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Resilience Metrics for Energy Transmission and Distribution Infrastructure

June 10, 2014

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Overview of Today's Discussions

- Goals and Context
- Resilience Analysis Process
- Use Case demonstrations
  - Electricity
  - Oil
  - Gas
- Discussion: Framing a Resilience Roadmap

Goals for Today

- Demonstrate an analytical framework to quantify resilience metrics and a process to utilize them
- Provide illustrustrative examples for 3 key energy infrastructures (electric, gas, oil)
  - Founded in real-world scenarios
- Solicit input for a national-level resilience roadmap which addresses:
  - Strategic national thrusts
  - Research & Development thrusts
- Build a multi-institutional team

Motivation

The President mandated a Quadrennial Energy Review to be jointly conducted by several US Departments which:

- Provides an integrated view of, and recommendations for, Federal energy policy
- Reviews the adequacy of existing executive and legislative actions
- Assesses and recommends priorities for research, development
- Identifies analytic tools and data needed to support further policy development and implementation

Defining Resilience

Presidential Policy Directive (PPD) 21

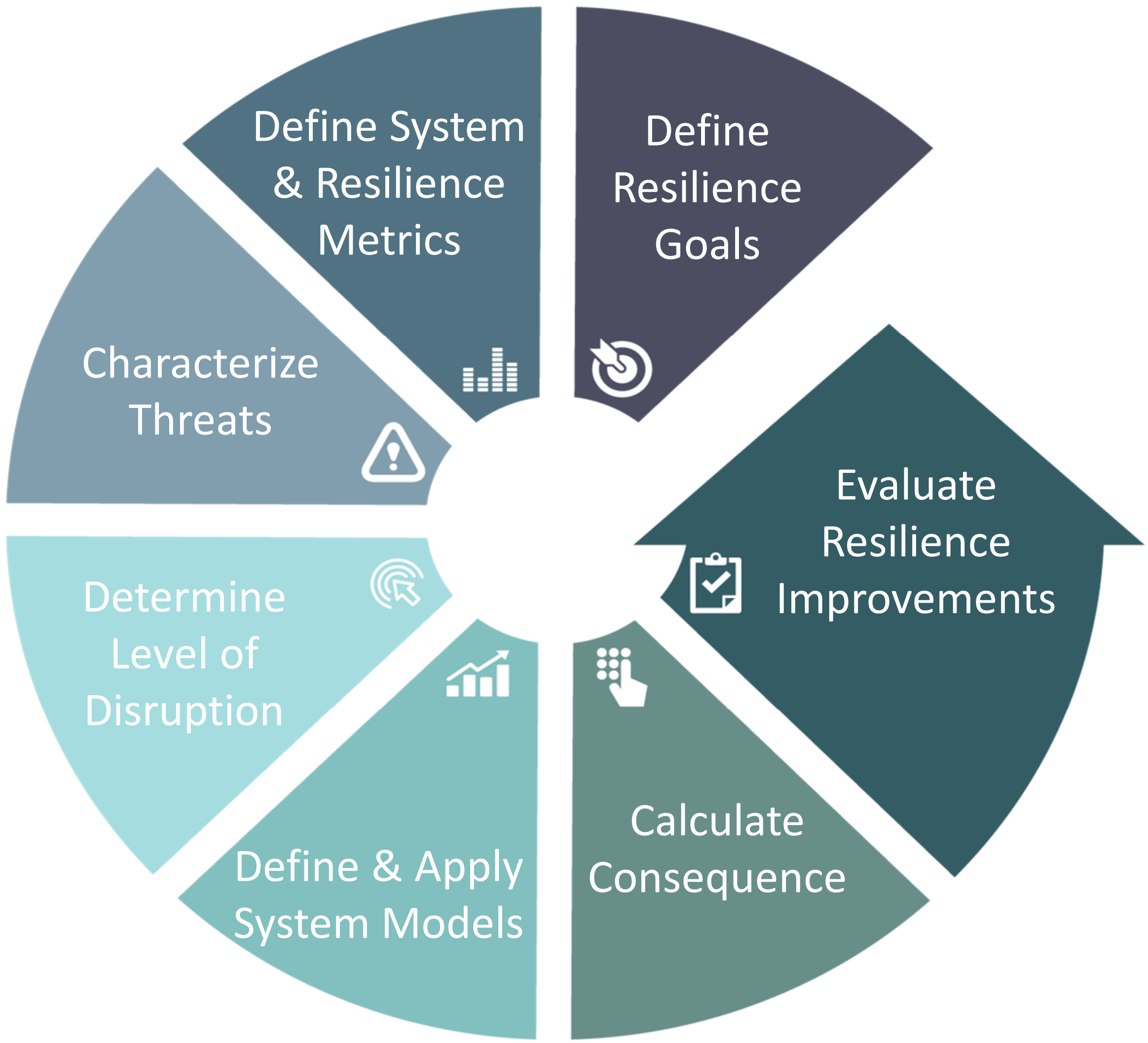
“the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.”

-PPD-21: Critical Infrastructure Security and Resilience

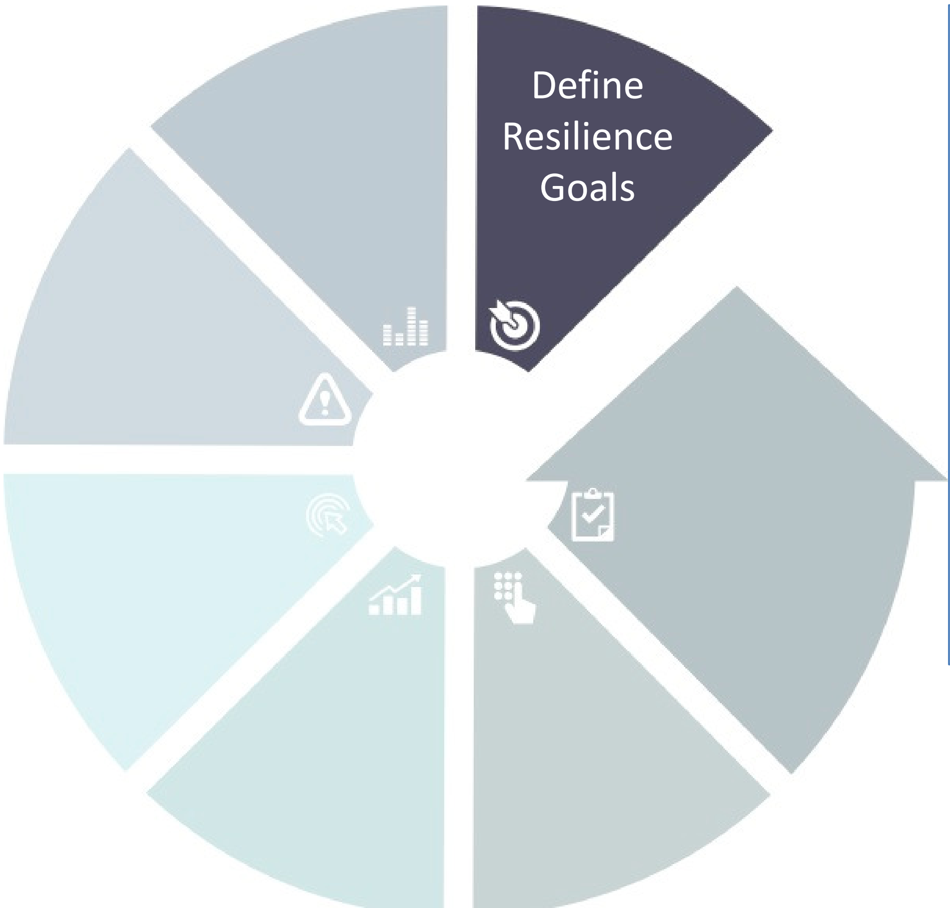
“without some numerical basis for assessing resilience, it would be impossible to monitor changes or show that community resilience has improved. At present, no consistent basis for such measurement exists…”

-Disaster Resilience: A National Imperative, National Academy of Sciences

Resilience Analysis Process



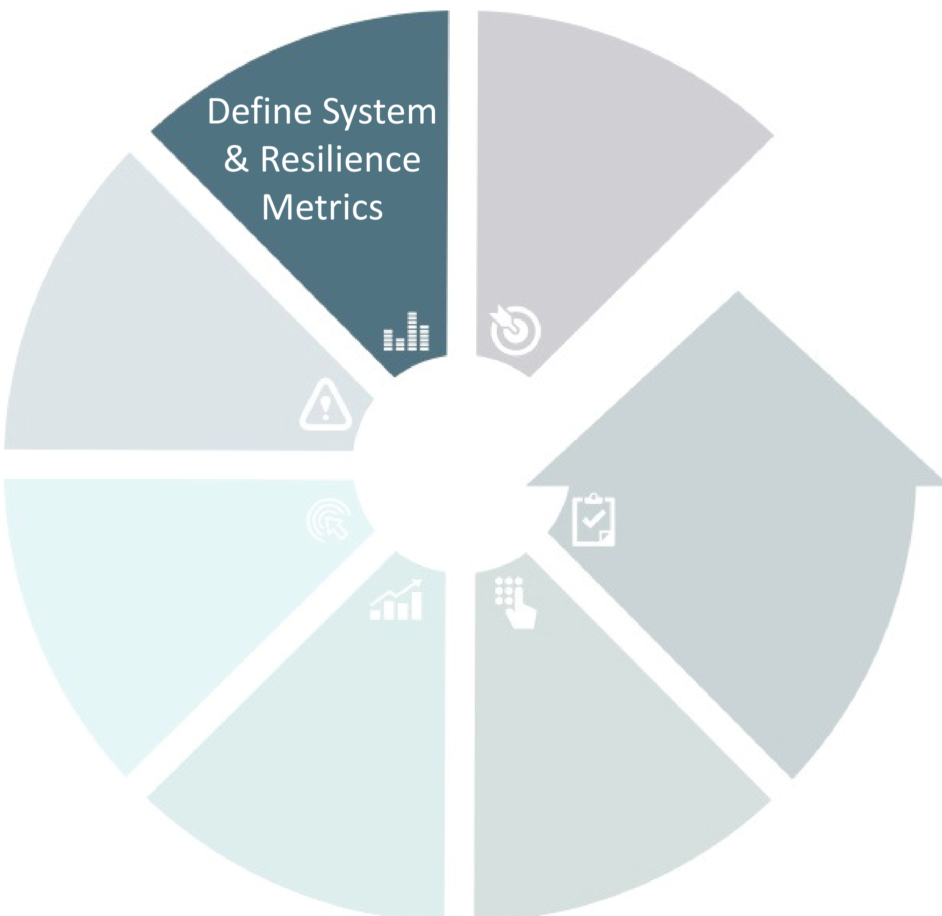
Define Resilience Goals



Determine:

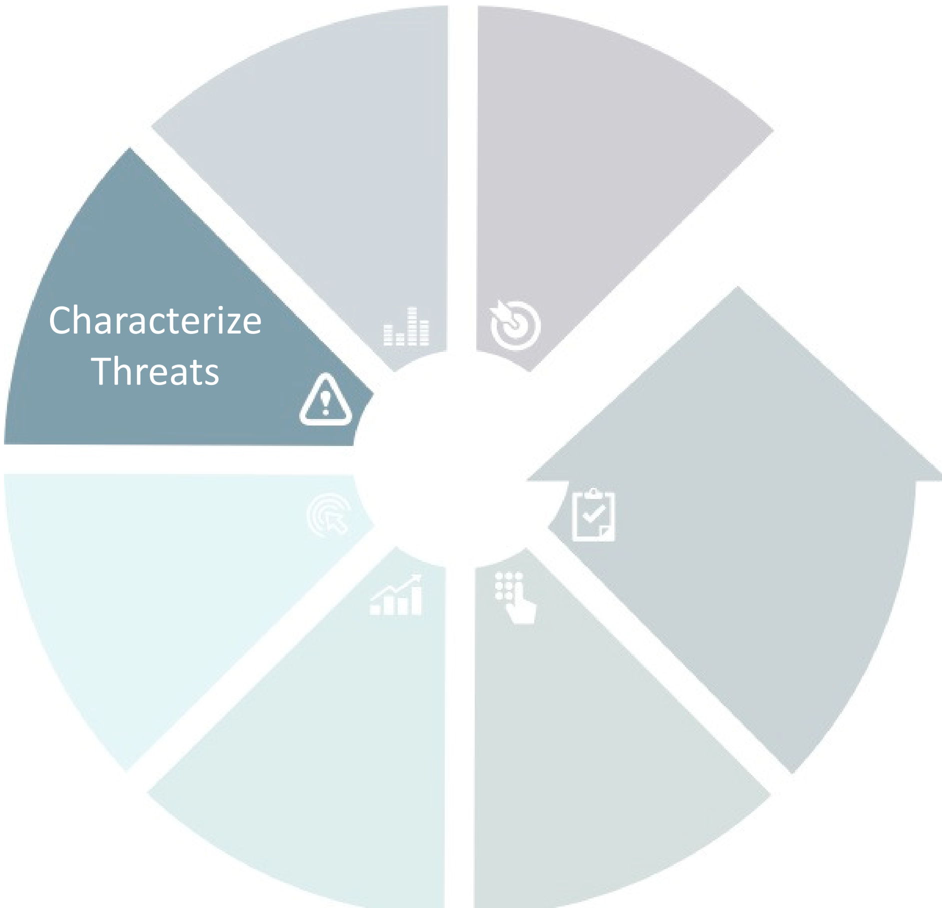
- The decisions to by made
  - Assess vs. improve
- For improvements, the scope of potential changes
- The questions to address
- How resilience aligns with current processes
- The stakeholders and their concerns
- Where goals are in competition and where they align

Define System & Resilience Metrics



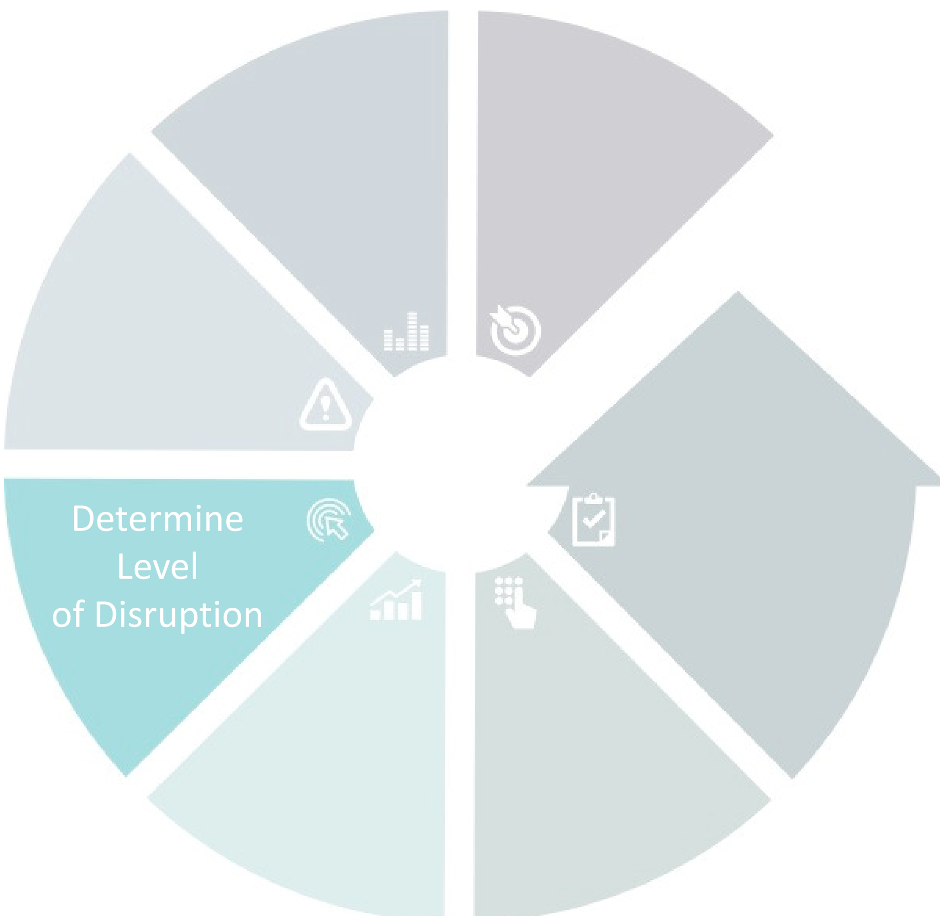
- Determine system boundaries
  - As broad or narrow as necessary to address goals
  - Dependent on stakeholders
- System will usually include multiple interdependencies
  - Infrastructure
  - Repair
  - Economics
  - ...
- Determine metrics necessary to measure progress

Characterize Threats



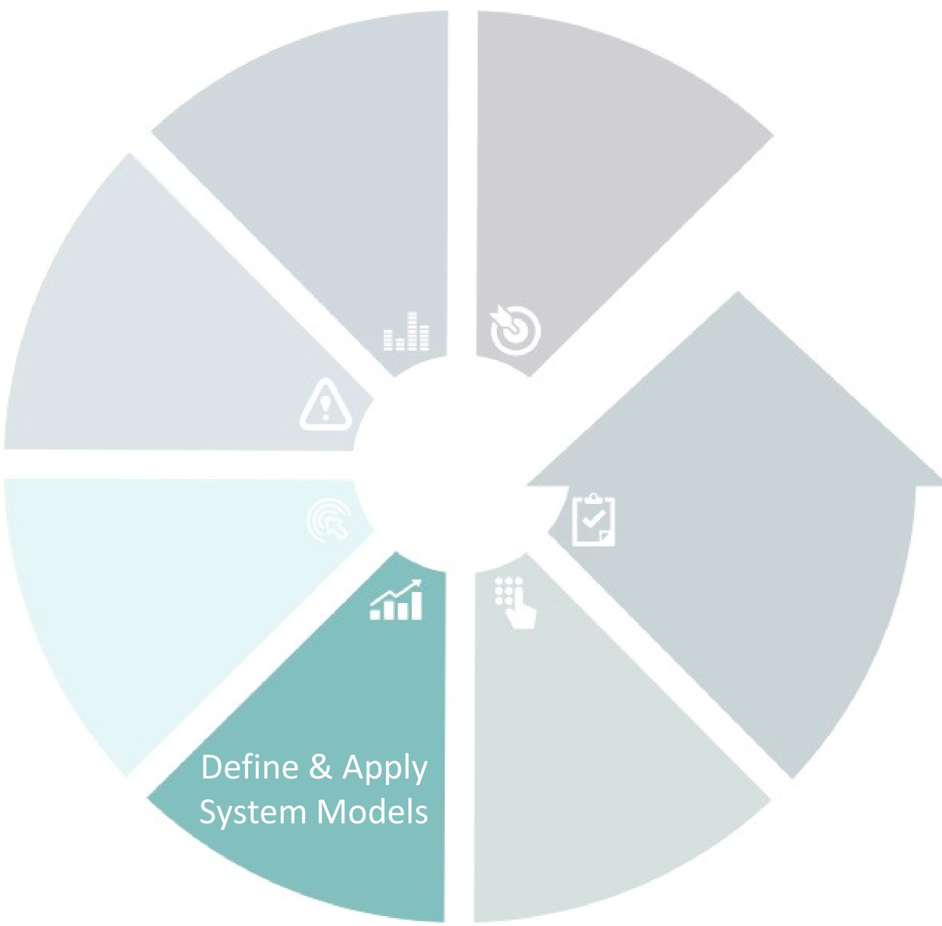
- Identify threats to the system
  - Natural disasters
  - Terrorism
  - Accidents
  - Aging
  - Global issues (i.e. climate)
- Characterize the threats and associated uncertainties
  - Subject Matter Experts (SMEs)
  - Historic data
  - Analytics
- Single-event vs. multi-event analysis

Determine Level of Disruption



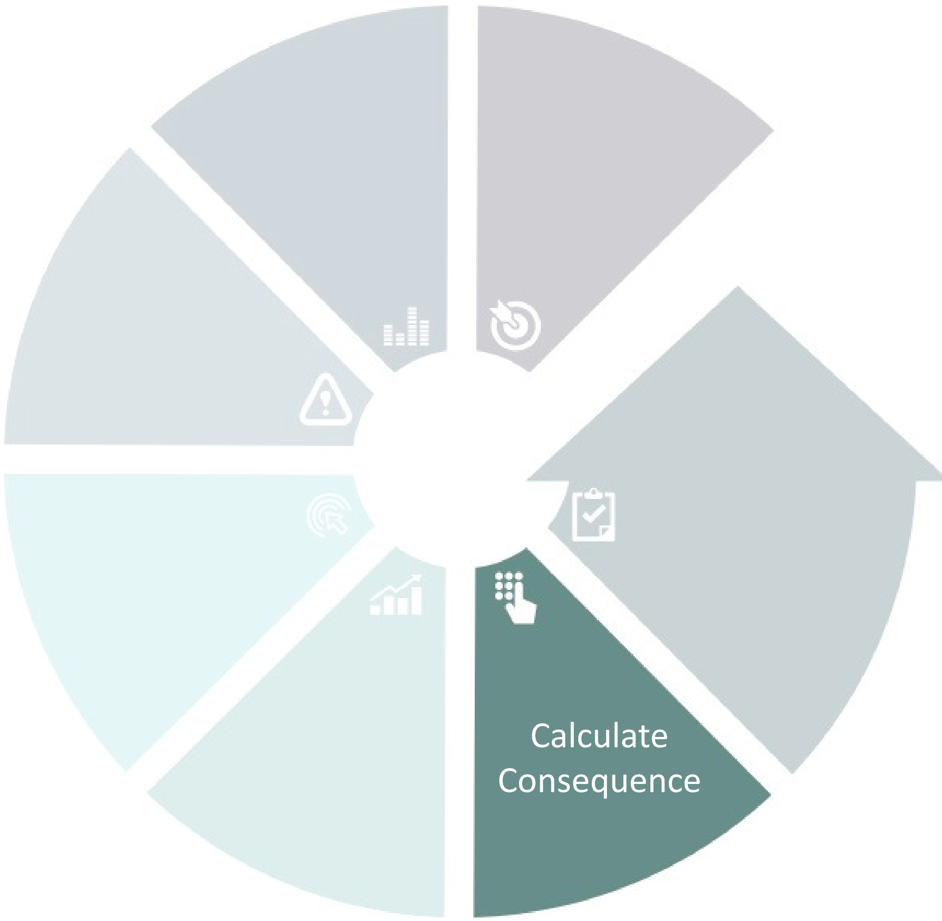
- Determine how the system is impacted by the identified threat
  - What elements are impacted?
  - What is the level of disruption?
- Determine in a similar manner to threats
  - SMEs
  - Historic data
  - Analytics (i.e. FEMA's HAZUS model)
- Characterize damage uncertainty

Define & Apply System Models



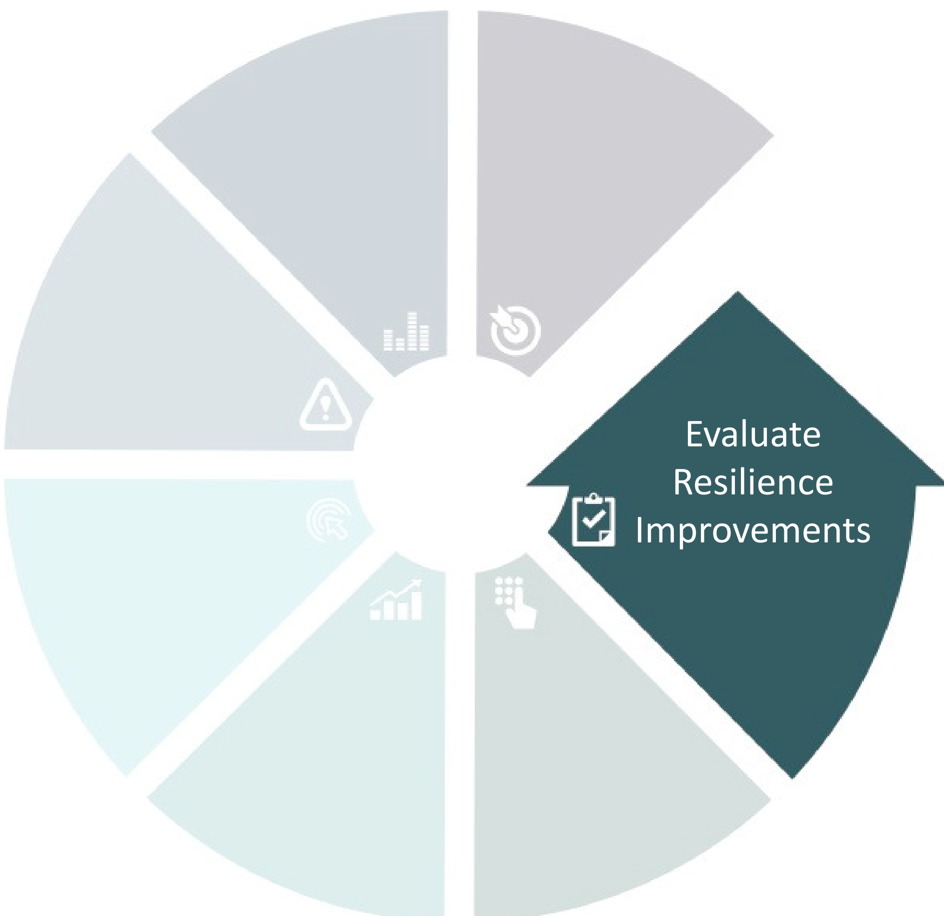
- Identify needs to assess system performance given disruption scenario
- Capture relevant aspects of sub-systems
- Many types of information may be required
    - Direct infrastructure models
    - Data, subject matter expertise
    - Economic, safety, and other analyses
- Interdependencies between different infrastructures will likely exist
- Additional uncertainty will arise
    - i.e., repair time uncertainty

