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Boosting Grid Resilience Using Microgrid Concepts

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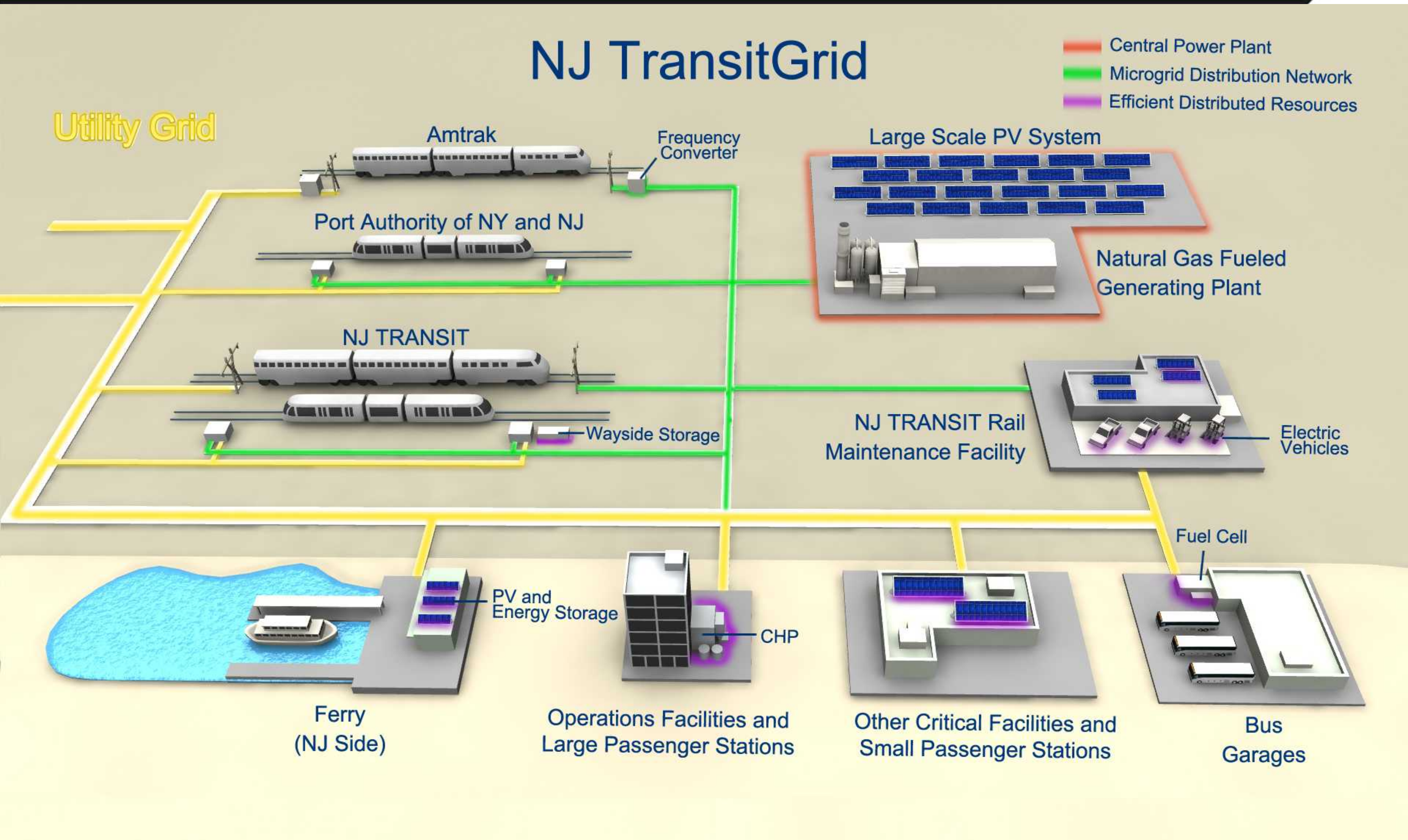
What is Resilience?

- We define resilience to be:
  - Risk-based: Vulnerability, Threat, Consequence
  - Low probability, high consequence threats
  - Characterized by a probability density function
- It complements reliability
  - Reliability is not risk based
  - Reliability focuses on high probability, low consequence events
  - Operationally, reliability is binary. E.g there is no difference between N-5 and N-10


