Designing Resilient Electrical Distribution Grids—R&D Challenges

Scott Backhaus

Los Alamos National Laboratory

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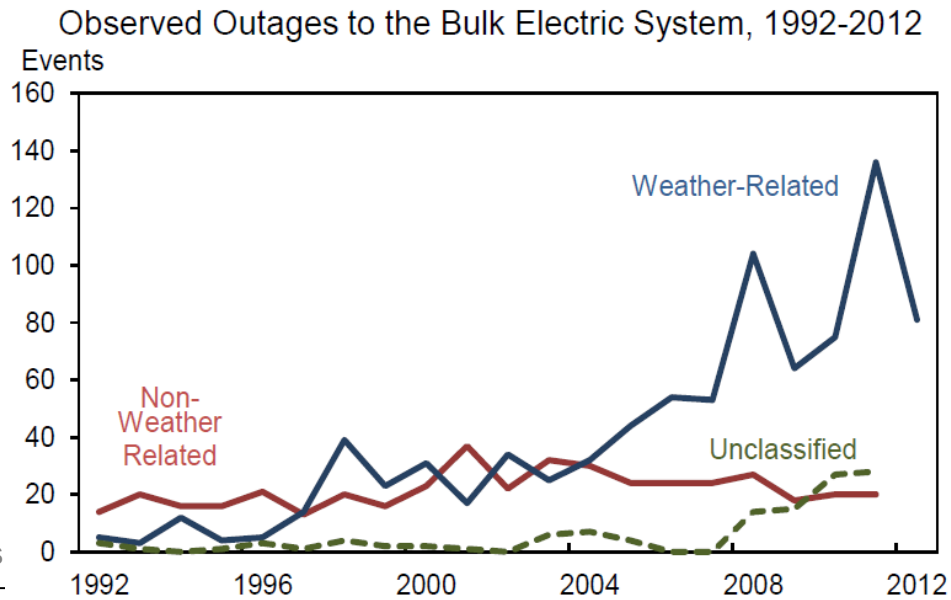
Electrical Grid Outage Statistics

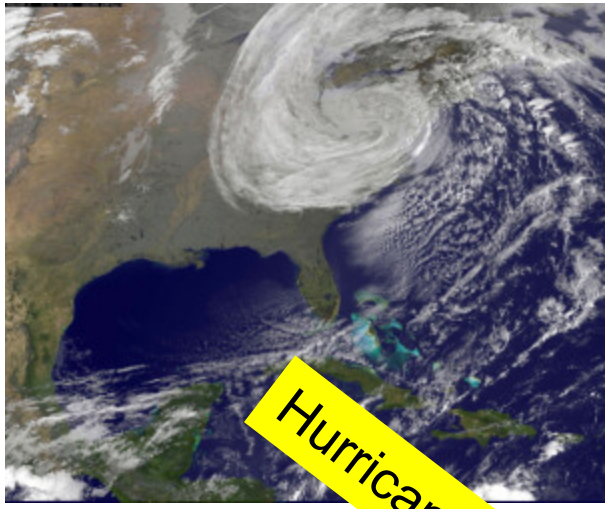
- Severe weather is the single leading cause of power outages in the United States.
- Outages caused by severe weather such as thunderstorms, hurricanes and blizzards account for
- 58 percent of outages observed since 2002 and
- 87 percent of outages affecting 50,000 or more customers
- The incidence of both major power outages and severe weather is increasing.

ECONOMIC BENEFITS OF INCREASING ELECTRIC GRID RESILIENCE TO WEATHER OUTAGES. Executive Office of the President , August 2013



Source: Energy Information Administration

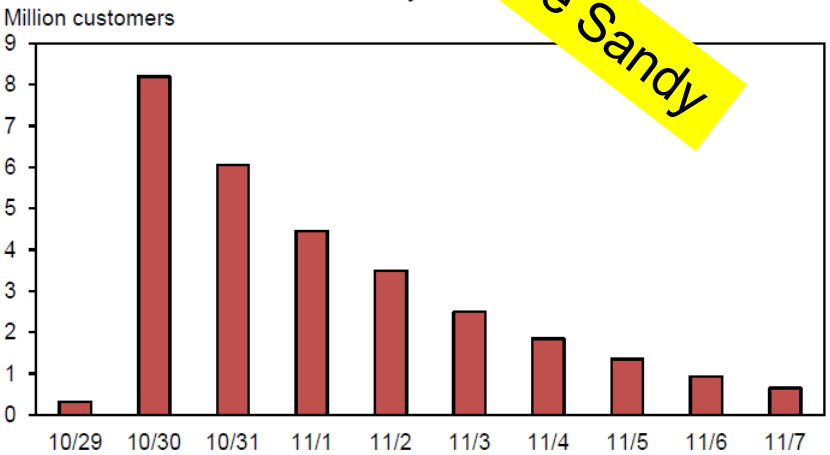
“Typical” Electrical Grid Outages From Extreme Weather



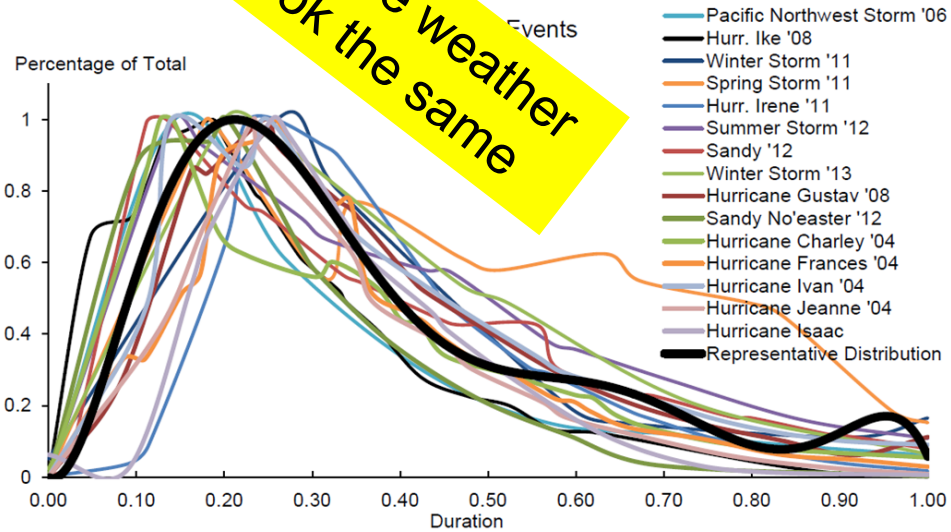
Hurricane Sandy

Most extreme weather events look the same

Hurricane Sandy Pow



Source: Department of Energy



Source: Department of Energy, Office of Electrcity Delivery and Energy Reliability

ECONOMIC BENEFITS OF INCREASING ELECTRIC GRID RESILIENCE TO WEATHER OUTAGES. Executive Office of the President , August 2013

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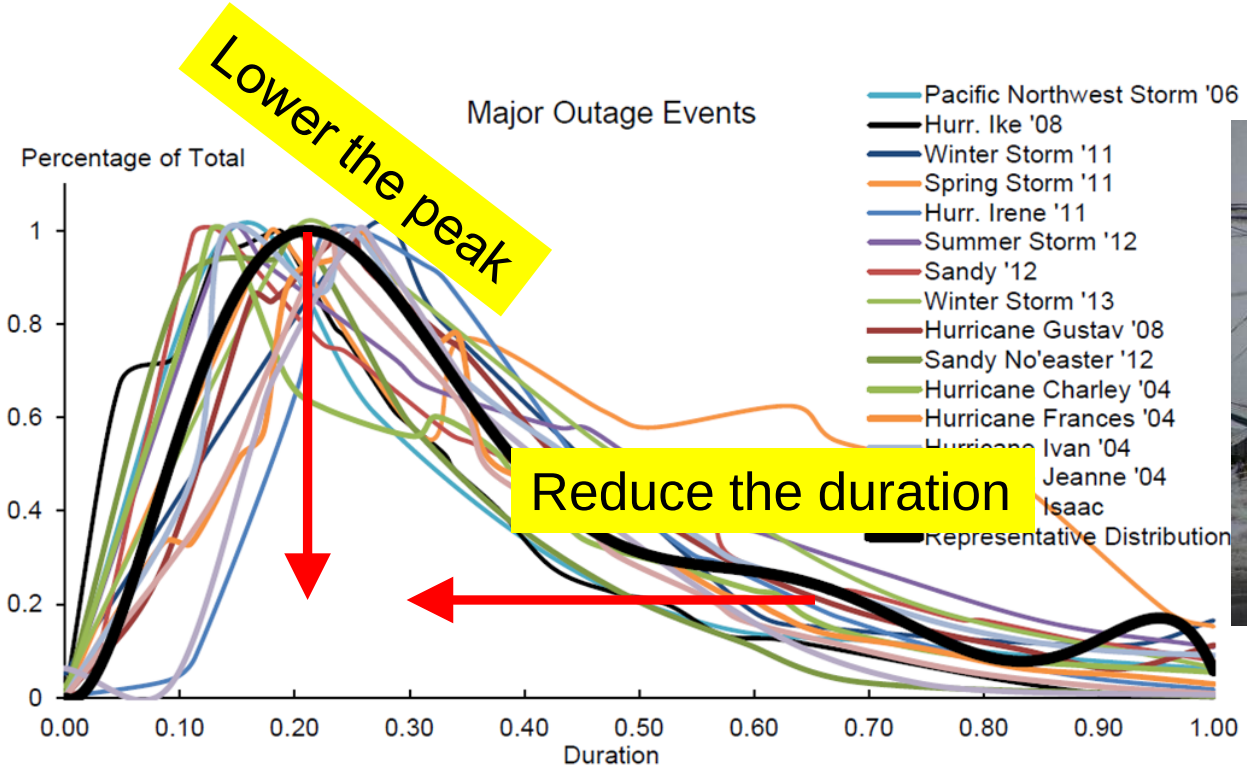
Properties of a Resilient Distribution Grid (or any other infrastructure)

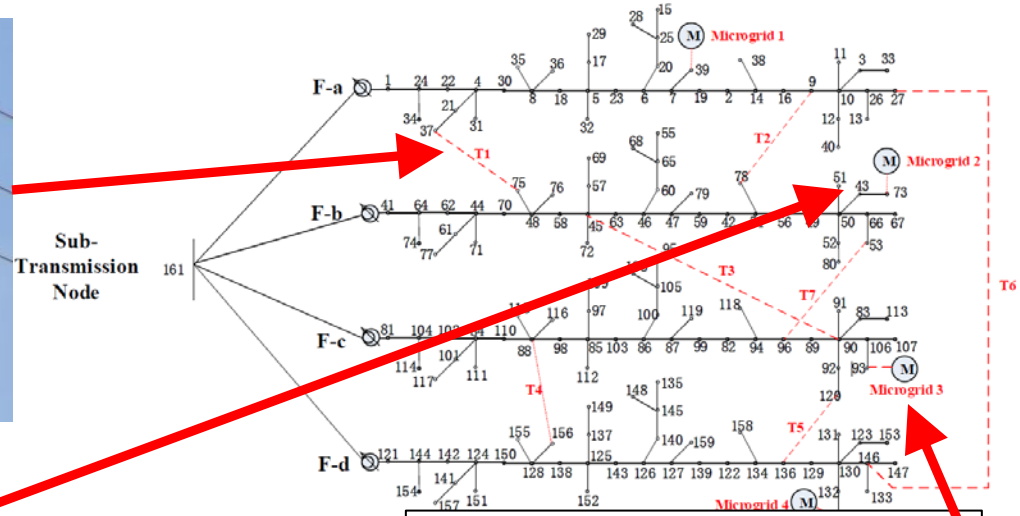
Presidential Policy Directive 21 - Critical Infrastructure Security and Resilience

*"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."*



Source: Department of Energy, Office of Electrcity Delivery and Energy Reliability