Calculate Consequence



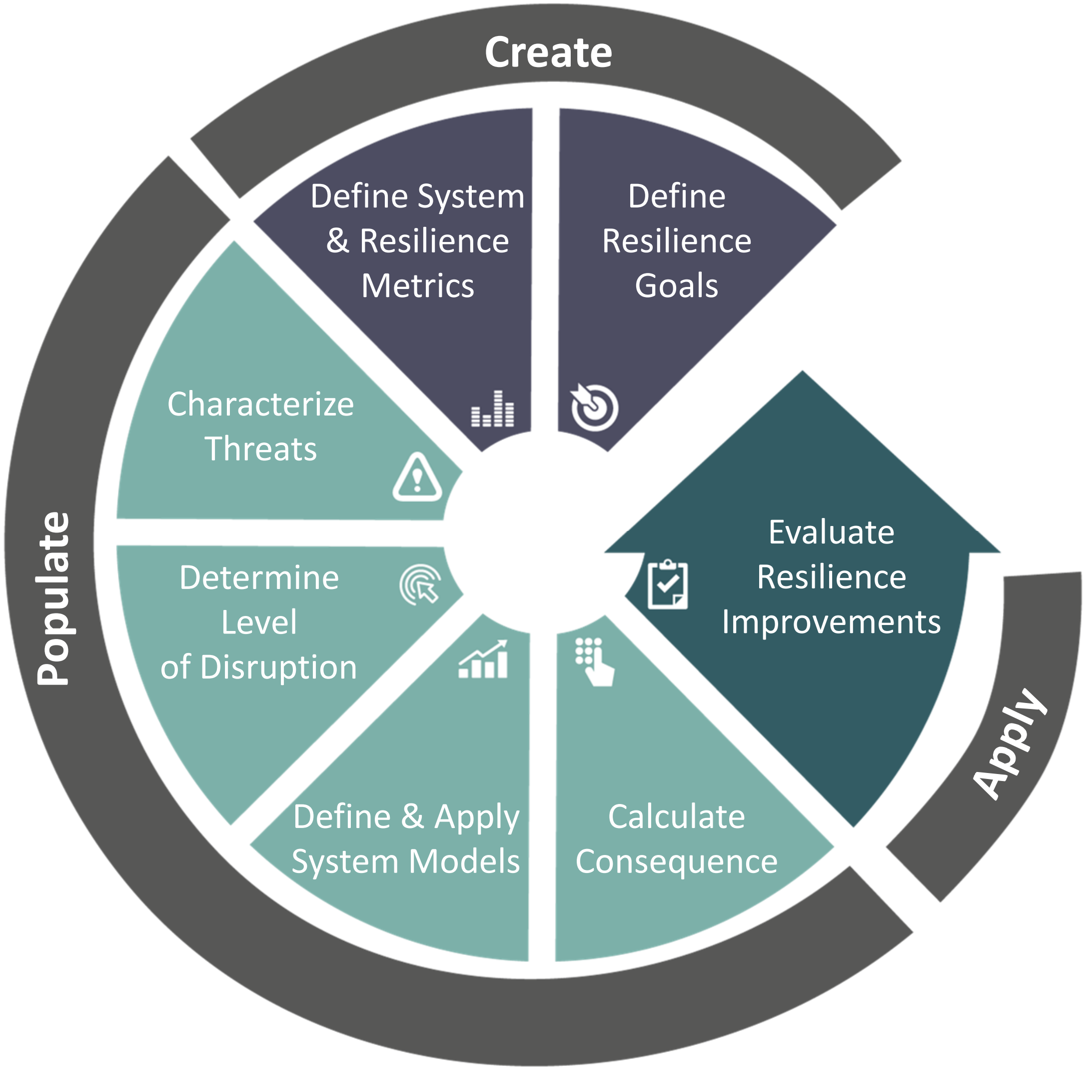
- Convert system performance indicators to defined resilience metrics
- Provides numerical basis for assessing system resilience
- Metrics characterized by probability distributions

Evaluate Resilience Improvements



- Assess alternatives to improve resilience
  - Infrastructure improvements
  - Policy or operational changes
  - Additional resources for recovery
- Identify constraints (i.e. budget)
- Analyze alternatives and identify best strategies
- Track progress over time

Resilience Analysis – An Iterative Process



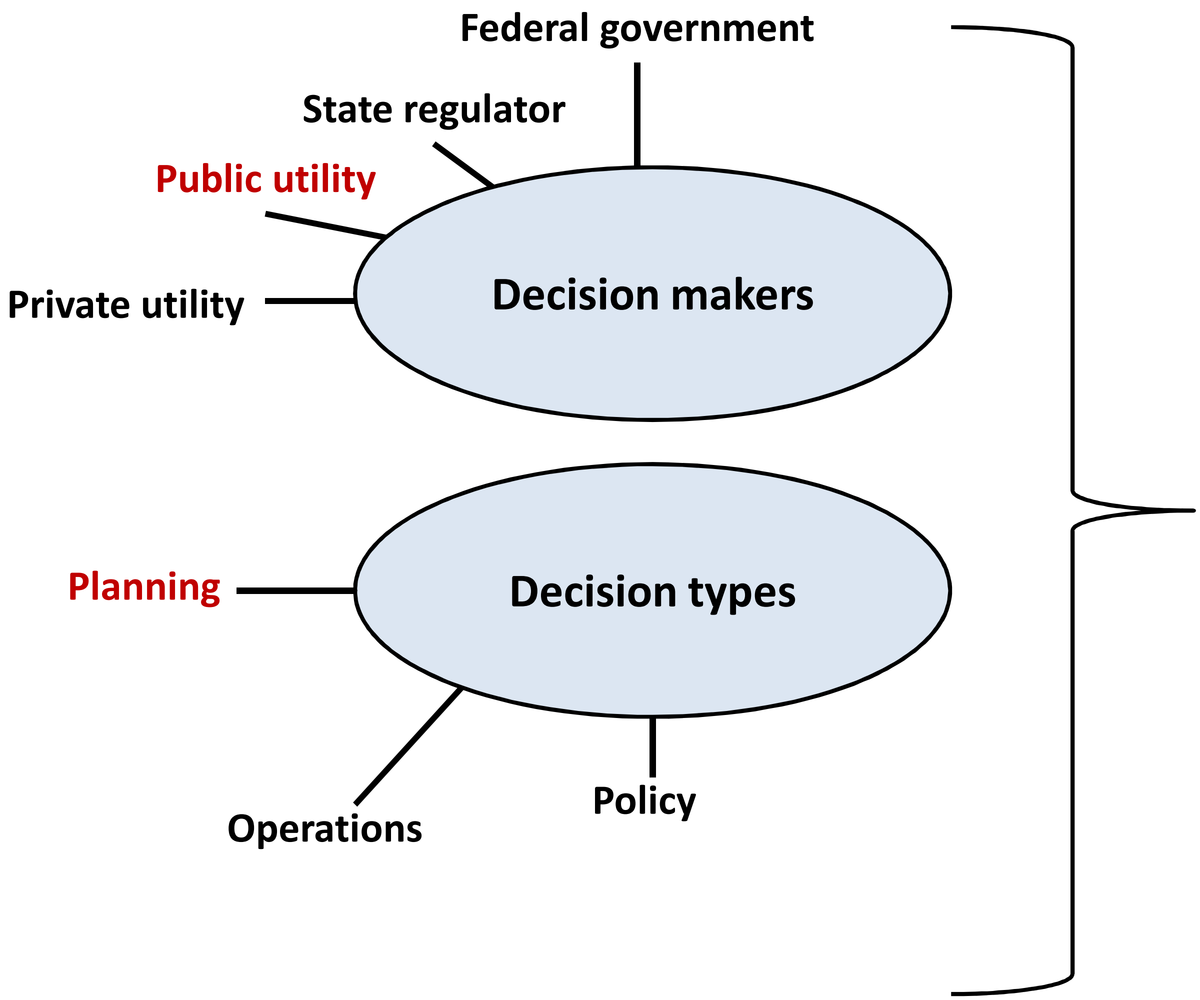
- Illustrative example
- Resilience analysis process demonstrated for 3 use cases
  - Electricity
  - Oil
  - Gas
- Topics for afternoon discussion: Social, Technological, Economic, Political

The benefits of resilience metrics

An Illustrative Scenario

Image credit: Julio Cortez/AP Photo

Goals, decisions, and metrics go hand-in-hand



Example Goals:

Deliver energy at reasonable cost, and with minimal negative impact to public productivity accounting for the possibility of extreme events.

In this case, for hurricanes:

The system and metrics are defined based on goals

Define System & Resilience Metrics

Deliver energy → **Unmet Demand**

(Nominal Demand – Energy Delivered)

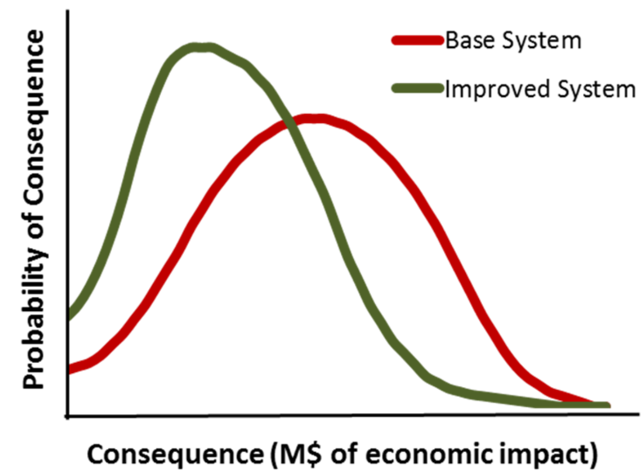
Reasonable cost → **Increased cost of operation**

(Operating Costs – Nominal Op. Costs)

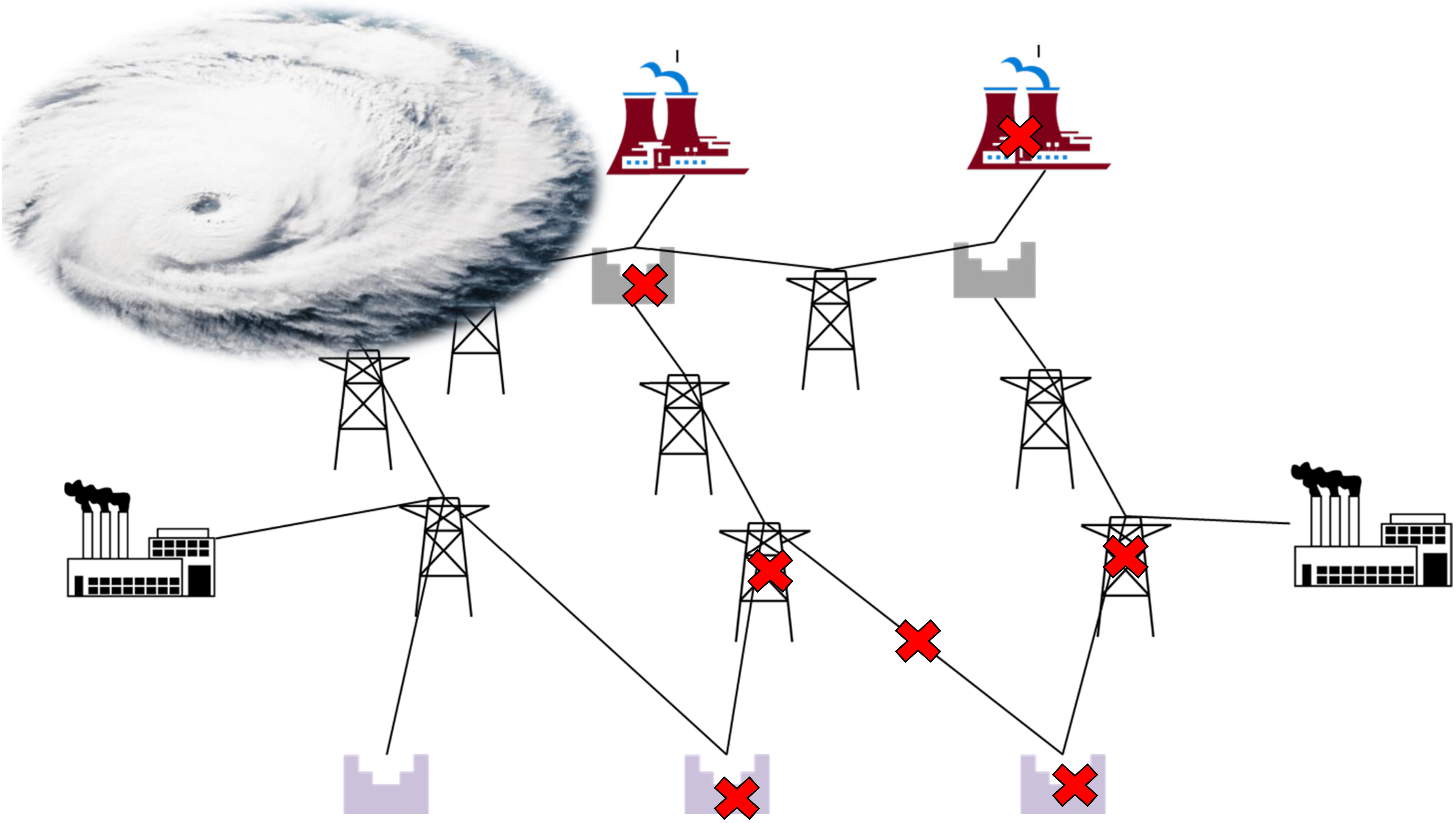
Productive public → **Decreased labor hours**

(Nominal Labor Hours – Labor Hours)

Distribution of Consequence, Hurricane

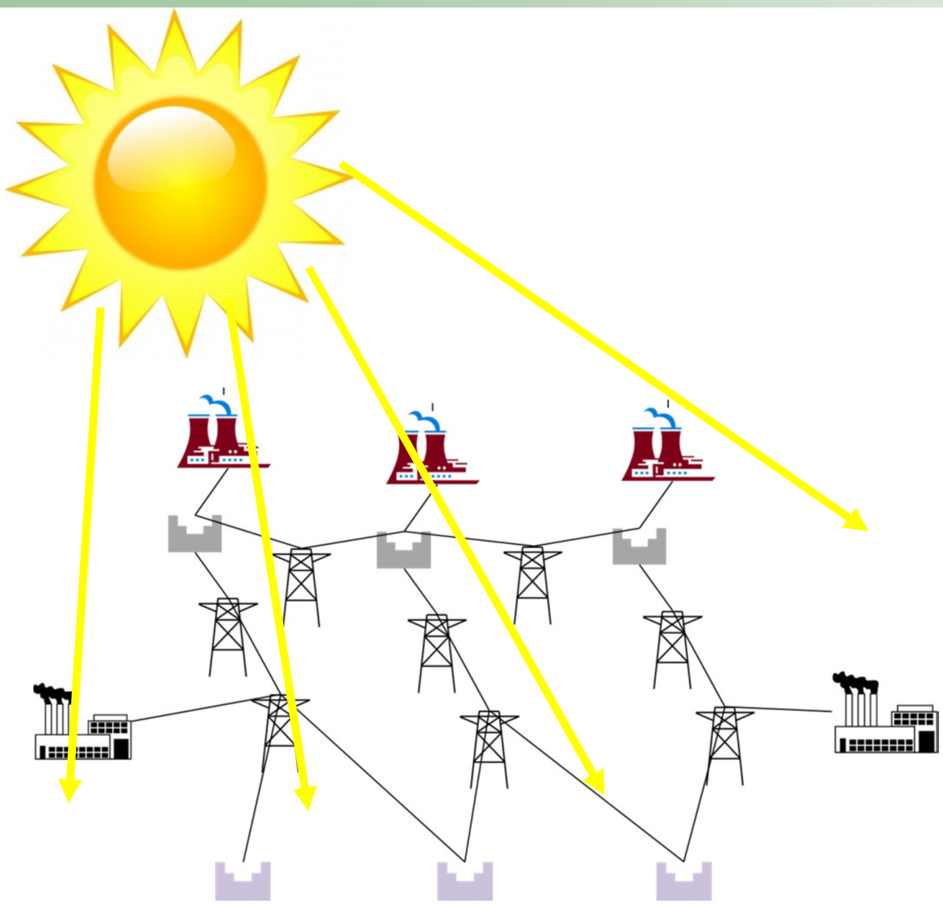


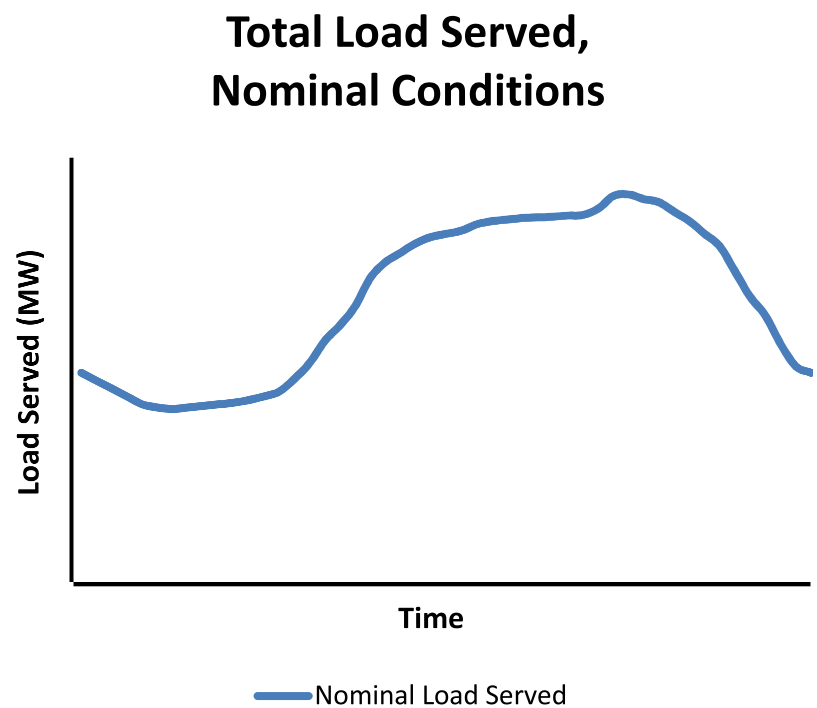
Threat: System is impacted by a hurricane



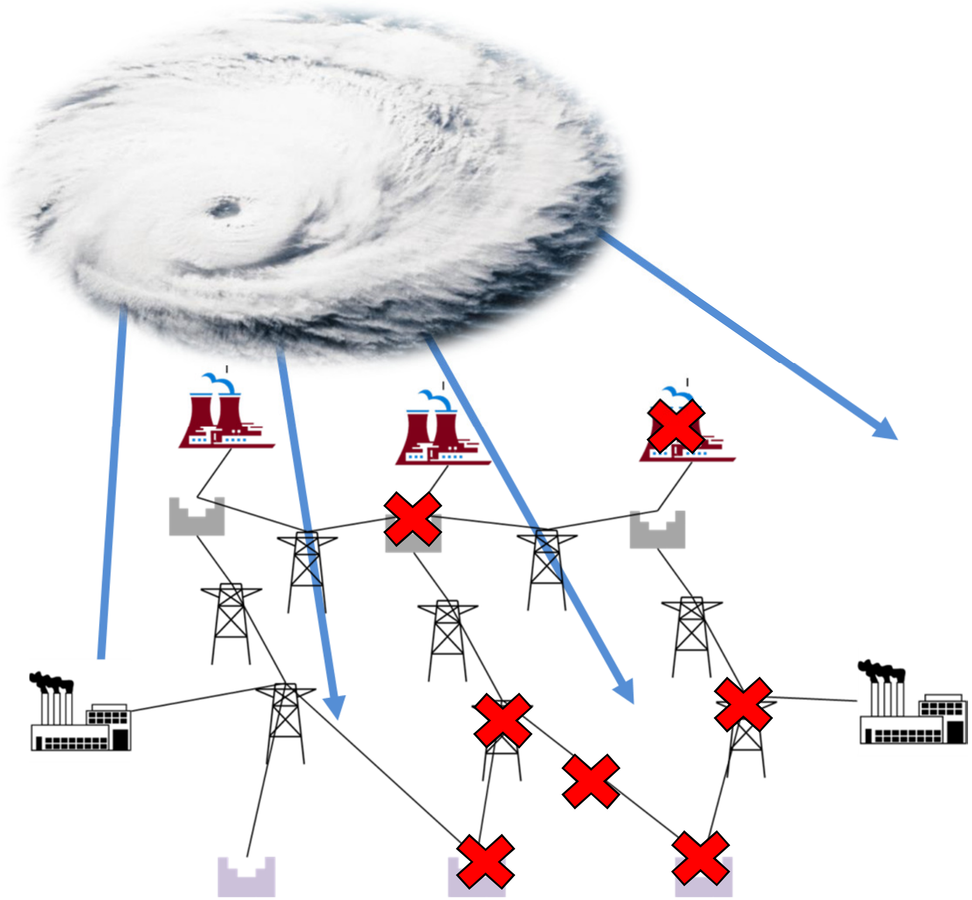
Under nominal conditions, the system is efficient and reliable

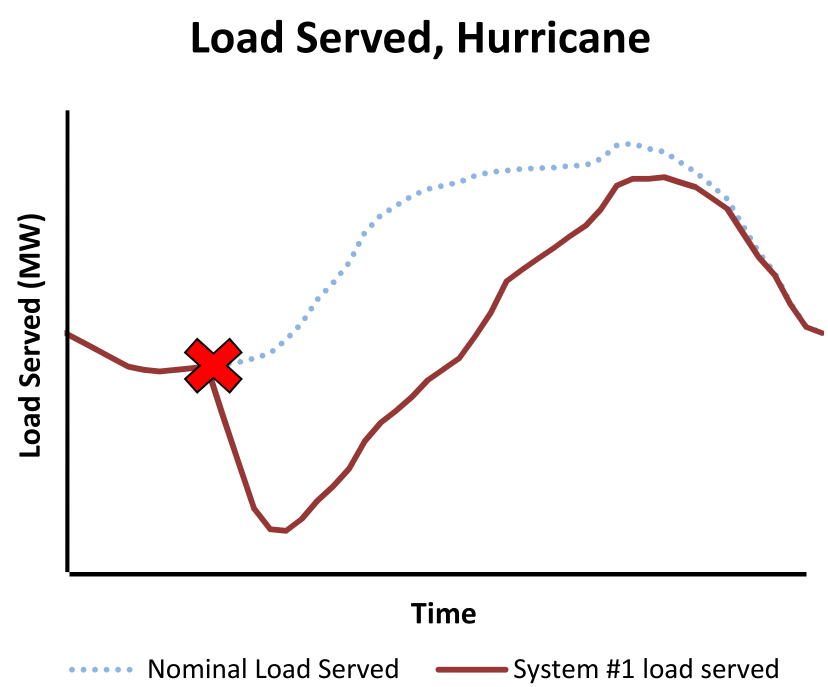
Determine Level of Disruption





The hurricane disrupts the system, impacting performance

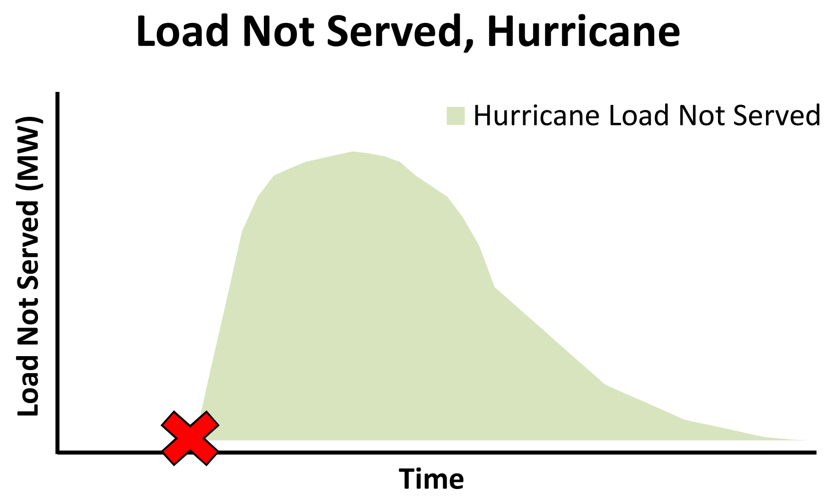


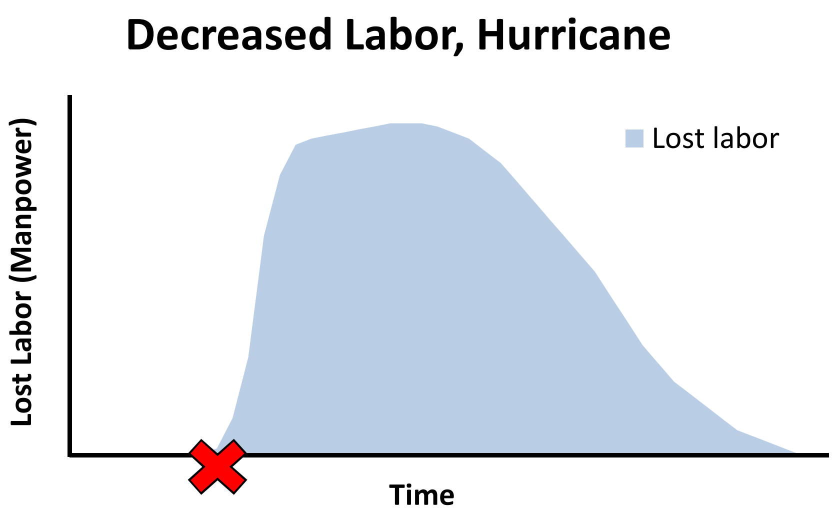


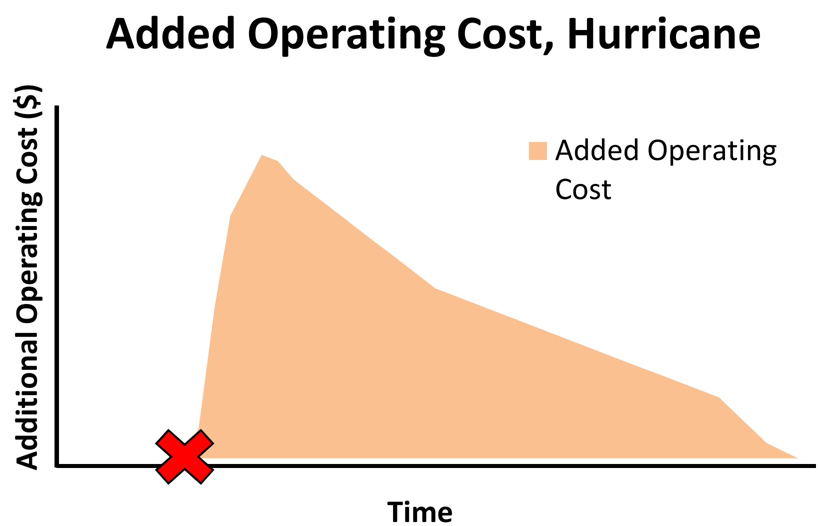
Hurricane affects ability to provide grid services