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

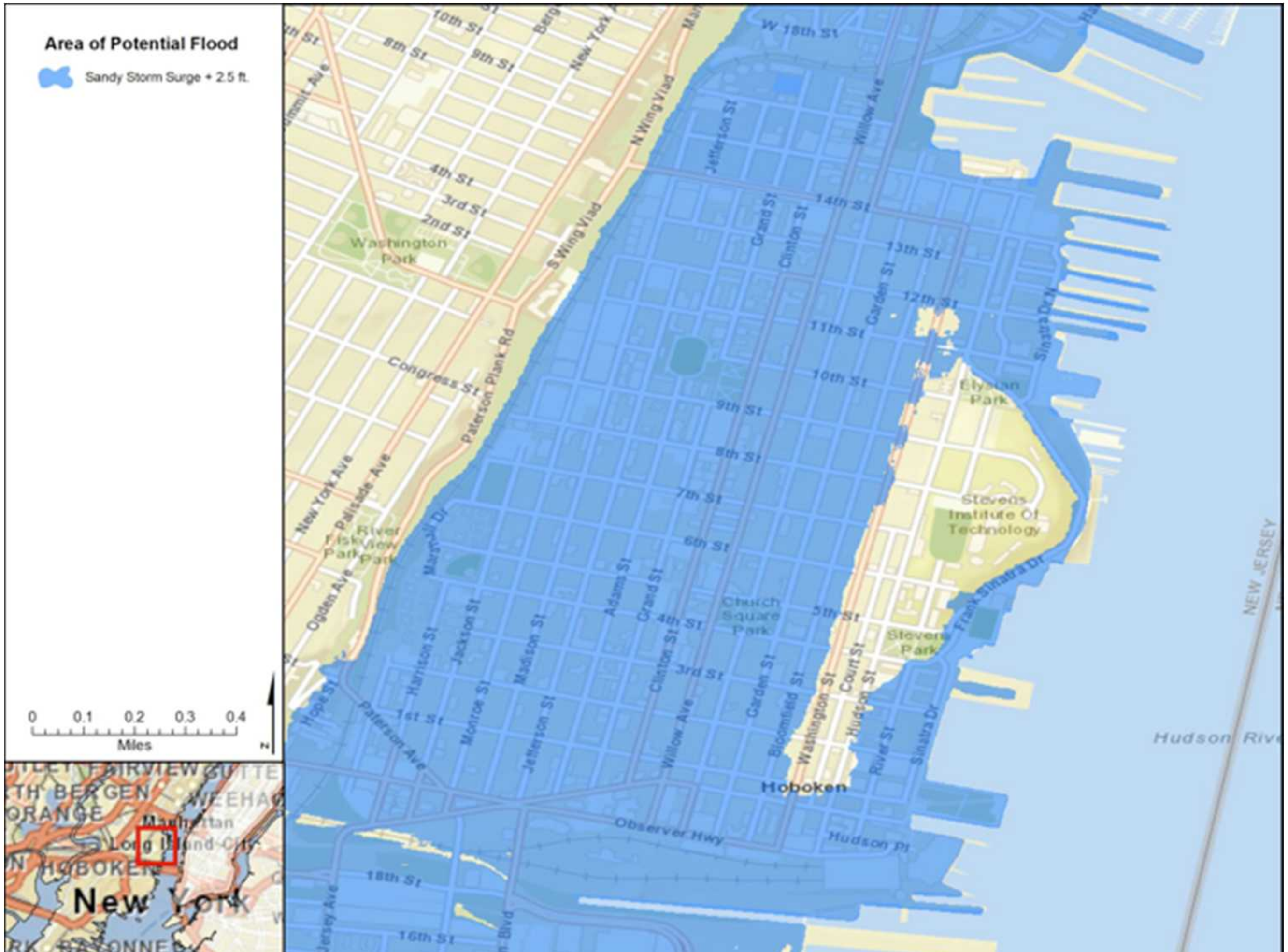
Solution Subset:
Steiner Tree Problem

How Do We Design for Resilience?

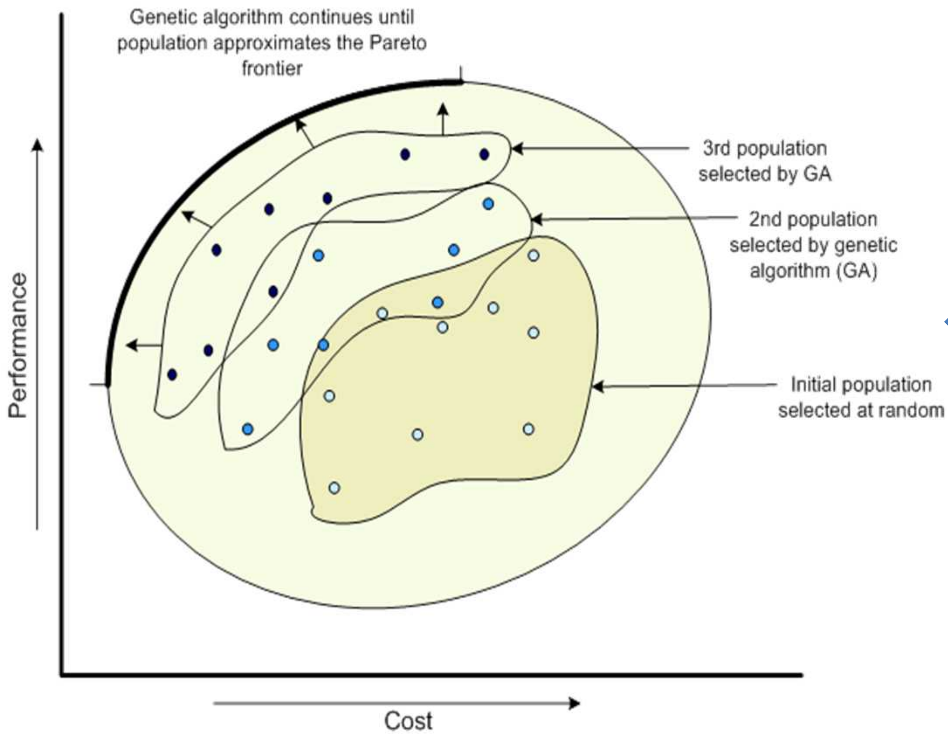
- Engage stakeholders
- **Establish a design basis (design basis threat doc)**
- Define performance metrics
- Define system boundaries
- Collect system and operations info and data
- Generate feasible designs
  - **measure performance against the design basis**
  - improve the design
  - repeat

