# Extreme Events and Grid Resilience

## Los Alamos National Laboratory

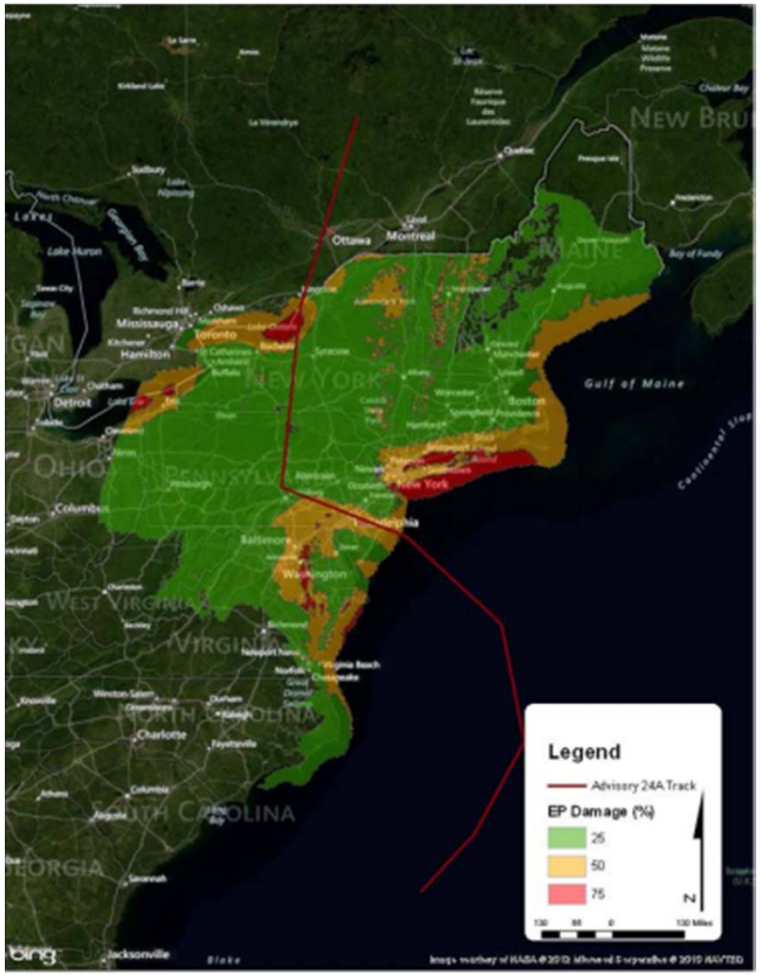
# Planning for Natural Disasters

## Short-term

- Operational changes
- Crew and supply readiness
- Understanding potential impacts to supporting infrastructures

## Long-term

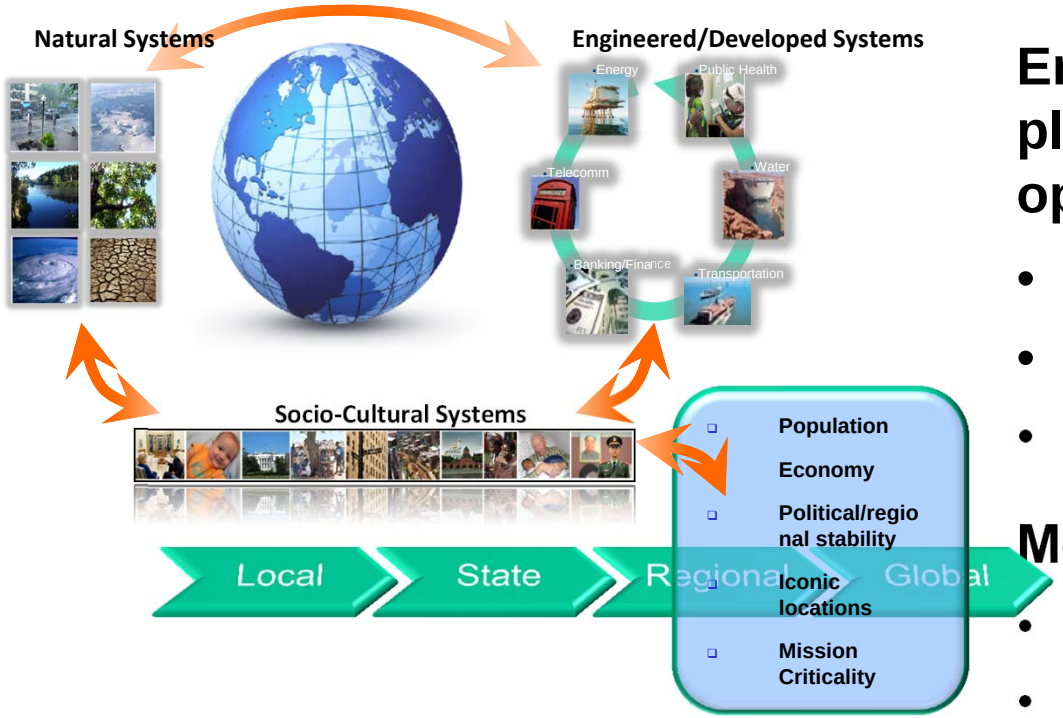
- Exercises, including modeling hypothetical events
- Increasing maintenance programs
- Designing systems based upon risks
- Incorporating new technologies



# Grid Resilience Requirements

- **Translation of policy definition into a technical definition/specification**
- **Metrics for assessing resilience**
- **Right mixture of policy/regulation/financing to support resilience**
- **Modern tools to design, retrofit and operate power systems for resilience**
  - Account for all-hazards
  - Operate at multiple spatial and temporal scales/resolutions
  - Support integration of emerging science and engineering
  - Beyond the standard restoration/recovery model
  - Supportive of cradle to grave cost benefit analysis
    - Engineering cost assessment
    - Economic impact assessment