Performance is assessed using indicators

Define & Apply System Models

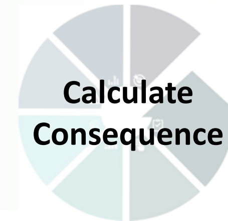




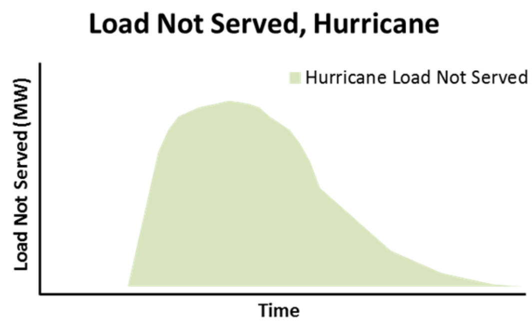


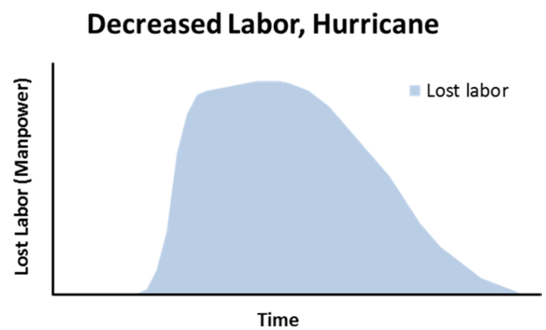
Damage from the hurricane impacts all three indicators of performance

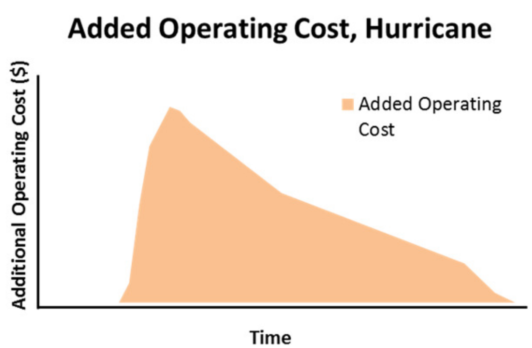
Performance indicators are translated to units of consequence

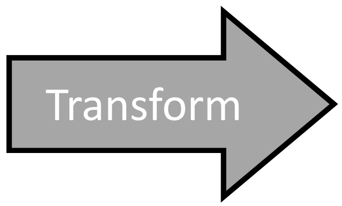


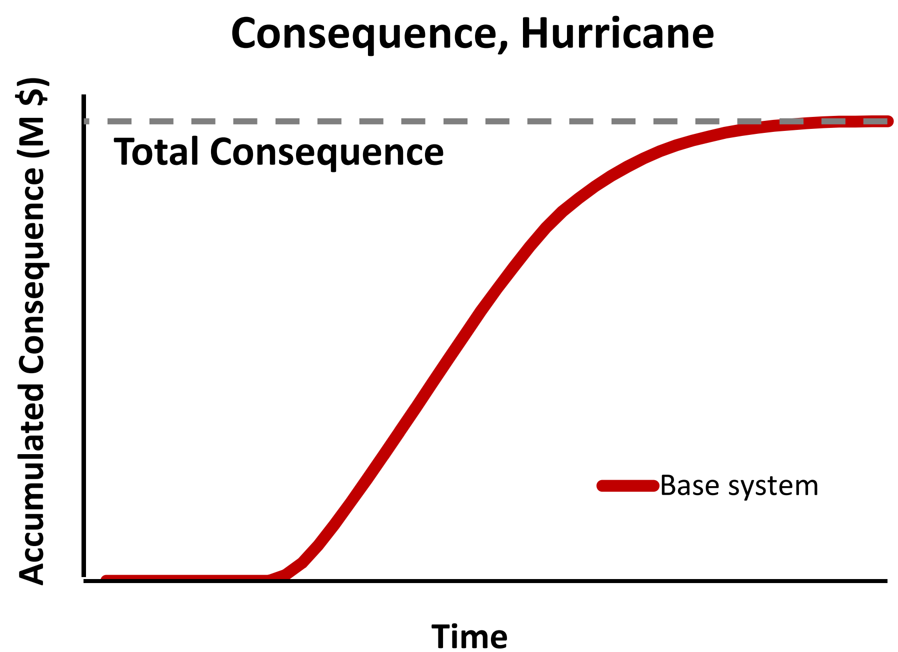
Performance Indicators











Alternative units:

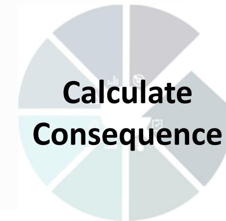
Safety

Economics

Population affected

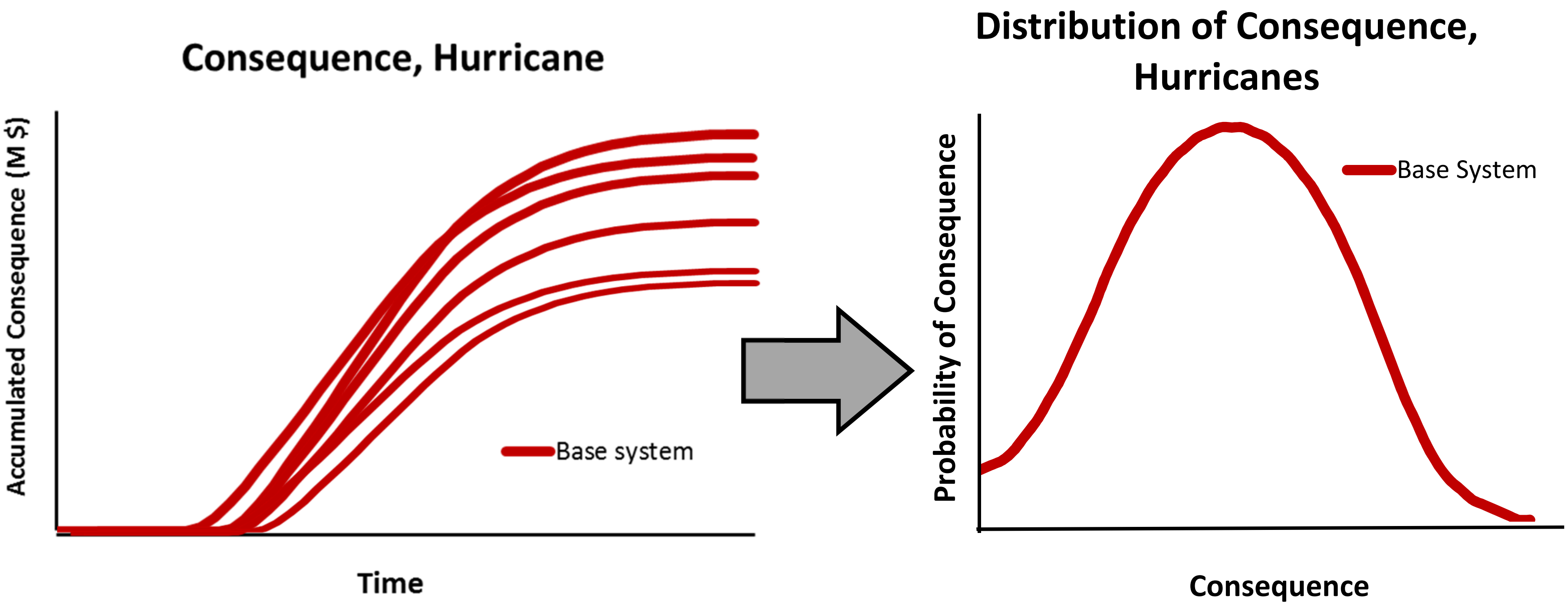
etc…

A consequence distribution is created to account for uncertainty



<u>Uncertain</u>:

- Disruption impacts
- Interdependencies
- Repair time
- System response
- Available resources
- Threat intensity
- ○ ○ ○

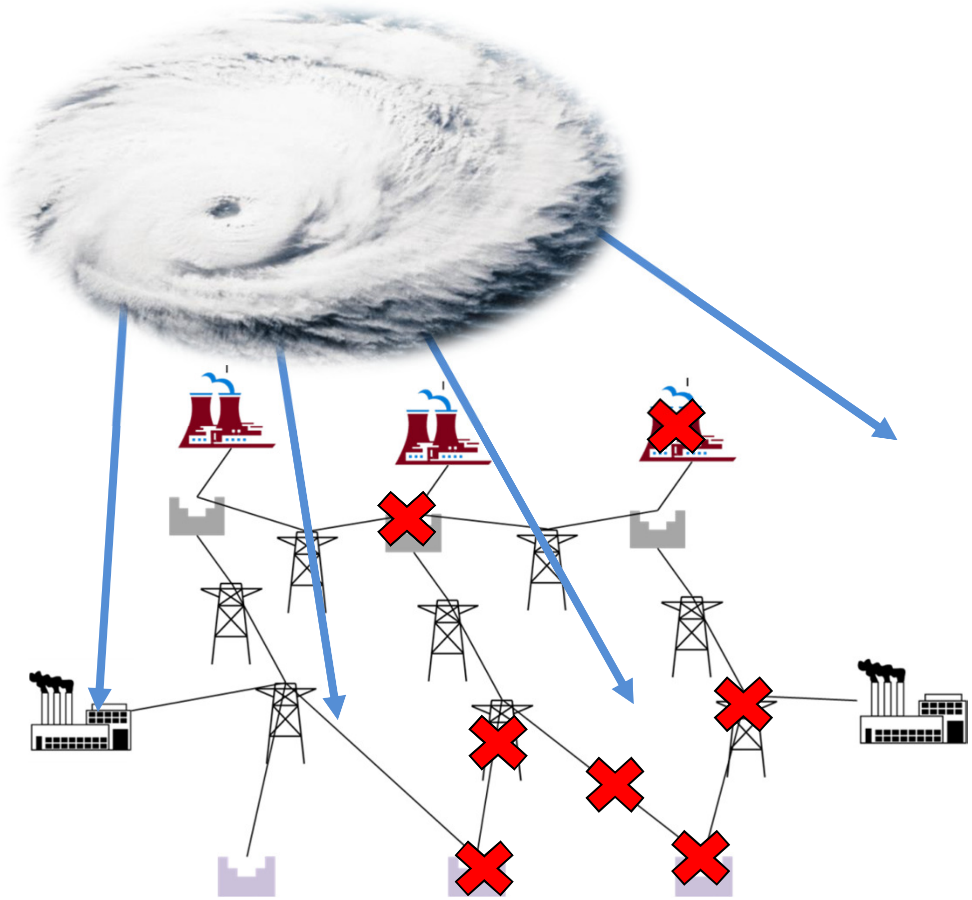


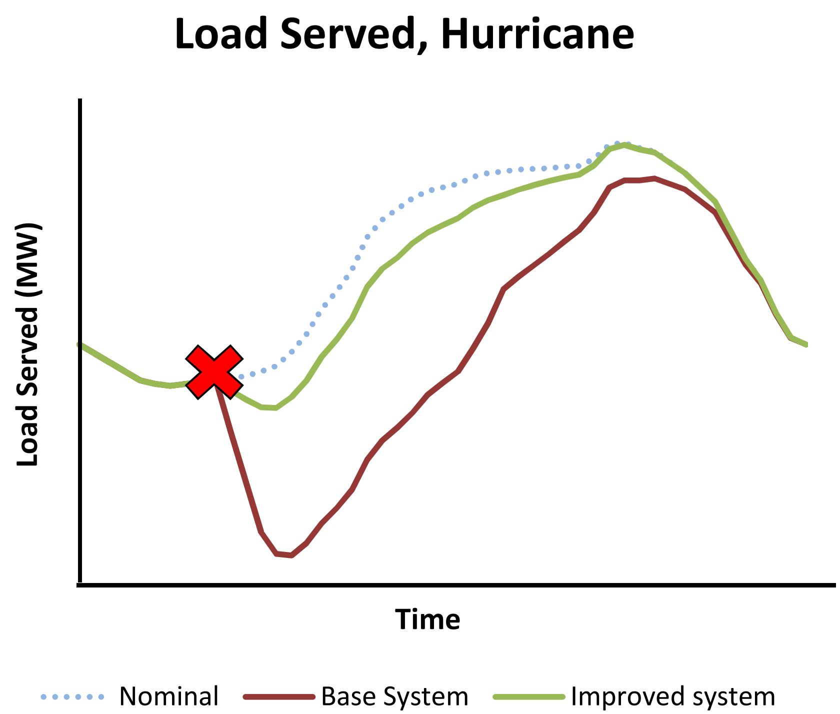
This distribution is the RESILIENCE METRIC

Resilience-Enhancing Alternatives

- Utility prepares for hurricane
  - Pre-positions recovery supplies
  - Key assets outside of flooding areas
  - Charges battery reserves
- While trying to cope with effects of damage, the utility
  - Brings backup generation online
  - Reconfigures lines to circumvent damaged assets
  - Uses battery and reservoir discharge
- More rapid, less resource-intensive recovery

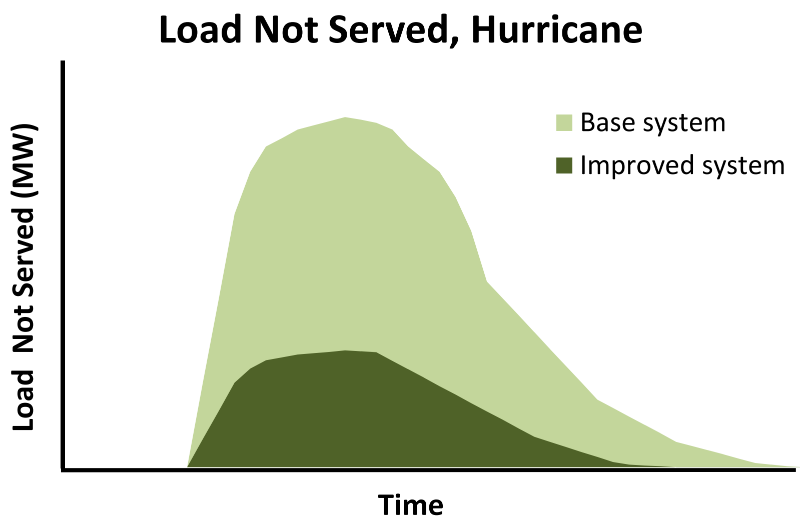
Performance of a more resilient system

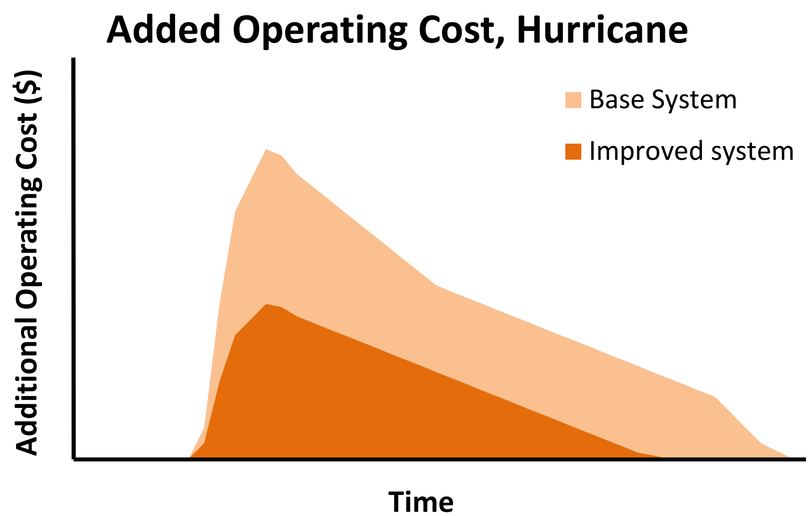


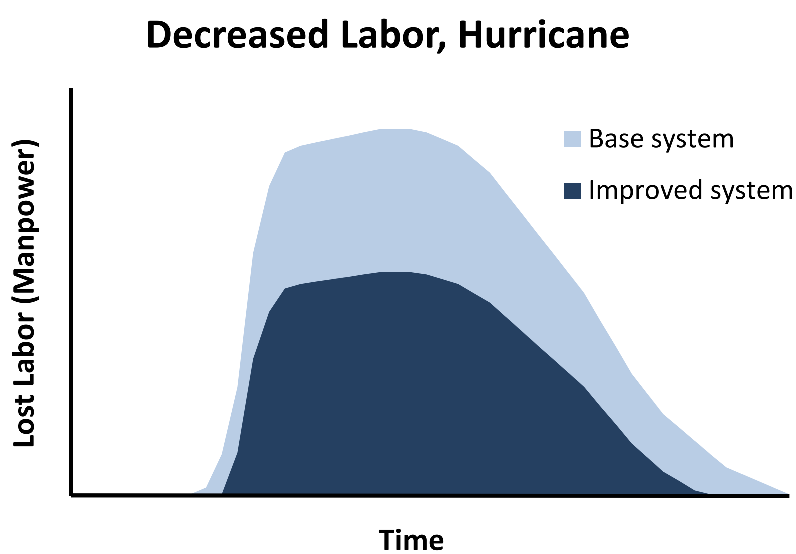


The system exhibits improved performance due to investments

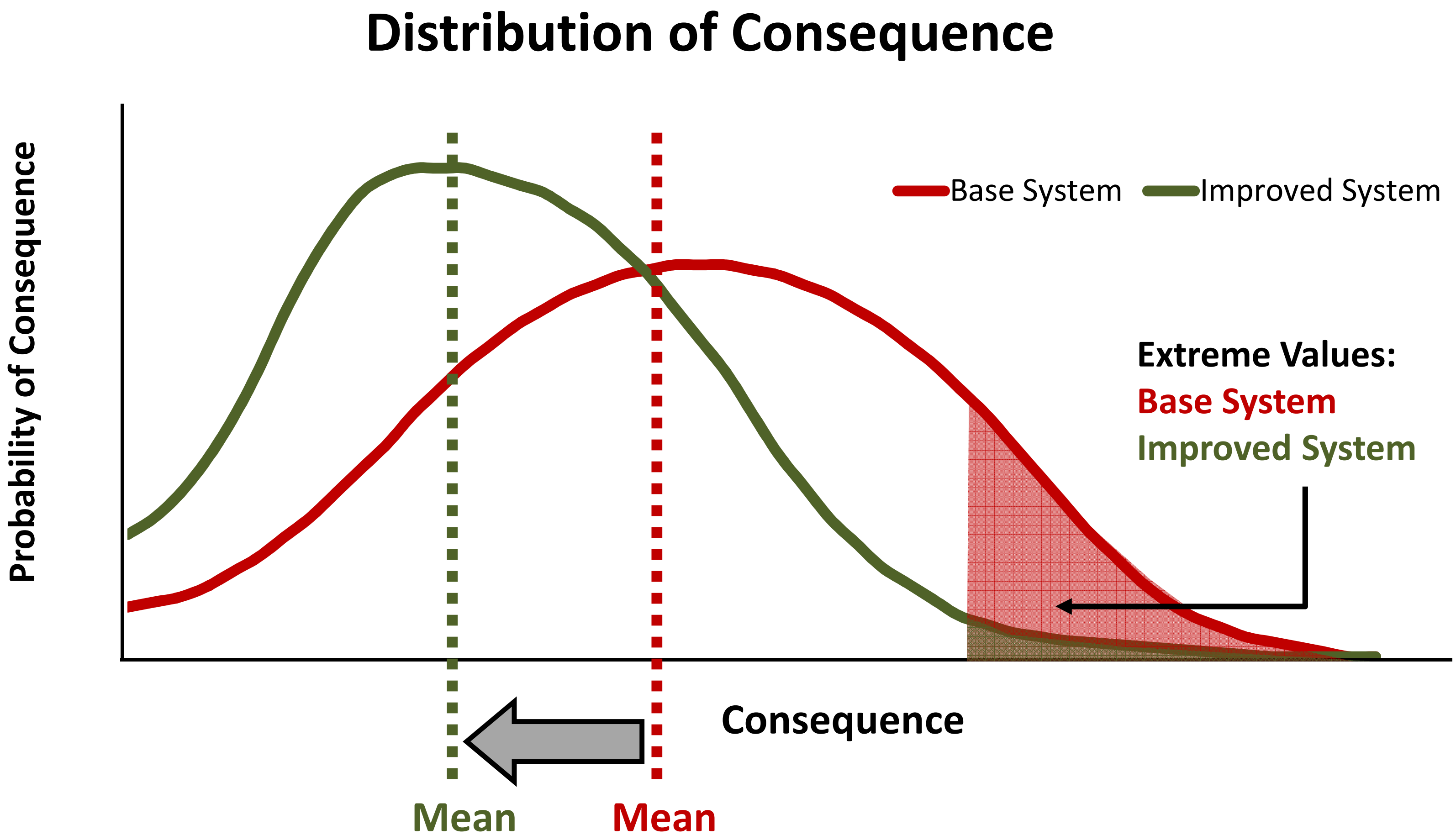
Comparison of performance indicators







Decisions are enabled by comparison of the energy system resilience metrics



Summary of key principles

- A system is more resilient if it has decreased consequences
- The proposed resilience metric is a distribution of consequences
  - The types of threats, number of distributions, and their units are defined by stakeholders and/or decision makers
- What new tools, models, and techniques are needed to populate these metrics?
- Who are the decision makers and what are their goals?
- How do we fit metric-based decision-making into their framework?