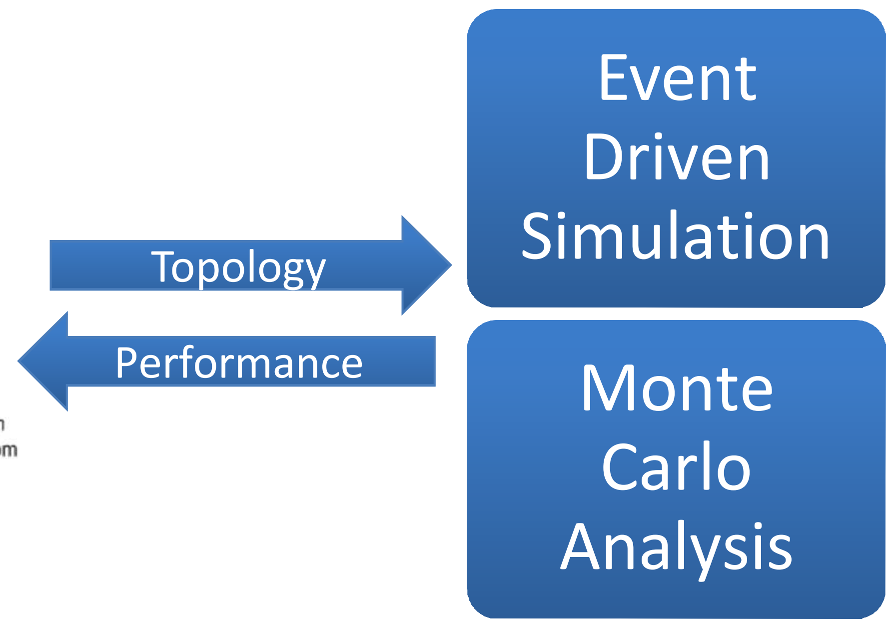
Flood Maps for Hoboken

FEMA 100 Year Flood + 2.5 Feet



Pareto Optimality Using Genetic Algorithms



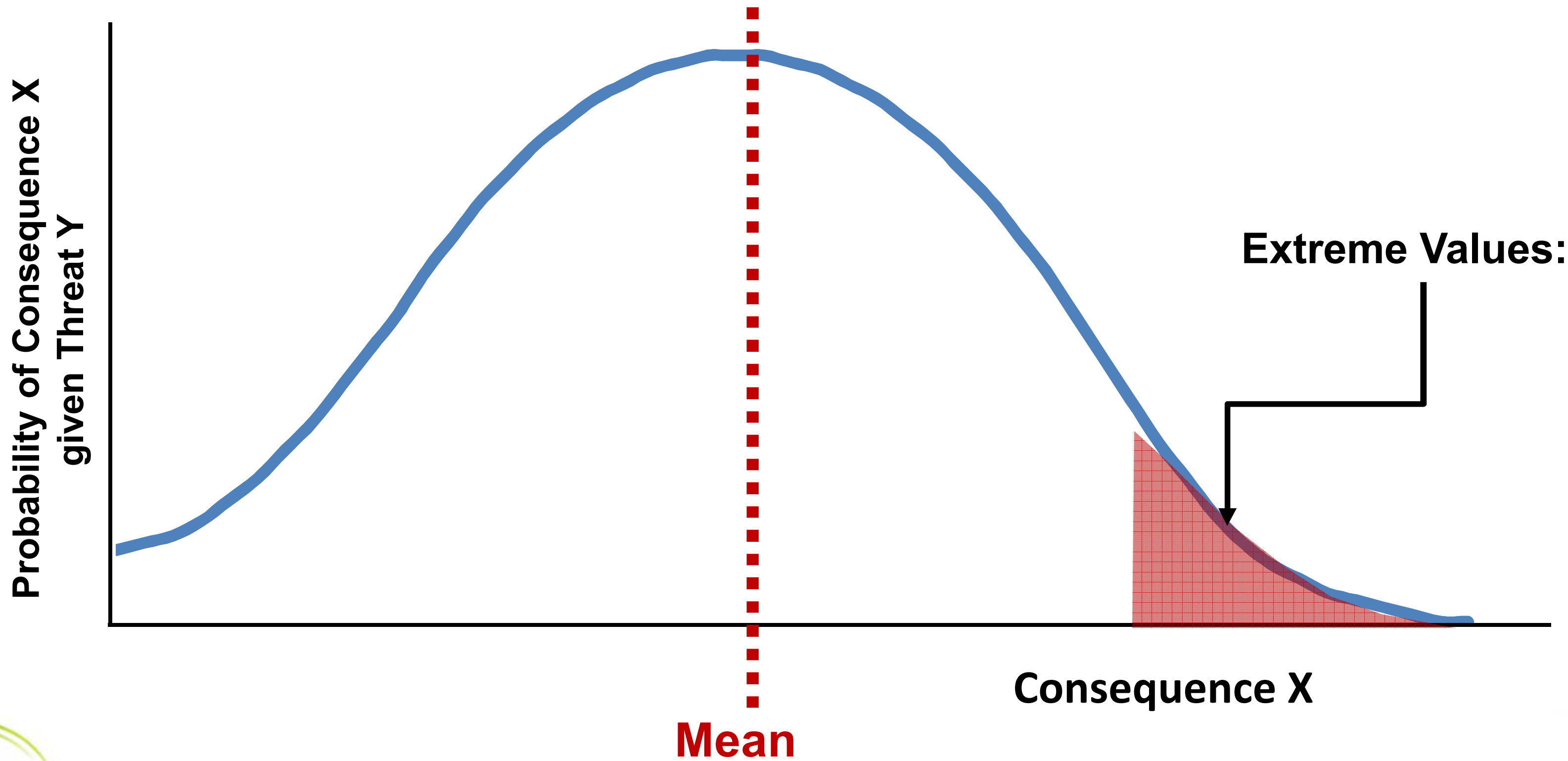


A Hoboken Microgrid Solution

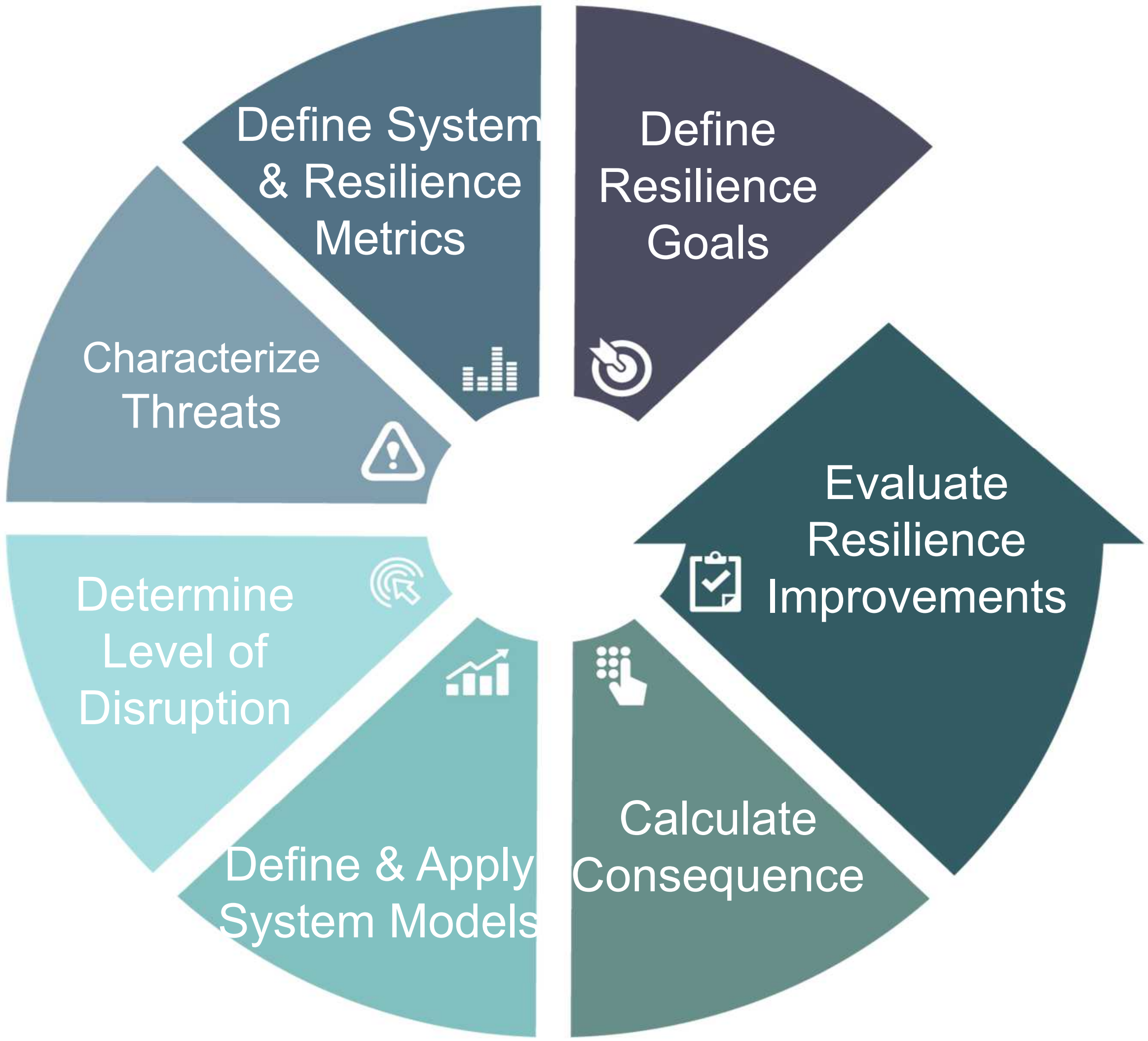
Standardizing Resilience Metrics

- Desirable Properties of Resilience Metrics
  - Useful for making decisions
  - Provide a means of comparison
  - Can be used for operations, planning and policy
  - Are scalable in geography, time, and analytic methodology
  - Are quantitative
  - Quantify uncertainty
  - Support a risk-based approach
  - Consider recovery time

Energy System Resilience Metric Framework



Moving Forward with Resilience Analysis



Identify Threat Types

A infrastructure is designed to be resilient to a specific set of possible disruptions

Definition of possible disruptions can proceed via construction of a ***scenario tree***

Alternatives exist, but they are more nuanced in terms of definition

We begin with high-level threat definitions

Probabilities are uniform (all-hazard), or skewed to reflect different emphases

High-level scenario identification is expected to be an output from an iterative and interactive stakeholder-driven process

Characterize Individual Threat

Characterize Threats

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

Historical information and forecast models is used to guide specification of possible events and their relative likelihoods