# Grid Resilience Assessment Tools at LANL




## Energy system models for planning, design, and operation

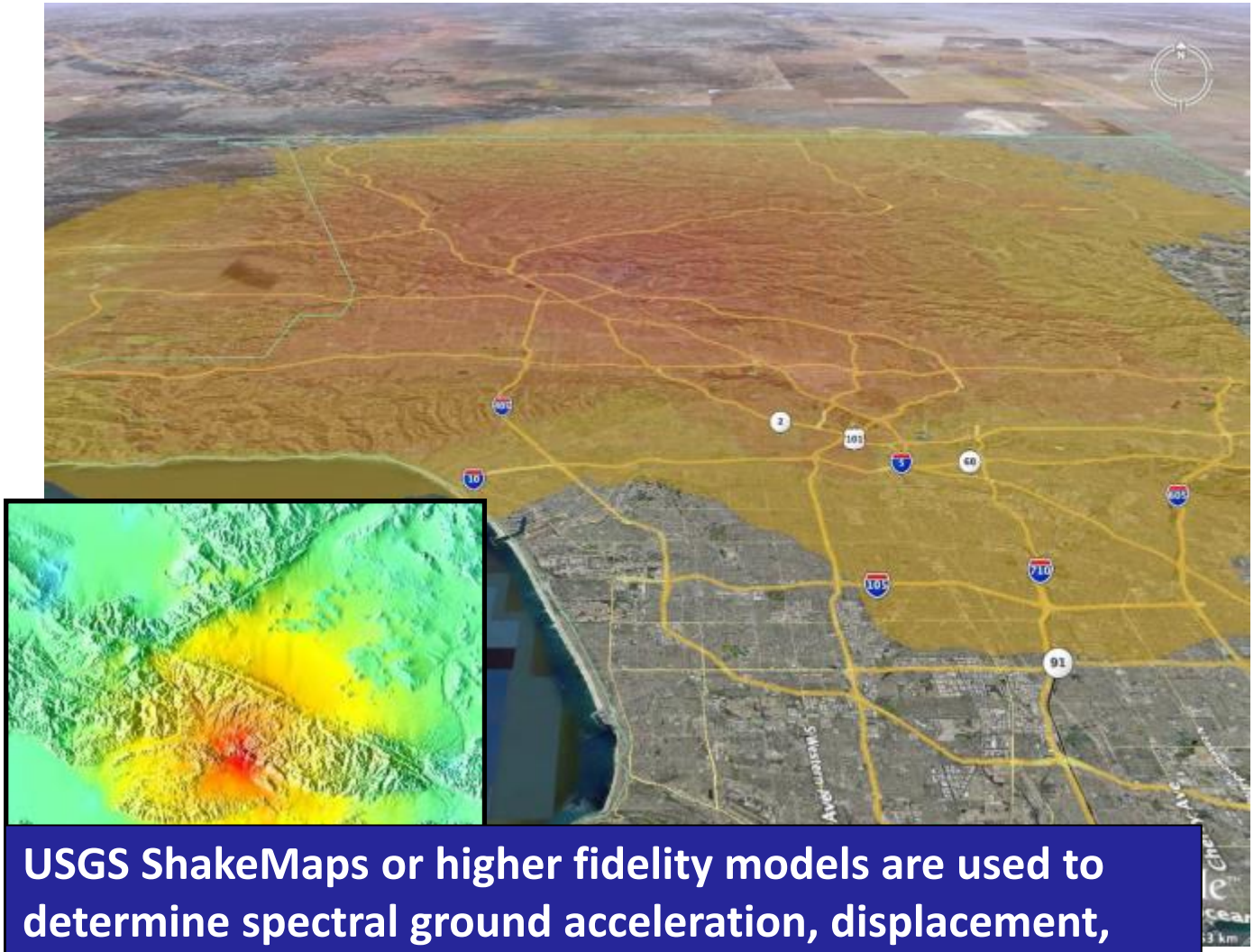
- Network reliability (N-1, N-K)
- Control systems models
- Recovery/restoration models

## Models to quantify metrics

- Demographics
- Economic impact models
  - Positive and negative GDP impact of grid component addition/loss

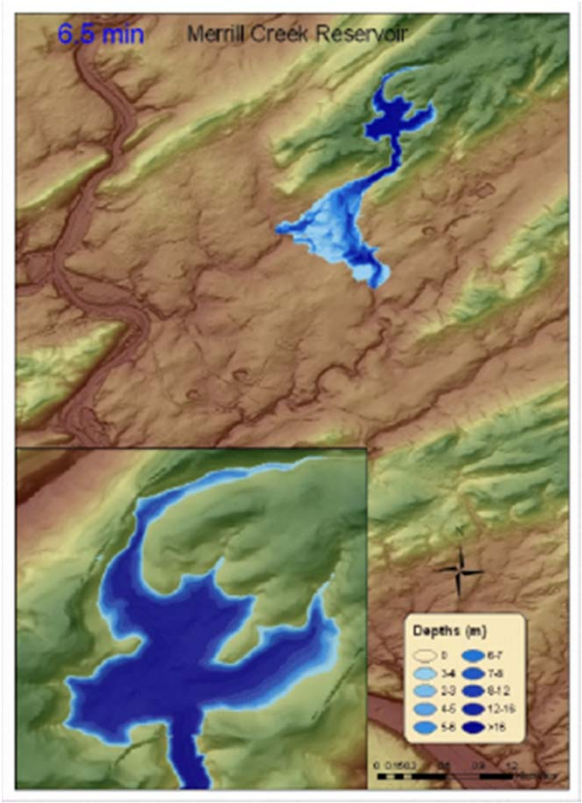
Opportunity to leverage 12 year $120M DHS investment in simulation and analysis tools and OE $2M/year investment in advanced grid analytics