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Electricity Infrastructure Resilience

Use Case Development and Analysis

Use Case: Baseline and Resilience-Informed Operations

- Baseline resilience: Operation without guidance from resilience metrics
- Resilience metrics enable quantification of consequences associated with infrastructure delivery failures
  - They can inform planning and operations as demonstrated in next use cases
- Resiliency metrics enable shift from operations from economic-focused (business-as-usual) to consequence-focused dispatch and commitment
  - Resiliency metrics directly impact pre-event operations

Goals for Electricity Use Cases

- Assess baseline resilience of IEEE-118 Bus system against a hurricane event
- Evaluate resilience change of using consequence-driven operations
- Compare resilience of two modified system configurations
- Identify optimal investment strategies to improve system resilience

Electricity System and Metrics

Define System & Resilience Metrics

- System: IEEE-118 Bus
- Metric
  - Economic loss (impact on the economy)
- Metrics capture randomness due to event uncertainty

Scenario Analysis: Identify Threat Types

Characterize Threats

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

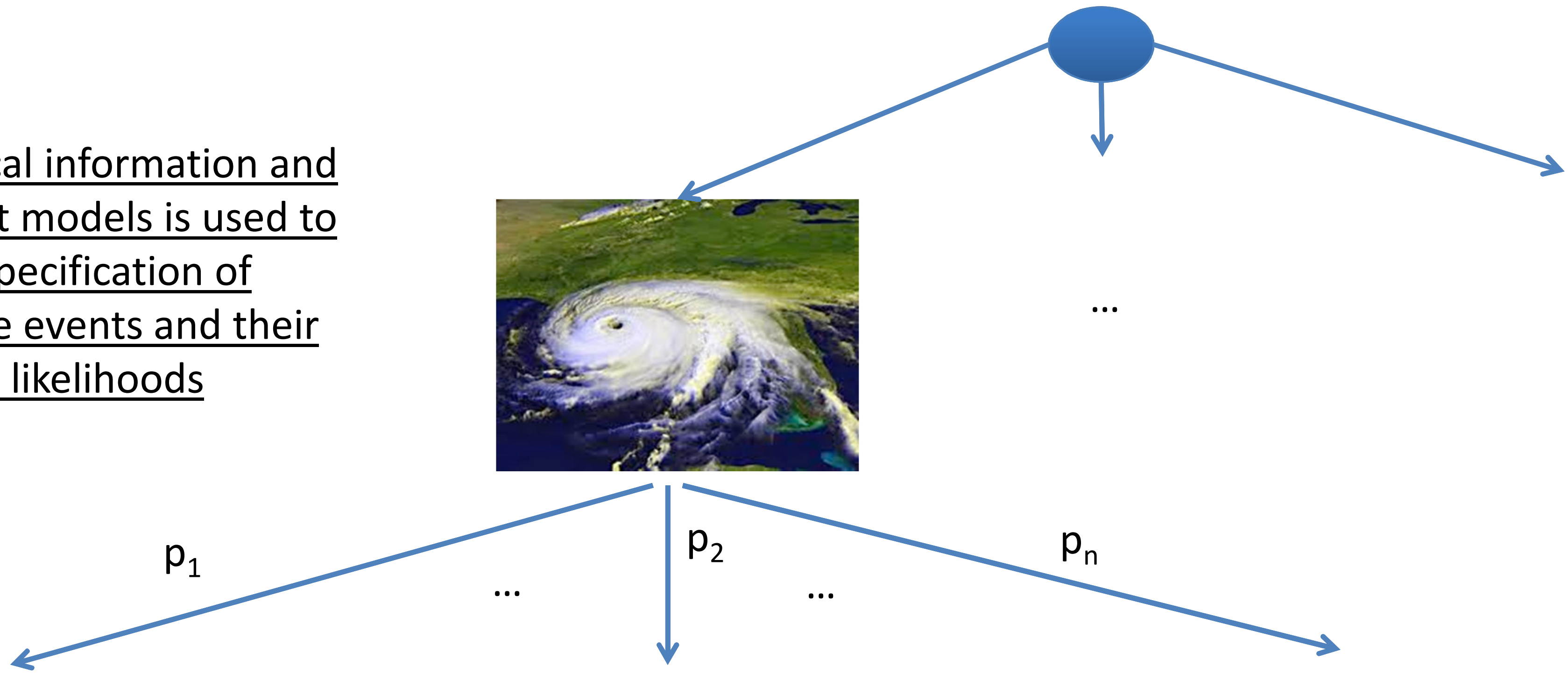
High-level scenario identification is expected to be an output from an iterative and interactive stakeholder-driven process

Scenario Analysis: 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 is used to guide specification of possible events and their relative likelihoods</u>



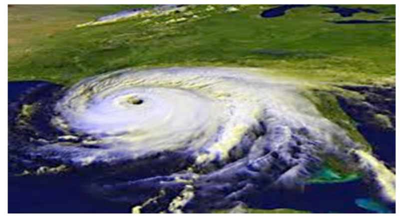
Category 2, landfall at high tide

Category 4, north-of-peninsula storm track

Category 5, eye tracks over metropolitan area

Scenario Analysis: Disrupting the System

The final step is to translate disruption events into system impacts



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

… …

Damage Realization K

Damage Realization N

Assume uniform probabilities

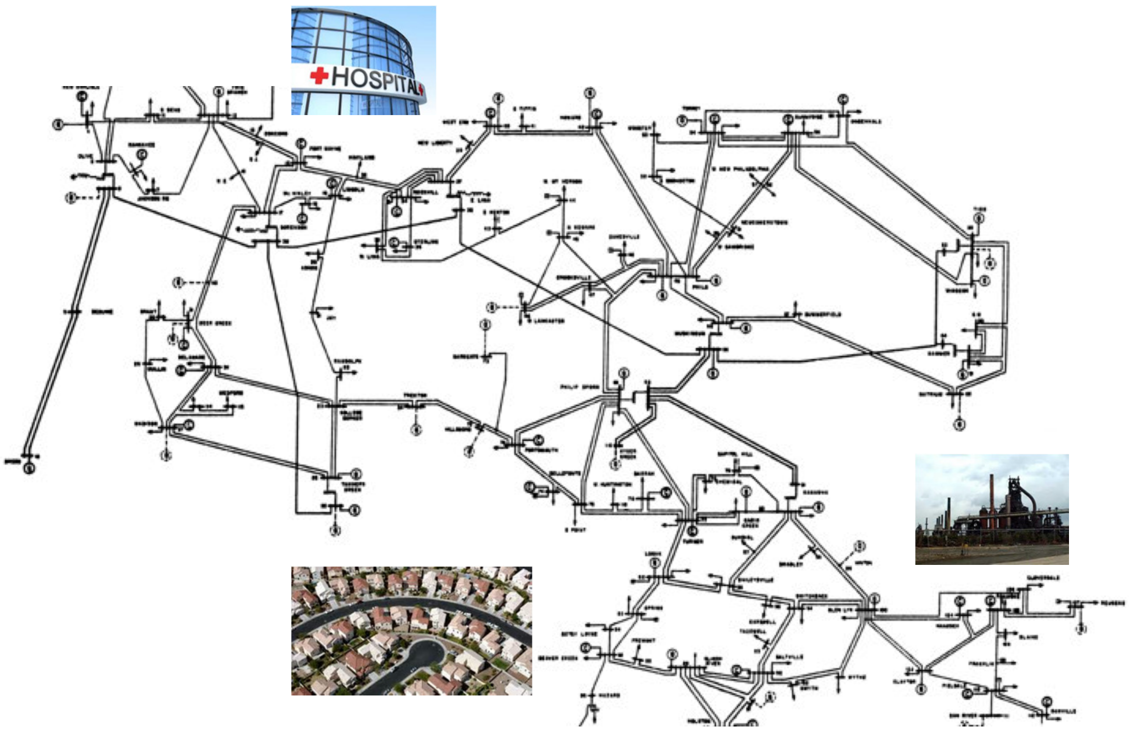
Given a specific manifestation of a disruption event, we then specify a *distribution* of infrastructure impacts

For IEEE 118 bus system:

1. Normal distribution of generator failures, with $\upsilon=20$, $\sigma=5$
2. Normal distribution of line failures, with $\upsilon=40$, $\sigma=7$

Resiliency Analysis Requires an Operations Model

Define & Apply System Models



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

Operations model is used to quantify system impact, and is expressed as delivery failure

91 loads
54 generators
186 lines

Basic Model:

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

Operations Model Expressed as 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

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

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

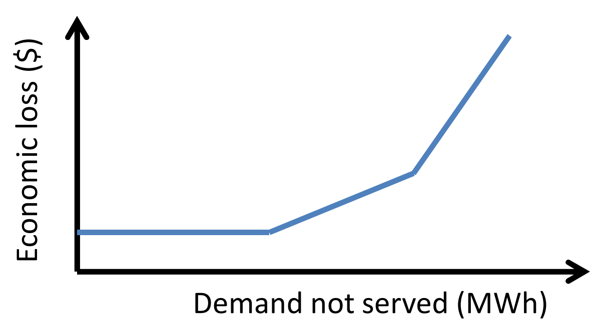
where

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

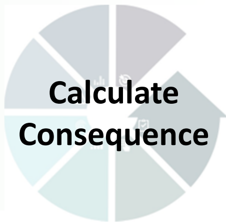
Consequences for IEEE-118 Bus Case

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



Use Case: Assess Baseline Resiliency



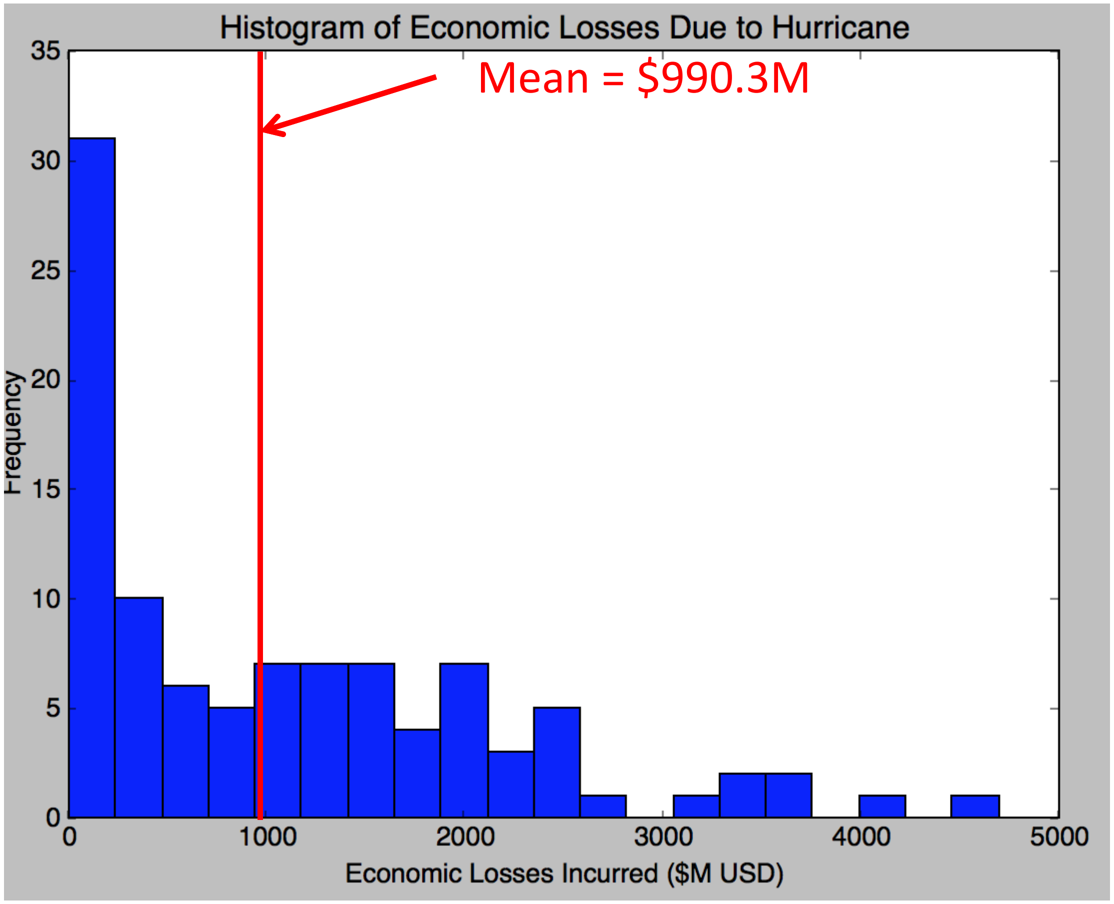
Assessing the economic losses incurred by a hypothetical hurricane event on the IEEE 118 bus test system

Methodology

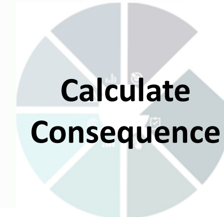
1. Sample 100 scenarios specifying potential damage from a hurricane
2. For each scenario, compute a minimal-cost dispatch and associated loss of load
3. For each scenario, compute the cumulative economic losses incurred

Assumptions

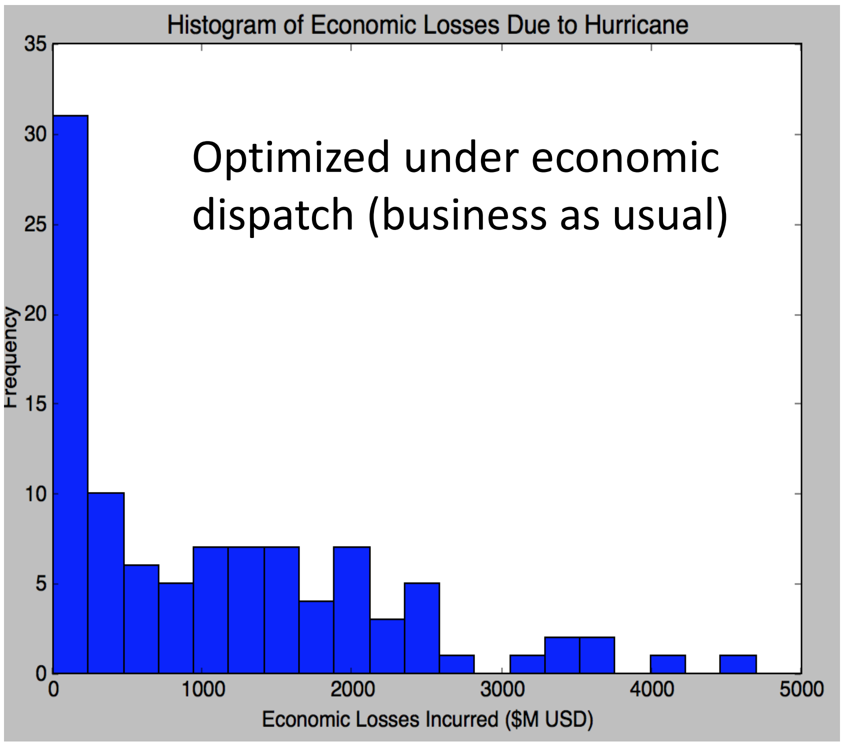
1. No recovery possible for first 48 hours
2. Independent scenario analysis



Shifting from Economic to Consequence-Driven Dispatch



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



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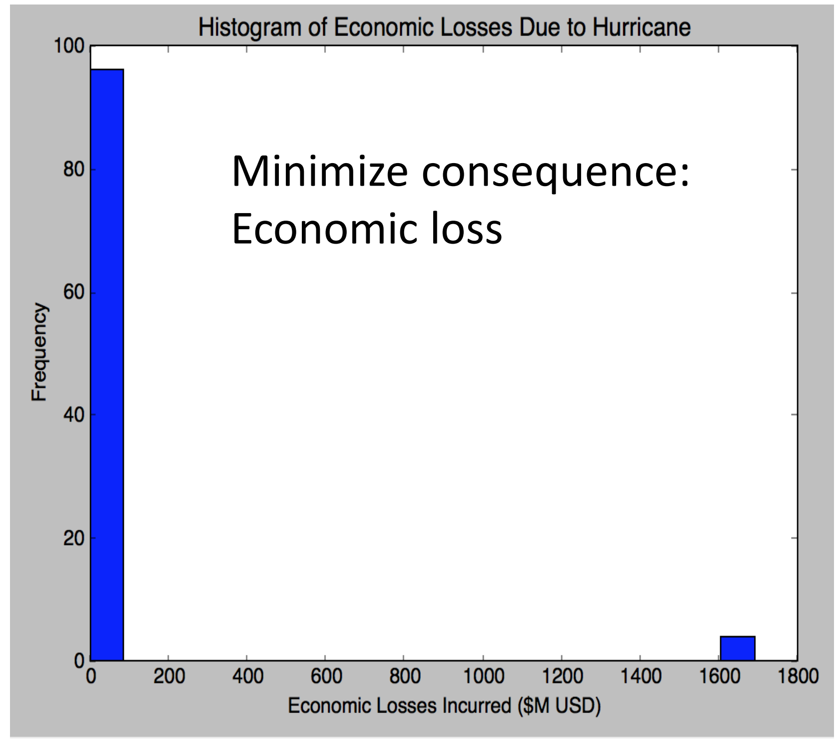


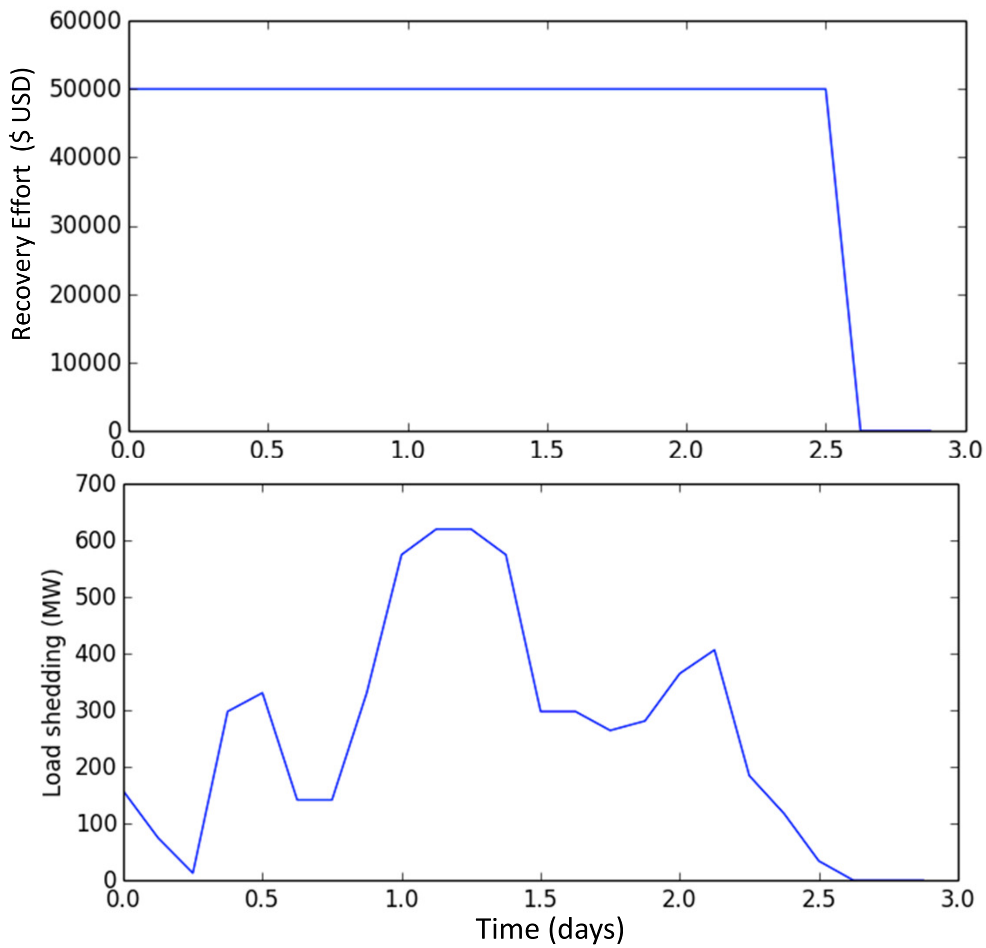
In our IEEE 118 bus resiliency example, it is possible to mitigate nearly all economic consequences of the posited hurricane

Modeling Recovery and Restoration

Calculate Consequence

Consequences are only one form of resiliency metric – another key metric quantifies restoration / recovery costs and time

- The recovery/restoration process is modeled as happening over a three day period after the day of the event
- Assume there is a fixed budget (resources):
  - Assume we have 5 crews, 3 dedicated to line restoration and 2 on generator restoration
  - Each crew takes 3 hours to repair one line
  - Each crew takes 18 hours to repair a generator
  - Lines are repaired in random order
  - Generators are repaired from largest to smallest



Total Recovery Effort

Calculate Consequence

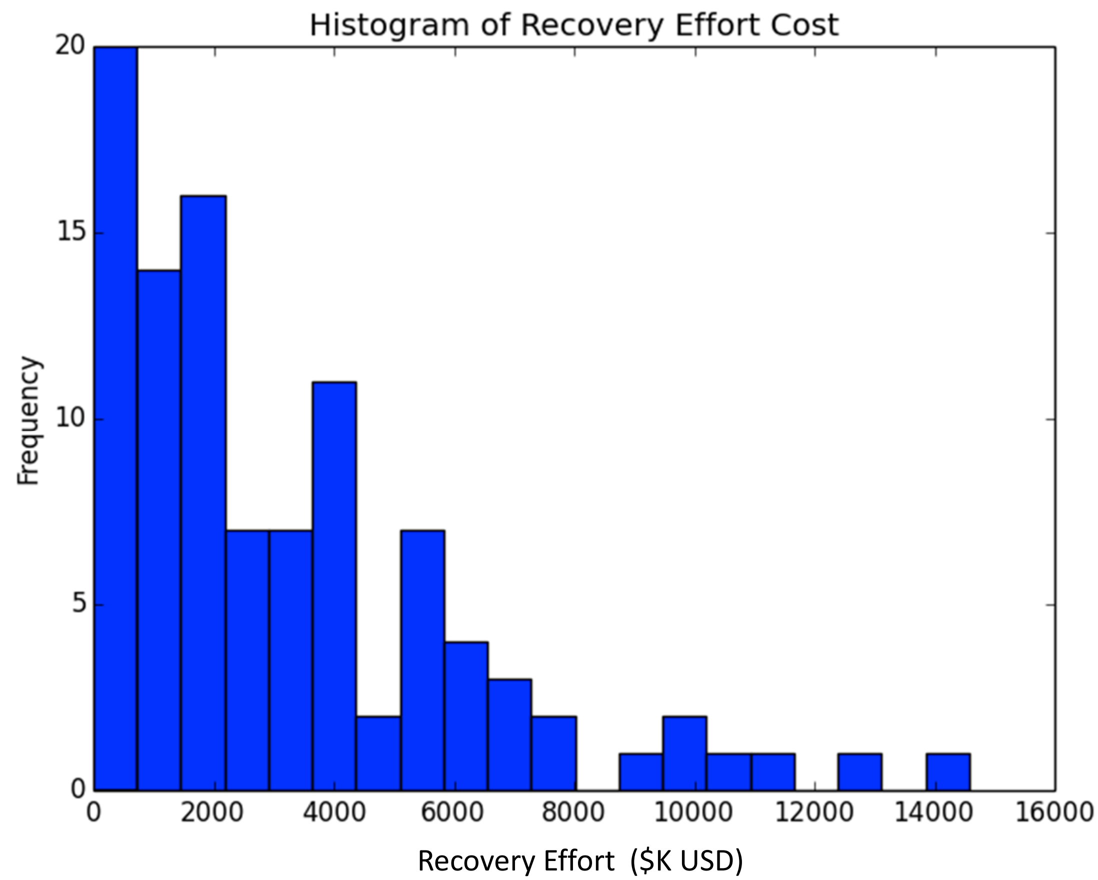
Restoration costs and times are also uncertain

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 recovery effort incurred

Assumptions

1. Recovery takes 72 hours
2. Independent scenario analysis



Use Case: Investment Analysis

Evaluate Resilience Improvements

Planning: Analysis of Investment Portfolio Alternatives

- Primary question:
  - How do proposed investment portfolio alternatives change system resiliency relative to the baseline conditions?
- Ancillary (but critical) question:
  - What impact do changes in system resiliency have on nominal (reliability) operations?

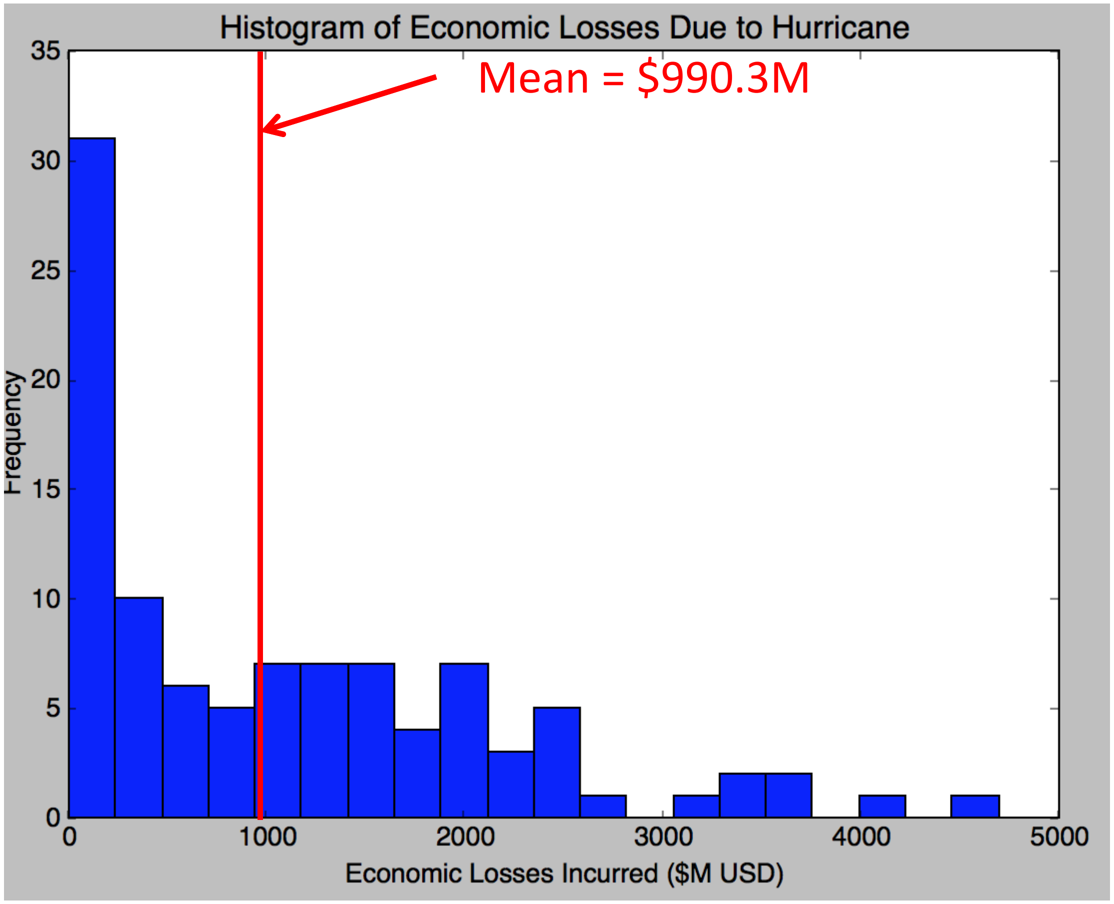
Investment Options

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

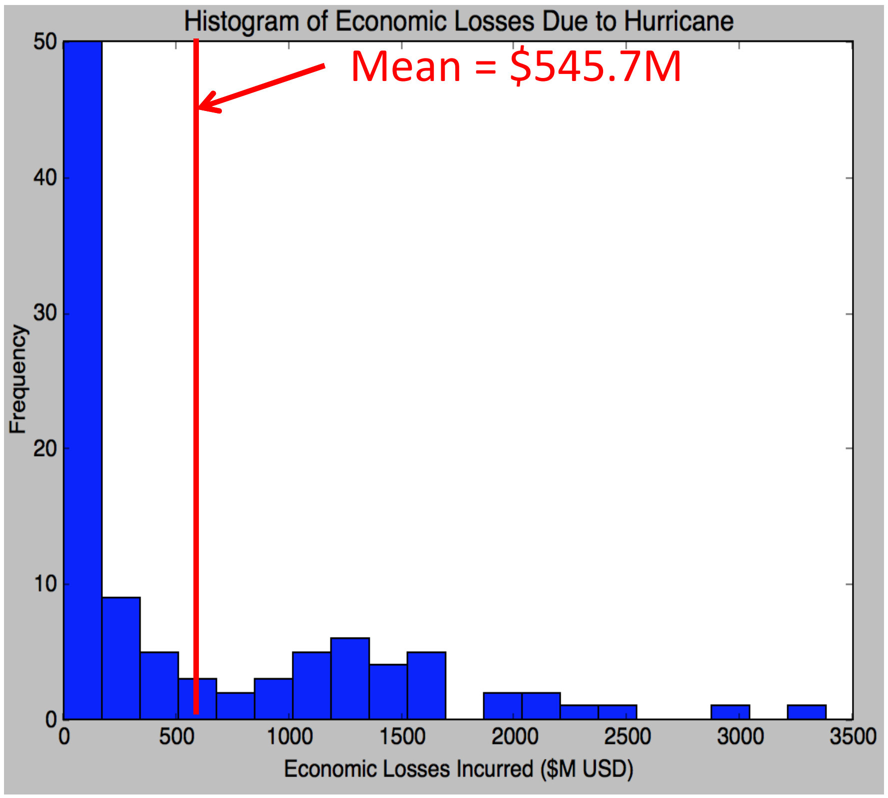
Evaluate Resilience Improvements



Analysis of Investment Alternatives

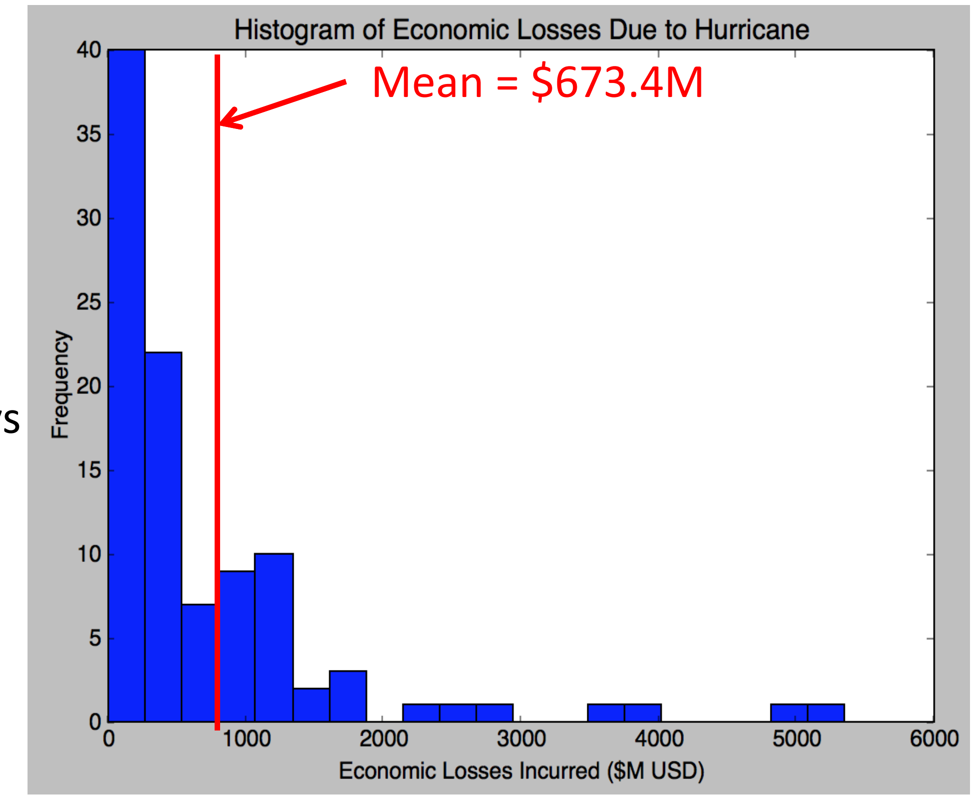
Both alternatives improve baseline

With generator flood walls



vs

With line burying



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

Use Case: Advanced Planning

Evaluate Resilience Improvements

Planning: Optimization of Investment Portfolio

- An alternative to evaluating competing investment portfolios is to determine the optimal portfolio directly
  - Availability of this option depends on the specifics of the operations models used in resiliency analysis
- Analysts specify budget allocations and limits on specific acquisitions
  - Optimization models determine investments that maximize increase in system resiliency