…

p_1 … p_2 … p_n

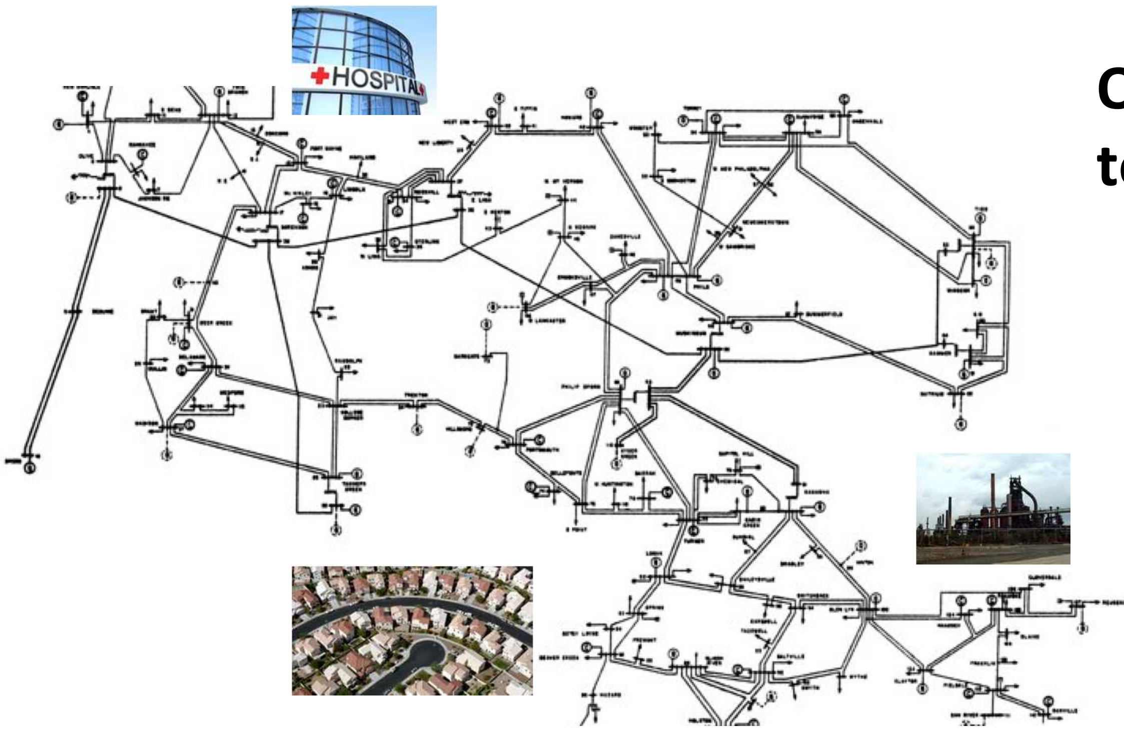
Category 2, landfall at high tide

Category 4, north-of-peninsula storm track

Category 5, eye tracks over metropolitan area

Define & Apply System Models

Operations Model



Operations model is used to quantify system impact

91 loads
54 generators
186 lines

Basic Model:

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

Modified IEEE 118 Bus Test Case System
http://motor.ece.iit.edu/data/ltscuc

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

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

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

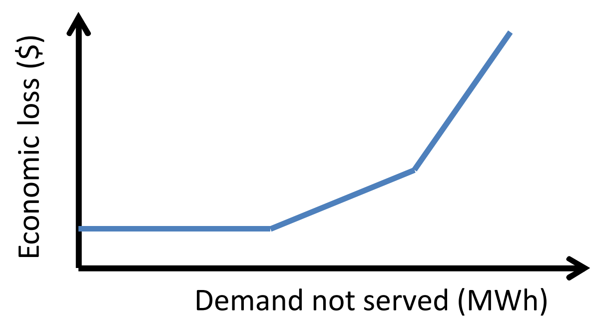
where

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

Consequences

Calculate Consequence

- Consequence data, on a per-bus basis, is defined for the economic impact on the economy
- We assume the following for purposes of resilience analysis
  - Economic impact is different at different load buses according to factors such as type of load
  - A piecewise linear transformations is employed to translate MWh not served to consequence (economic loss) at those load buses



Assess Baseline Resiliency

Calculate Consequence

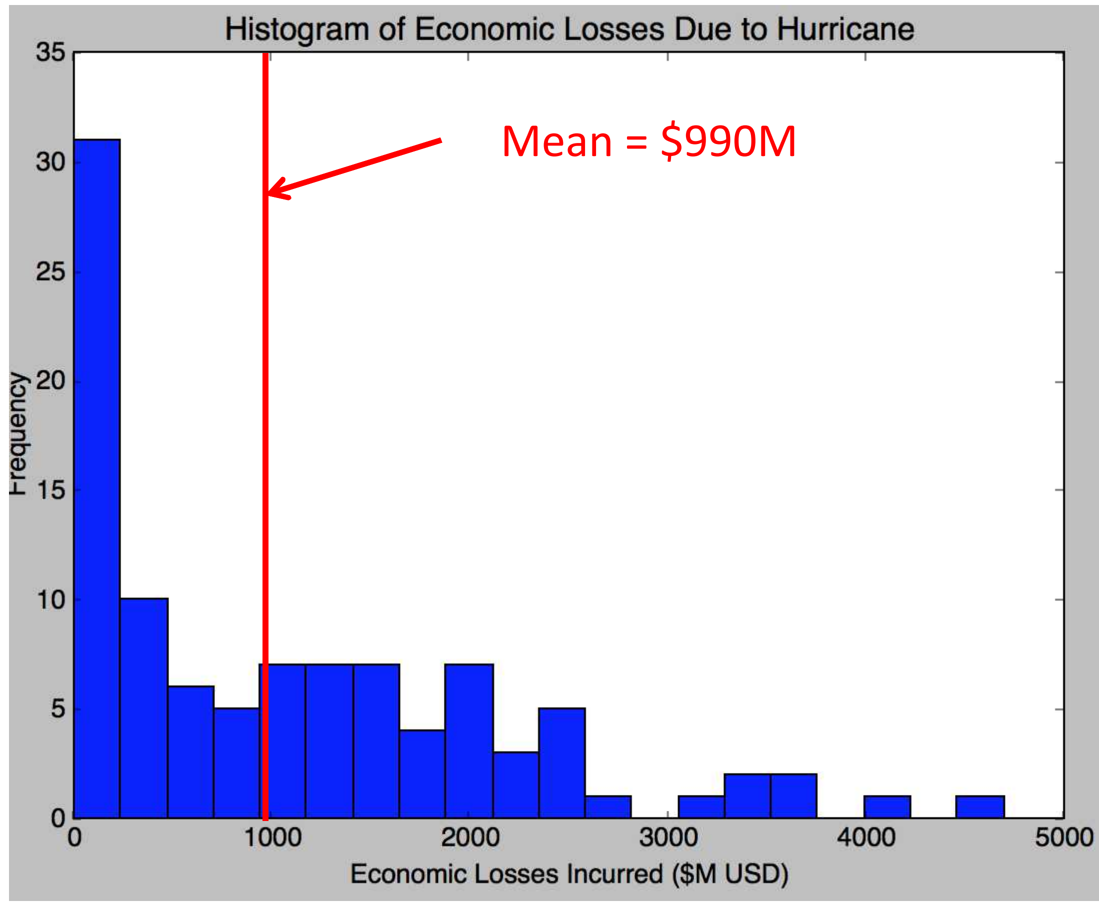
Assessing the economic losses incurred by a hypothetical hurricane event on the IEEE 118 bus test system

