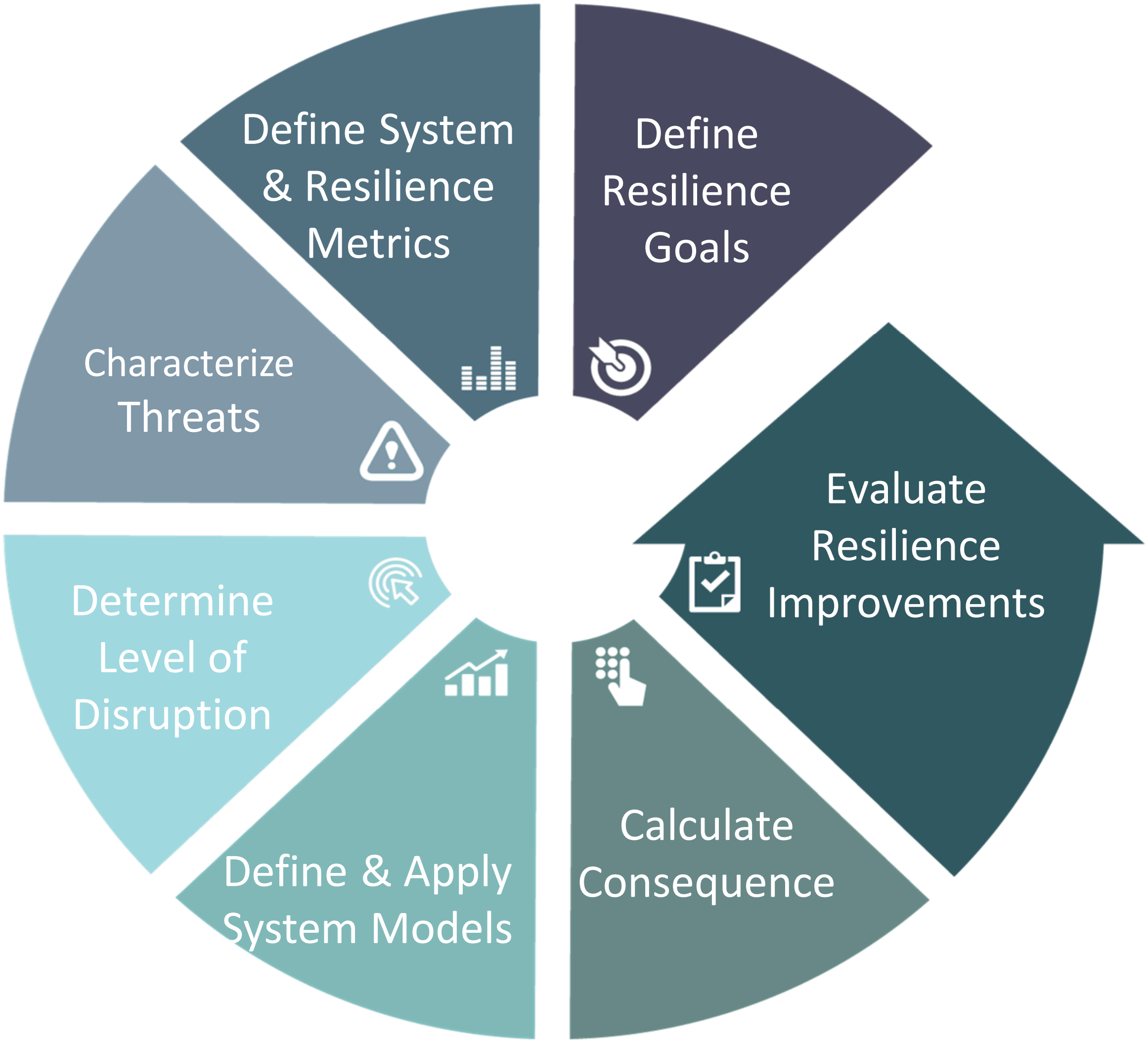
One-Size-Fits-All Metrics May Not Be Appropriate