Analysis: Advanced Planning

Evaluate Resilience Improvements

Planning: Optimization of Investment Portfolio

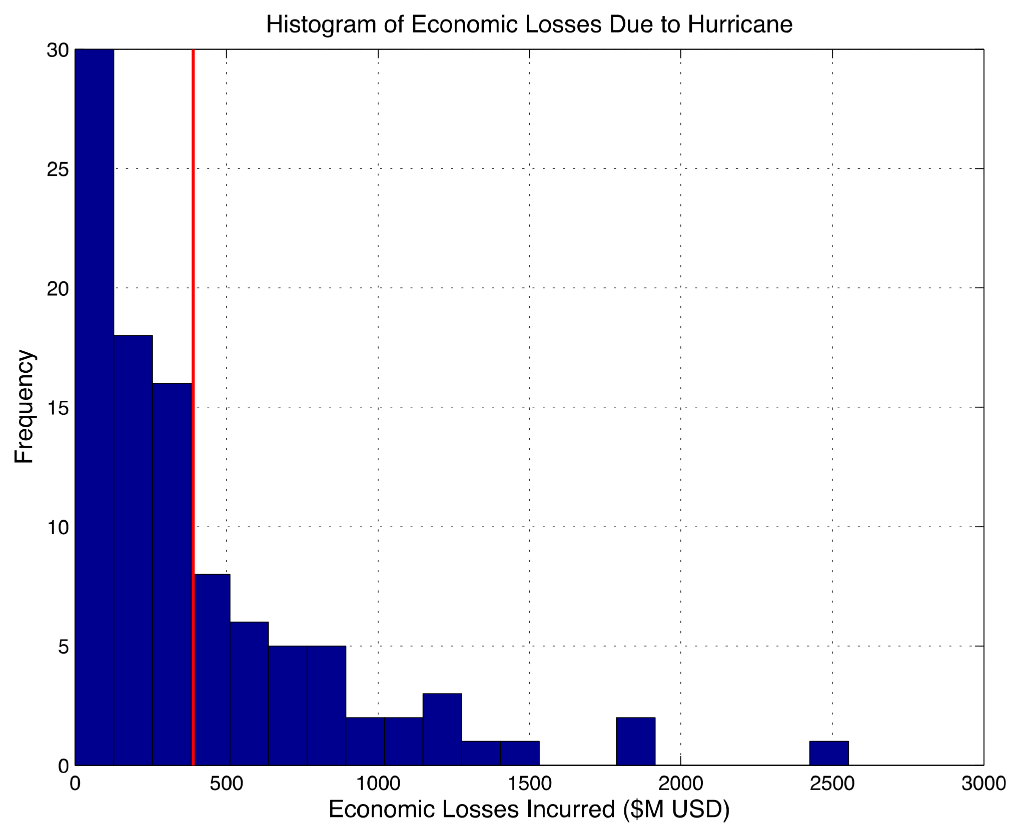
- Total budget of $100M
- Two assets considered
  - Build flood walls around generators at $9.1M/generator
  - Bury transmission lines at $4M/line
- Find the optimal investment portfolio to minimize economic losses
- This example maximizes resiliency considering one dimension (economic impact) and one threat (hurricane CAT 2) but other dimensions and threats could be added

Optimal Investment Portfolio

Evaluate Resilience Improvements

Once resiliency can be quantified, additional capabilities can be developed to inform decision-makers

- Formulate optimization as an stochastic program
  - First stage variables: Generators and lines to be modified
  - Second stage variables: Operations through hurricane realizations
- Objective is to minimize the expected economic losses
- Other objective functions can be employed (e.g., CVaR)
- All scenarios are considered equally likely (uniform distribution)



Summary

- Resilience metrics have been applied in context
- Resilience analysis for the electric grid builds on established models designed for operational reliability
- These baseline models are augmented with
  - Disruption scenario specifications
  - Translation of failure-of-delivery to consequences
  - Restoration and recovery processes

Exceptional service in the national interest

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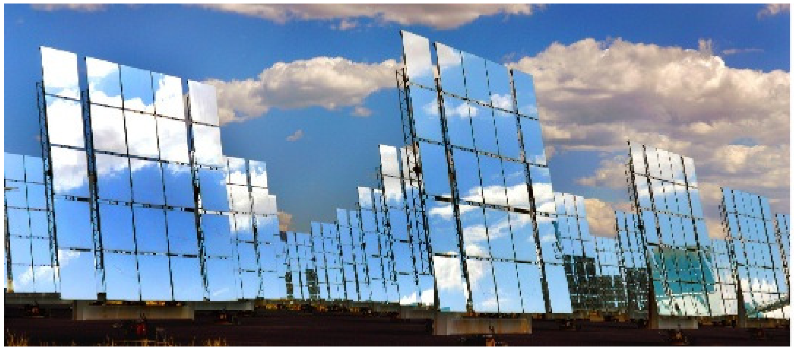


Oil Infrastructure Resilience

Use Case Development and Analysis

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

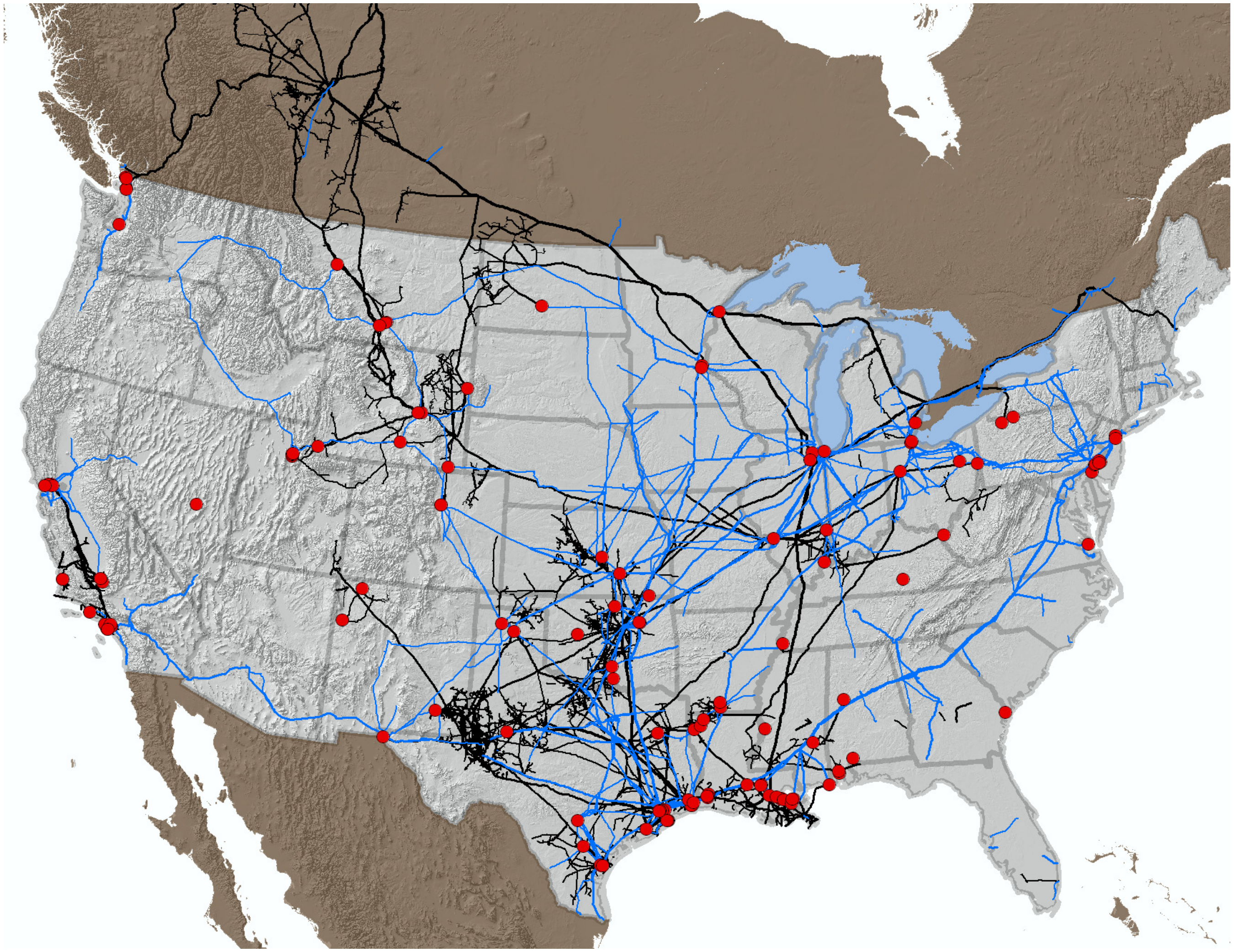
Goals

Define Resilience Goals

- Evaluate the resilience of U.S. oil infrastructure to a large earthquake in the New Madrid Seismic Zone
- Demonstrate use of the process to:
  - identify potential alternatives to increase resiliency
  - measure the increase in resilience due to implementing these options
- Specifically, we will calculate the increase in resilience gained by re-engineering two major pipelines to decrease down time after a New Madrid earthquake

North American Oil Infrastructure

Define System & Resilience Metrics

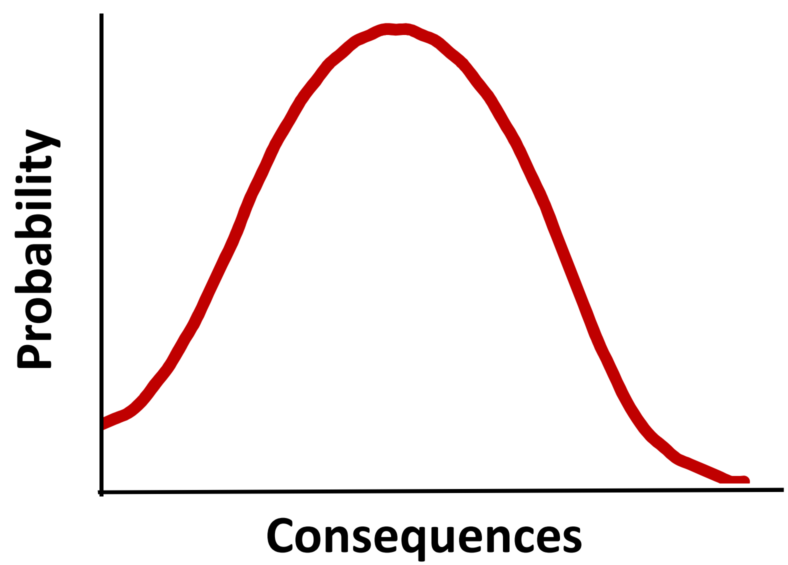


Define a Resilience Metric

Define System & Resilience Metrics

- Added fuel cost to consumers (relative to undisturbed costs)
  - Amount of fuel consumed decreases, but fuel prices increase

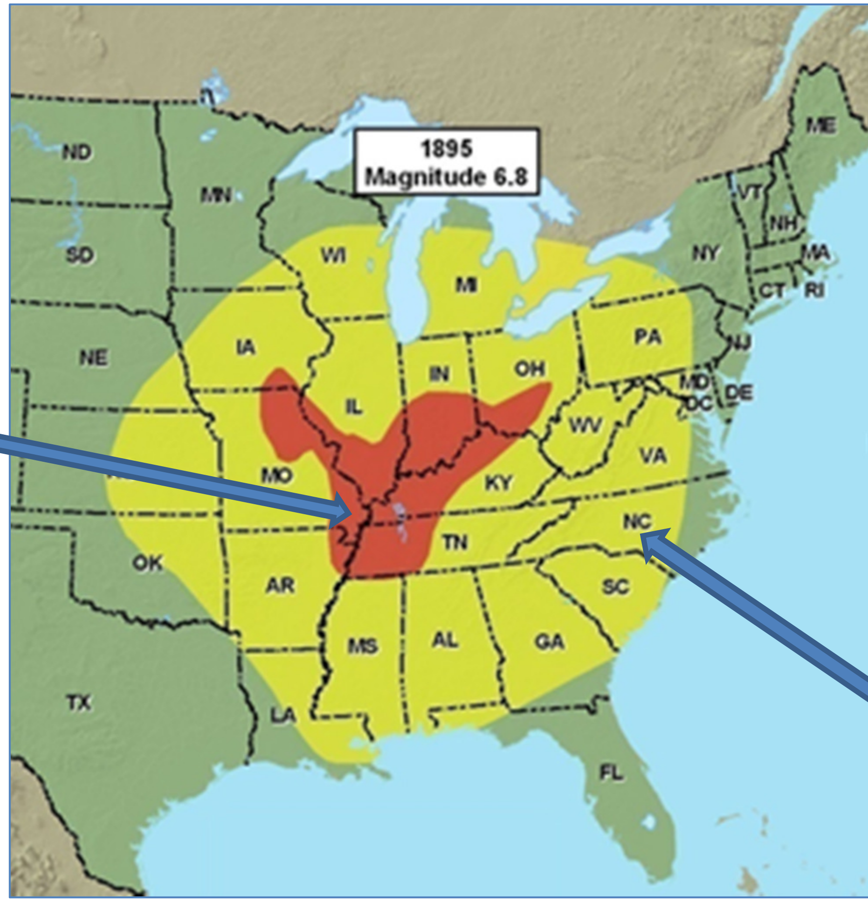
Distribution of Consequence



Earthquake Threat:
The New Madrid Seismic Zone

Characterize Threats

Minor to major damage to buildings (red)



Shaking can be felt (yellow)

Schweig, E., J. Gomberg, and J. W. Hendley II, 1995

New Madrid: Extensive Damage is Likely

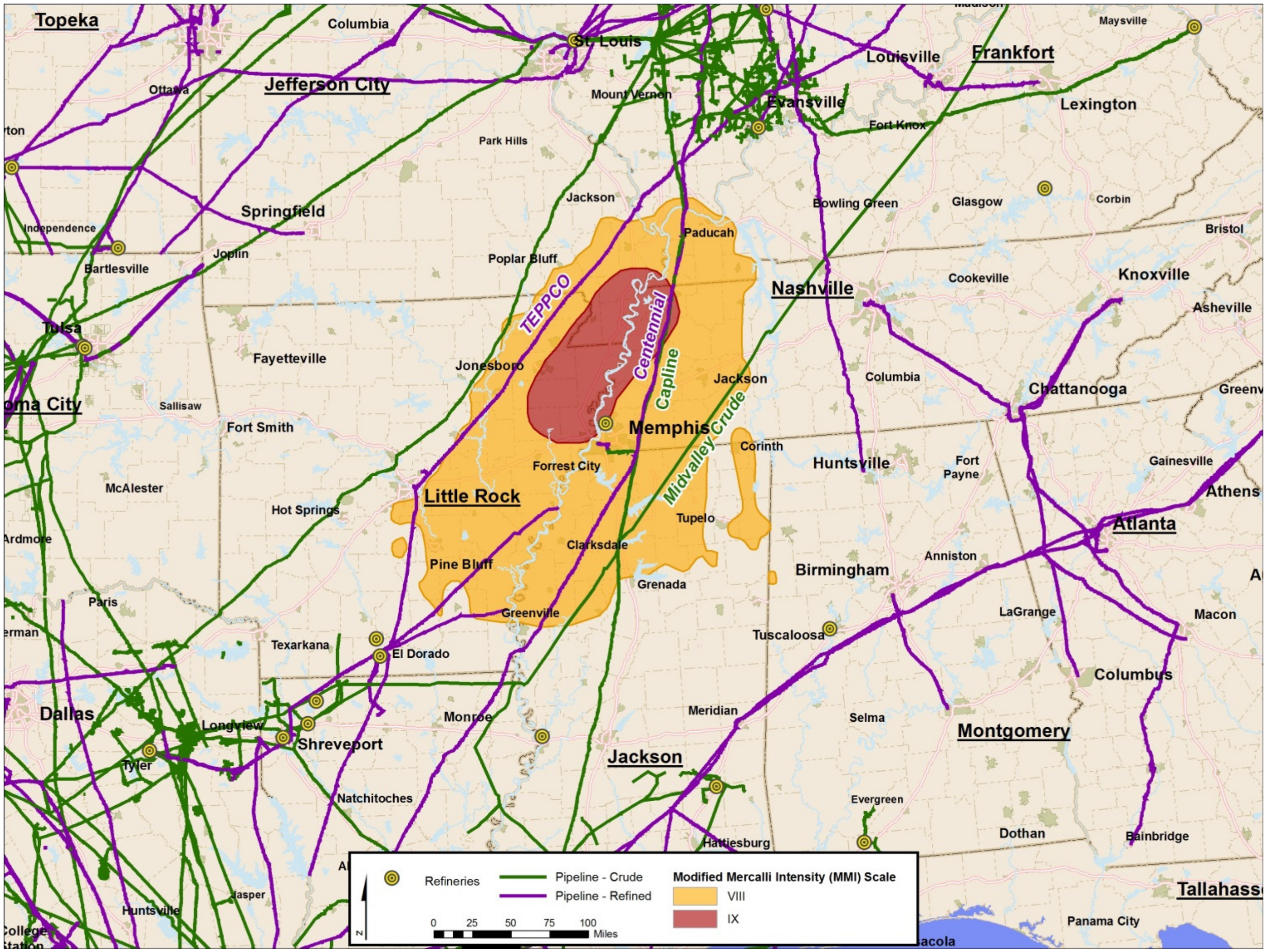
Characterize Threats

- The New Madrid Seismic Zone is the site of some of the largest historical earthquakes to strike the continental U.S.
- The last of these very powerful earthquakes occurred in the winter of 1811-1812
- Thick, unconsolidated, saturated sediments along the Mississippi River valley amplify shaking and could liquefy
- In the next 50 years, the New Madrid region faces a 7 to 10% probability of a repeat of the 1811 - 1812 type earthquakes

USGS, Center for Earthquake Research and Information Fact Sheet 2006-3125

Four Transmission Pipelines Could be Damaged by a New Madrid Earthquake

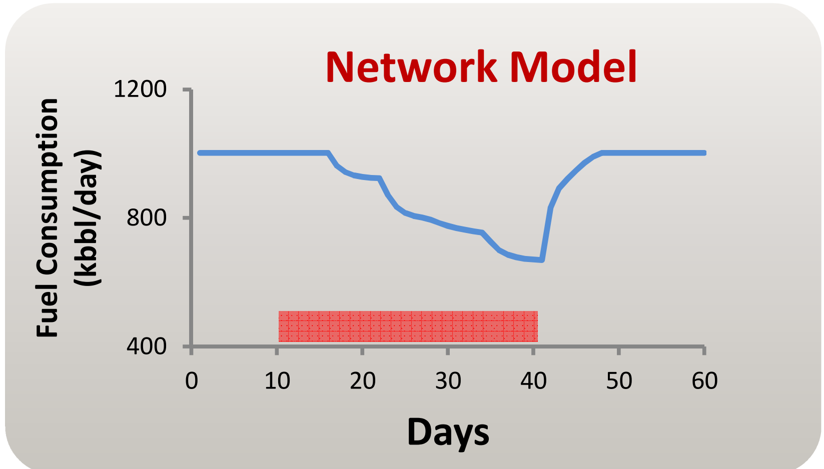
Determine Level of Disruption

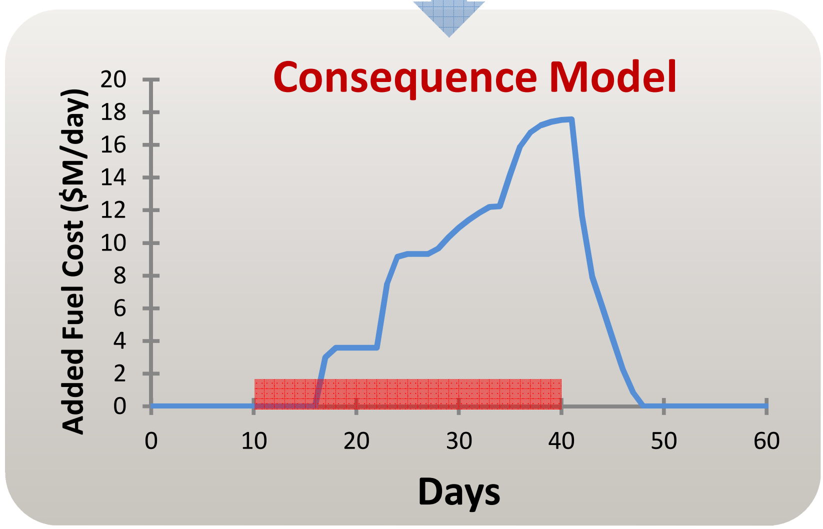


Apply Two Models to Calculate Metric

Define & Apply System Models

Damage Repair Duration

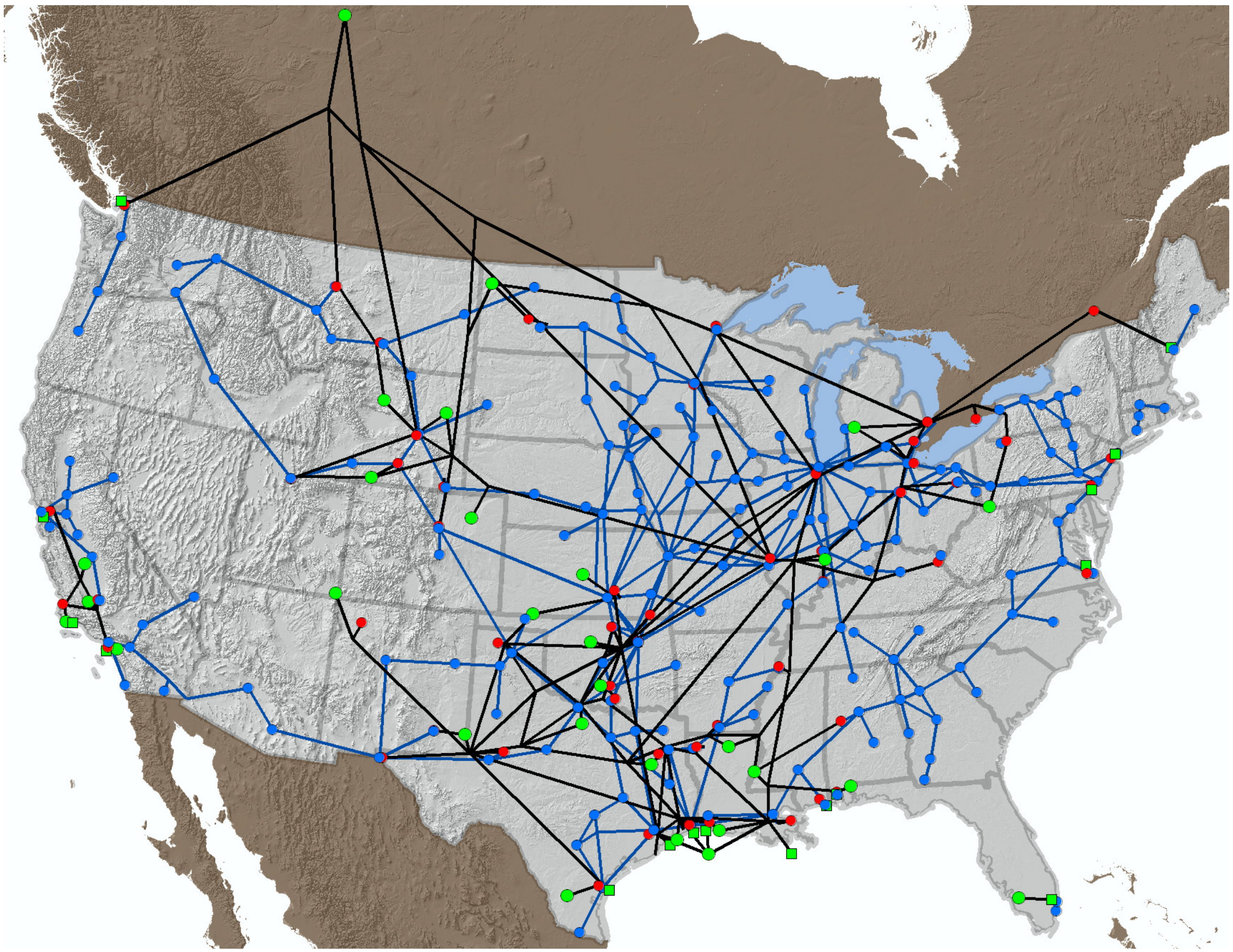




- For this use case, we assumed a distribution of repair times to show how to account for one source of uncertainty
- Alternatively, a model could be used to calculate a distribution of repair times