Methodology

1. Sample 100 scenarios specifying potential damage from a hurricane
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

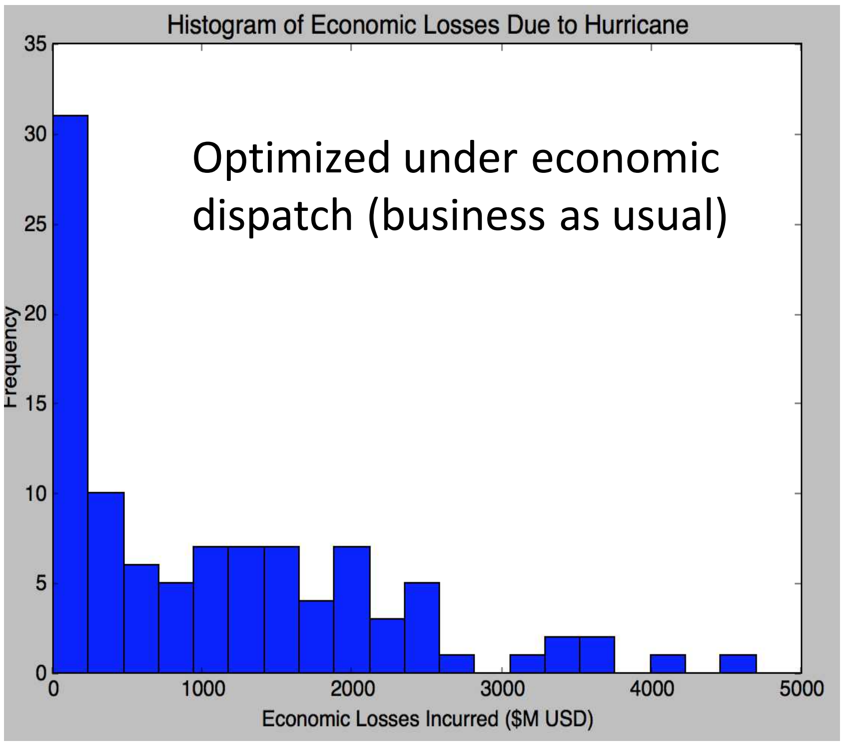
1. No recovery possible for first 48 hours
2. Independent scenario analysis



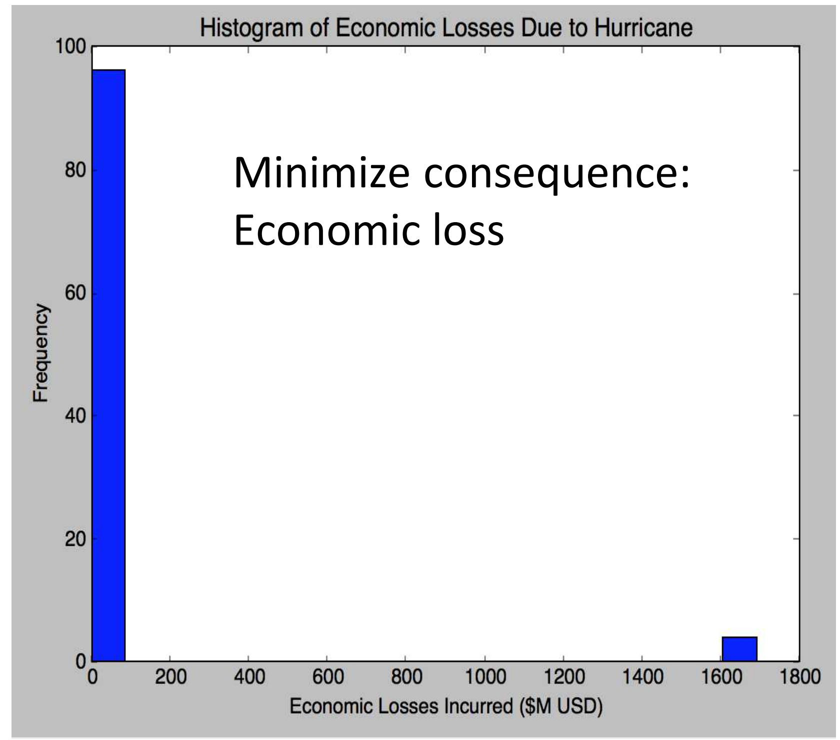
Change the Dispatch Objective

Calculate Consequence

Operating in a resilience-focused, as opposed to standard economic- and reliability-focused, manner leads to dramatic reductions in consequence