Activities/Processes Before and During an Outage
Grid Operations—Withstand



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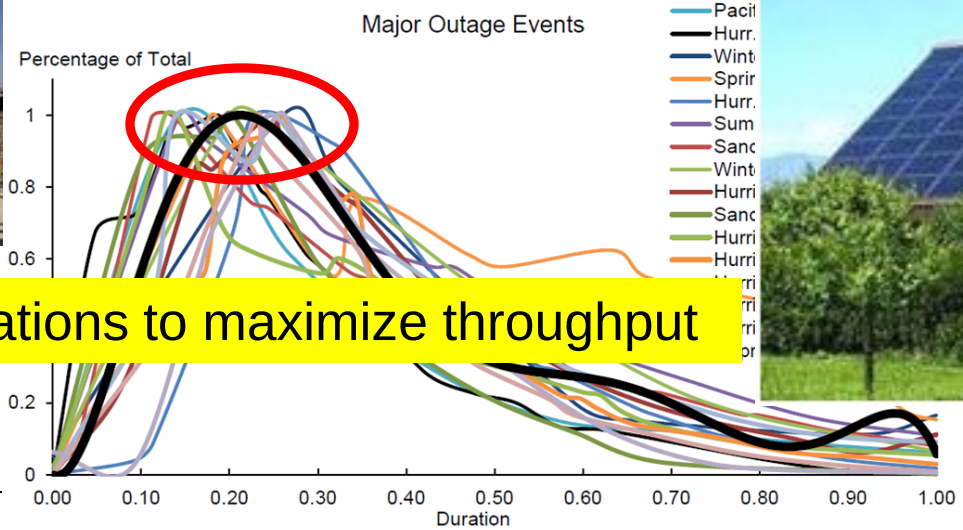
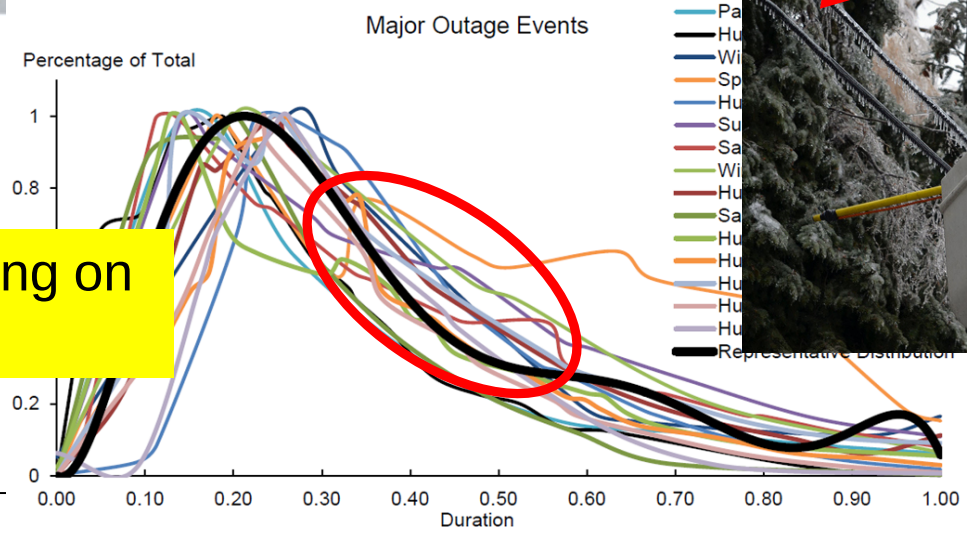


Network operations to maximize throughput

Source: Department of Energy, Office of Electrcity Delivery and Energy Reliability

Activities/Processes Before and During an Outage
Crew Routing and Restoration—Recover

Restoration dependent on:
- Spares location
- Transportation network

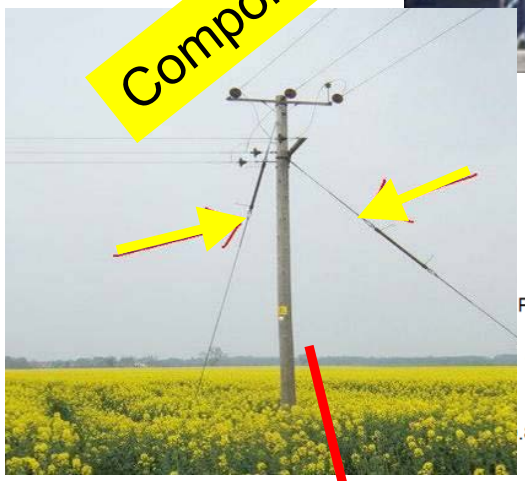


Source: Department of Energy, Office of Electrcity Delivery and Energy Reliability

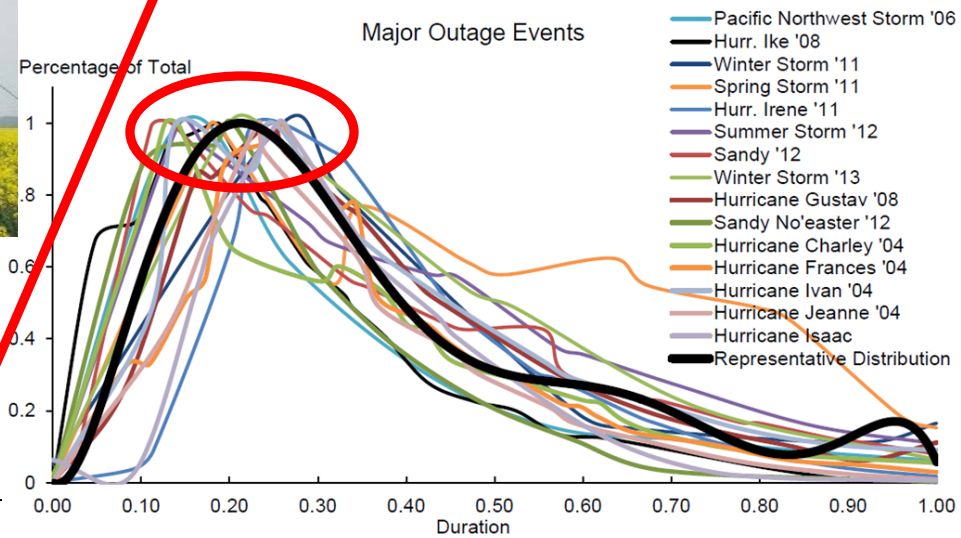
Scheduling and routing on multiple networks

Activities/Processes Before and During an Outage
Designing Component Hardening—Prepare

Component hardening

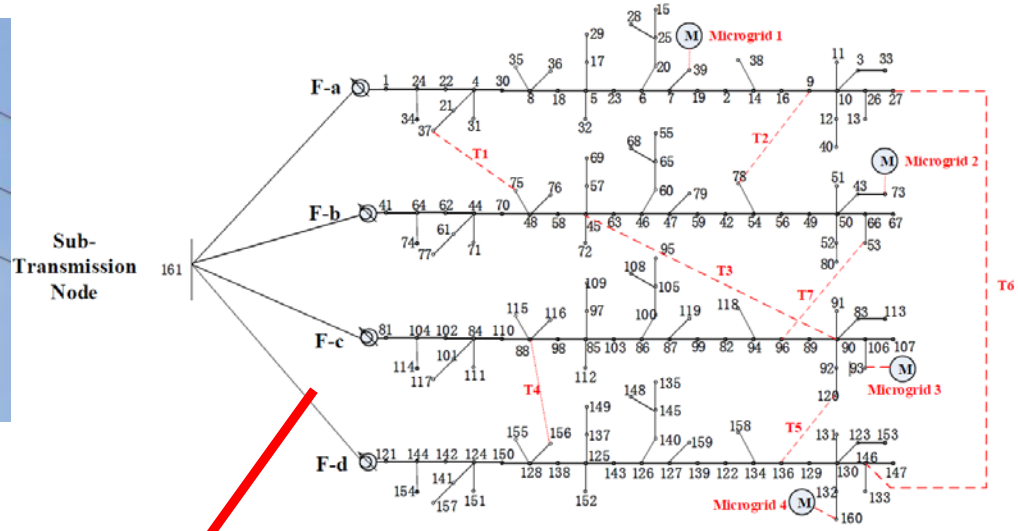


Robust/Stochastic network design and optimization



Source: Department of Energy, Office of Electrcity Delivery and Energy Reliability

Activities/Processes Before and During an Outage
Designing For Operational Flexibility—Prepare



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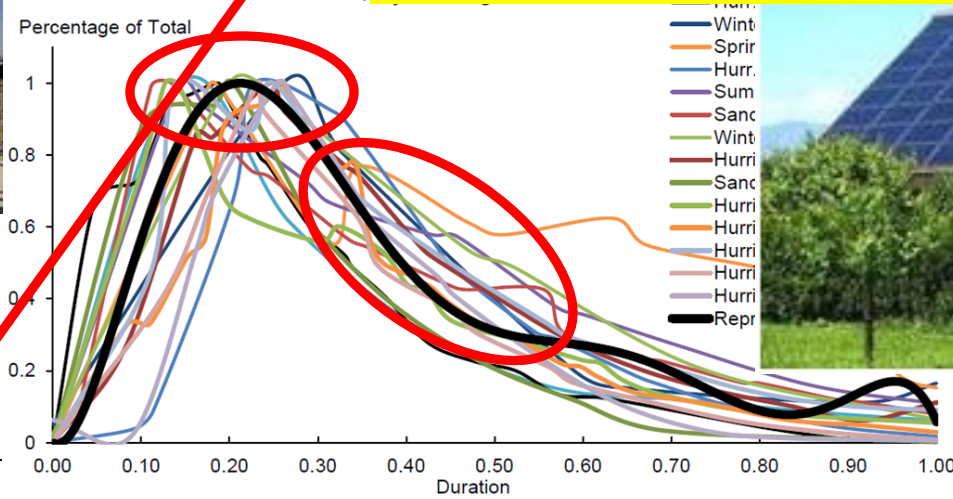
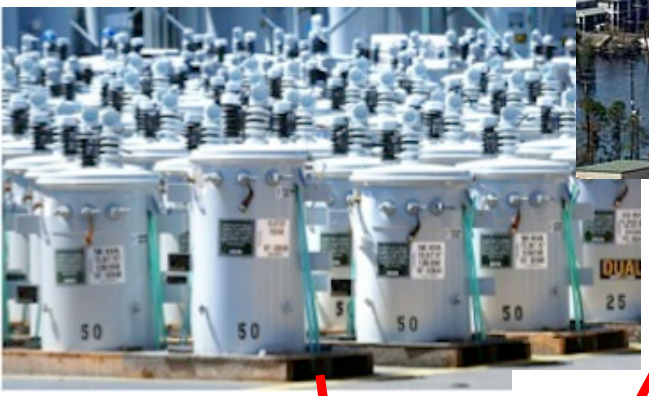
Operations-based planning on networks

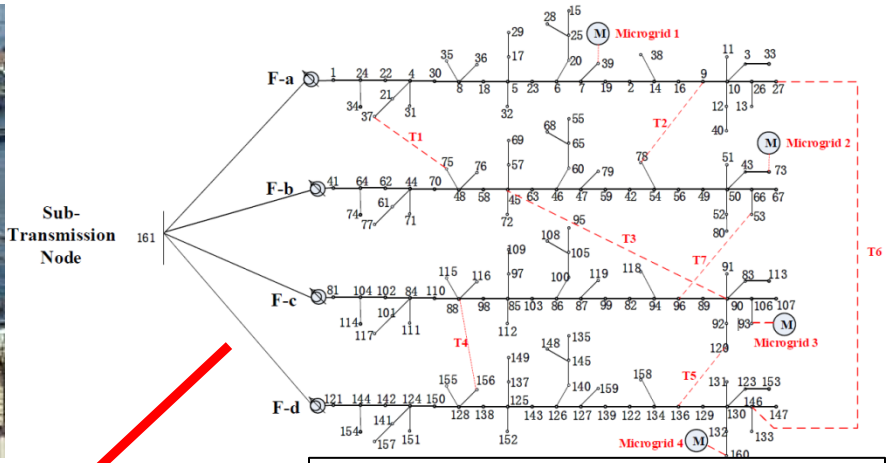


Source: Department of Energy, Office of Electrcity Delivery and Energy Reliability

Activities/Processes Before and During an Outage
Designing For Restoration—Prepare

Optimizing inventory and warehousing of spares on multiple networks





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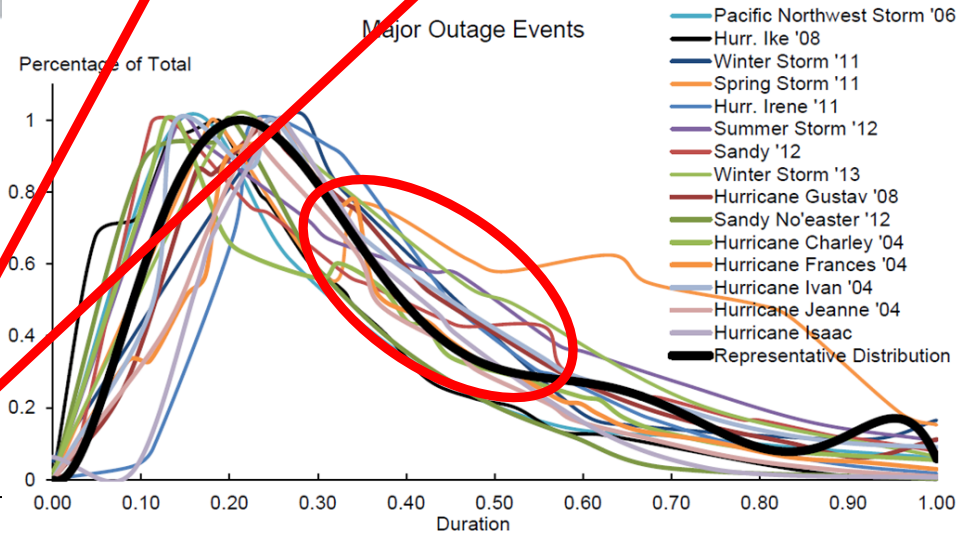
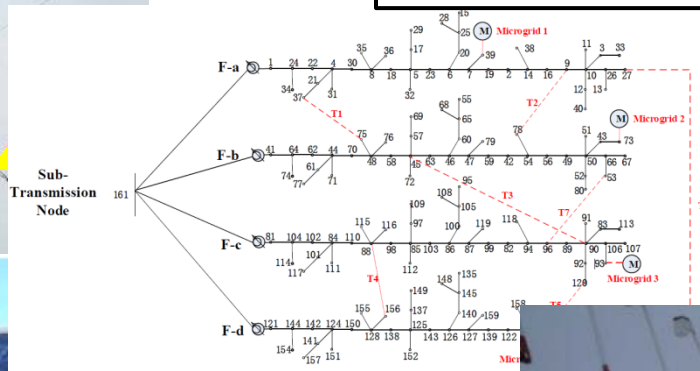