National Transportation Fuels Network Model

Define & Apply System Models



Network Model Description

Define & Apply System Models

- Market-driven Resilience Attributes minimize fuel shortages
  - Re-routing shipments
  - Drawdown of inventory
  - Use of surge capacity
  - Increasing imports
  - Reducing consumption
- Constrained by connectivity of the system and capacity of individual system components:
  - Pipeline flow
  - Refinery throughput
  - Tank Farm storage
  - Import terminal throughput

Some Model Assumptions and Limitations

Define & Apply System Models

- Includes transmission system (pipelines, water*), but not distribution (trucks)
  - For example, the model does not know that fuel can’t be delivered because roads are damaged
- Market behavior is based on fuel availability
  - No hoarding behavior (by consumers or suppliers)
  - No price increases until inventories decline
- Desired consumption of fuel not decreased by damage to other infrastructures

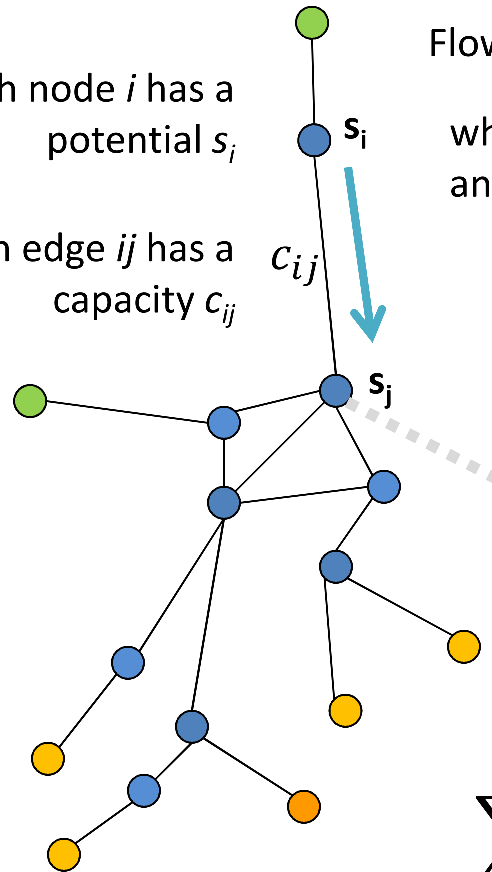
* Yep … we know, rail is important … it’s coming

Minimize shortages while balancing mass and not exceeding capacities

Define & Apply System Models

Each node i has a potential s_i

Each edge ij has a capacity c_{ij}

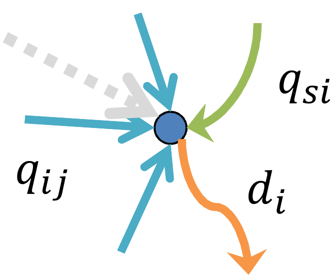


Flow rates are given by : $$q_{ij} = c_{ij}\, f\big((s_i - s_j)u_{ij}\big) \quad (1)$$

where u_{ij} is a utilization parameter and the function f(x) is: $$f(x) \equiv 1 - e^{-x} \quad (2)$$

In equilibrium, the net flow at each node i is 0: $$\sum_j q_{ji} + q_{si} - d_i = 0 \qquad \forall i \quad (3)$$

The equilibrium solution $\{\hat{s}_i\}$ is obtained by solving equations (1-3)



In the transient case, net inflow into a node results in the accumulation of stored fluid:

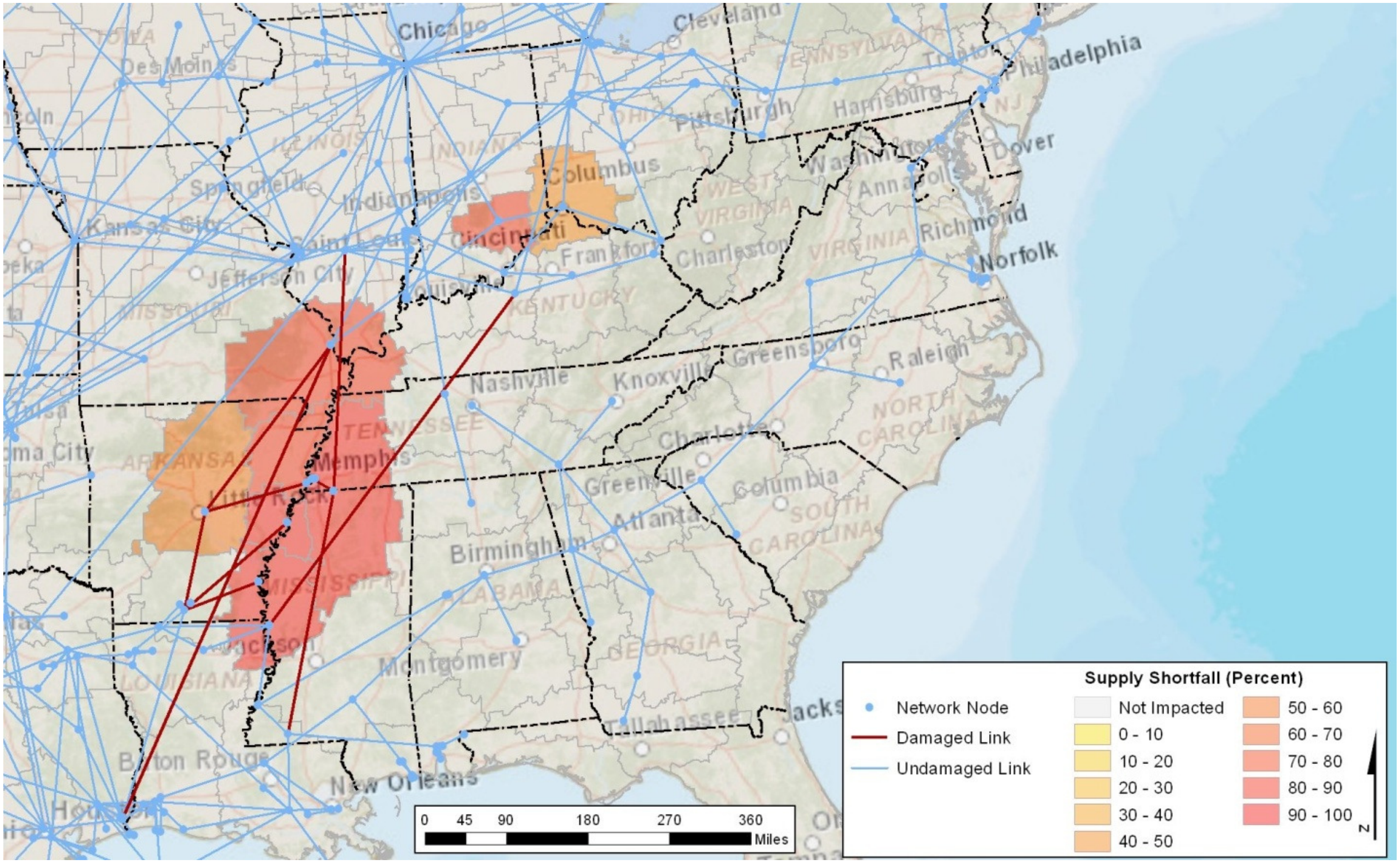
$$\sum_j q_{ji} + q_{si} - d_i = \frac{dv_i}{dt} = r_i \left[1 + \left(\frac{s_i - a_i}{b_i}\right)^2\right]^{-3/2} \frac{ds_i}{dt} \qquad \forall i$$

where r_i , a_i and b_i are storage parameters

Beyeler, Corbet, and Hobbs, 2012

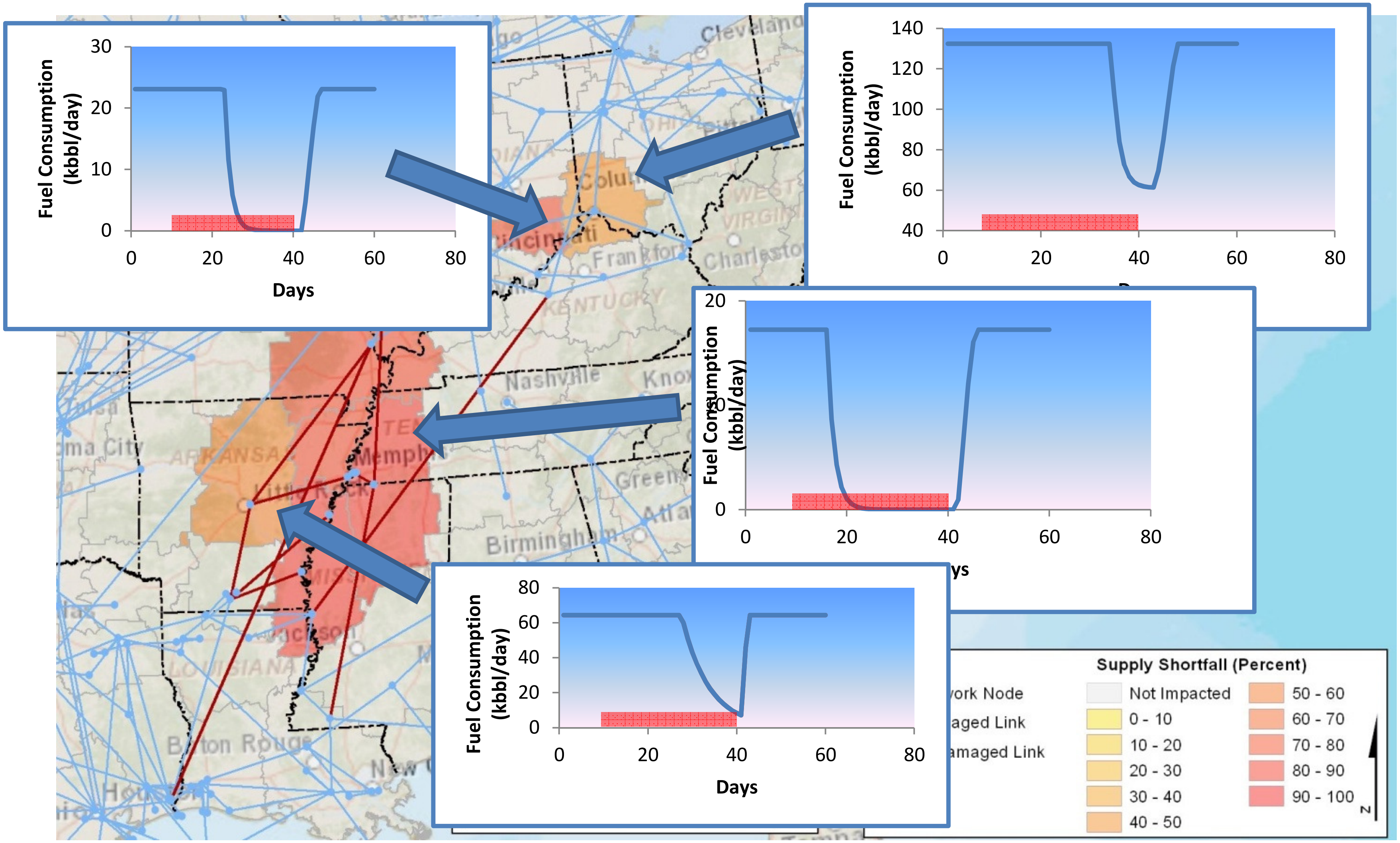
Calculated Consumption Shortfall of Fuel Due to a New Madrid Earthquake

Calculate Consequence



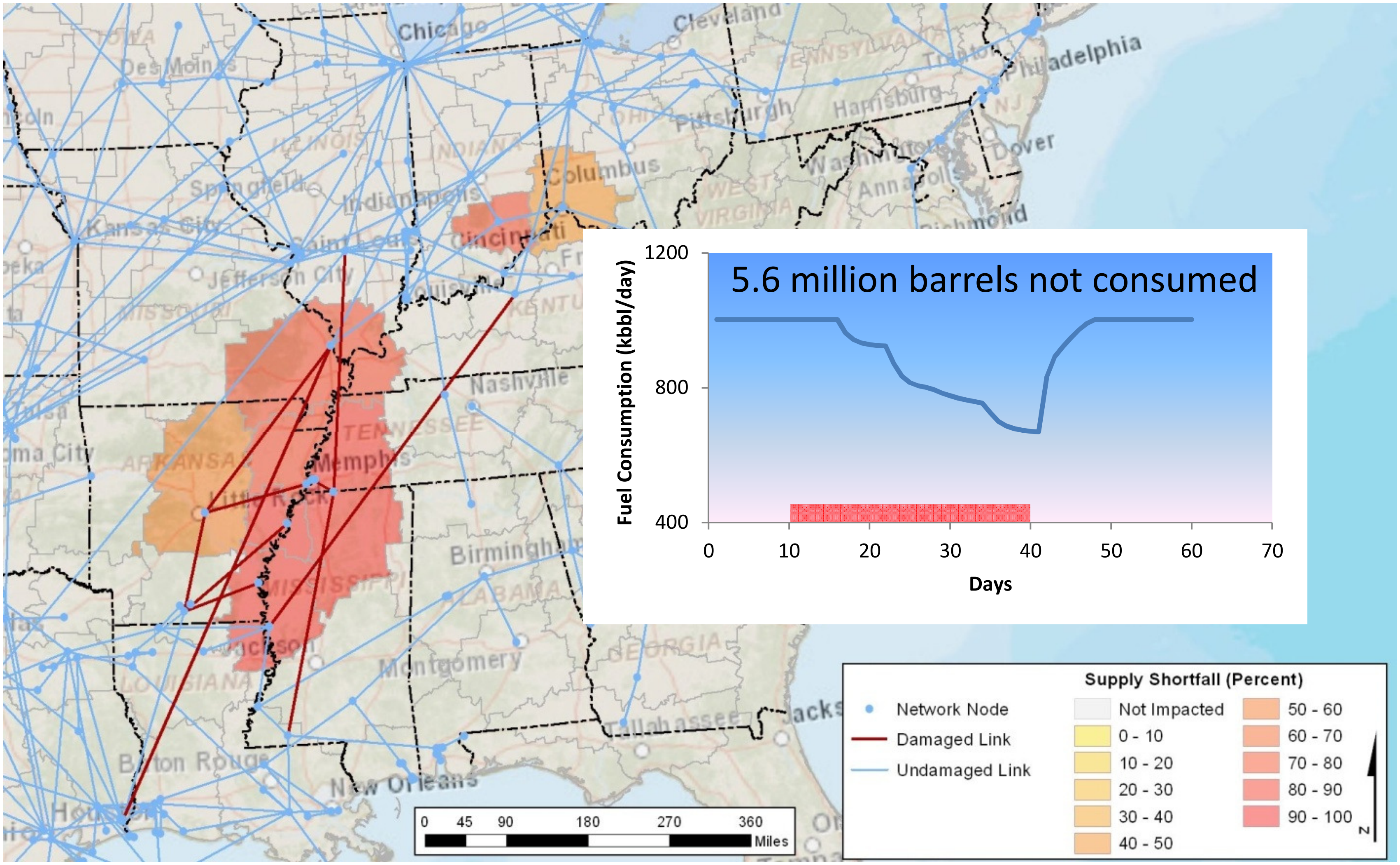
Calculated Consumption Shortfall of Fuel Due to a New Madrid Earthquake

Calculate Consequence



Calculated Consumption Shortfall of Fuel Due to a New Madrid Earthquake

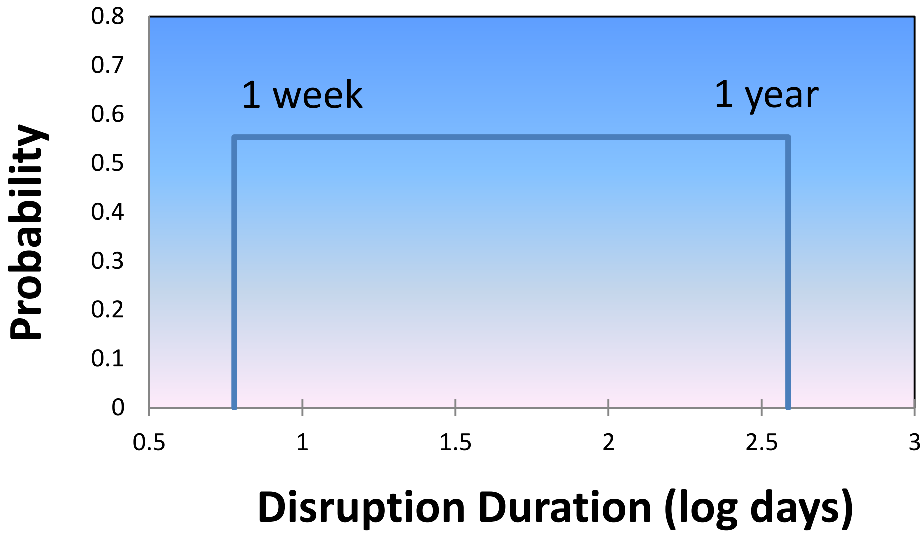
Calculate Consequence



Uncertainty of Repair Time

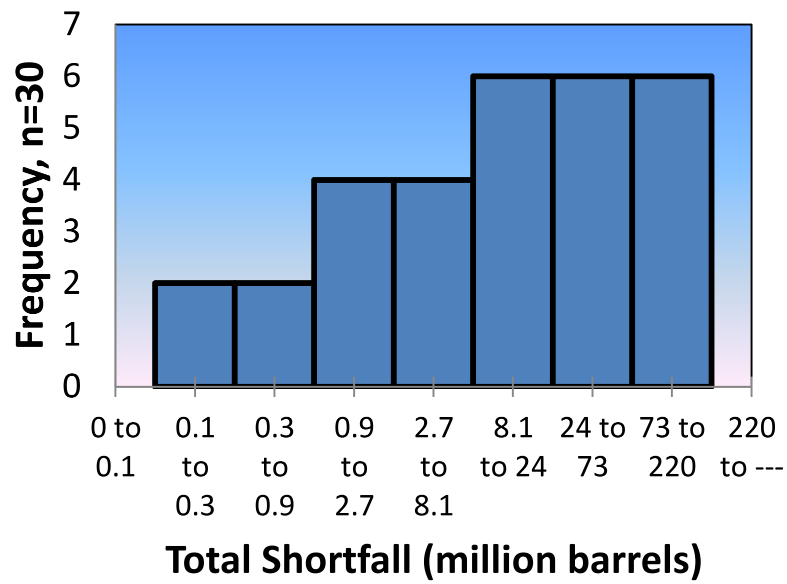
Calculate Consequence

Assumed Probability of Repair Times

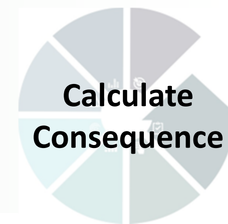


Network Model

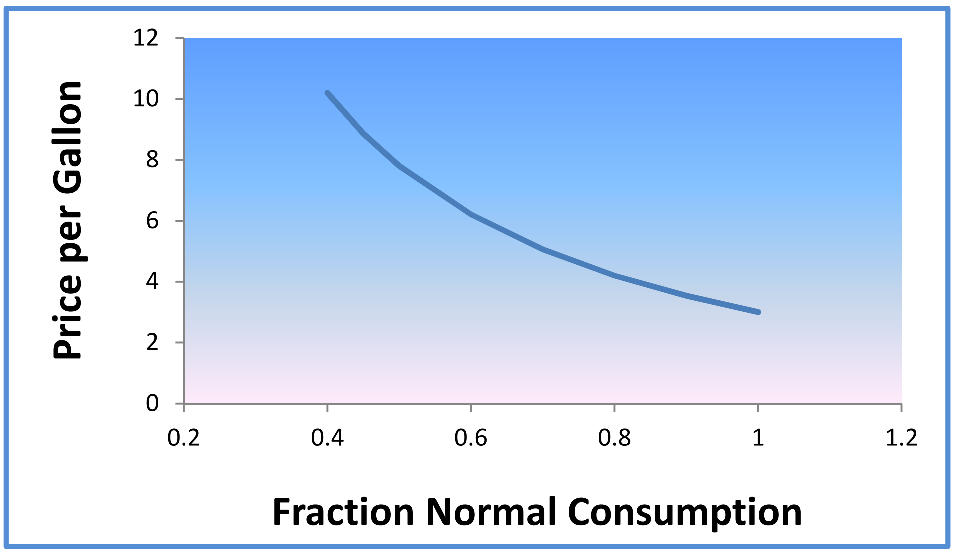
Histogram of Performance Indicator (barrels fuel not consumed)



Consequence Model



- Main Assumptions:
  - During a fuel shortage that is expected to be temporary (weeks) services, businesses, and individuals will try to maintain normal output despite fuel shortages
  - Market behaviors will act to decrease fuel consumption by raising prices



Assumed Demand Curve

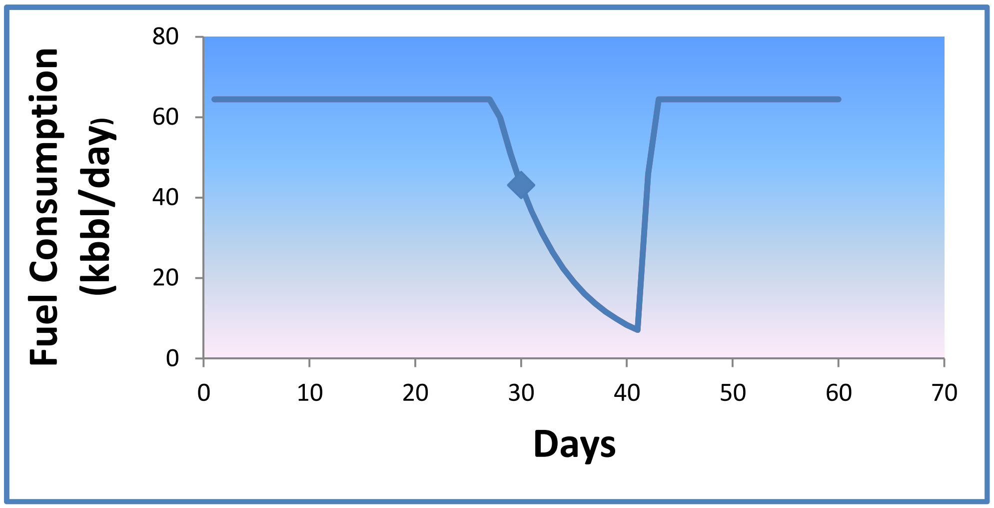
Informed by price data from the 2004 Phoenix fuel disruption**

** http://www.doney.net/aroundaz/gas_lines.htm

Calculate Additional Cost of Fuel Consumed

Calculate Consequence

1. For each impacted distribution terminal, calculate the daily price of fuel (using the calculated consumption fraction and the assumed demand curve)
2. Multiply the price times the amount consumed to get the daily cost of fuel
3. Subtract the undisturbed daily cost of fuel



At day 30 in Little Rock:

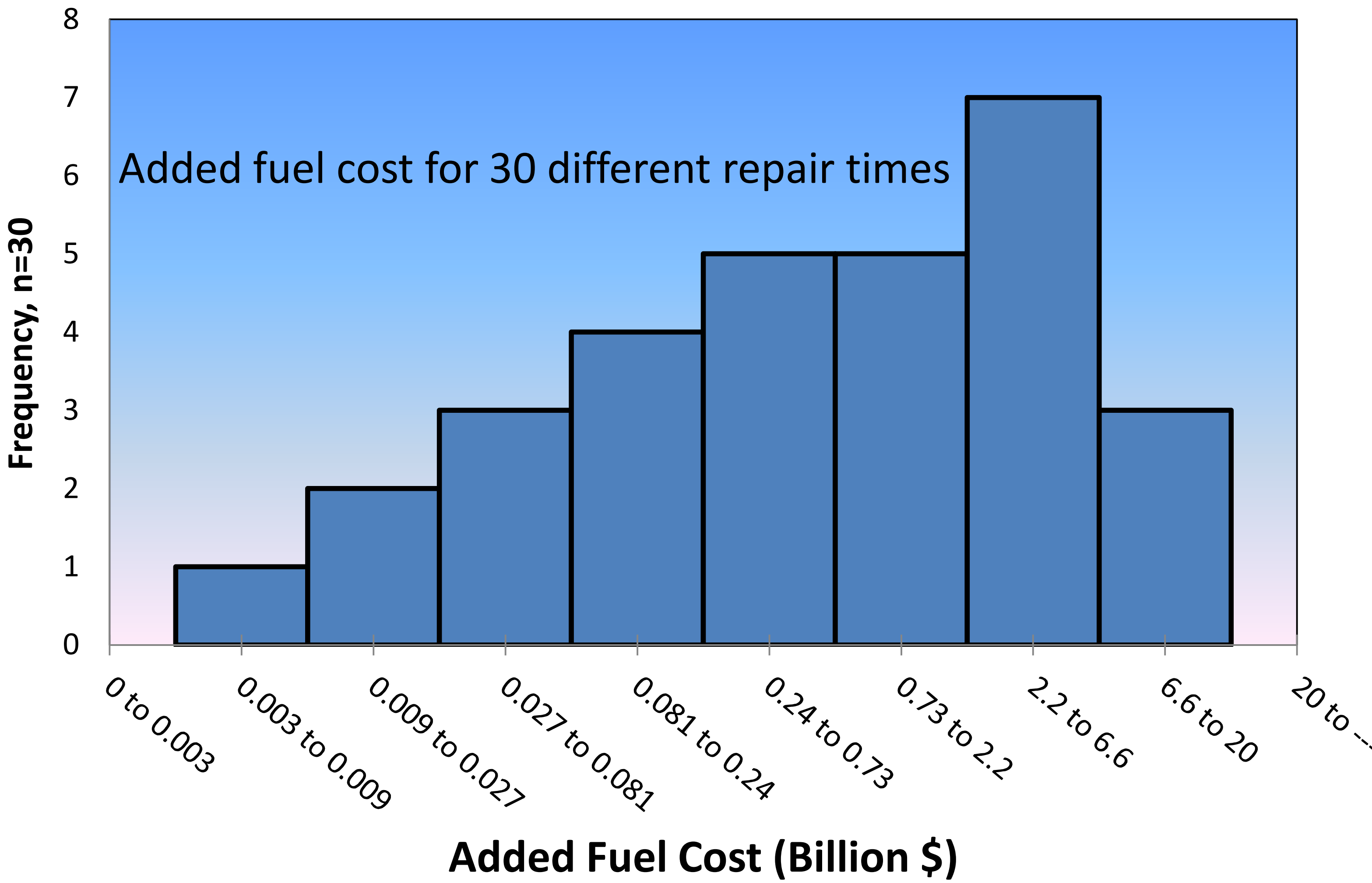
Consumption = 43,125 bbl/day
Consumption fraction = 0.67
Price = $5.36/gal
Cost = $9,708,300

Undisturbed:
Consumption = 66,400 bbl/day
Price = $3.00/gal
Cost = $8,114,400

Added cost = $1,593,900

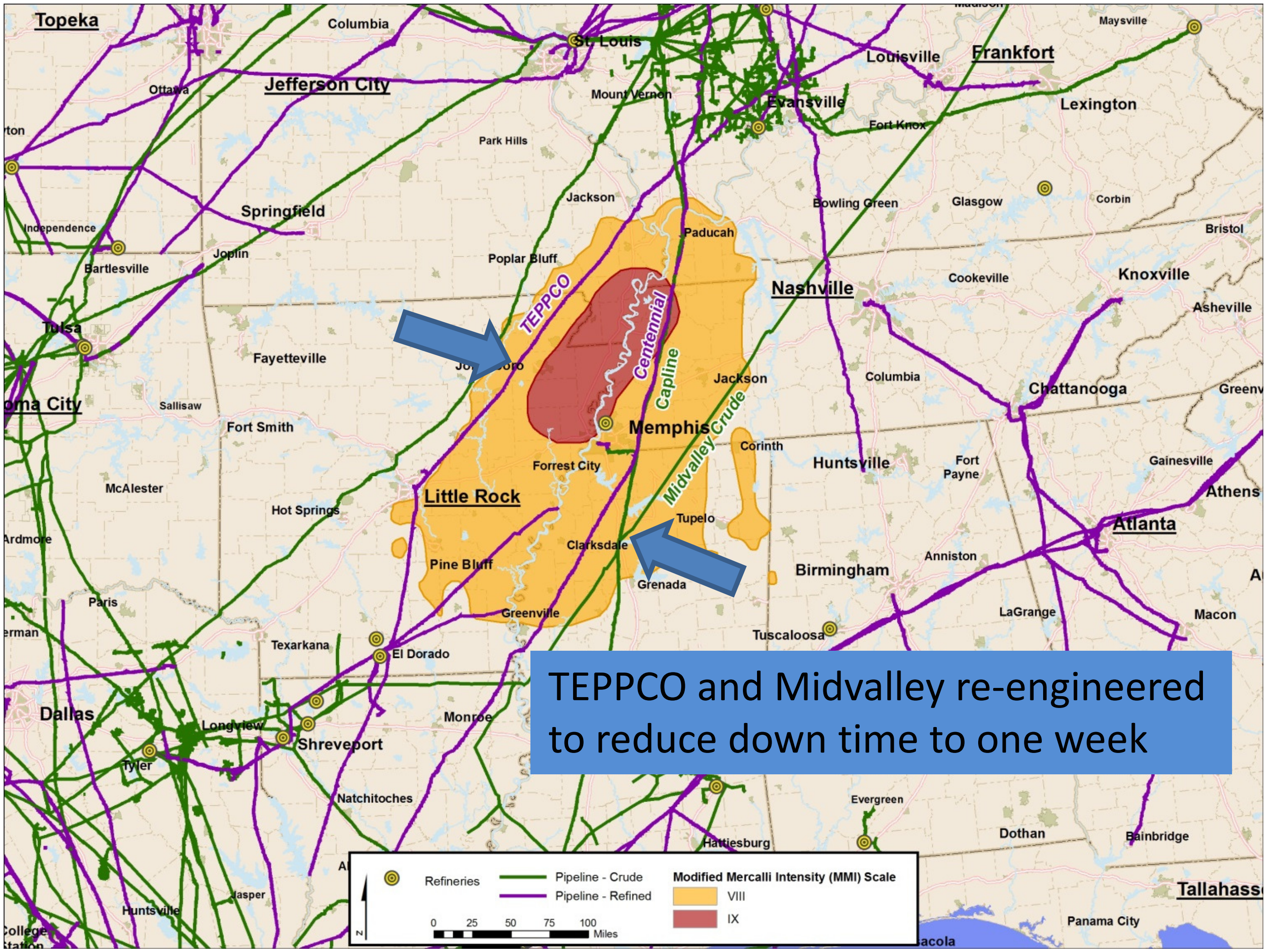
Consequence: Likelihood of Added Fuel Cost

Calculate Consequence



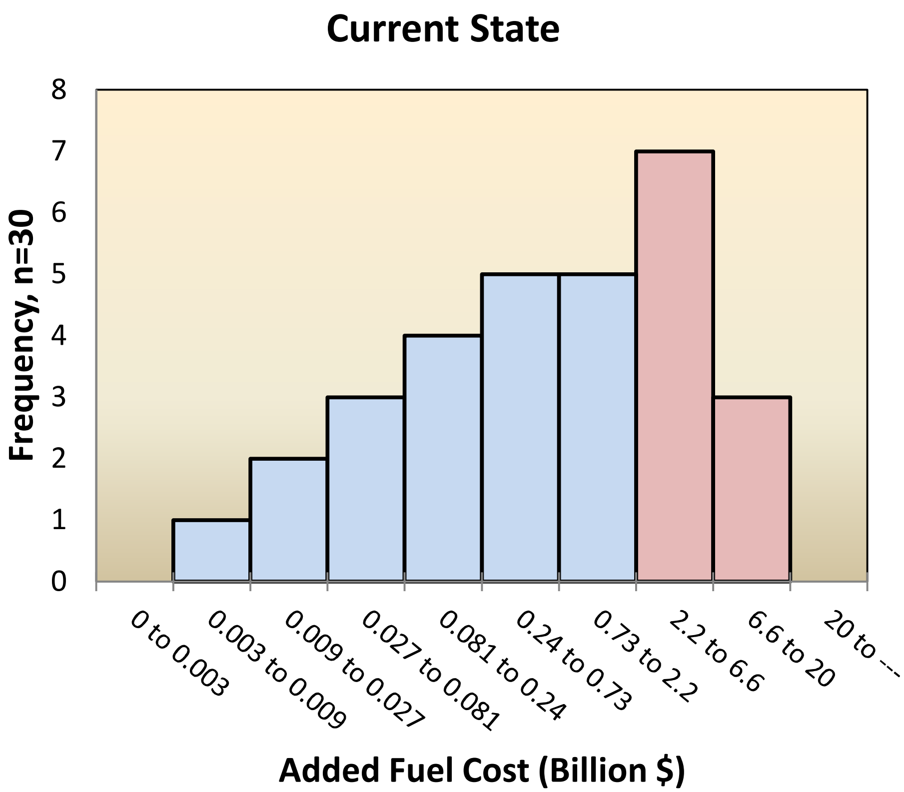
Pipeline Modifications to Increase Resilience

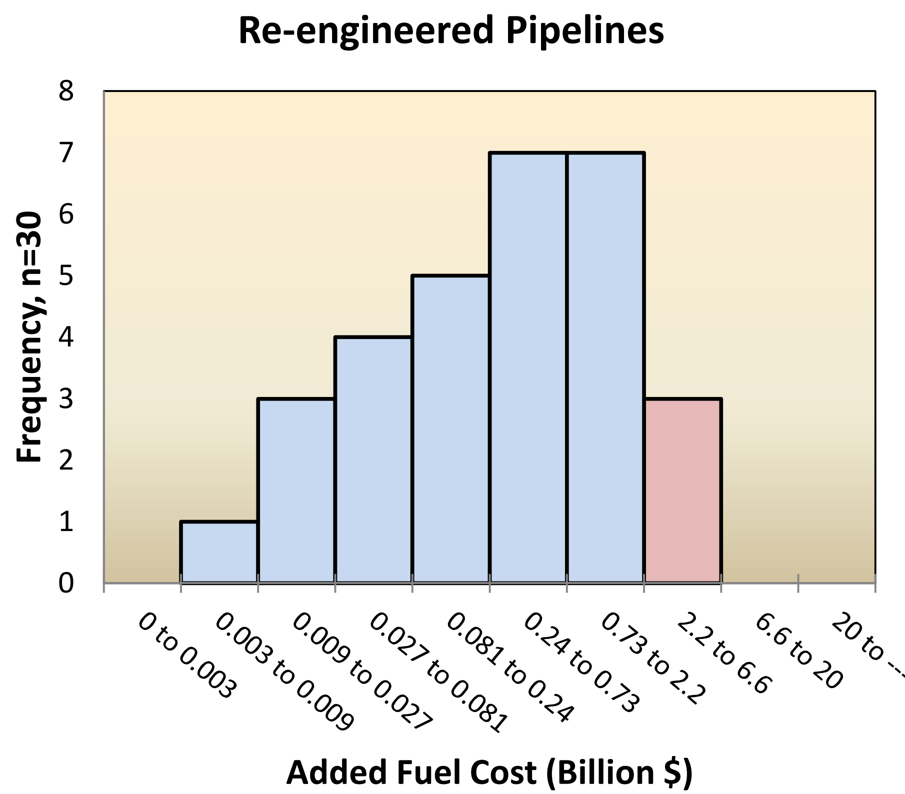
Determine Level of Disruption



Evaluating Investment to Increase Resilience

Evaluate Resilience Improvements





Histograms show the likelihood of cost >$2.2B drops from 1/3 to 1/10

Summary

- Applied the metric development process to evaluate the resilience of U.S. oil infrastructure to a large earthquake in the New Madrid Seismic Zone
- Calculated the increase in resilience gained by re-engineering two major pipelines to decrease down time after a New Madrid earthquake

Exceptional service in the national interest

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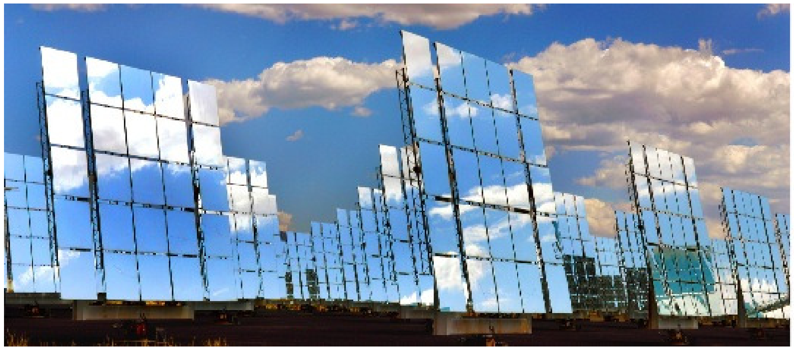

Natural Gas Infrastructure Resilience

Use Case Development and Analysis

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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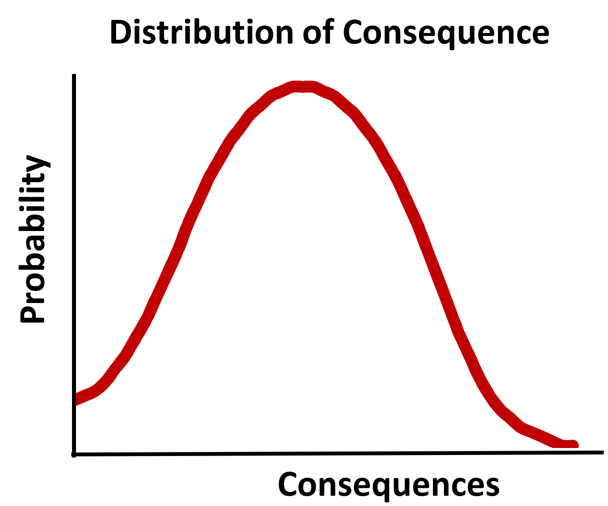
Natural Gas Use Case Purpose

Define Resilience Goals

- Evaluate the resiliency of the Southern California natural gas system to a large San Andreas Fault earthquake
- Compare resilience of system with historical storage withdrawals to one of increased storage withdrawals

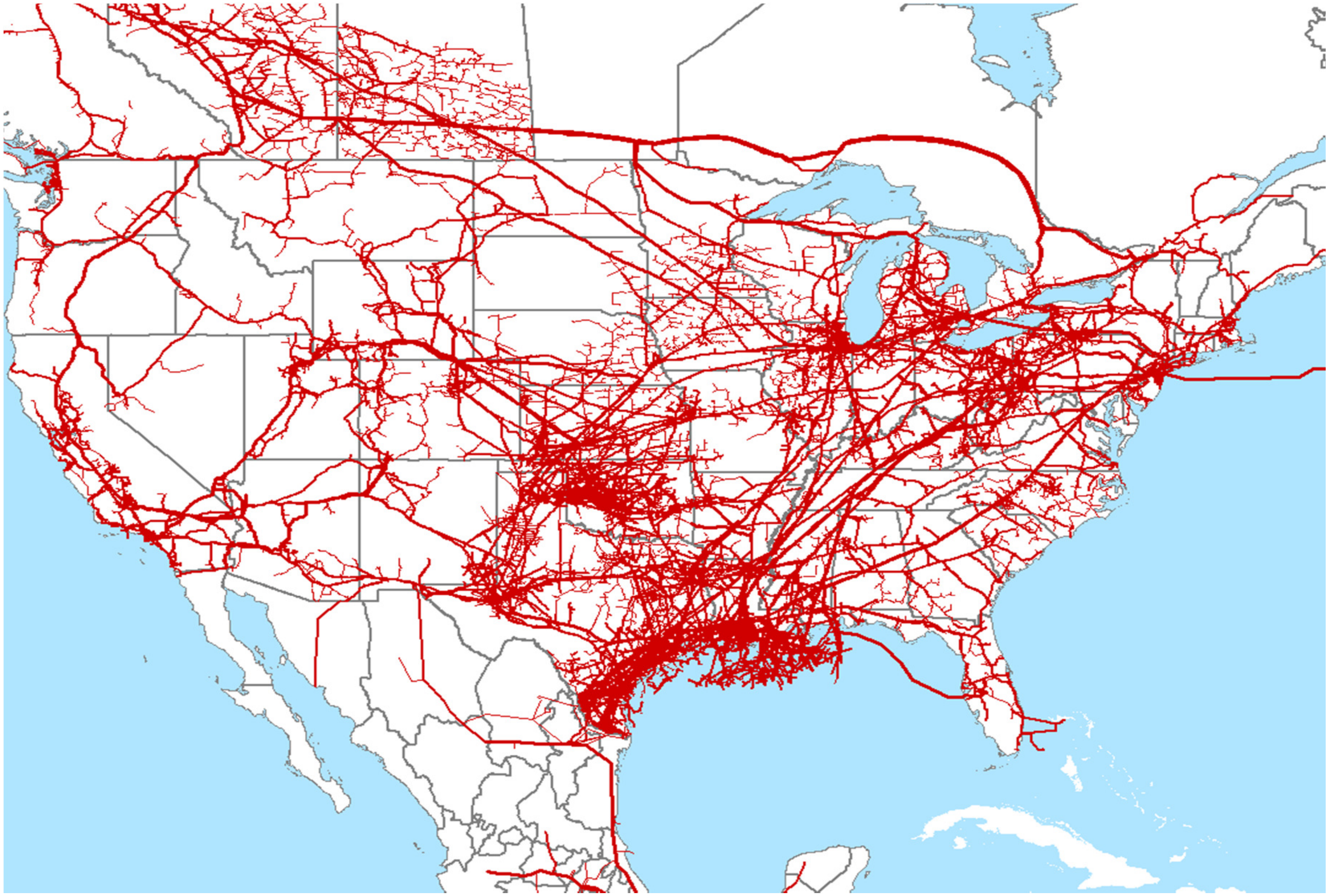
Natural Gas System and Metrics

- System: Southern California portion of the North American Natural Gas Network
- Metric: Economic impact caused by delivery shortfalls
  - Accounting for uncertainty in restoration time



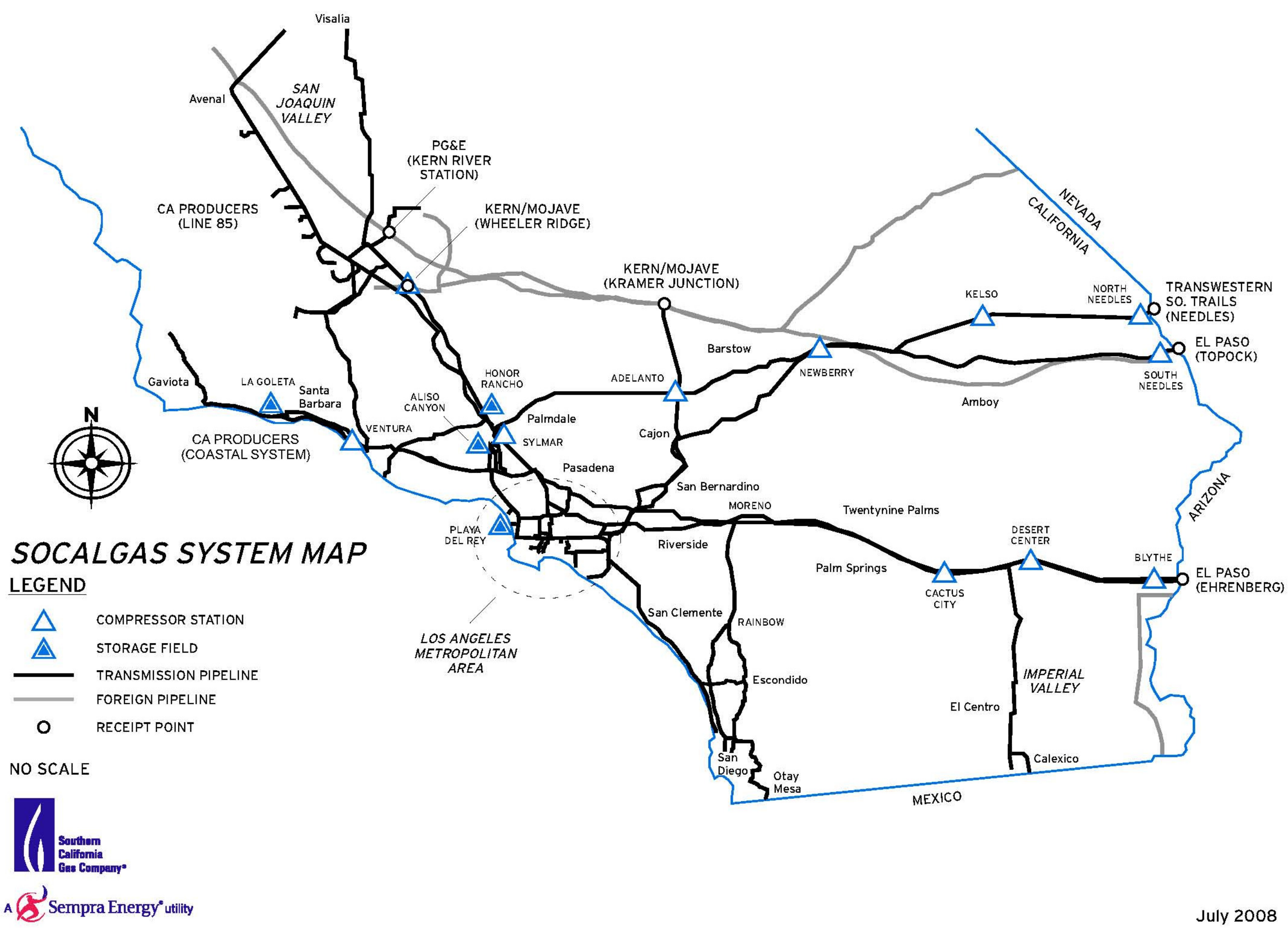
North American NG Network

Define System & Resilience Metrics



NG Network Area of Interest

Define System & Resilience Metrics



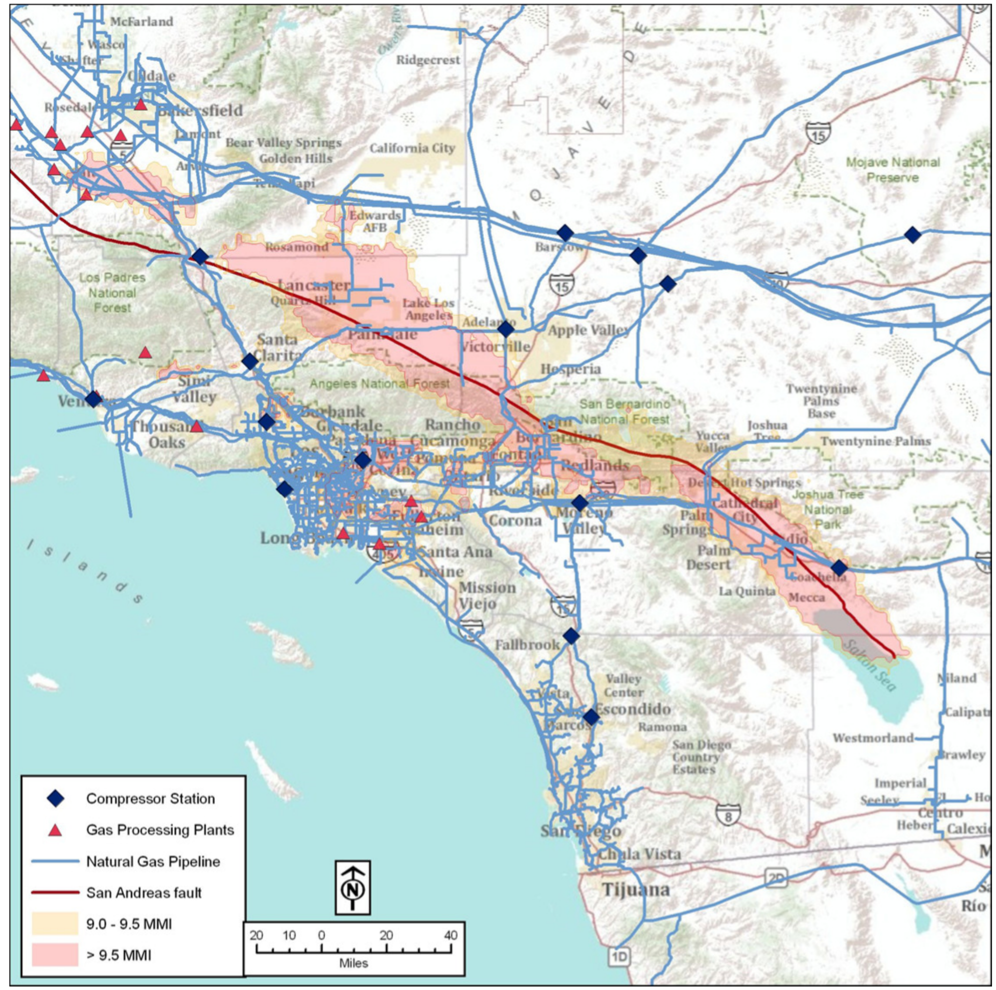
"ShakeOut Scenario" Earthquake

- 7.8 magnitude earthquake
- Located along the southernmost 200 miles of the San Andreas Fault, near the Salton Sea
- Occurs in December

Impact to NG System

Determine Level of Disruption

- Impact determined from engineering assessment
- Severe damage to two gas transportation corridors likely
- Damage to a third pipeline corridor possible