Moving Forward with Resilience Analysis

An Example Using Electricity Infrastructure

Oil and Gas Infrastructure examples are included in the report



Characterize Individual Threat

Characterize Threats

Given high-level threat characterization, the next step is to further refine the description of the specific threats

<u>Historical information and forecast models are used to the guide specification of possible events and their relative likelihoods</u>

…

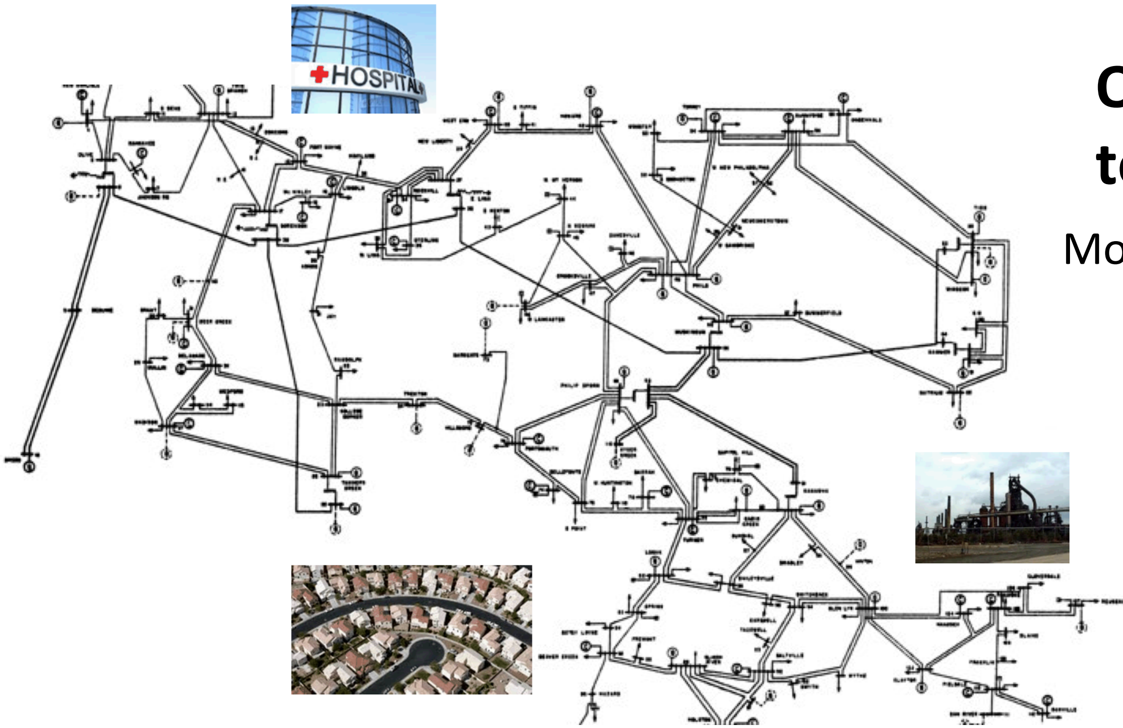
p_1 … p_2 … p_n

Category 2, landfall at high tide

Category 4, north-of-peninsula storm track

Category 5, eye tracks over metropolitan area

Operations Model



Operations model is used to quantify system impact

Modified IEEE 118 Bus Test Case System

91 loads
54 generators
186 lines

Basic Model:

- Reliability unit commitment
- Multi-period scheduling
- 24 hour horizon
- Dispatch and commitment

Research Need:
Identify Failure Probabilities Under Threat

Expressing Model as a Mixed-Integer Program

Define & Apply System Models

Core electricity grid operations problems are expressed as algebraic optimization problems, typically mixed-integer or linear programs