# Earthquake Damage Assessment



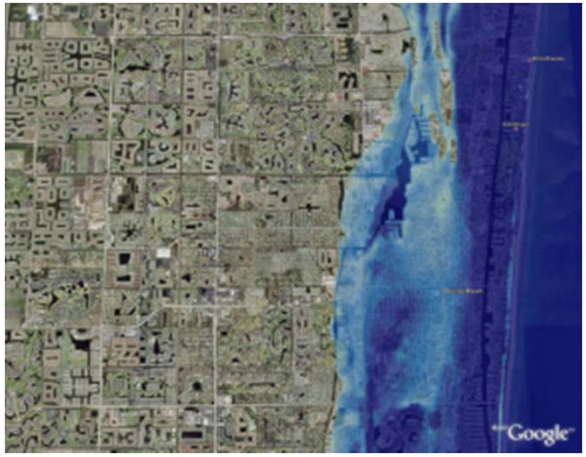
**USGS ShakeMaps or higher fidelity models are used to determine spectral ground acceleration, displacement, and uncertainty information.**

# Flood Analysis



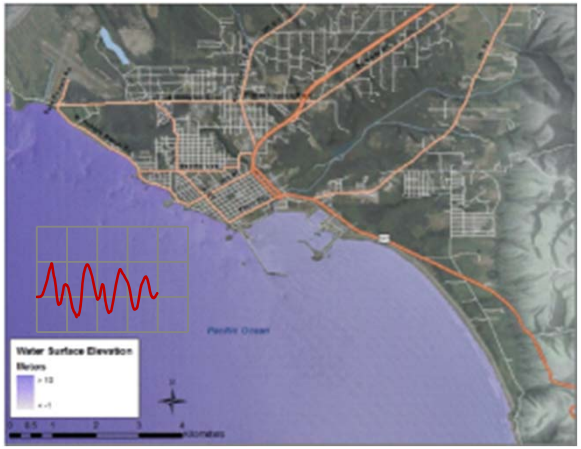

**High-resolution dam failure with known bathymetry**

**Coastal "surge" boundary defined by NOAA SLOSH model output**



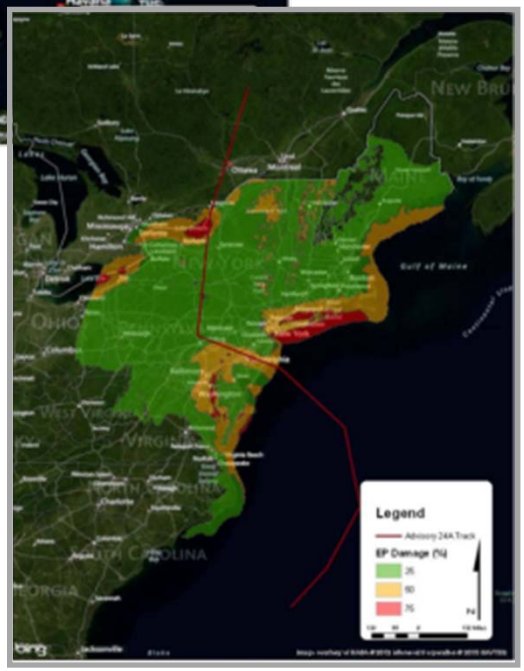

**Ingest lower resolution NOAA tsunami marigrams for high resolution flood impact analysis**

- **Many types of flood events analyzed by characterizing the boundary condition**
  - Over 100 studies
    - Dam/levee failure, river flooding, surge, tsunami
  - Adapting to watershed hydrologic analysis
    - Infiltration
    - Evaporation