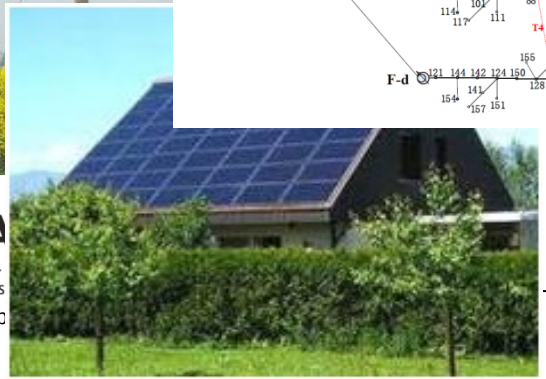
Source: Department of Energy, Office of Electrcity Delivery and Energy Reliability

Activities/Processes Before and During an Outage "Summary"

Prepare

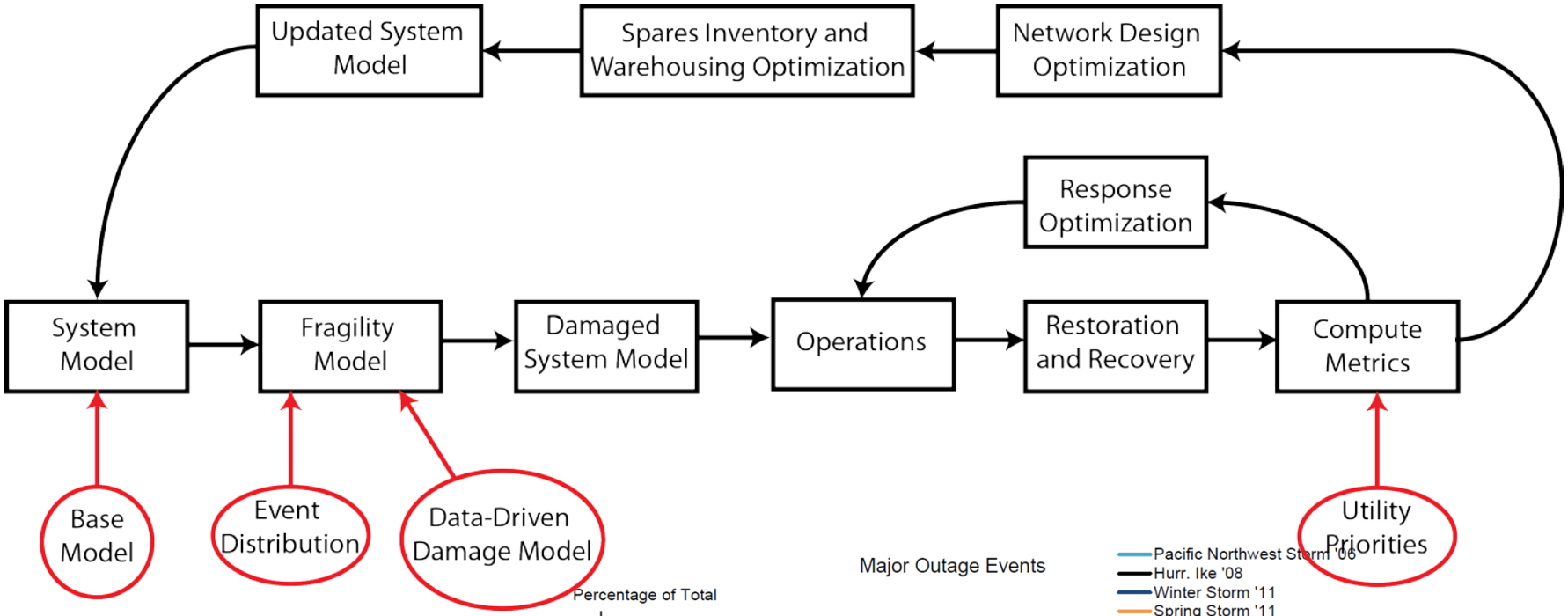
Withstand

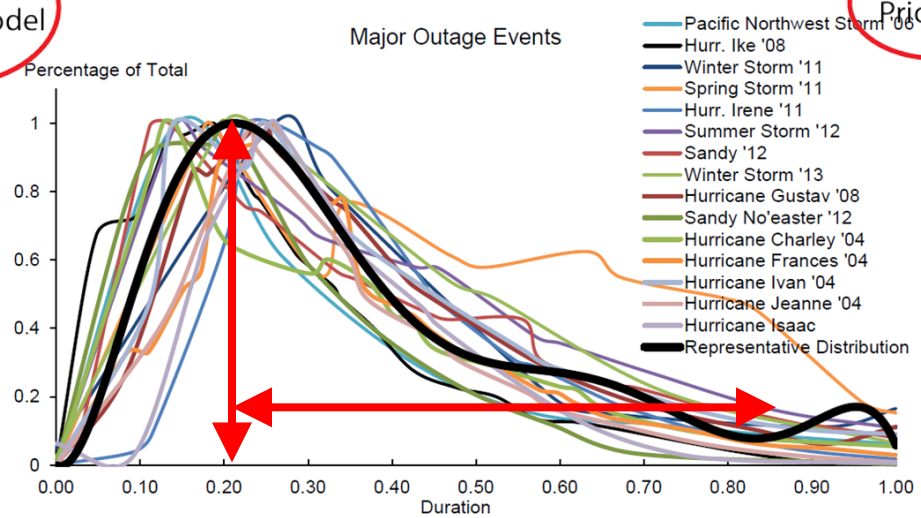




Recover

Resilience Design Process Flow





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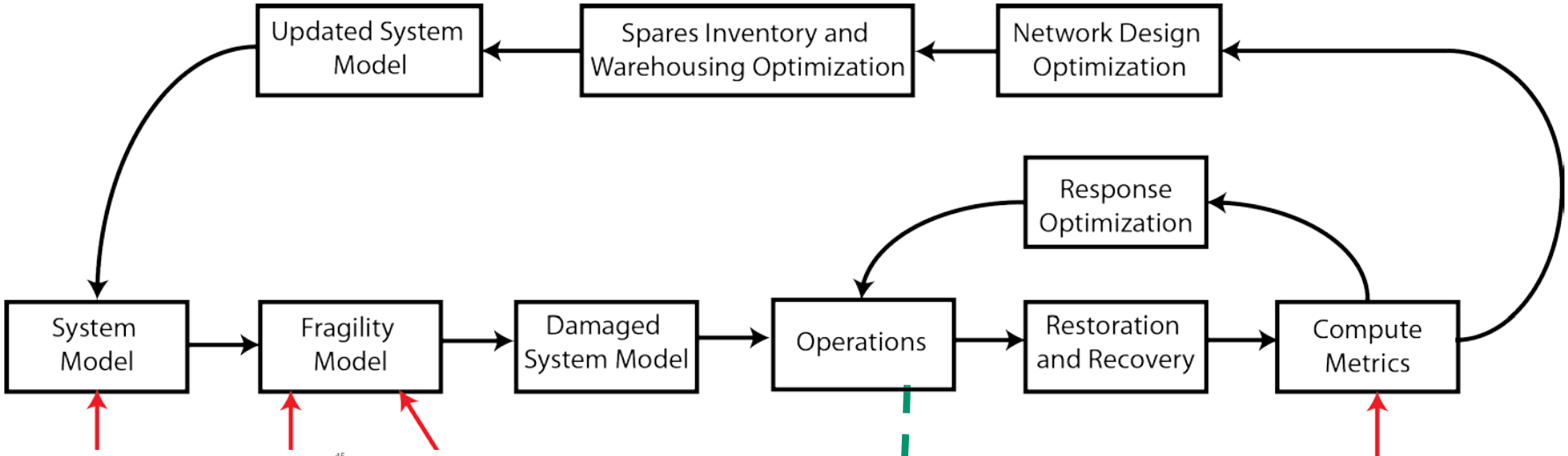
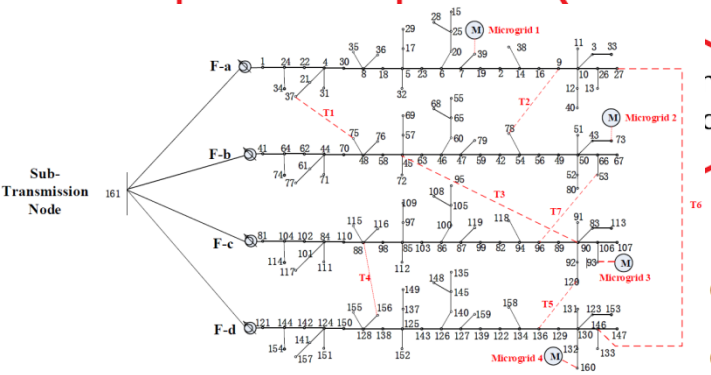
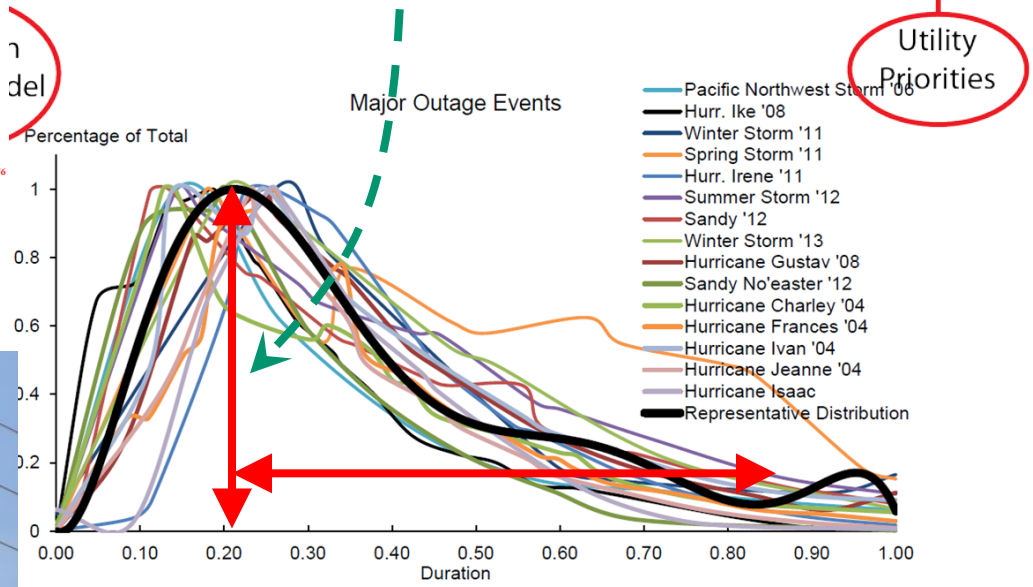
Resilience Design—Process Flow Organization







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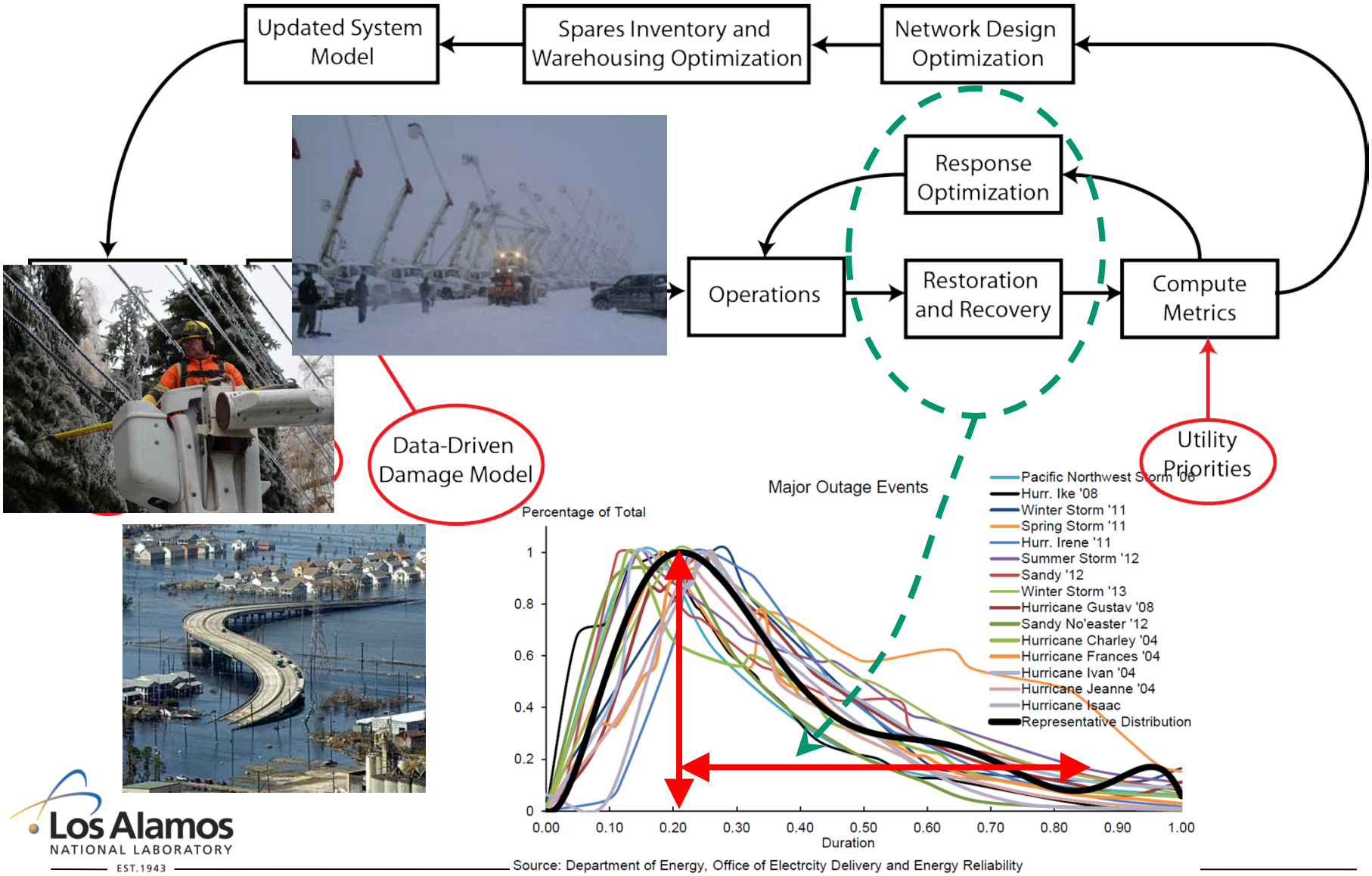