VS



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

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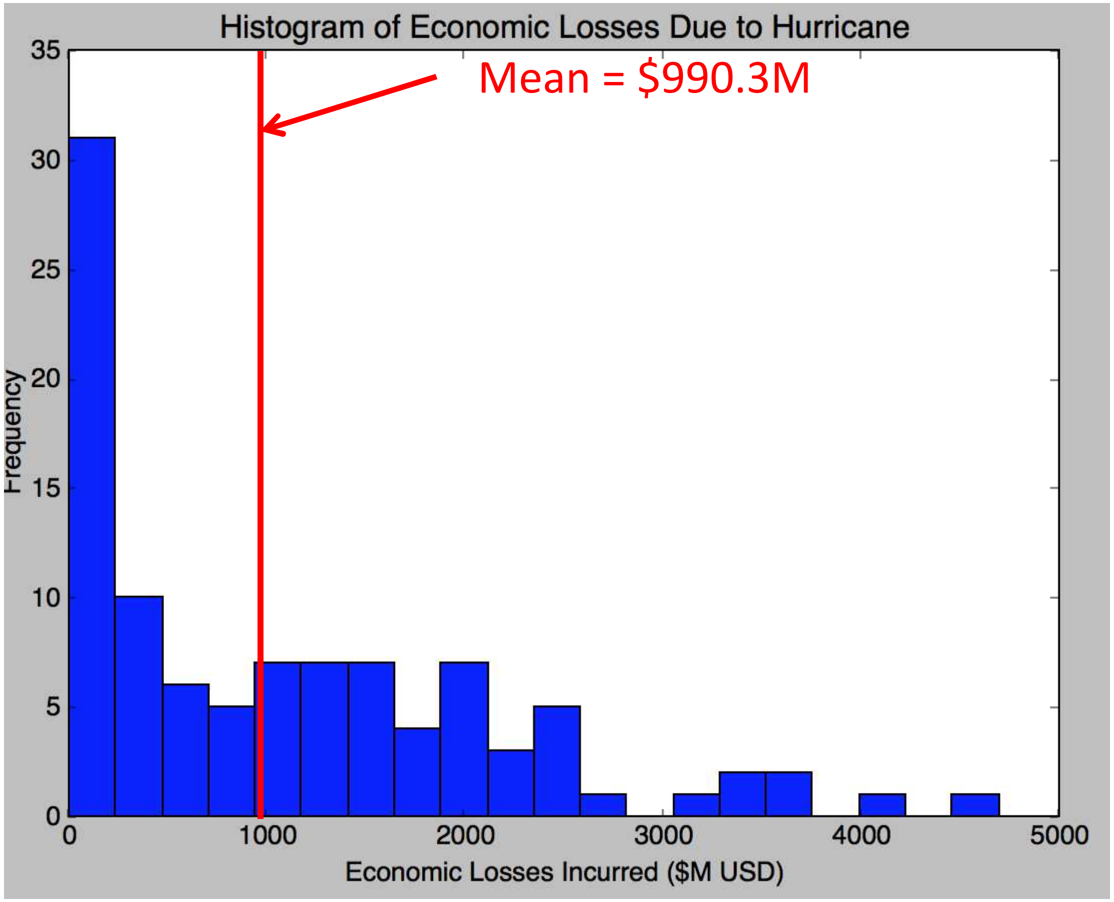
Investment Options