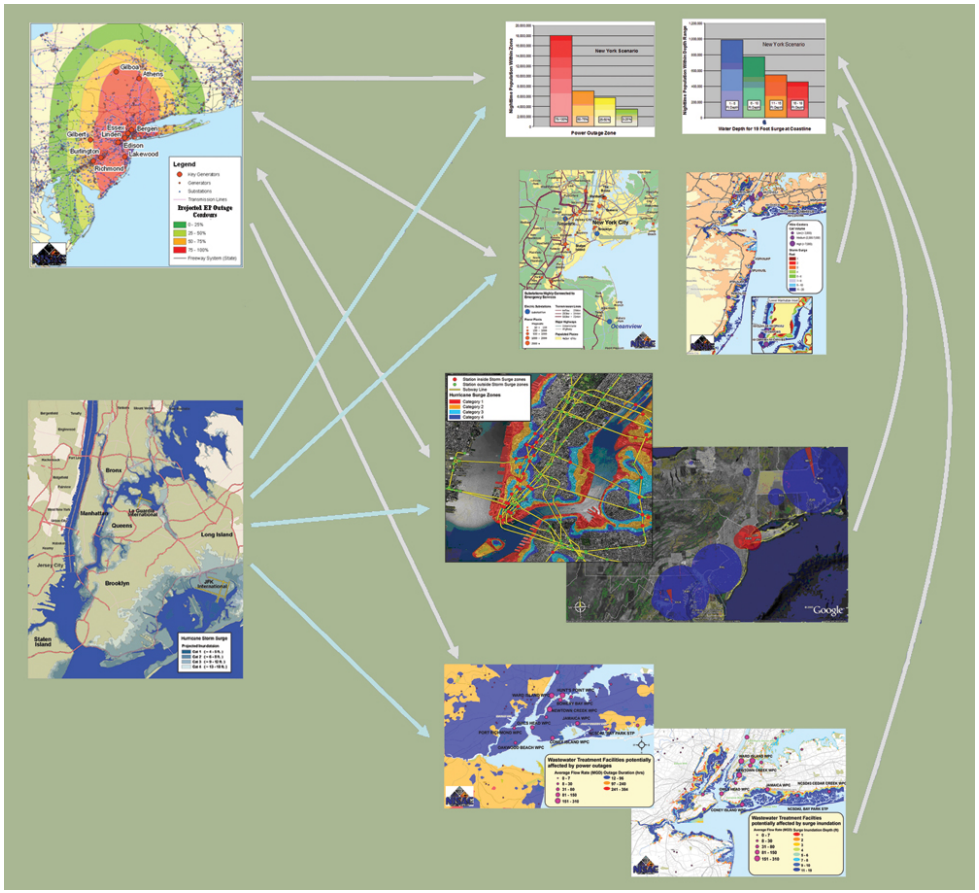
# Electric Power Outage Risk Map



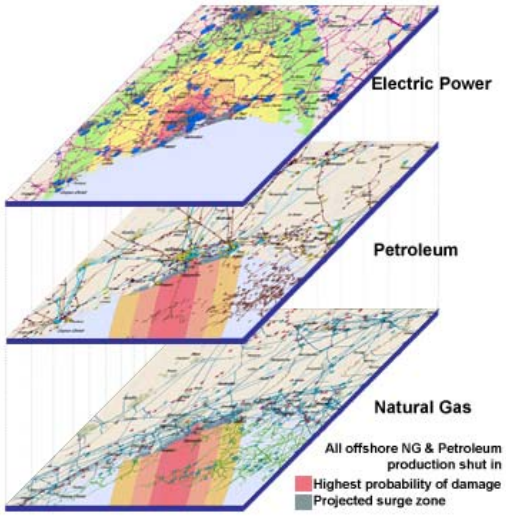



- Electric Power Outage Risk Map
  - Using NOAA 7-day wind forecast
  - Tested for hurricanes and tropical storms in 2012
  - Used for Hurricane Sandy
- Short-term
  - Incorporate into AGAVE
  - Step through time periods
  - Export contours as ESRI Shapefiles
- Long-term
  - Add severe weather watch areas
  - Incorporate precipitation (snow, rain)
  - Better damage/fragility estimates focusing on regional differences

# Interdependency Impacts Across Infrastructures



- **Critical interdependencies among electric power, telecommunications, transportation, and emergency services intensify disruption to population, extend restoration times for all infrastructures.**
- **Flood conditions can prevent access to areas.**
- **Interdependency issues can occur days or weeks after the initiating event.**



# Grid Resilience Design and Operation Tool Requirements - Met

- ✓ **Geospatially registered infrastructure (including grid) models** to accurately represent the impact of extreme weather events on the grid (wind, water, fire, heat, ice and ground acceleration) and to accurately overlay multiple damaged infrastructures
- ✓ **Models of infrastructure restoration** to understand the constraints on grid restoration and the potential duration of outages
- ✓ **Economic and population impact models coupled to power system outage models** to provide a dollars-to-dollars basis for utility resilience investment decisions.
- ➢ **Interdependence with natural gas pipeline networks** to reveal the impact of extreme weather on the availability of natural gas to distributed generation

# Grid Resilience Design and Operation Tool Requirements - Needed

- **Interdependence with the transportation infrastructure** to provide better estimates of grid restoration time
  - provides a basis for utility investment in spare component inventory management
  - Accounts for repair crew routing.
- **Energy expansion/upgrade planning models that include risks from extreme weather and other events**
- **Advanced grid control models to estimate reductions in outages during grid restoration**
  - distribution grid reconfiguration
  - aggregate microgrid models
- **Real-time integration of data from existing and emerging sensors** (AMI/OMS and traffic data) to improve restoration performance.