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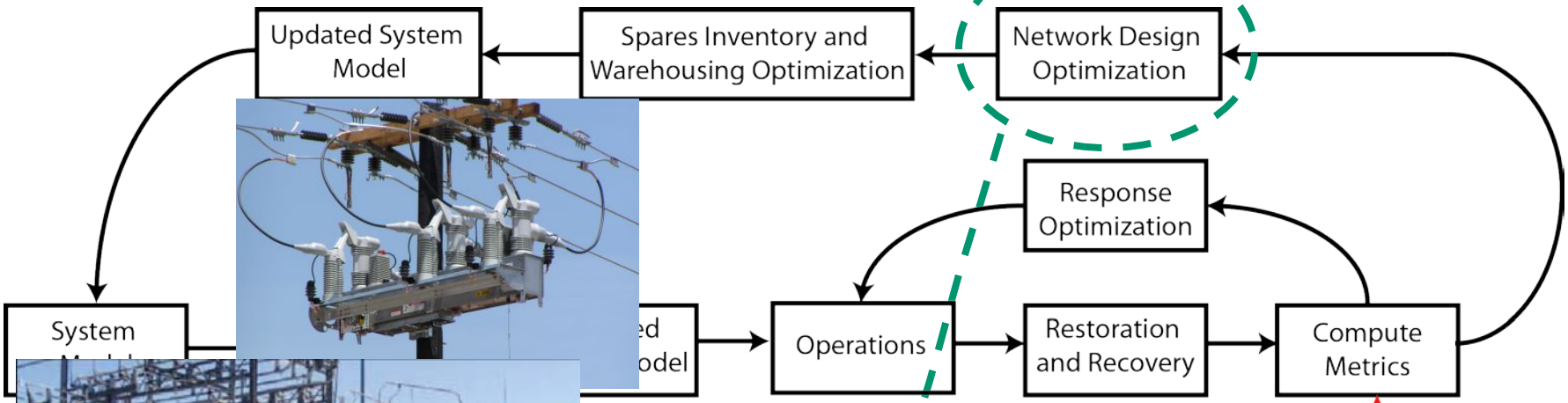

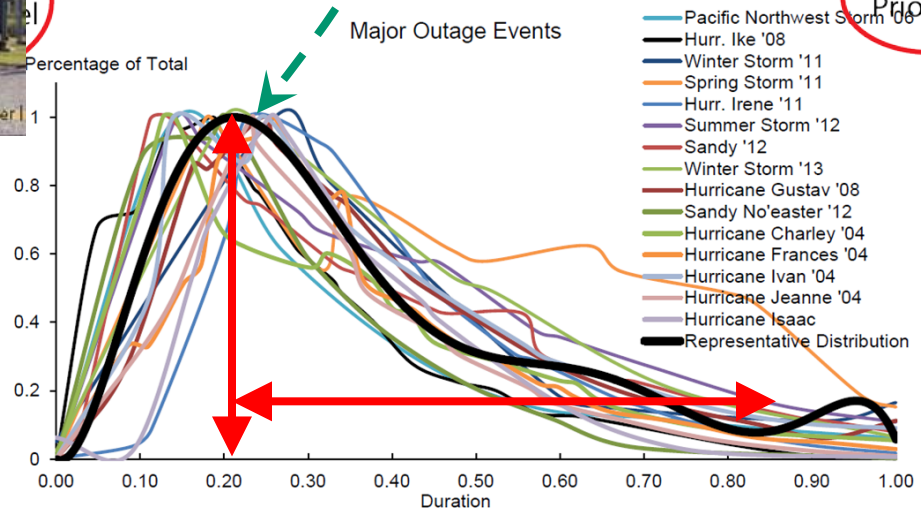

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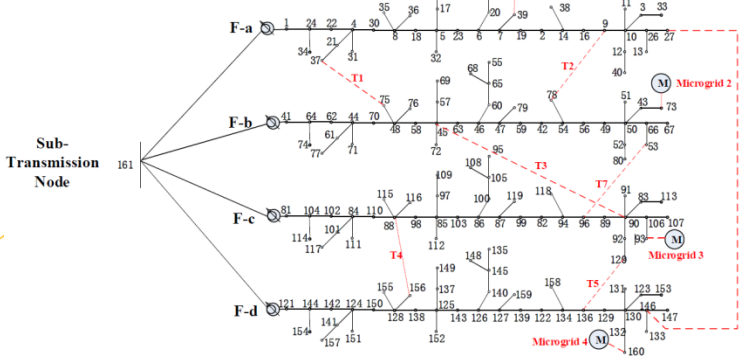

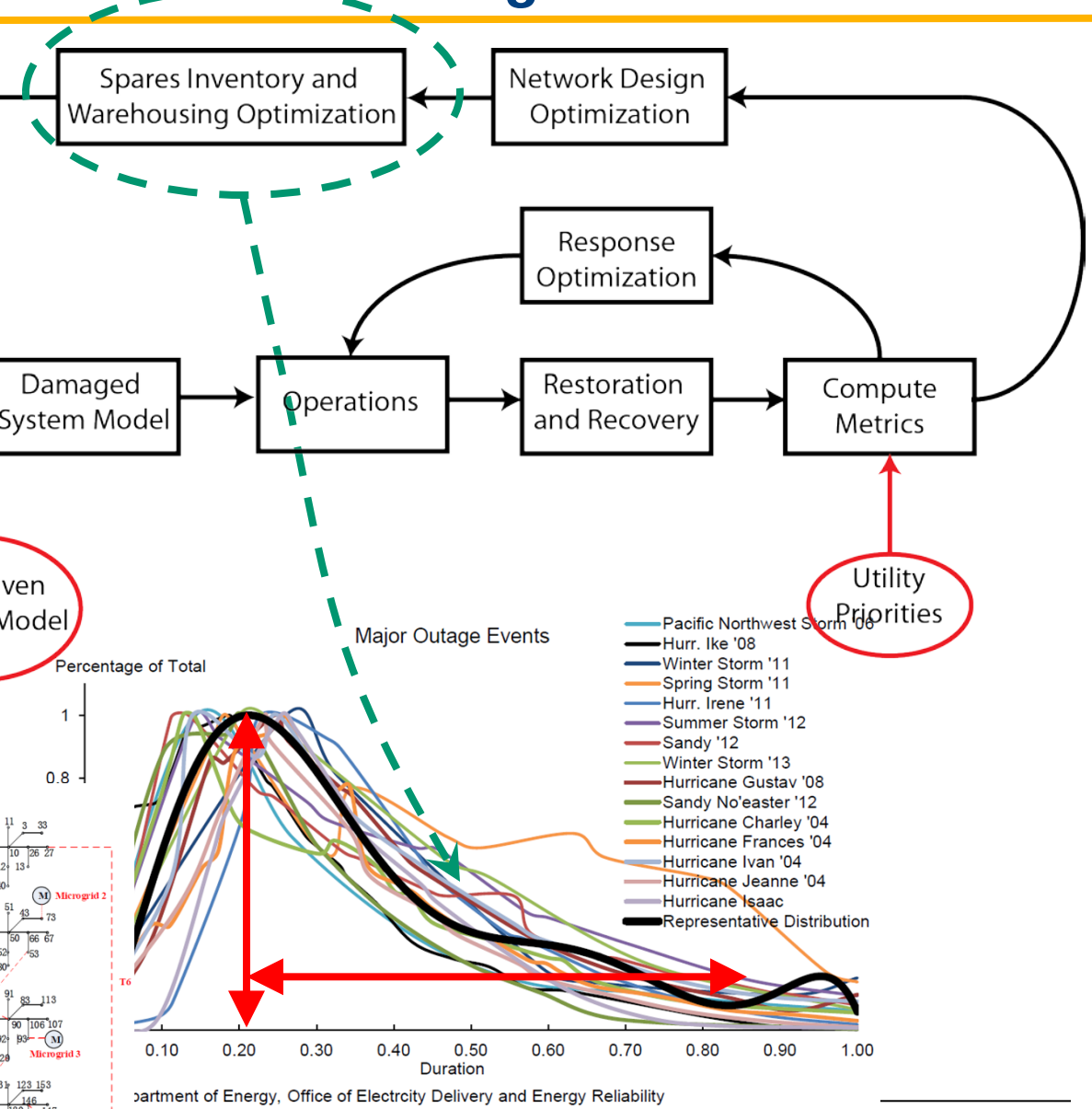

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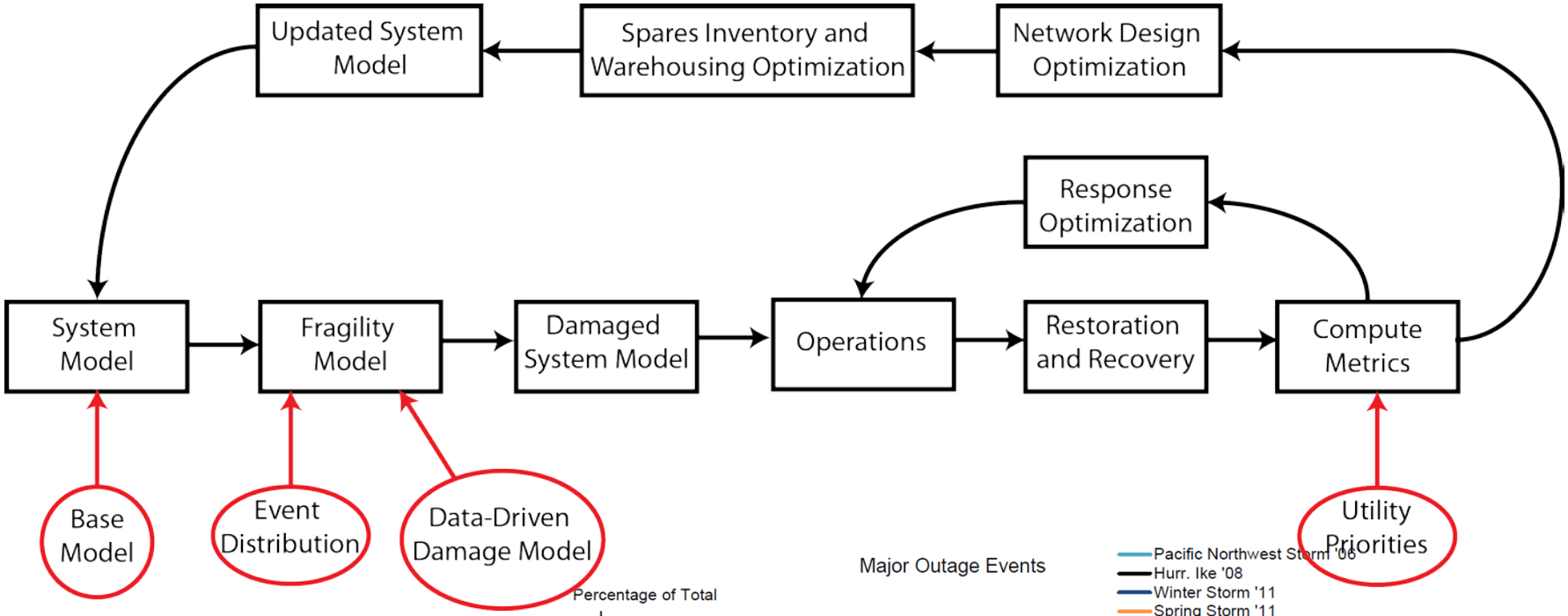