Evaluate Resilience Improvements

- 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

Baseline Resiliency

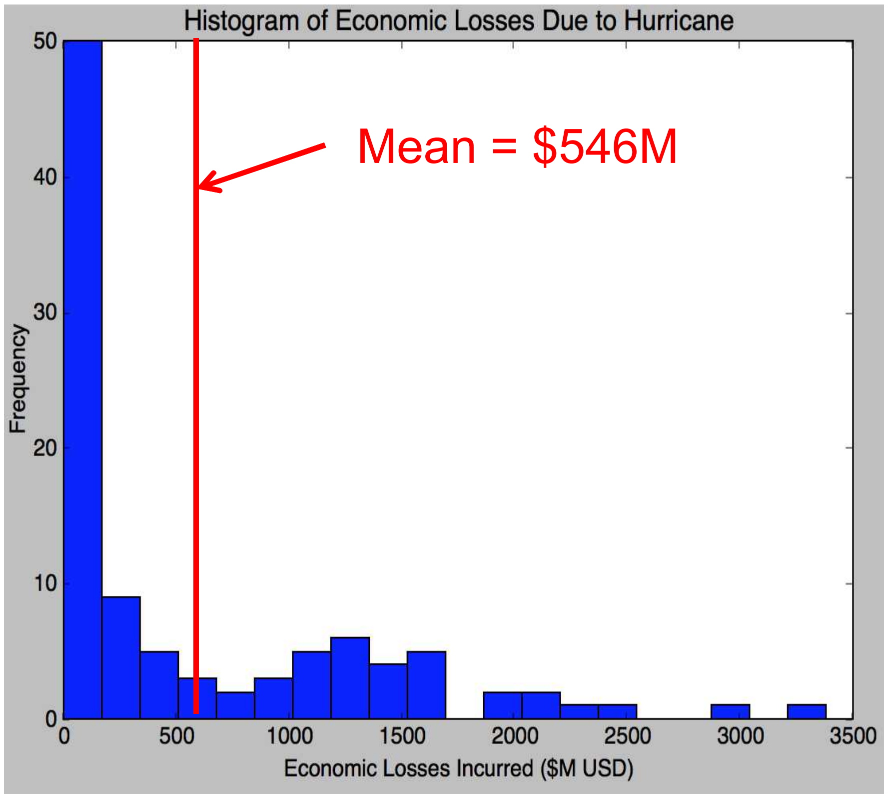


Evaluate Resilience Improvements

Analysis of Investment Alternativ

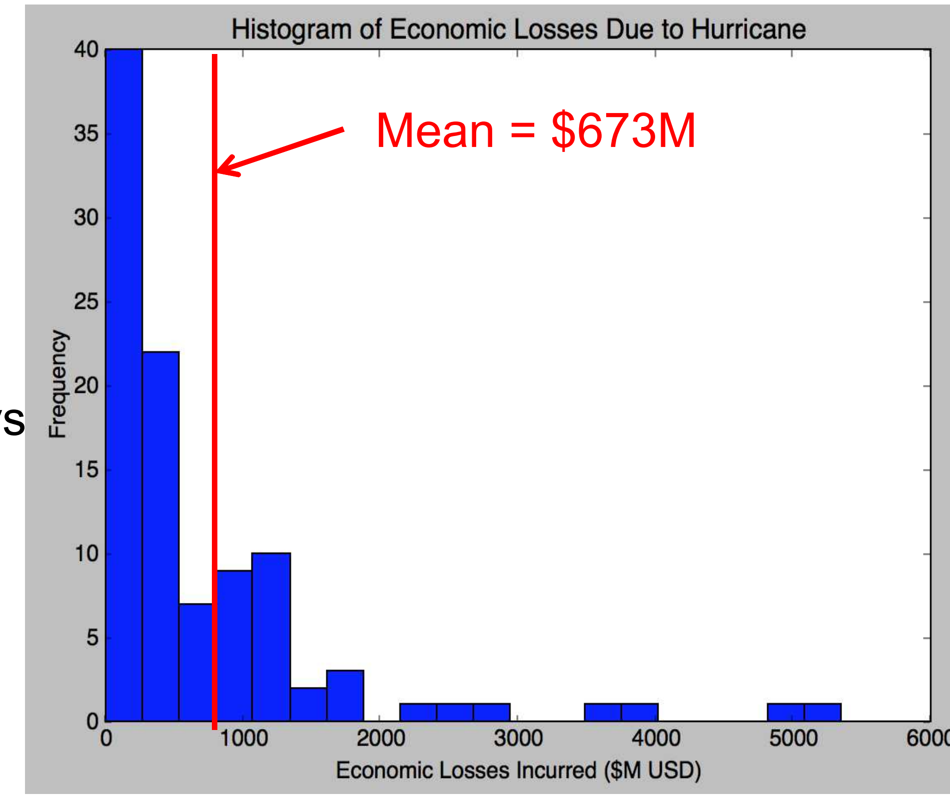
Both alternatives improve baseline mean of $990M

With generator flood walls



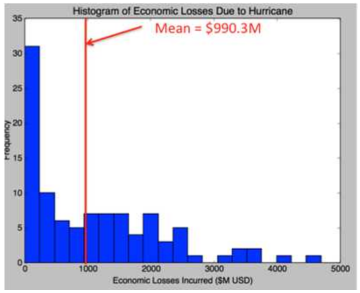
vs

With line burying



Result: Line burying admits some higher-consequence events, with approximately the same mean impacts

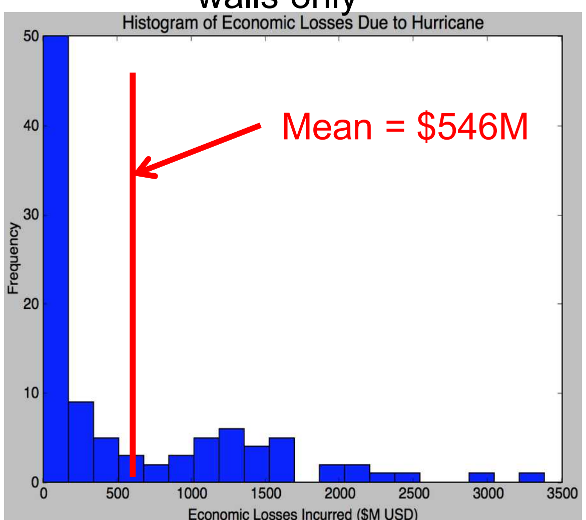
Optimal Investment Portfolio



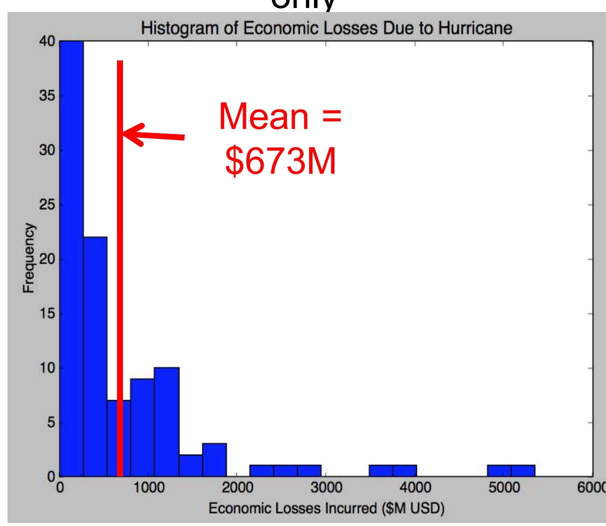
Baseline mean was $990M

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

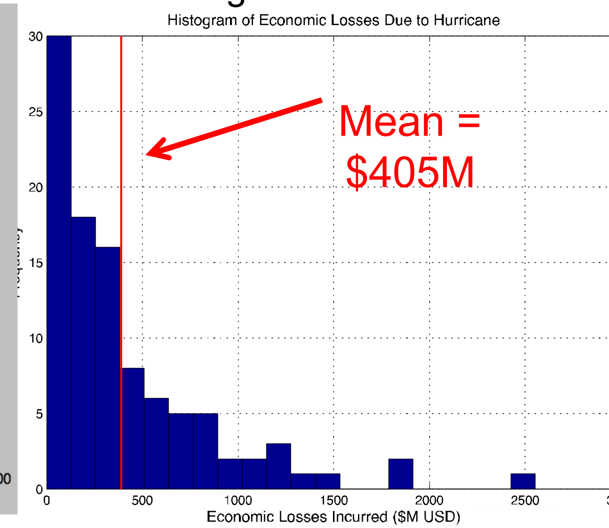
$100M of generator flood walls only



$100M of burying lines only



$100M of burying lines and generator flood walls



Advanced Metrics and Control Strategies for Grid Resiliency