# Past & Current R&D - Overview

**All-Hazards**

Over 20 years of investment

Event Response Plans

Hazard Damage Estimator

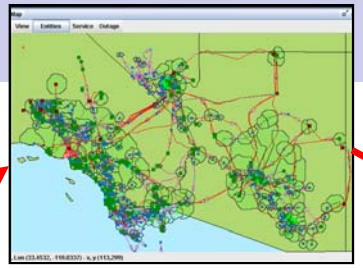
Energy Infrastructure GeoDatabase

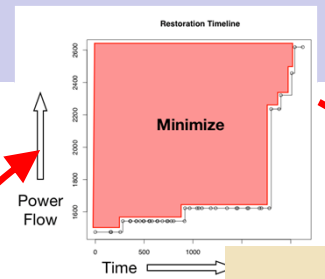
Energy Network Model

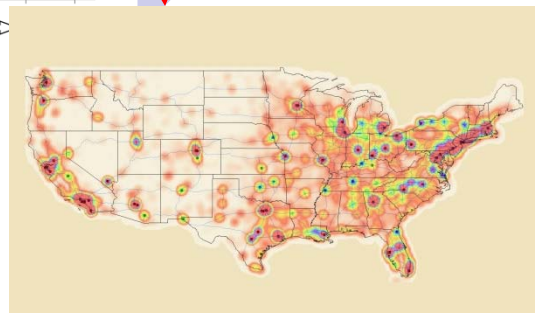
Outage Area of Influence Model

Restoration/ recovery Model

Economic & Population Impacts Model

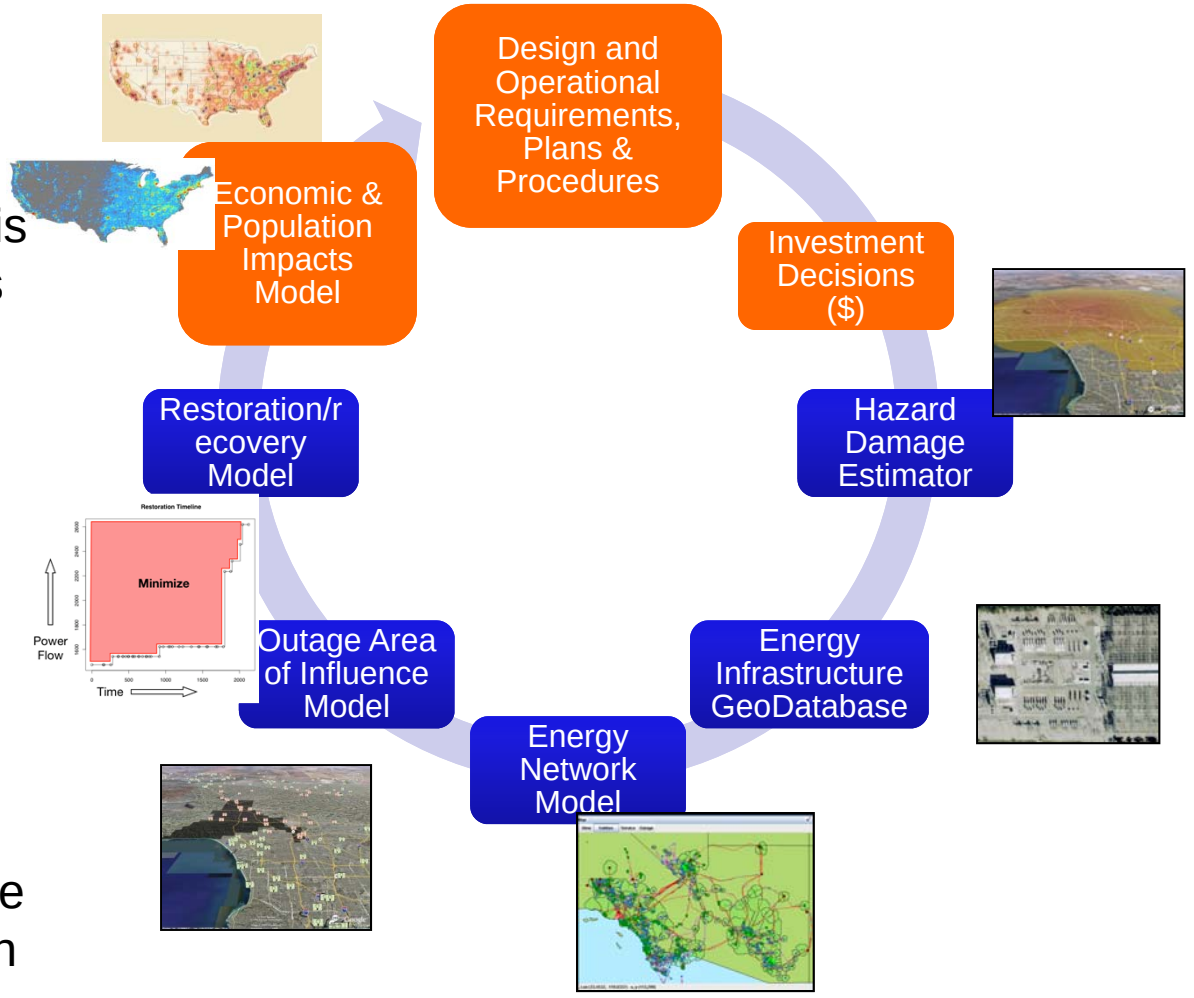




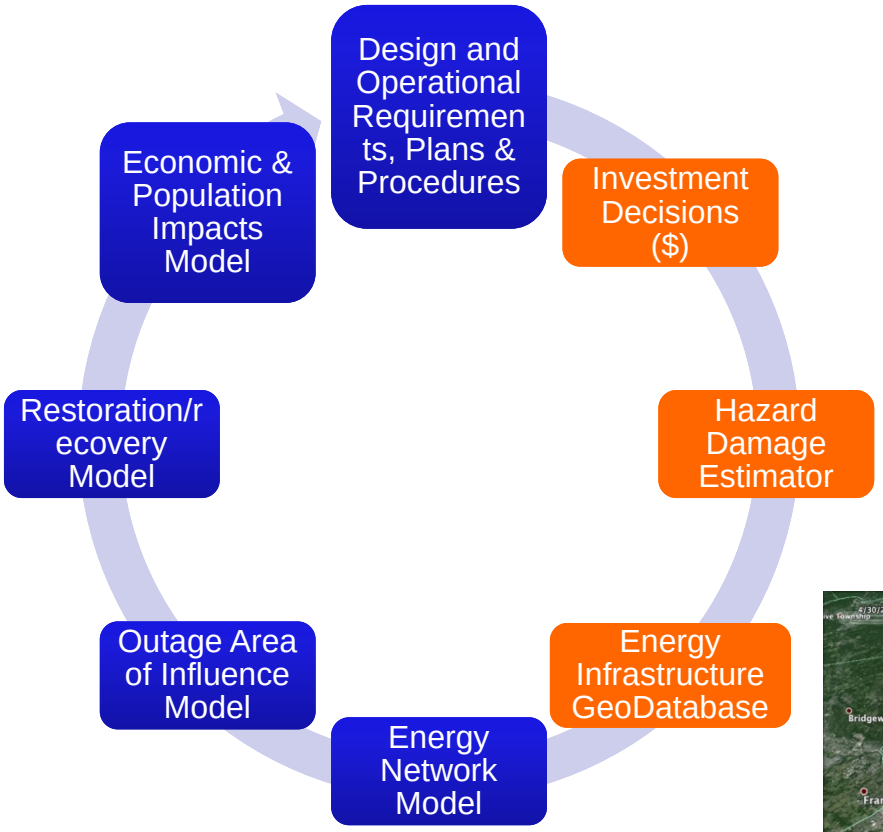



# Planned R&D Overview – Close the Resilience Design Loop

- **Develop and deploy of resilient system design and operation tools**
  - Full cost benefit analysis of investment decisions
  - Account for interdependencies between power distribution, natural gas and transportation systems
  - Multi-level optimization techniques
  - Run-time performance improvement to promote full value of optimization