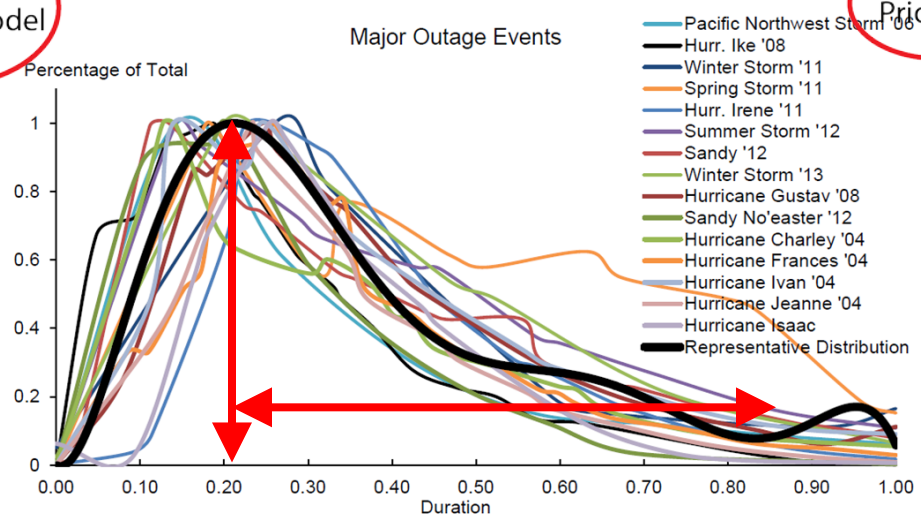

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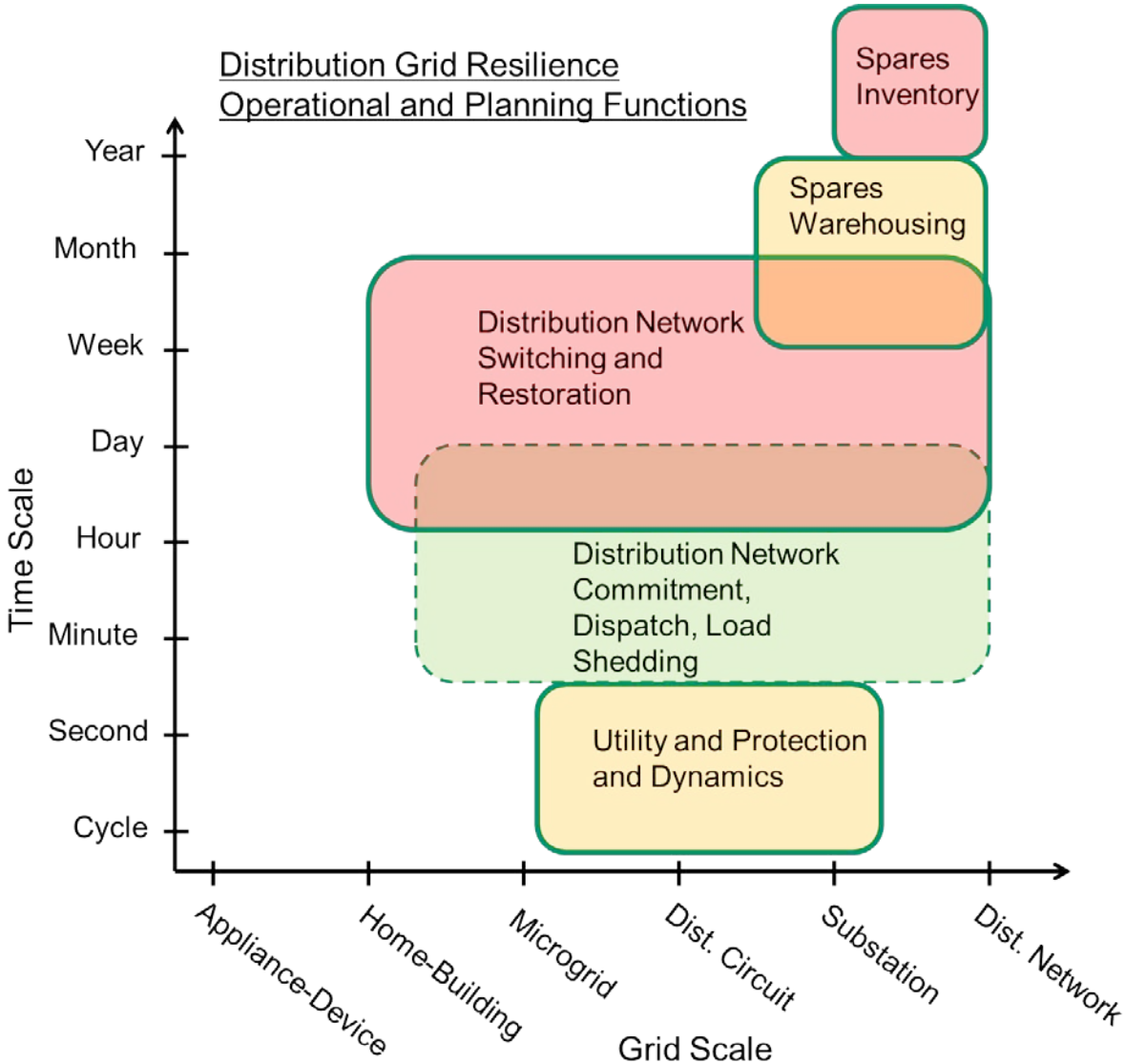
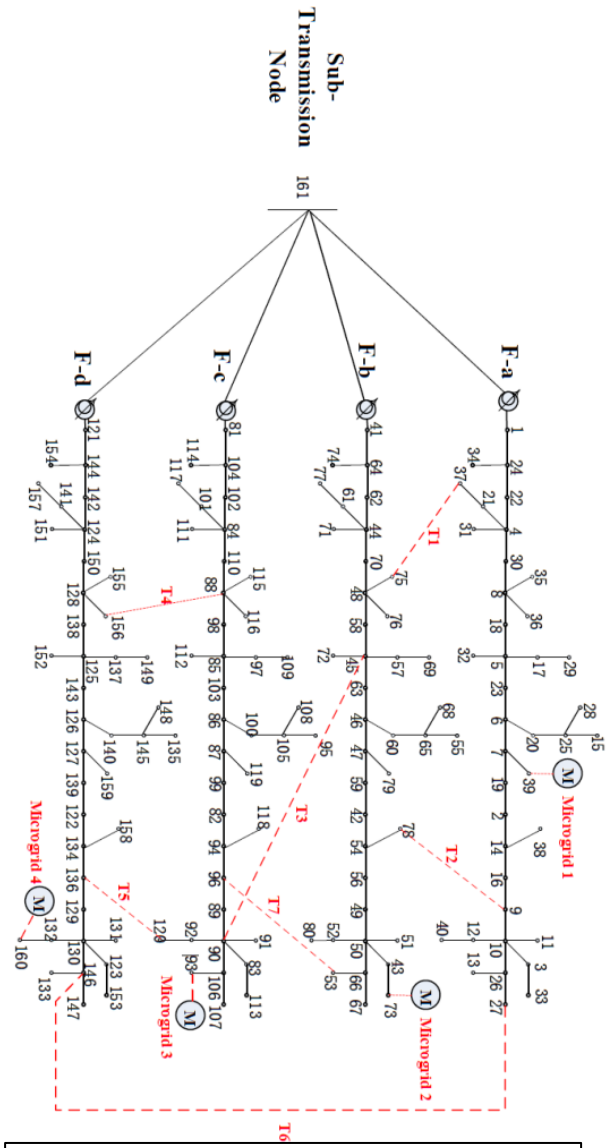
Resilience Design—Interfaces—Spatiotemporal Organization





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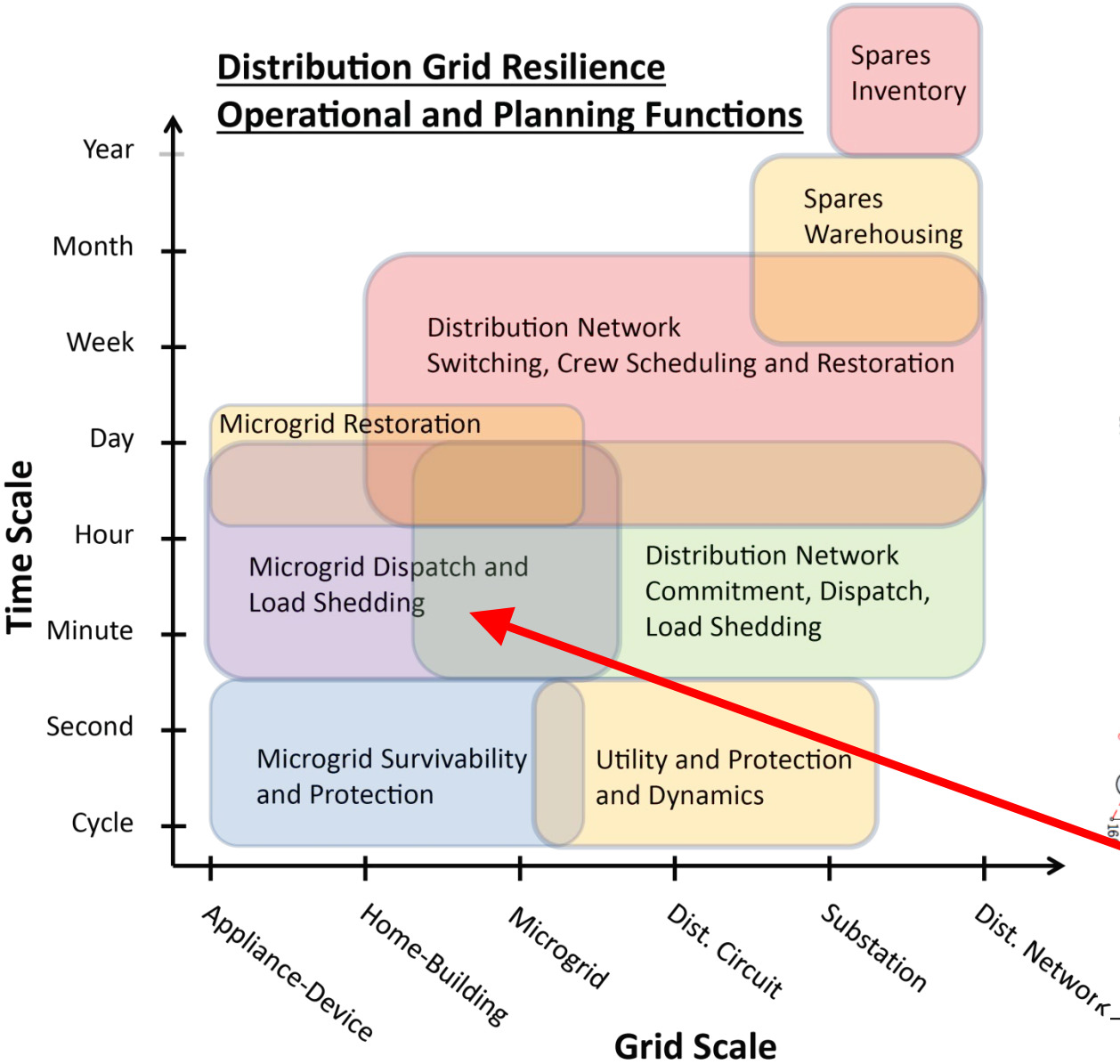
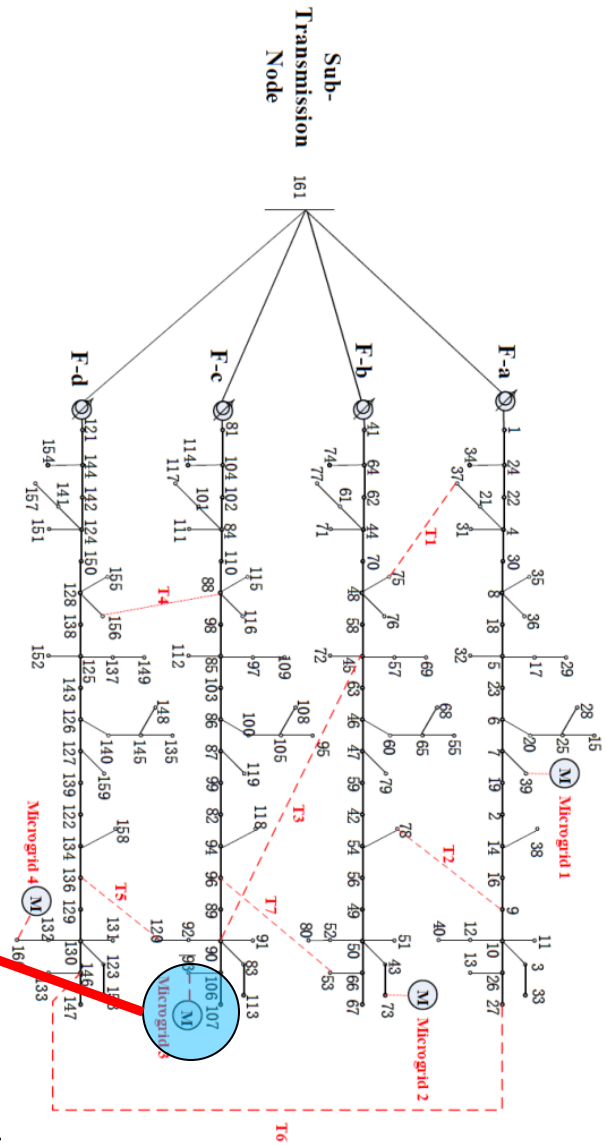
Resilience Design—Interfaces—Spatiotemporal Organization