Standard unit commitment formulation

$$
\begin{aligned}
\min_{\boldsymbol{x}} \quad & c^u(\boldsymbol{x}) + c^d(\boldsymbol{x}) + \overline{Q}(\boldsymbol{x}) \\
\text{s.t.} \quad & \boldsymbol{x} \in \mathcal{X}, \\
& \boldsymbol{x} \in \{0,1\}^{|G|\times|T|}
\end{aligned}
$$

The feasible set X implicitly captures minimum up and down-time constraints on thermal units

Transmission elements modeled via DC power flow, with possible integration of AC feasibility checks

Multi-period economic dispatch

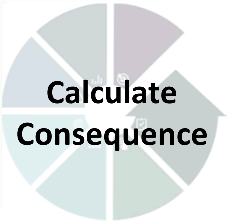
$$
\overline{Q}(\boldsymbol{x}) = \mathrm{E}_{\boldsymbol{\xi}} Q(\boldsymbol{x}, \boldsymbol{\xi}(\omega))
$$

$$
\begin{aligned}
Q(\boldsymbol{x}, \boldsymbol{\xi}(\omega)) = & \\
\min_{p,q} \quad & \sum_{t\in T}\sum_{g\in G} c_g^P(p_g^t) + \sum_{t\in T} M q^t \\
\text{s.t.} \quad & \sum_{g\in G} p_g^t - q^t = D^t(\boldsymbol{\xi}(\omega)), \quad \forall t \in T \\
& \underline{P}_g x_g^t \le p_g^t \le \overline{P}_g x_g^t, \quad \forall g \in G, t \in T \\
& p_g^t - p_g^{t-1} \le RU(x_g^{t-1}, x_g^t), \quad \forall g \in G, t \in T \\
& p_g^{t-1} - p_g^t \le RD(x_g^{t-1}, x_g^t), \quad \forall g \in G, t \in T.
\end{aligned}
$$

where

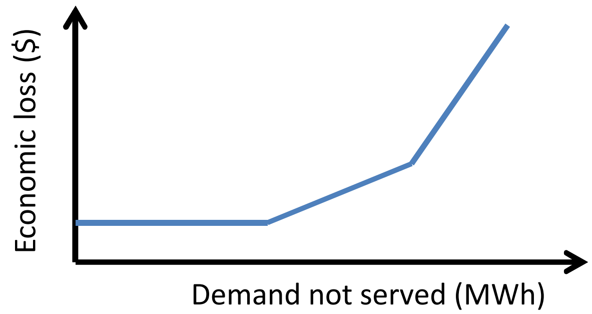
$$
\begin{aligned}
RU(x_g^{t-1}, x_g^t) &= R_g^u x_g^{t-1} + S_g^u(x_g^t - x_g^{t-1}) + \overline{P}_g(1 - x_g^t) \\
RD(x_g^{t-1}, x_g^t) &= R_g^d x_g^t + S_g^d(x_g^{t-1} - x_g^t) + \overline{P}_g(1 - x_g^{t-1})
\end{aligned}
$$

Consequences



- Consequence data, on a per-bus basis, is defined for the economic impact on the economy
- We assume Economic impact is different at different load buses according to factors such as type of load