# Planned R&D Overview – Adapt Existing Tools to Grid Resilience

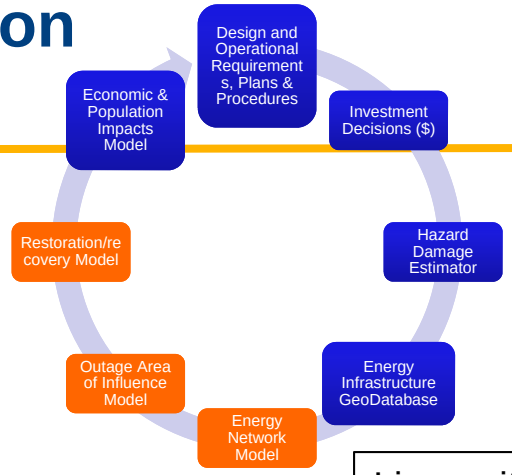



**Adapt existing damage analysis system to distribution scale problems**

- Probabilistic damage assessment
- Engineering cost estimator for hardening distribution systems
- Data structure for distribution system data

# Planned R&D Overview – Incorporation of New Models & Solvers

- **Apply transmission scale interdependency models to distribution grid solvers**
  - Hooking into GridLab-D, OpenDSS
- **Integrate microgrid models to improve outage area influence model**
- **Apply multi-level optimization tools at the distribution scale**
  - 4 years algorithm development with extensive peer review
  - Transportation scheduling/routing model
  - Electrical grid/generation model




Line switching
Generator control
Load shedding

**Inputs:**

| | |
|---|---|
| $\mathcal{PN} = \langle N, L \rangle$ | the power network |
| $D$ | the set of damaged |
| $R$ | the set of repaired items |

**Variables:**

| | |
|---|---|
| $y_i \in \{0, 1\}$ | - item $i$ is activated |
| $z_i \in \{0, 1\}$ | - item $i$ is operational |
| $P_i^l \in (-\hat{P}_i^l, \hat{P}_i^l)$ | - power flow on line $i$ |
| $P_i^v \in (0, \hat{P}_i^v)$ | - power flow on node $i$ |
| $\theta_i \in (-\frac{\pi}{6}, \frac{\pi}{6})$ | - phase angle on bus $i$ |

**Maximize**

$$\sum_{b \in N^b} \sum_{i \in N_b^l} P_i^v \quad (1)$$

**Subject to:**

$$y_i = 1 \quad \forall i \in N \setminus D \quad (2)$$
$$y_i = 0 \quad \forall i \in D \setminus R \quad (3)$$
$$z_i = y_i \quad \forall i \in N^b \quad (4)$$
$$z_i = y_i \wedge y_j \quad \forall j \in N^b, \forall i \in N_j^g \cup N_j^l \quad (5)$$
$$z_i = y_i \wedge y_{L_i^+} \wedge y_{L_i^-} \quad \forall i \in L \quad (6)$$
$$\sum_{j \in N_i^l} P_j^v = \sum_{j \in N_i^g} P_j^v + \sum_{j \in LI_i} P_j^l - \sum_{j \in LO_i} P_j^l \quad \forall i \in N^b \quad (7)$$
$$0 \le P_i^v \le \hat{P}_i^v * z_i \quad \forall i \in N_j^g \cup N_j^l \quad (8)$$
$$-\hat{P}_i^l * z_i \le P_i^l \le \hat{P}_i^l * z_i \quad \forall i \in L \quad (9)$$
$$P_i^l \ge B_i * (\theta_{L_i^+} - \theta_{L_i^-}) + M * (\neg z_i) \quad \forall i \in L \quad (10)$$
$$P_i^l \le B_i * (\theta_{L_i^+} - \theta_{L_i^-}) - M * (\neg z_i) \quad \forall i \in L \quad (11)$$

Figure 1: A MIP Model for the Unserved Load.

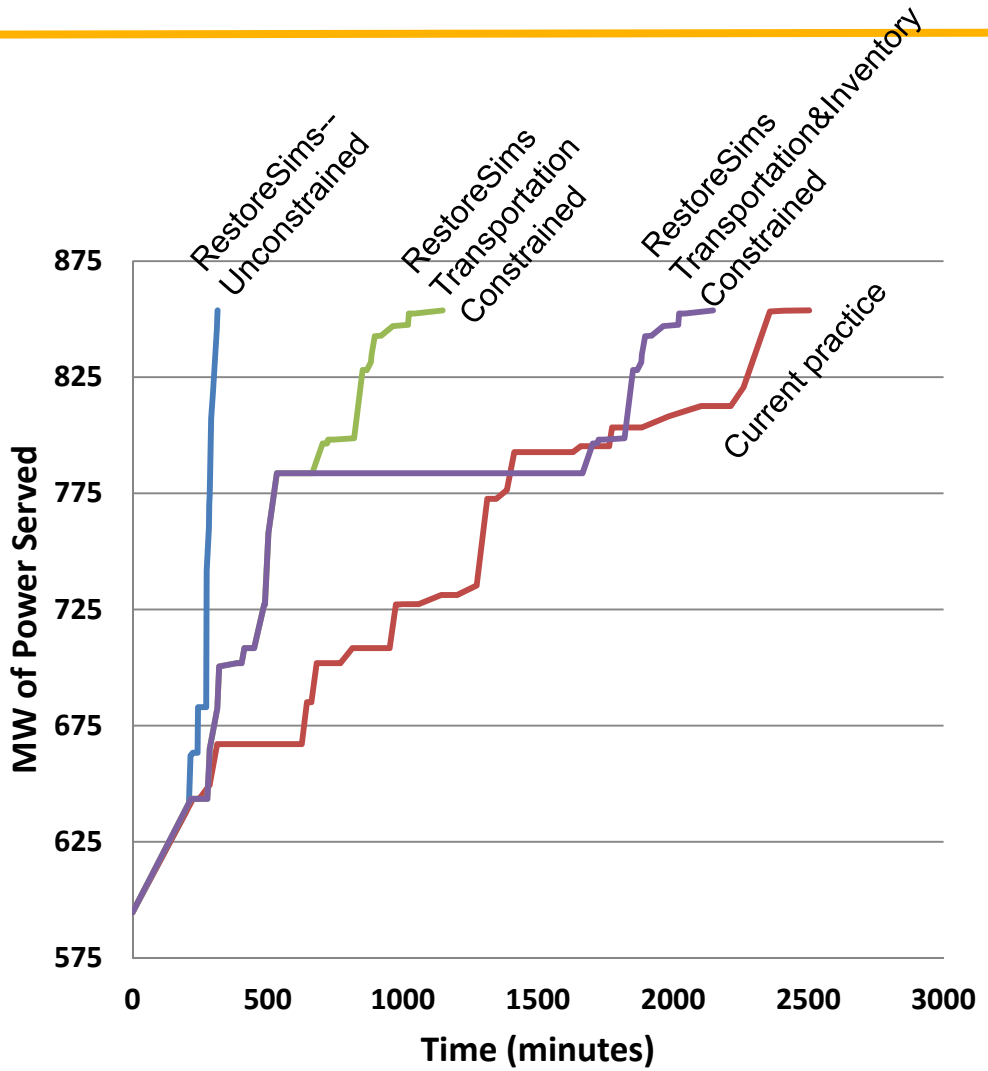
# Current Practice & Planned R&D – Transportation Interdependency