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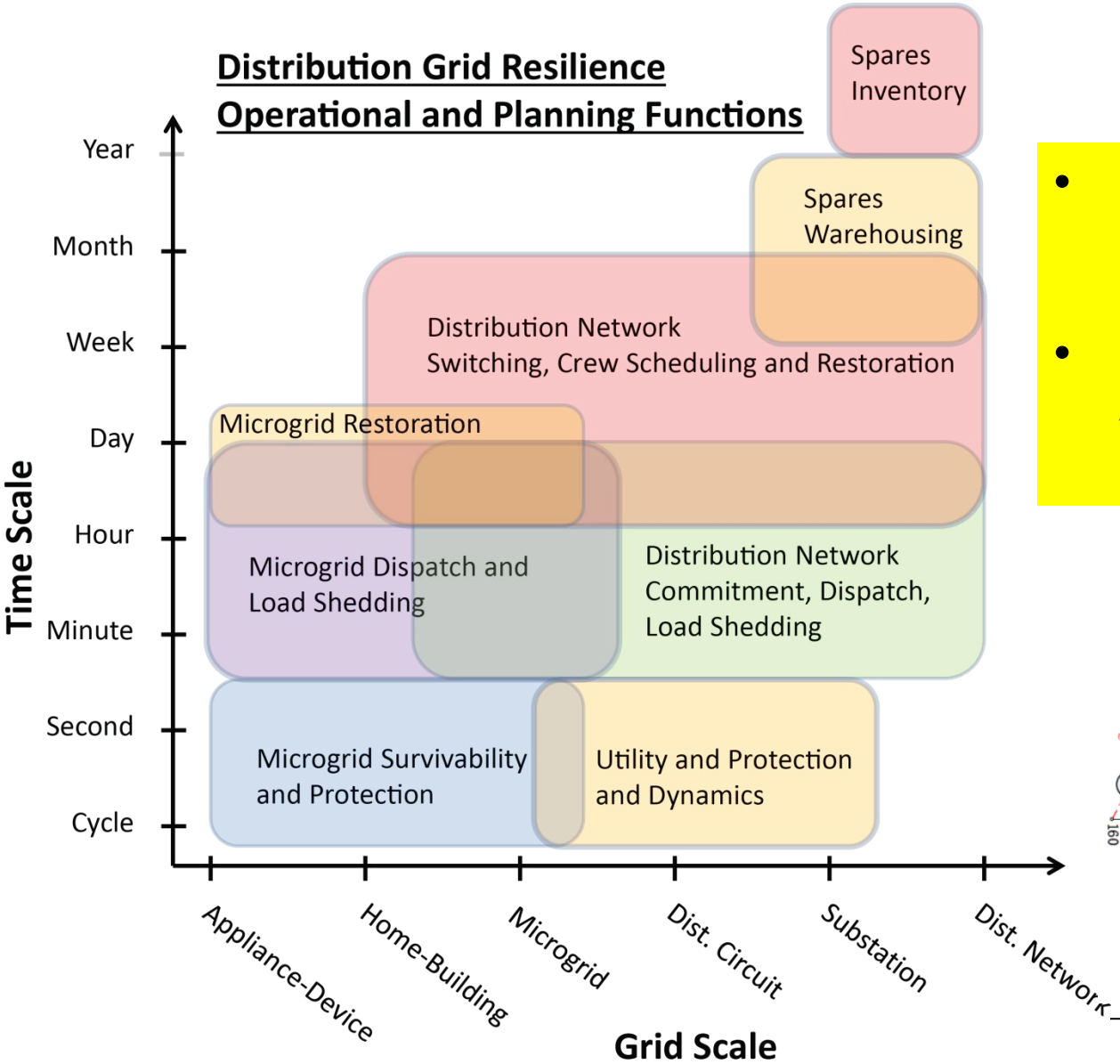
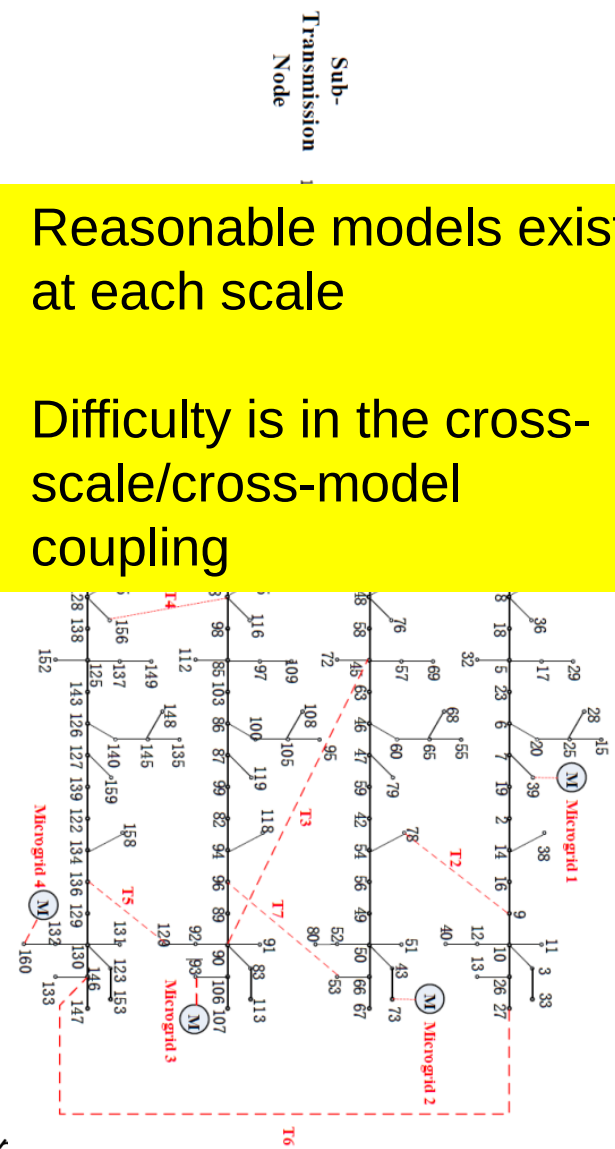
Resilience Design—Interfaces—Spatiotemporal Organization





- Reasonable models exist at each scale
- Difficulty is in the cross-scale/cross-model coupling

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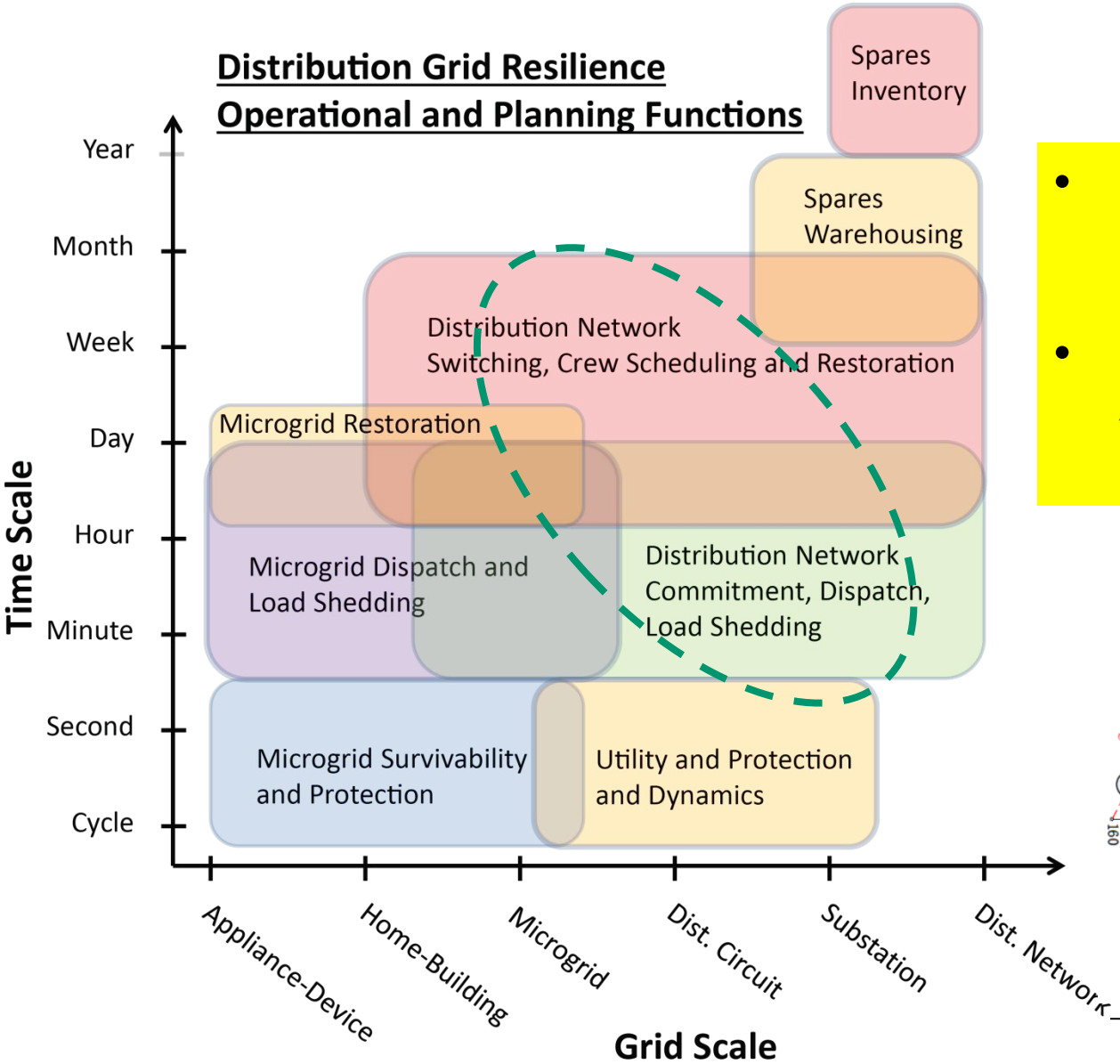
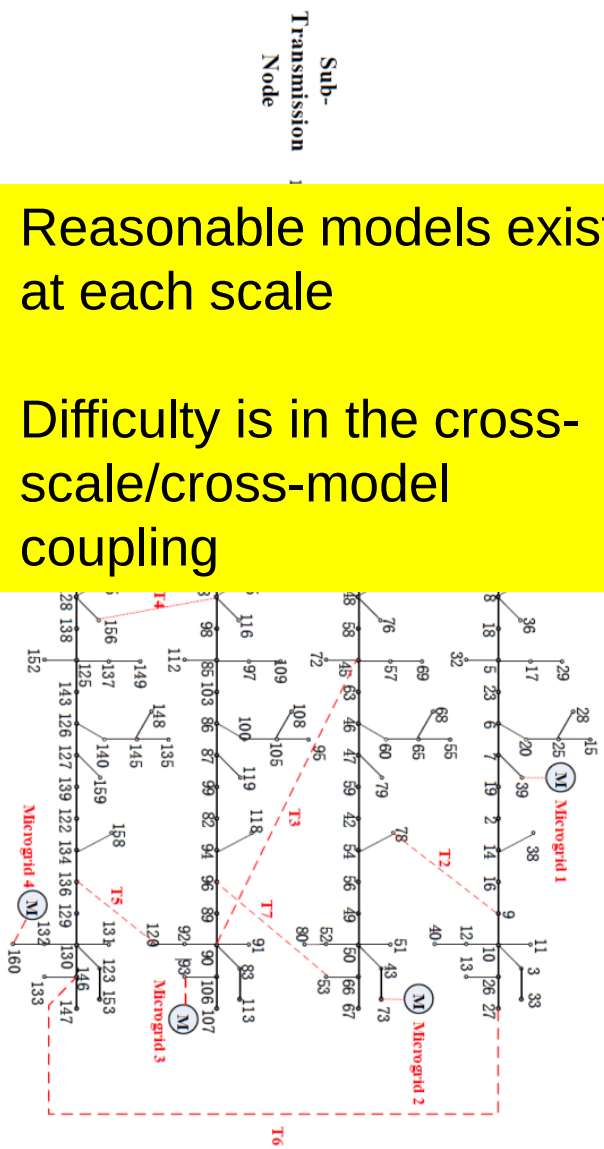
Resilience Design—Example of Cross Scale-Integration