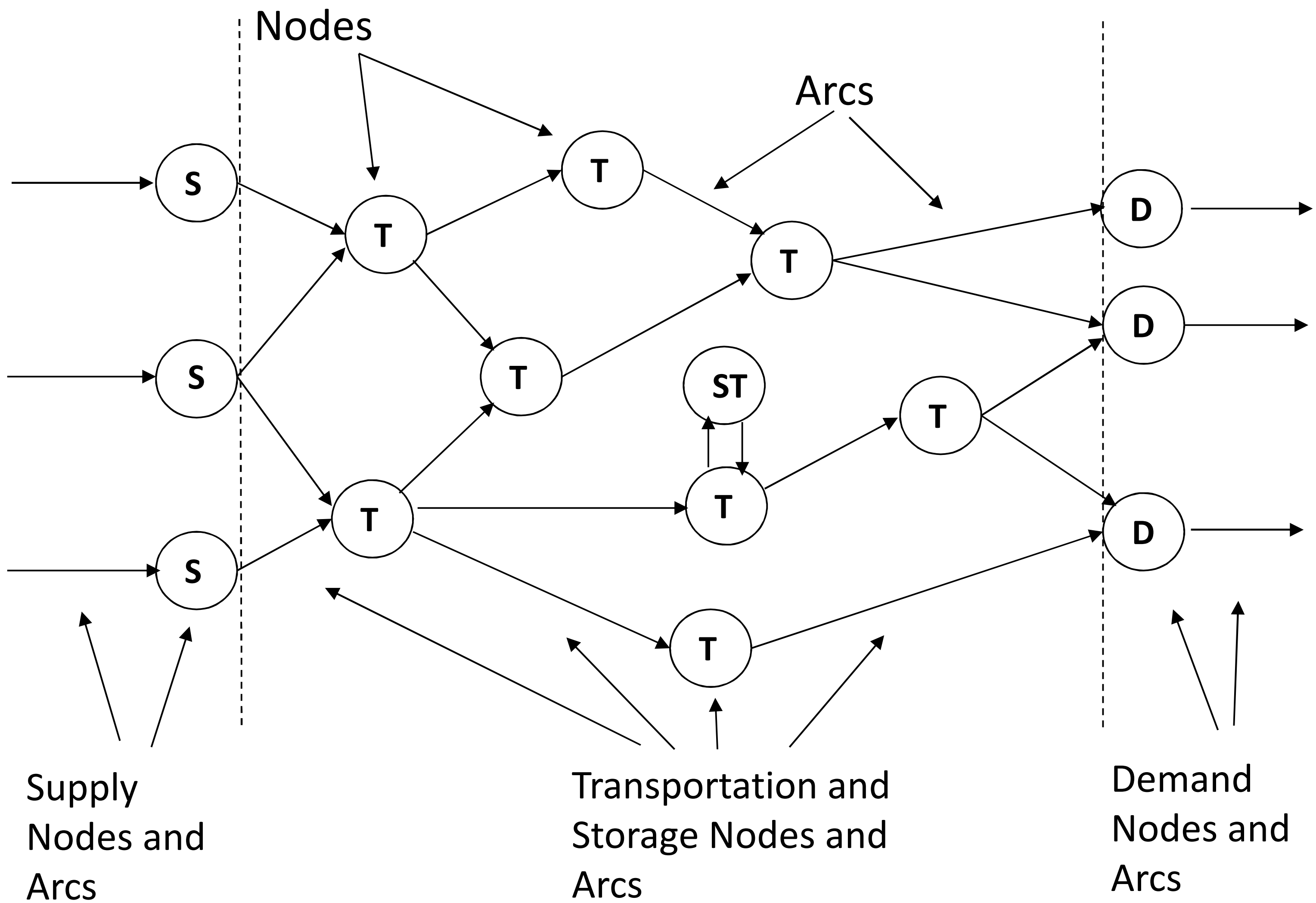
Natural Gas Model Overview

Define & Apply System Models

- GPCM – 'Gas Pipeline Competition Model'
- A 'pipeline specific' model
  - All major pipeline systems in North America represented (188 pipelines as of May 2009)
  - More challenging than 'corridor-based' model, but more analytical capability
- Basic economic principle – "market clearing"
  - In economics literature, it is called a "competitive, partial equilibrium model" of the natural gas sector

Natural Gas Model Overview

Define & Apply System Models



Natural Gas Model Overview

Define & Apply System Models

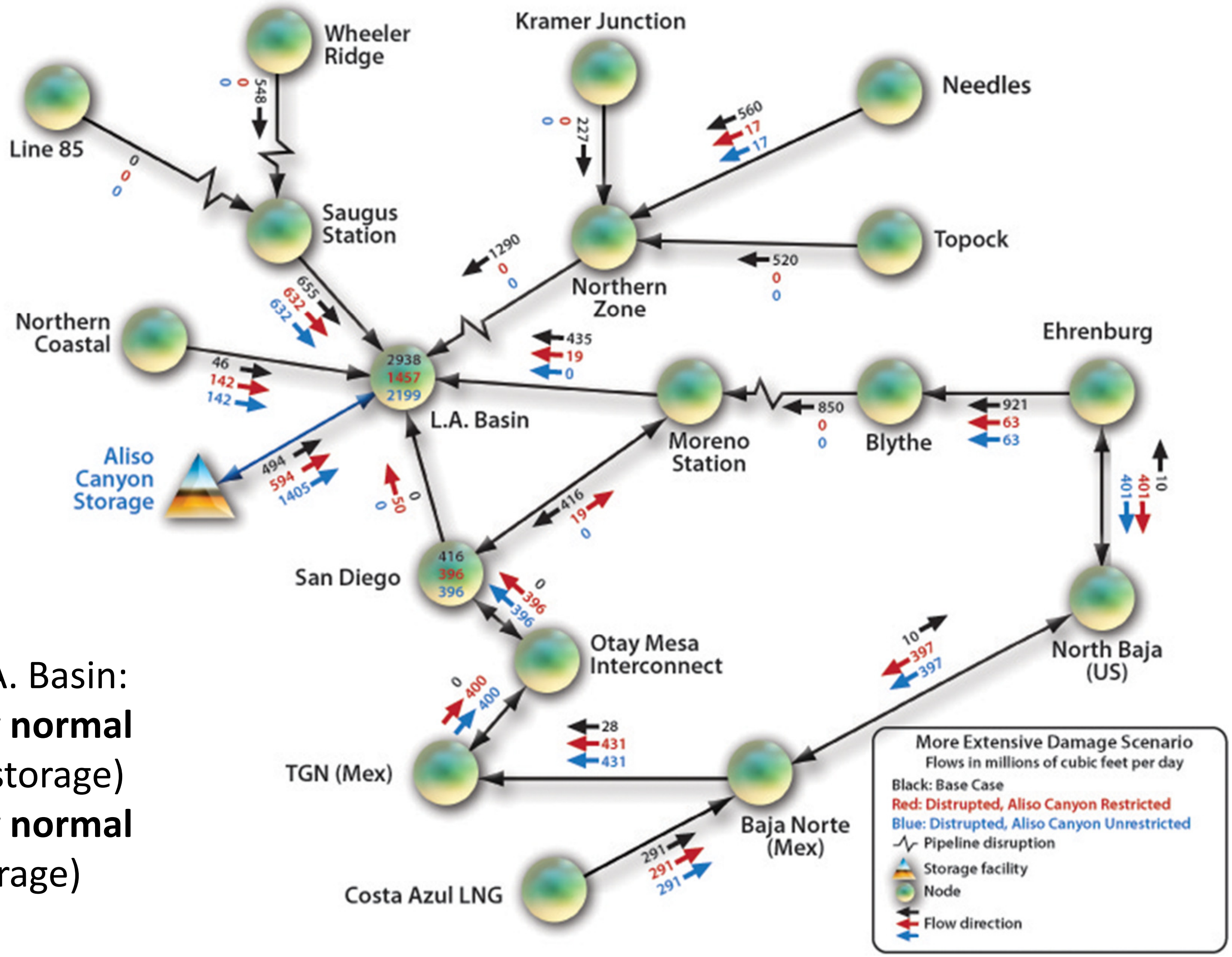
- Model's flow algorithm allows the network to adapt to disruptions
- Factors increasing resiliency
  - Use of gas in storage
  - Ability of network to reroute
  - Price increases reduce demand/stimulate production

Natural Gas Model Procedure

Define & Apply System Models

- Solve model for three cases
  - Base case (no damage)
  - Two bounding cases where three transportation corridors are damaged
    - Restricted Case: Aliso Canyon withdrawal rate limited to maximum historic rates
      - Aliso Canyon is a large storage facility
      - Gas in storage is owned, and owner may not wish to sell it to others in an emergency
    - Unrestricted Case: Aliso Canyon withdrawal rate limited to maximum physical rate

Natural Gas Model Results

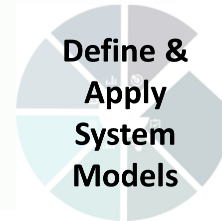


Results

Supplies to L.A. Basin:

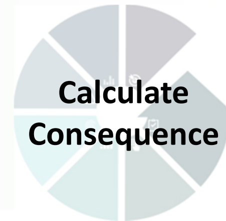
- **25% below normal** (unrestricted storage)
- **50% below normal** (restricted storage)

Recovery and Repair Estimation



- Need an estimate of outage duration to calculate total NG shortfall
- Assume the total repair time for all corridors can be modeled using a normal distribution
  - Mean: 1 month
  - Standard deviation: 0.5 weeks
- Cost of repairs not considered

Calculate Disruption Consequence



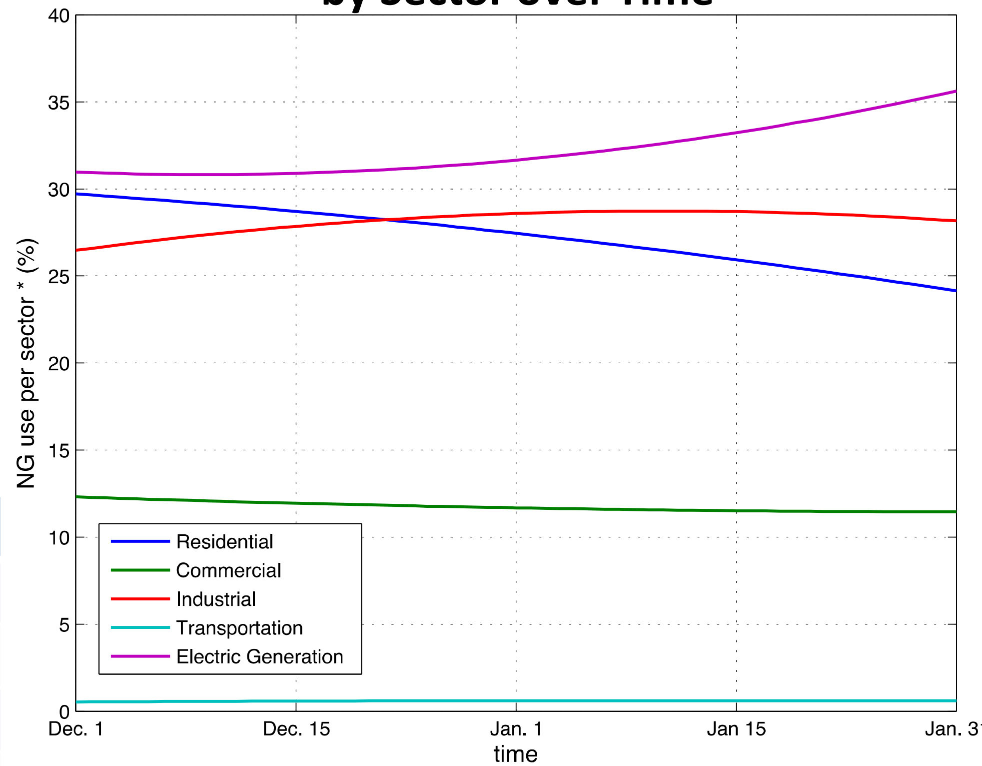
To calculate economic impact, we multiply

- NG prices for each sector
- Fraction of use for that sector

And sum to obtain an average price

Then, we multiply this by the gas shortfall

Historic Natural Gas Usage by Sector over Time

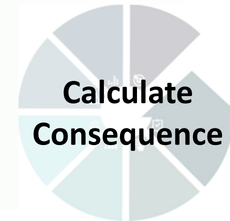


NG Prices by Sector

Sector	NG price ($/Mcf)*
Residential	10.02
Commercial	8.27
Industrial	7.14
Transportation	4.41
Electric Generation	5.14

* Source: www.eia.gov

Use Case: Assess Baseline Resiliency



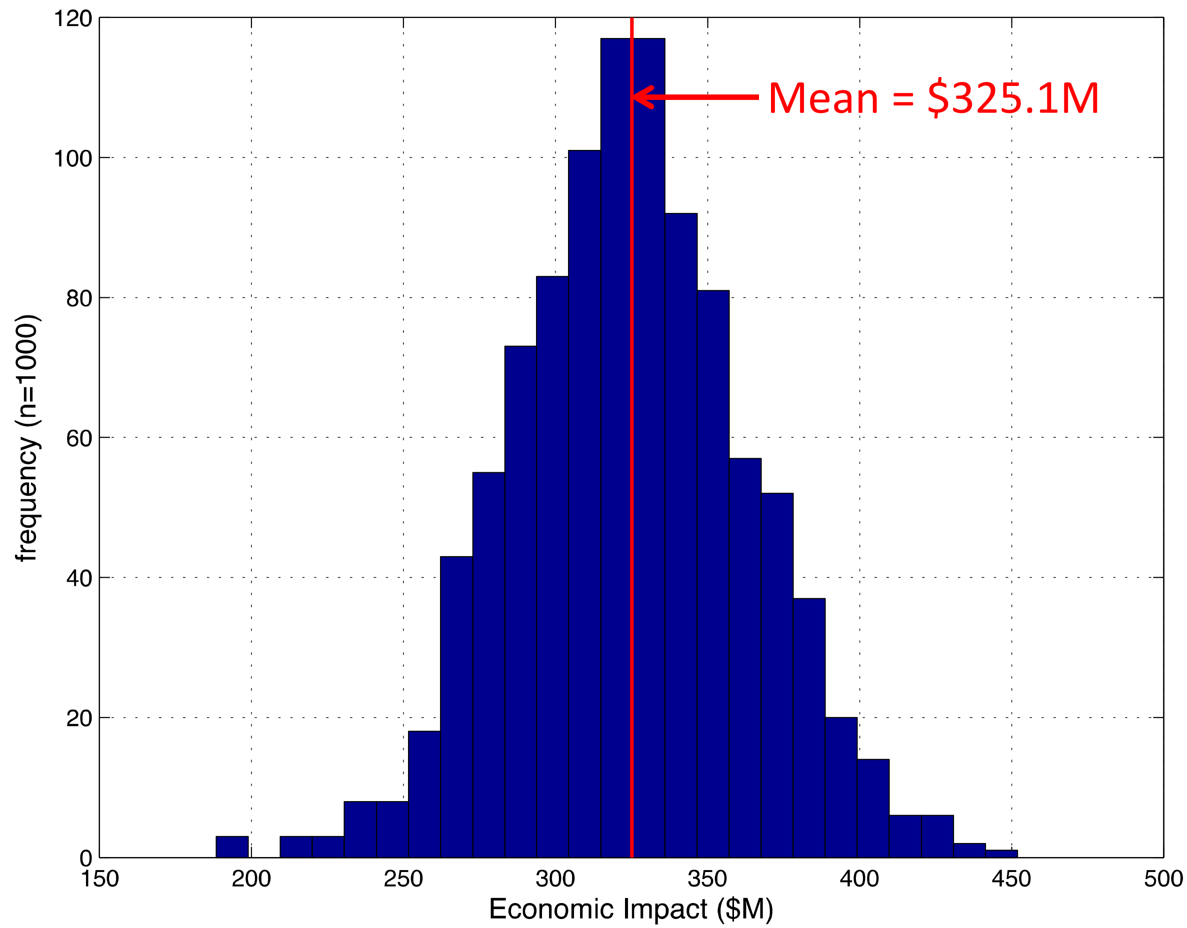
Assumptions:

1. Shortage per sector is proportional to historical fraction of usage per sector
2. Economic consequences of shortfall can be estimated by the value of gas not delivered (based on historical price data)

Methodology:

1. Sample 1000 scenarios specifying potential repair times on all damaged transportations corridors
2. For each scenario compute shortage per sector
3. For each scenario compute the cumulative economic losses incurred

Histogram of Economic Impact for Restricted Withdrawal Rate

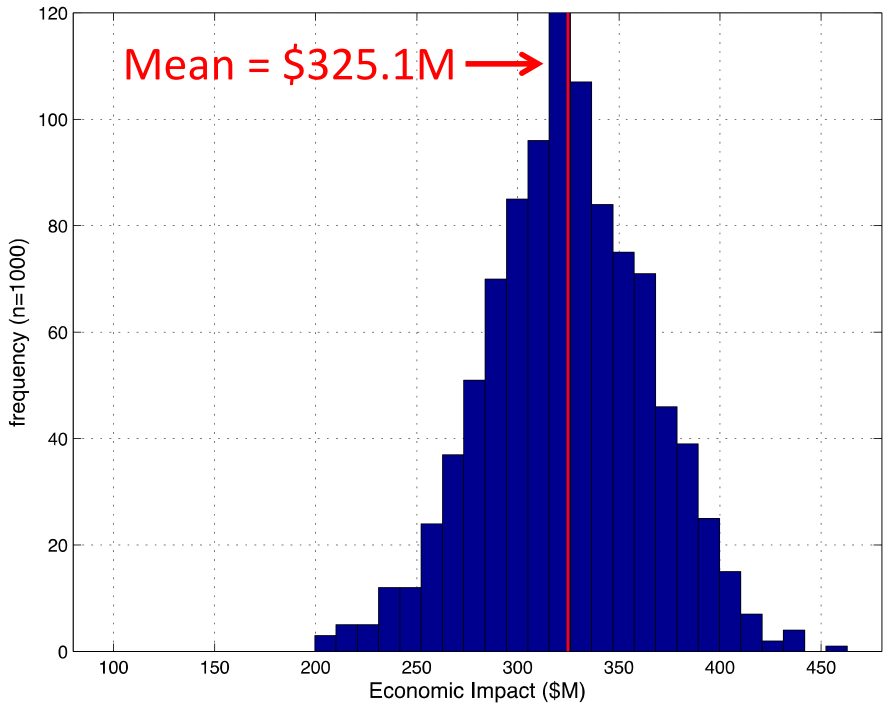


Use Case: Policy Planning/Operations for Increased Resiliency

Evaluate Resilience Improvements

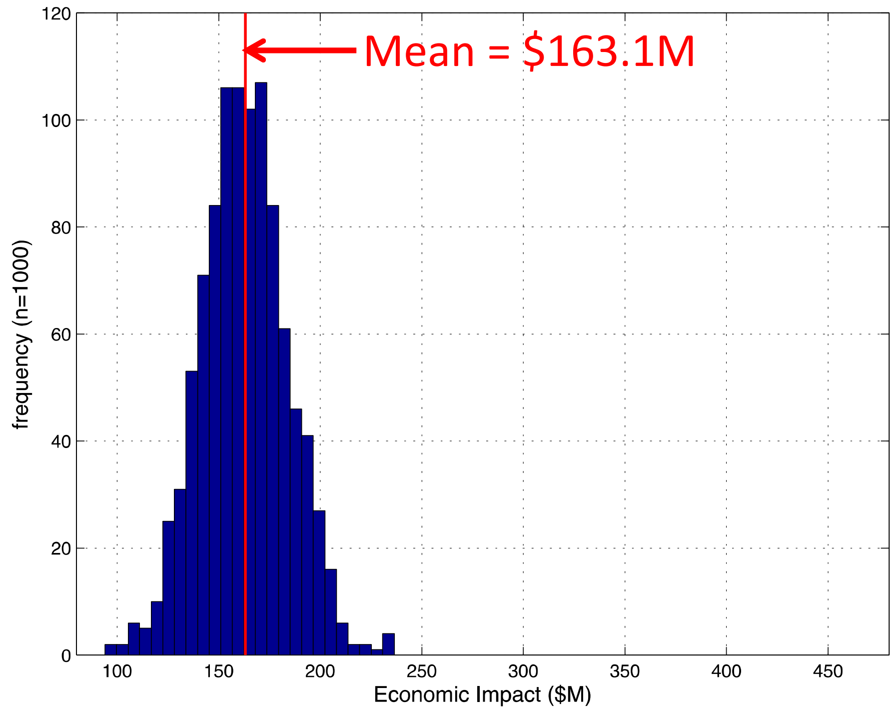
- Measures taken to facilitate unrestricted natural gas outflow from storage

Histogram of Economic Impact for Restricted Withdrawal Rate



VS

Histogram of Economic Impact for Unrestricted Withdrawal Rate



Summary

- Evaluated the resiliency of the Southern California natural gas system to a large San Andreas Fault earthquake
- Compared resilience of system with historical storage withdrawals to one of increased storage withdrawals
- There is uncertainty over how gas in storage might actually be used in an emergency
  - In this example, facilitating its use has a major impact on resiliency and involves no infrastructure changes

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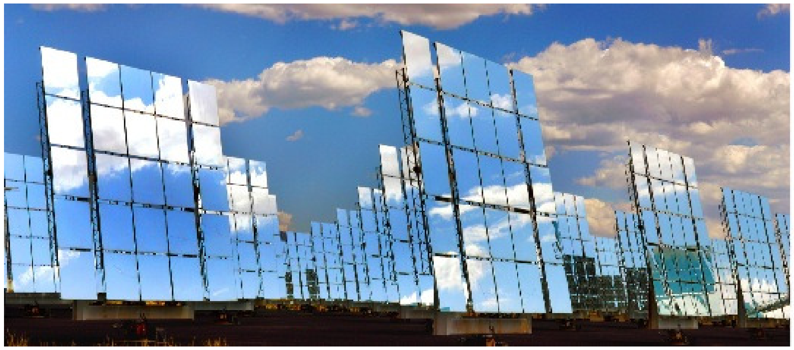
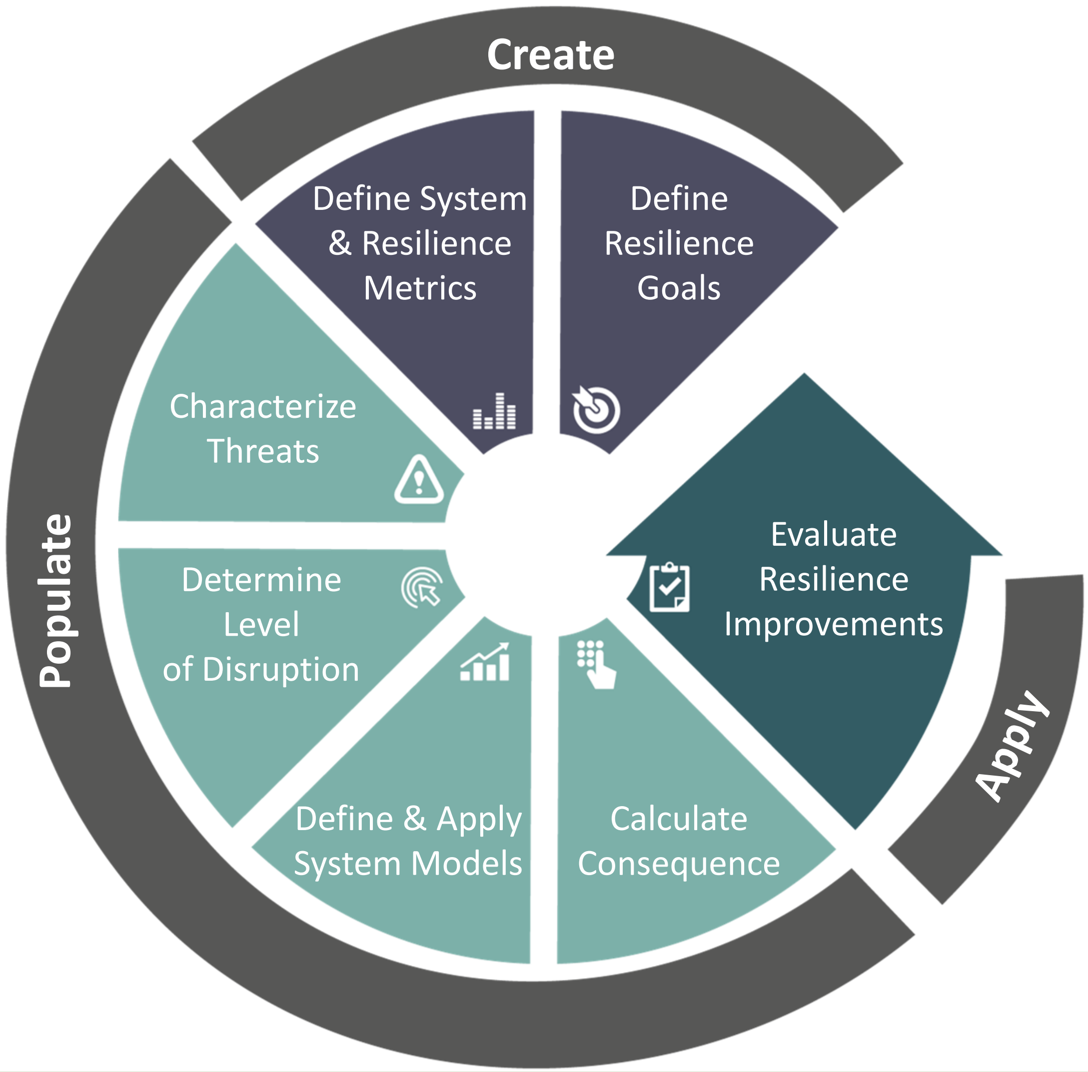


Framing a Resilience Roadmap

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Resilience Analysis – Recap



Breakouts: What We Need From You

- Topics
  - Defining end user needs for resilience metrics (Leader: Joe Eto)
  - Establishing R&D Priorities (Leader: Chen-Ching Liu)
  - Facilitating industry adoption (Leader: Gerald Stokes)
  - Promoting Standard Methods (Leader: Craig Miller)
  - Defining the role of government and utilities in enhancing resilience (Leader:)
- Bring Back
  - Challenges, Opportunities, Proposed Actions

Bring Back…

- Challenges
- Opportunities
- Proposed Actions

Takeaway Points

- R&D is needed to address this critical national problem
- Metrics are needed to enable resilience goals and decisions for our US national strategy
- The proposed framework applies common principles across energy sectors
- We’re looking forward to your help!