Research Need:
Associate System Performance to Consequences



Assess Baseline Resiliency

Calculate Consequence

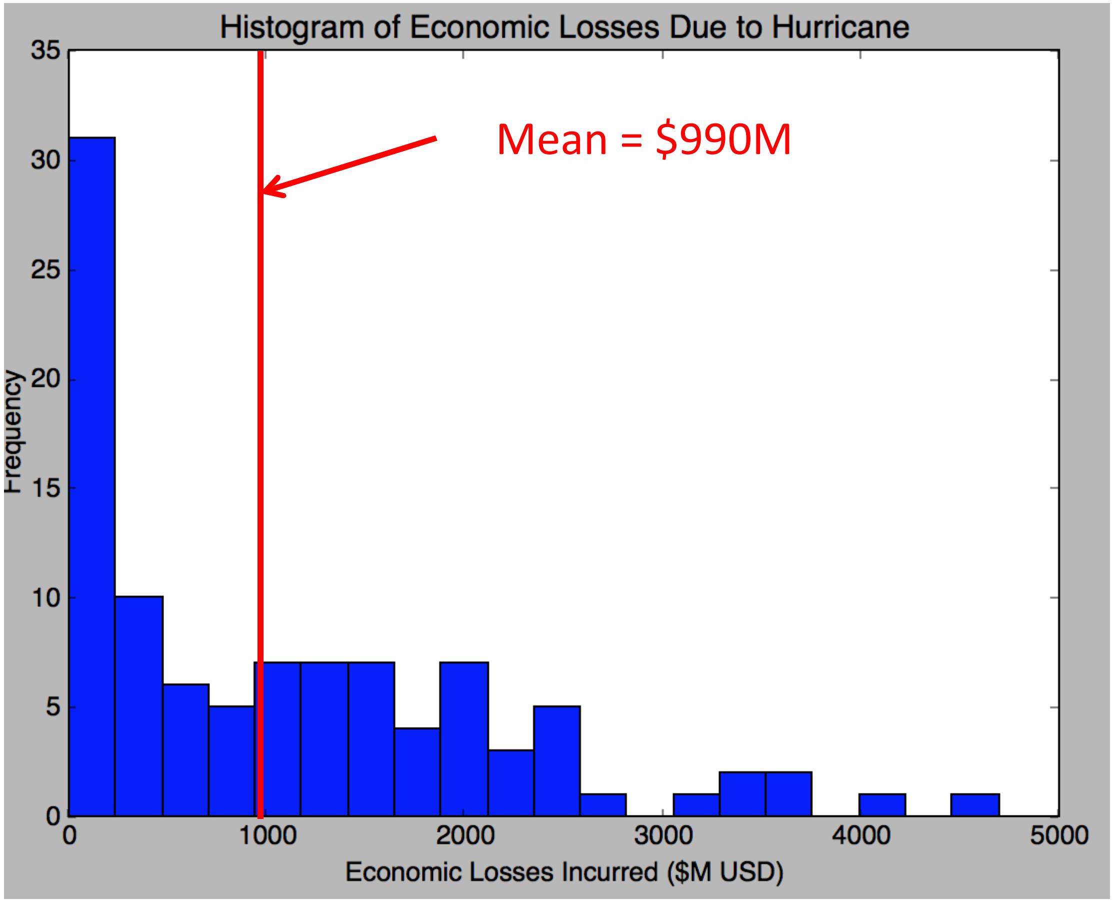
Assessing the economic losses incurred by a hypothetical hurricane event on the IEEE 118 bus test system

Methodology

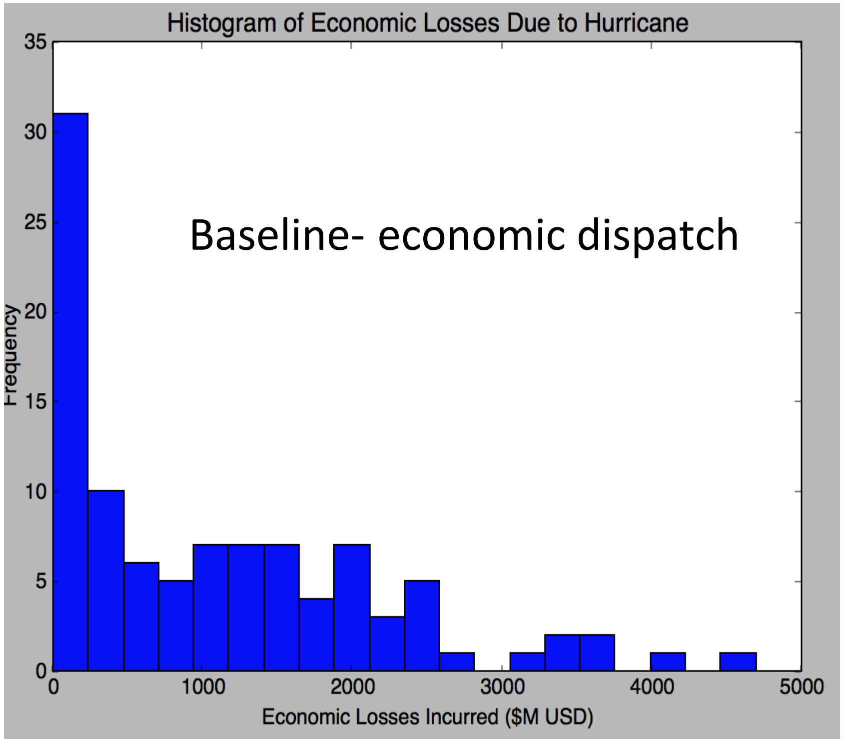
1. Sample 100 scenarios
2. For each scenario, compute a minimal-cost dispatch and associated loss of load
3. For each scenario, compute the cumulative economic losses incurred