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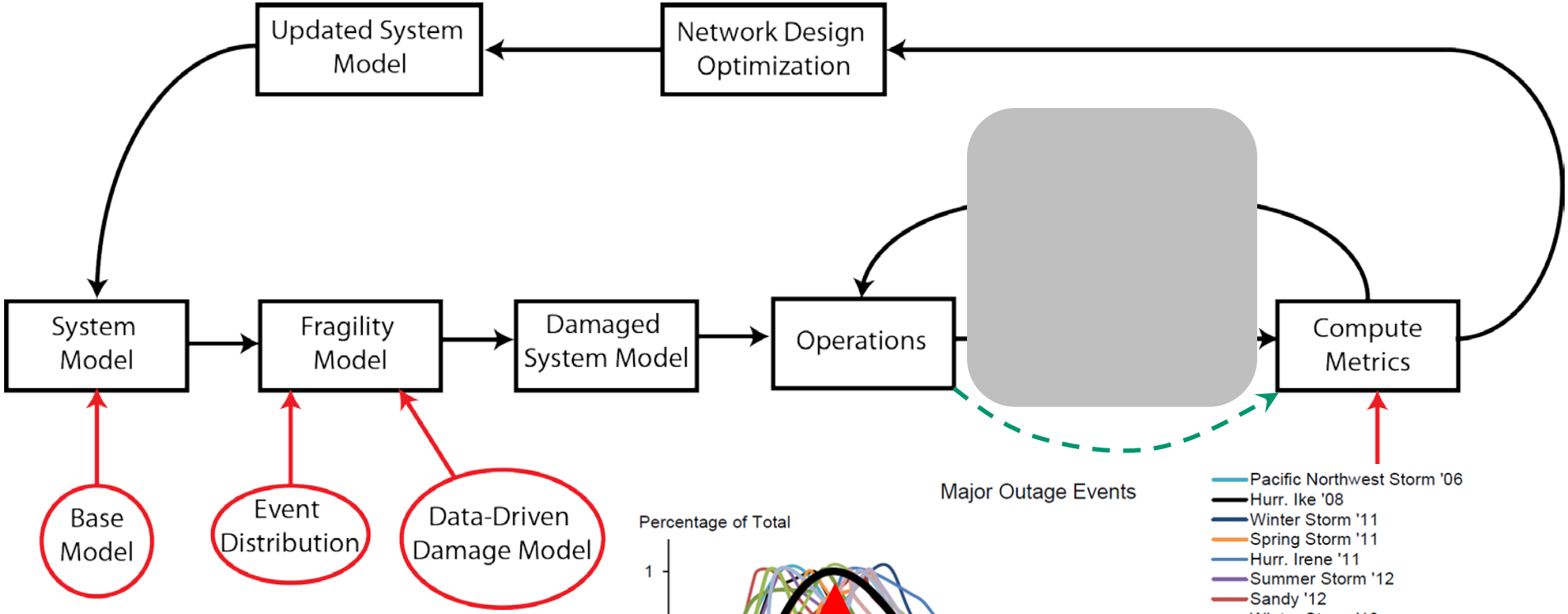
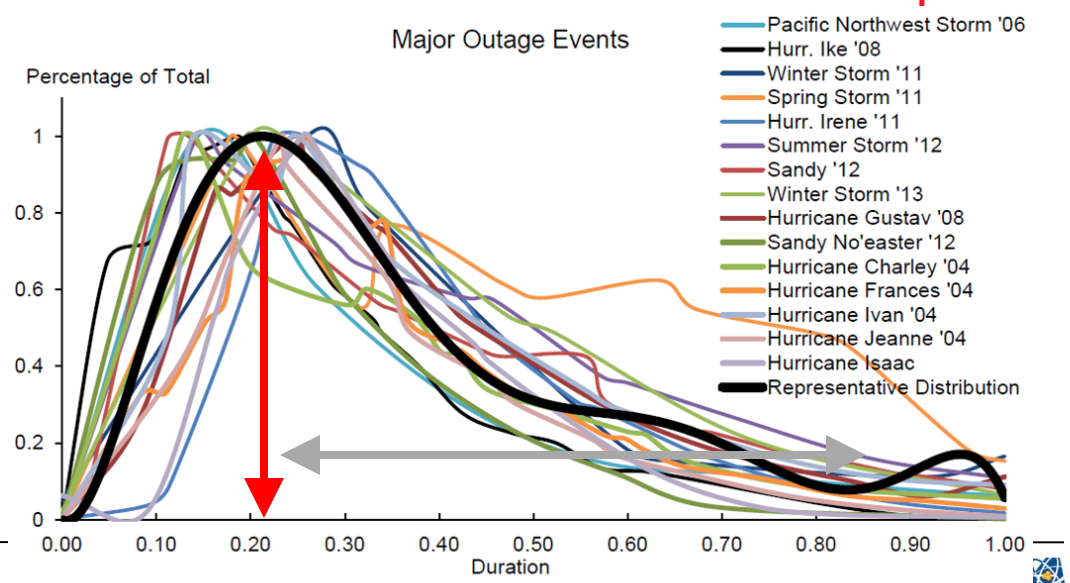
Resilience Design—Example



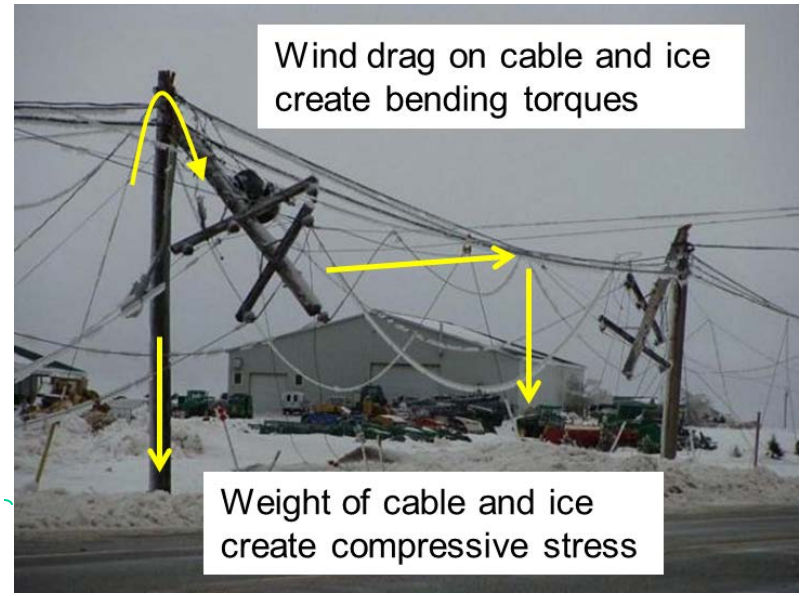


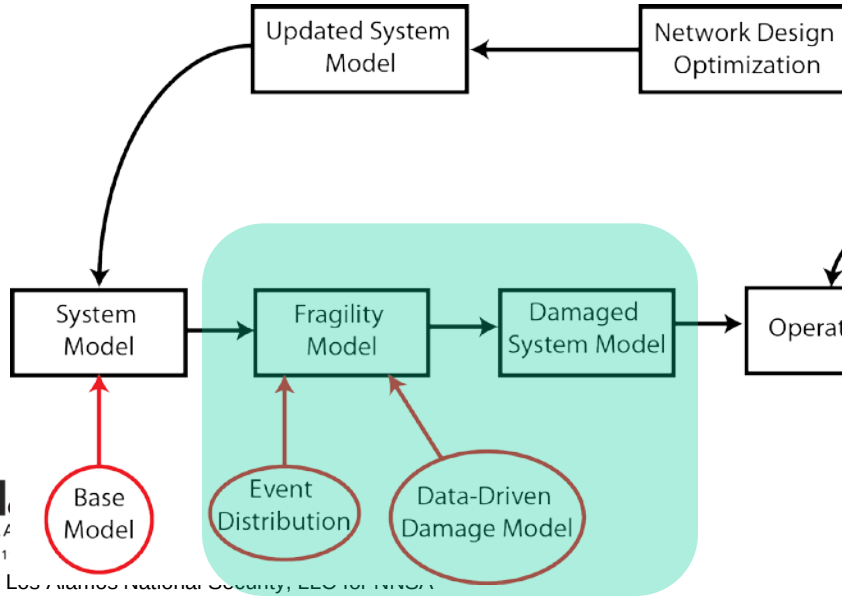
Source: Department of Energy, Office of Electrcity Delivery and Energy Reliability

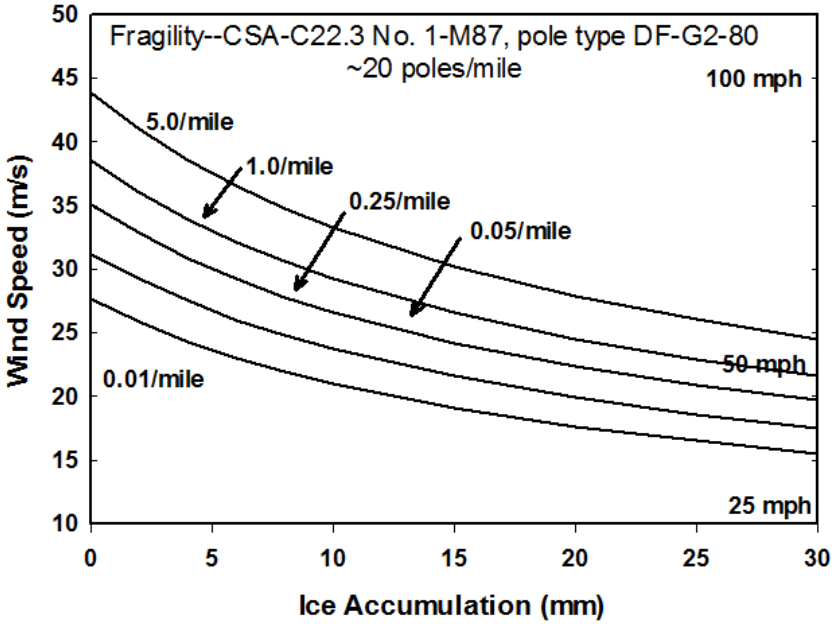
Resilience Design—Example

Flexibility for the user

- *User's base network model*
- *User-defined resilience metrics, e.g. critical load service*
- *User suggests upgrades*
- *User-defined costs and constraints*
- *User-defined threat and scenarios*