Current State of Practice

- RestoreSims integrates:
  - Grid, Gas
  - Transportation, Crew scheduling
  - Repair component inventory
  - Repair component warehousing
- Reveals impact of transportation and inventory constraints on restoration
- Enables utilities to design
  - Repair component inventory
  - Component warehousing
- Capability outperforms utilization based restoration practice, e.g. prioritizing based on pre-event utilization

Planned R&D

- Adapt to distribution grid models
- Convert to an operational tool




**Restoration Progression on 67 Asset Repair Scenario**

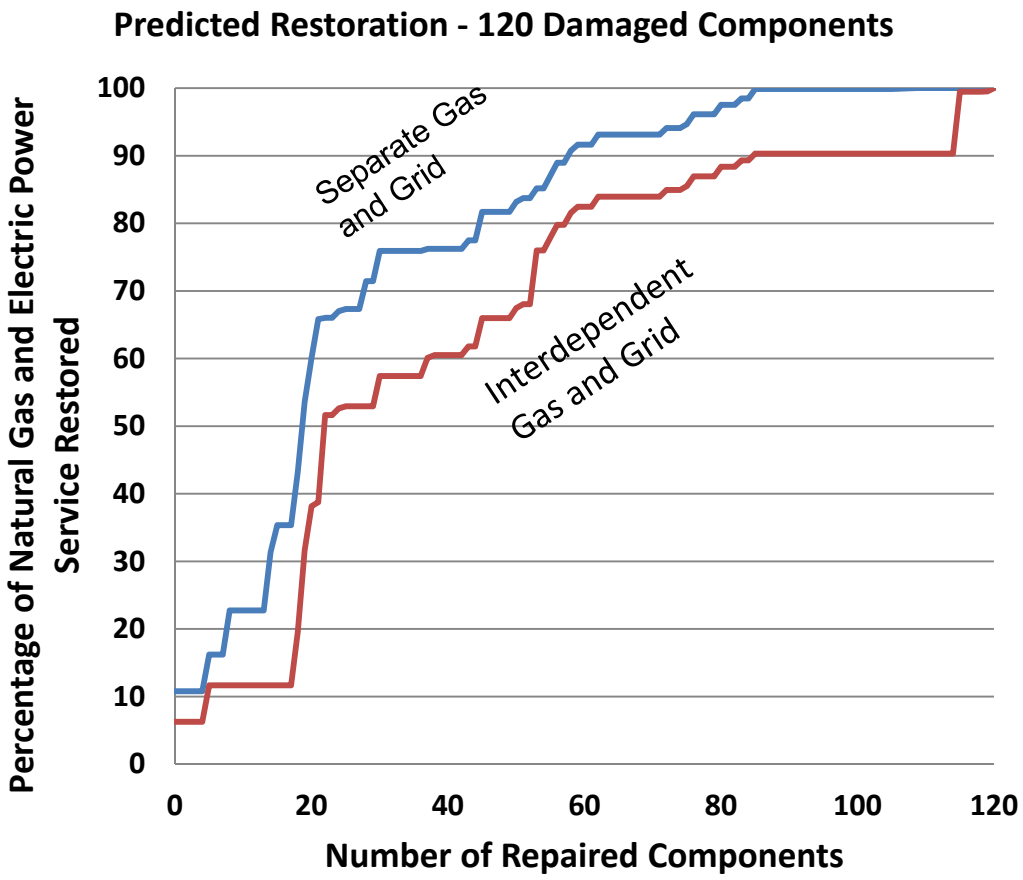
# Current Practice and Planned R&D – Gas-Grid Interdependency

Current Practice

- RestoreSims integrates:
  - Grid, Gas
  - Transportation, Crew scheduling
  - Repair component inventory
  - Repair component warehousing
- Reveals impact of gas infrastructure damage on restoration
- Reveals cross-utility vulnerabilities prioritizing based on pre-event utilization