Assumptions

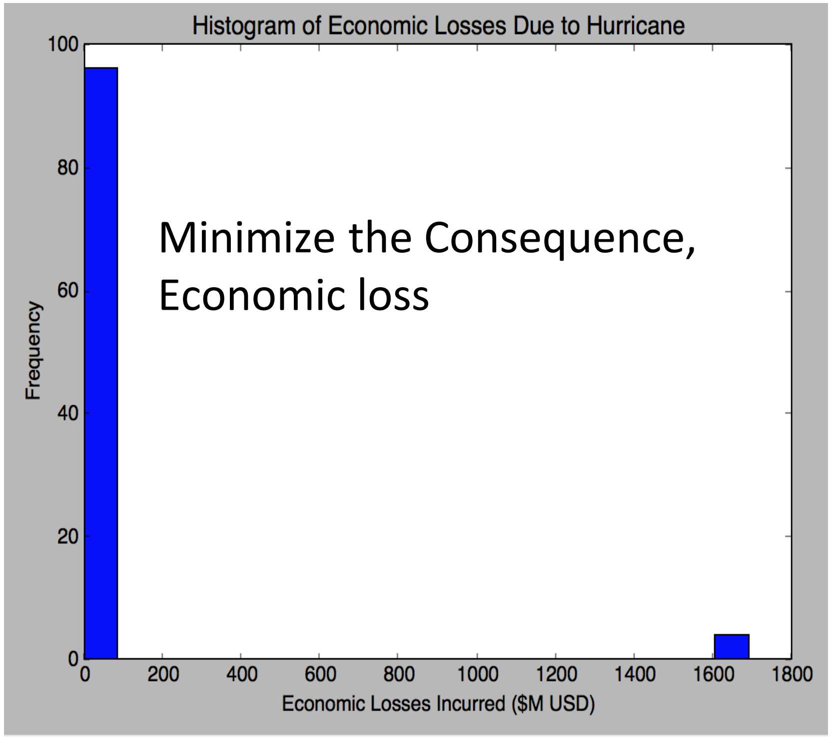
1. No recovery possible for first 48 hours
2. Independent scenario analysis



Change the Dispatch Objective



VS



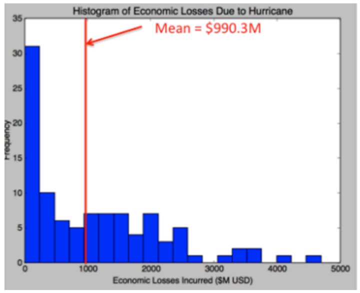
In our IEEE 118 bus resiliency example, it is possible to mitigate nearly all economic consequences of the posited hurricane

$100M Investment Options

- Investment Option A
  - Build flood walls around generators with greater than 180 MW capacity (~20% of the thermal fleet)
  - Proxy for protection against flooding
  - 11 Generators at $9.1M for a total of $100M
- Investment Option B
  - Bury high-capacity lines – those with greater than 250 MW thermal limits (~5% of the network)
  - Proxy for protection against high winds and tree faults
  - 25 lines at $4M for a total of $100M

How Should We Spend $100M?