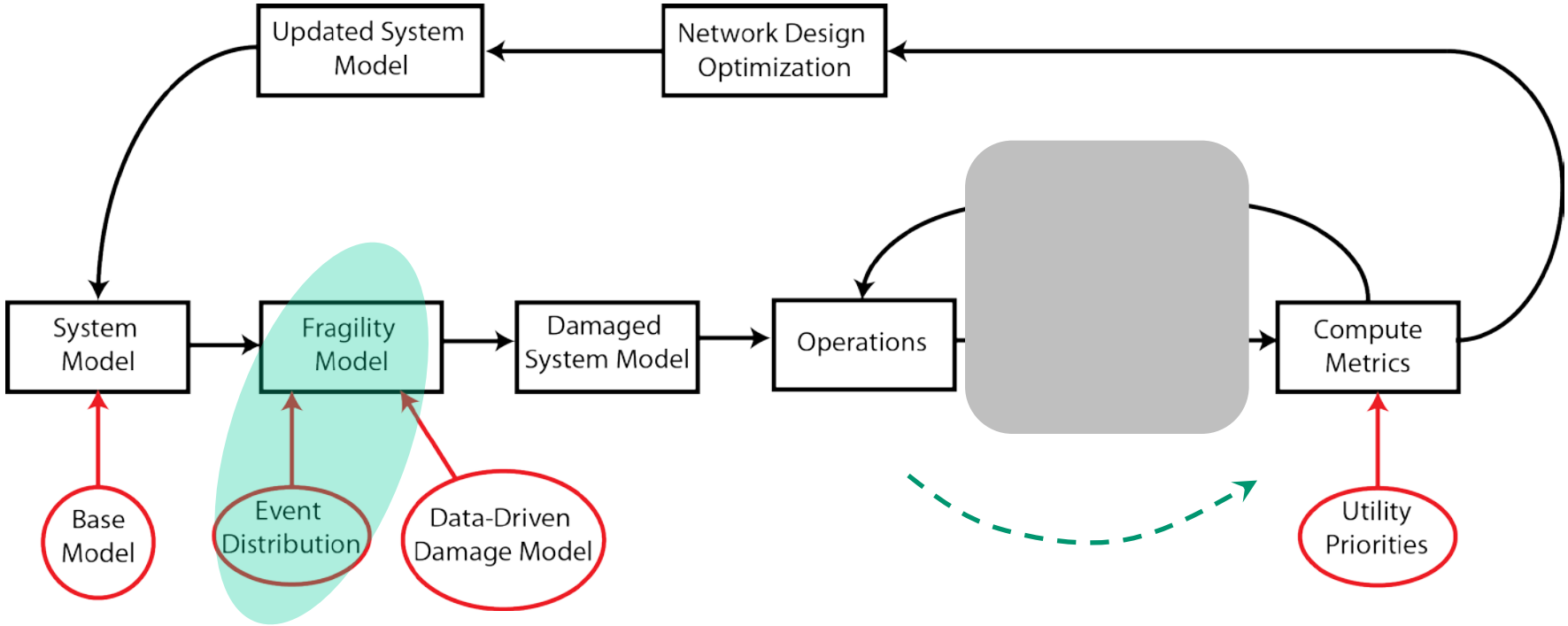


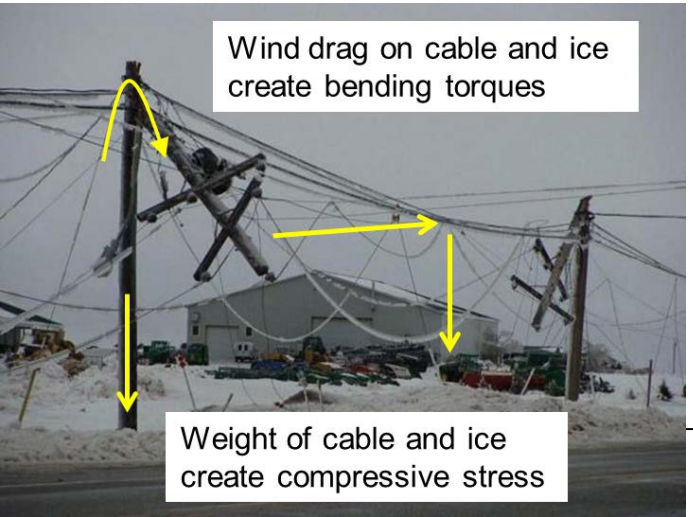


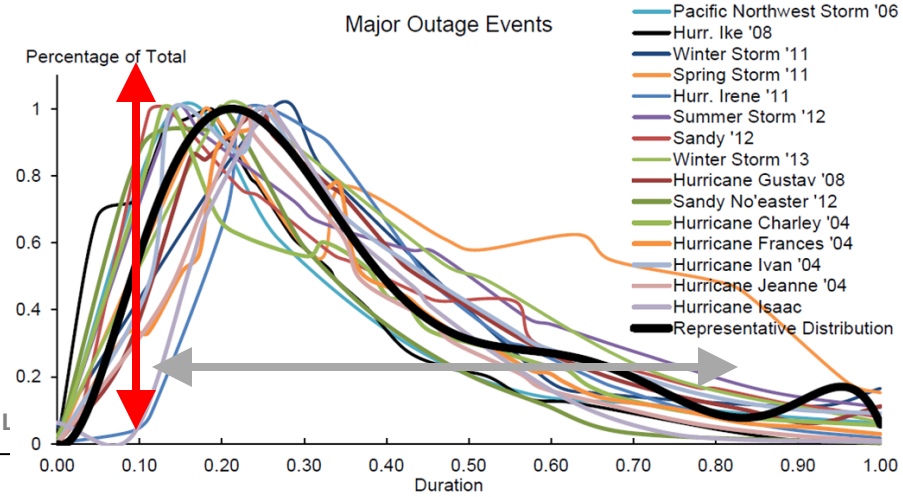
Resilience Design—Example
Hardening and Resilience Options

- Harden existing components (Asset hardening)
  - Reduce damage probabilities
- Add distributed generation in microgrids (System design)
  - Natural gas generators and/or CHP
  - Diesel generators
  - Renewables and storage (integration with GridLAB-D)
- Add (3-phase or 1-phase) inter-ties between (System design)
  - Distribution circuits
  - Loads
  - Distributed generators
  - Above ground(damageable) or underground
- Add manual or automatic switches (System operations)
  - Reconfigure circuits
  - Shed circuits and/or loads

Resilience Design—Example
Scenario Based Stochastic Network Optimization







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UNCL

Resilience Design—Example
Network Design Formulation

$$\text{minimize} \quad \sum_{ij\in E} c_{ij}x_{ij} + \sum_{i,j\in E} \kappa_{ij}\tau_{ij} + \sum_{i\in N,k\in p_i} \zeta_i^k z_i^k + \sum_{i\in N} \mu_i u_i$$

← Min cost for upgrade

$$\text{s.t.} \quad -x_{ij}Q_{ij}^k|p_{ij}| \le \sum_{k\in p_{ij}} f_{ij}^k \le x_{ij}Q_{ij}^k|p_{ij}|$$

$$-(1-\tau_{ij})Q_{ij}^k|p_{ij}| \le \sum_{k\in p_{ij}} f_{ij}^k \le (1-\tau_{ij})\,Q_{ij}^k|p_{ij}|$$

$$-\beta_{ij}\frac{\sum_{k\in p_{i,j}} f_{ij}^k}{|p_{ij}|} \le f_{ij}^{k\prime} - \frac{\sum_{k\in p_{i,j}} f_{ij}^k}{|p_{ij}|} \le \beta_{ij}\frac{\sum_{k\in p_{i,j}} f_{ij}^k}{|p_{ij}|}$$

← Respect the physics and engineering of the network

$$l_i^k = y_i d_i^k$$

$$0 \le g_i^k \le z_i^k + g_i^{k+}$$

$$g_i^k - l_i^k - \sum_{j\in N} f_{ij}^k = 0$$

← Respect engineering limits—generation, line, and load limits

$$0 \le z_i^k \le u_i Z_i^k$$

← Generation size constraints

$$\sum_{ij\in s}\left(x_{ij} + (1-\tau_{ij})\right) \le |s| - 1$$

← "No Loop"/Topology switching constraints

$$\sum_{i\in CL,k\in p_i} l_i^k \ge .98 \sum_{i\in CL,k\in p_i} d_i^k$$

$$\sum_{i\in N\setminus L,k\in p_i} l_i^k \ge .5 \sum_{i\in N\setminus L,k\in p_i} d_i^k$$

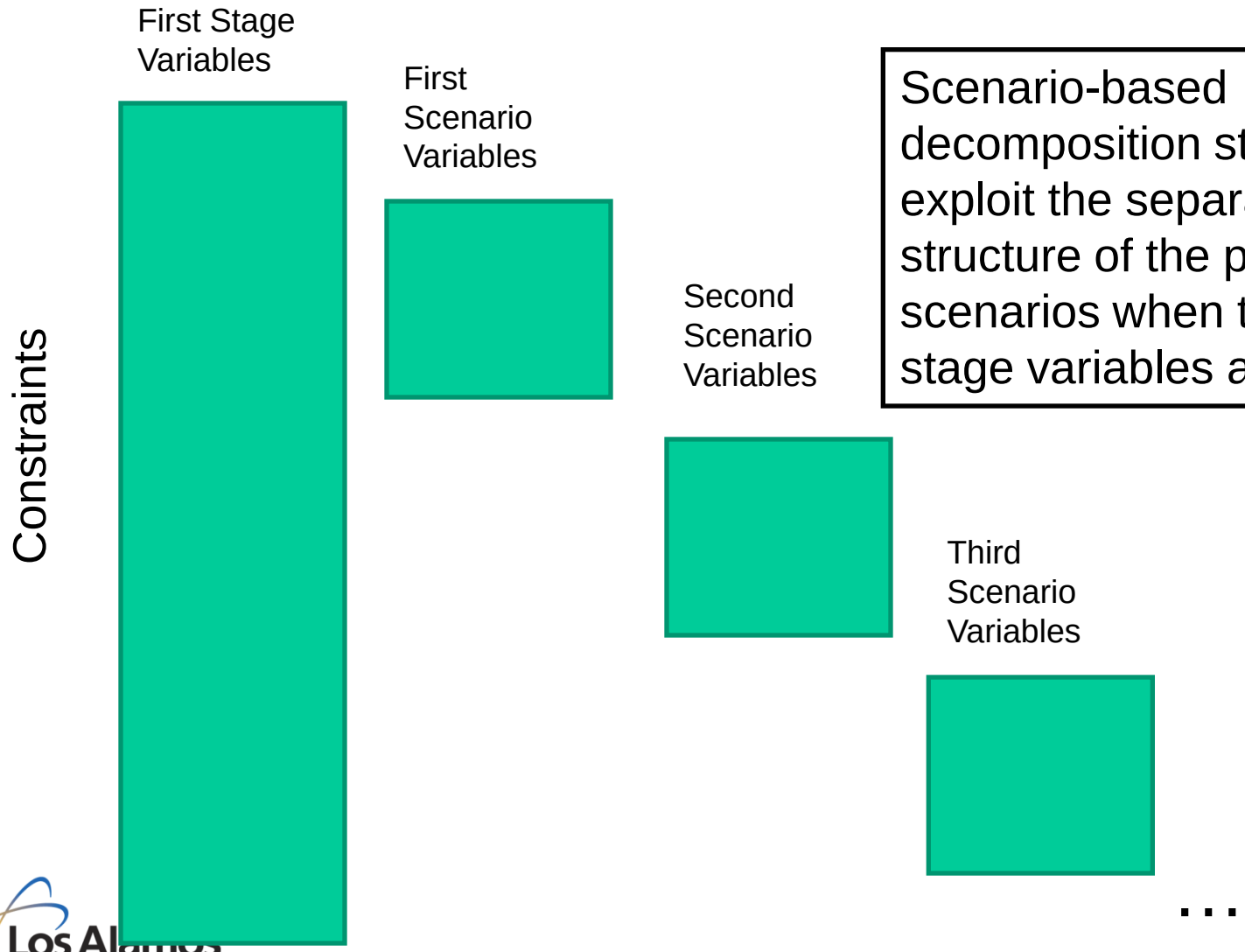
← Resilience performance

$$x, y, \tau, u \in \{0,1\}$$

Resilience Design—Example
Scenario Based Decomposition

- **Baseline Standard**
  - CPLEX 12.6—commercial mixed integer program solver
- **Decomposition Algorithms (cutting planes)**
  - Danzig-Wolfe
  - Benders
  - Disjunctive
  - Logic
  - Scenario ← Biggest computational gains

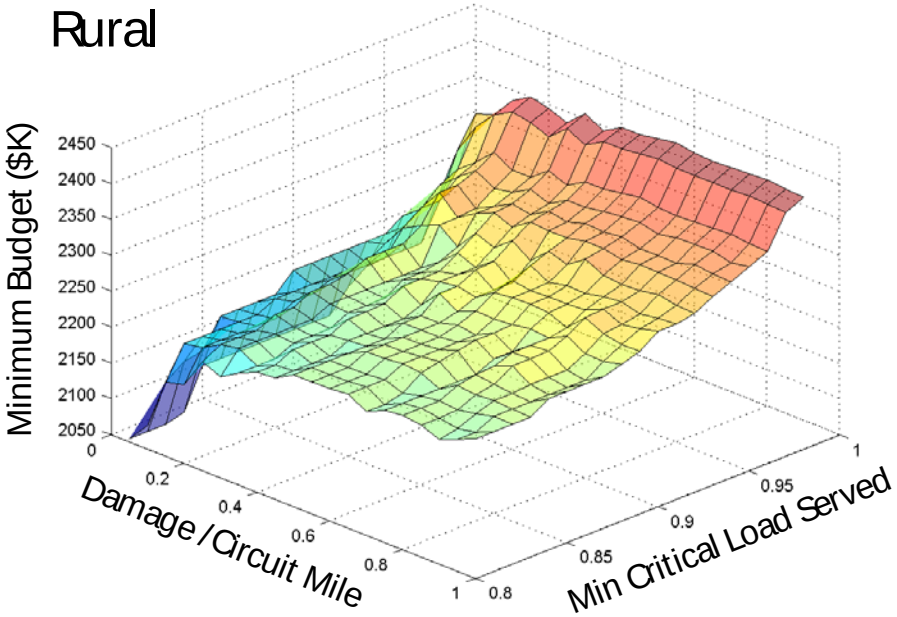
Resilience Design—Example
Scenario Based Decomposition



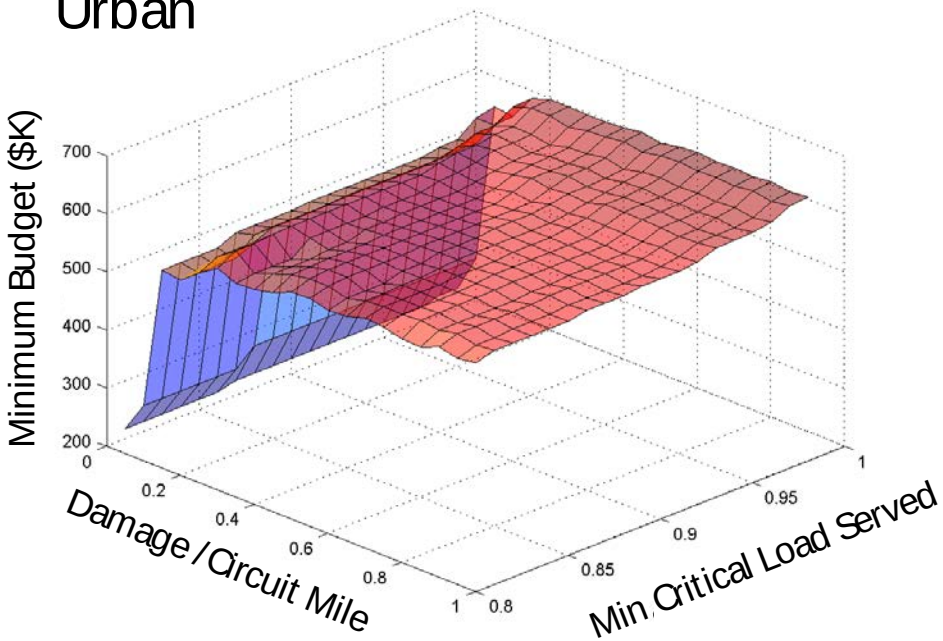
Scenario-based decomposition strategies exploit the separable structure of the problem over scenarios when the first stage variables are fixed

Resilience Design—Example Decision Support Outputs

Rural



Observations

- Rural networks require larger resilience budgets/MW served
- Both urban and rural budget are insensitive to damage rate beyond a relatively low threshold
- Urban budget is insensitive to critical load requirements

Urban