Planned R&D

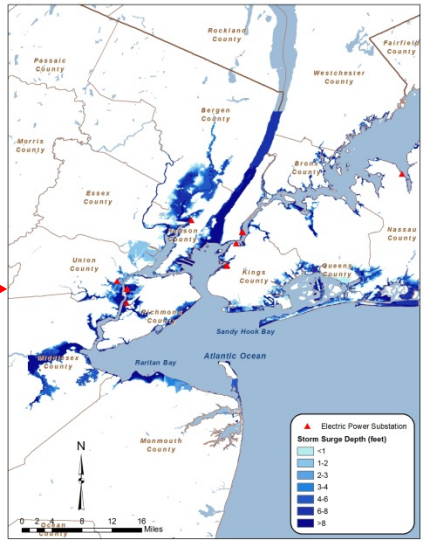
- Adapt to distribution grid models
- Add models of DG and microgrids
- Convert to an operational tool



# Superstorm Sandy Example

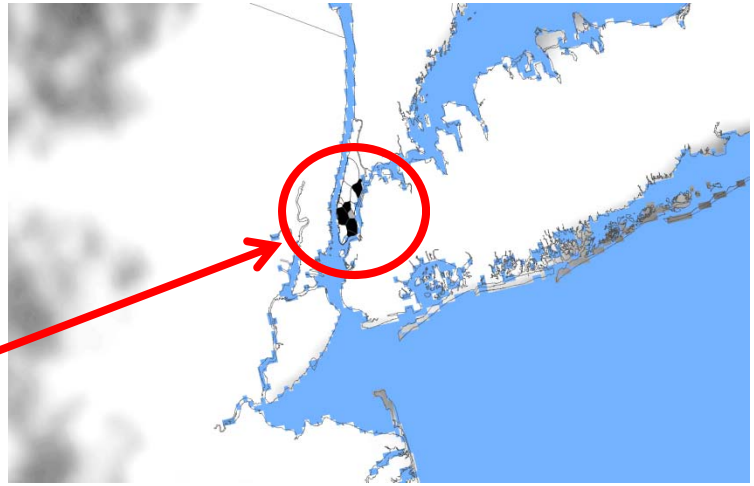
Flood Risk Areas


Geo-Registered Grid Model


Flood Damaged Substations

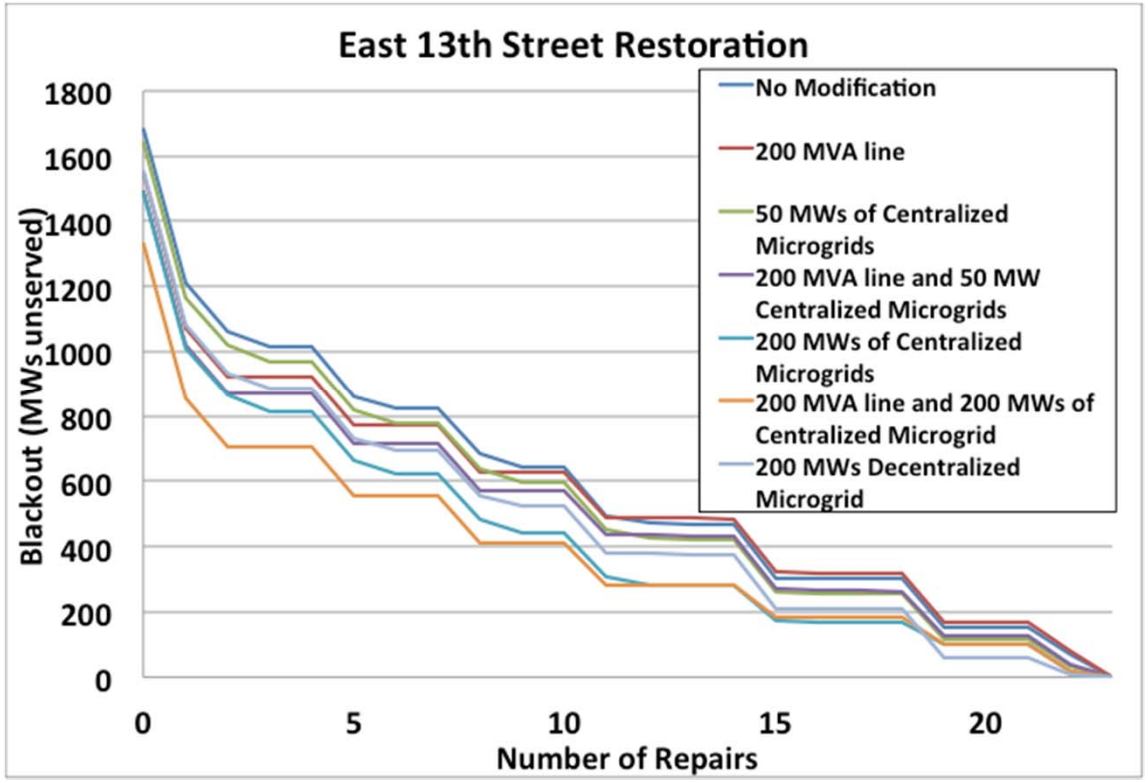
Example focuses on potential expansion options to minimize impacts of loss of the East 13th Street Substation, which outaged lower Manhattan



<u>Economic Loss</u>$196,484,000 GDP/day

# Potential value of adapted resilience framework

- **Expansion options evaluated**
  - Single large microgrid
  - Multiple distributed microgrids
  - Transmission expansion
  - Combinations of the above
- **All options reduce the impact of outage event relative to current system**
- **For this scenario, expansion using line and microgrid provides best early results**




A closed loop decision tool (including engineering cost and economic benefit) will help decisions on which option to pursue

# Summary

## Planning for disasters includes:

- Understanding natural threats to infrastructure systems
- Preparing for a disaster
- Incorporating infrastructure dependencies into restoration
- Recovering quickly following a disaster
- Developing more resilient systems

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