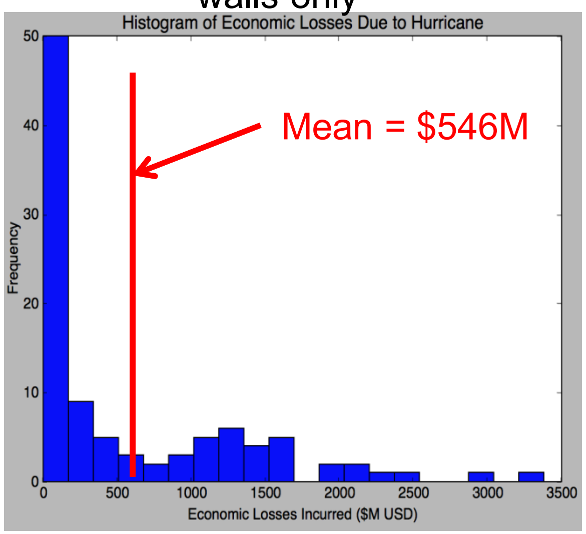
Evaluate Resilience Improvements



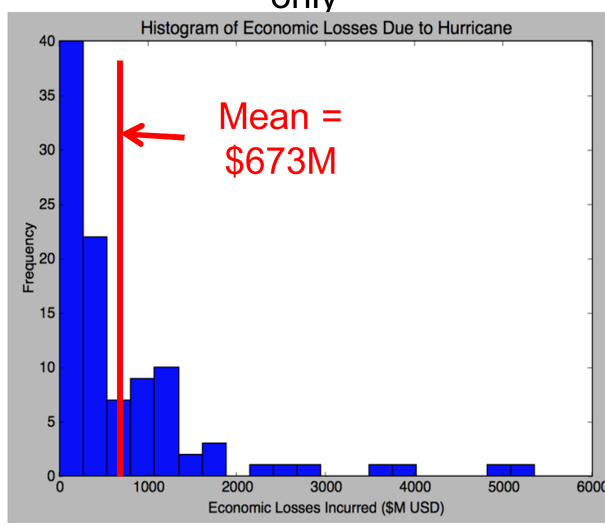
Baseline mean was $990M

Invest the same $100M in both flood walls and burying cables

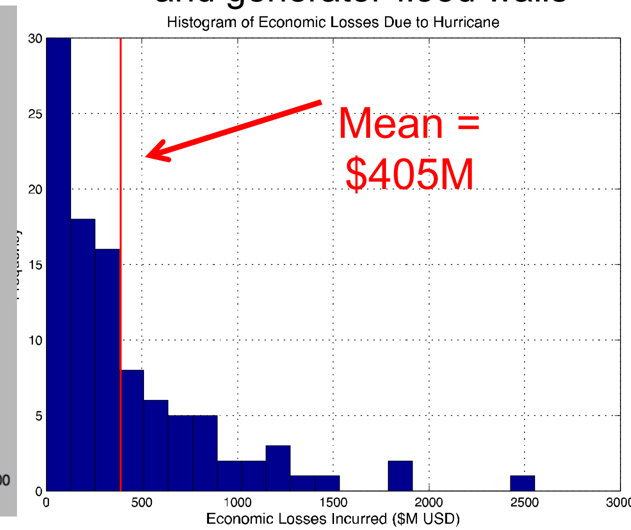
$100M of generator flood walls only



$100M of burying lines only



$100M of burying lines and generator flood walls



How Will We Use Resilience Analysis?

- Allows concrete goals for public and private resilience assessments, improvements and standards
- To provide a fair basis for resilience rate recovery
- In coordination with global warming studies
- Advanced oil, gas, and grid operations will mitigate consequences of impending threats
- To establish priorities for public and private investment

Advanced Metrics and Control Strategies for Grid Resiliency