SAND2018-12230PE

Fundamentals of Advanced Microgrid Evaluation, Analysis, and Conceptual Design

Oct. 24, 2018 – St. Croix, USVI
Oct. 26, 2018 – St. Thomas, USVI

Sandia National Laboratories

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U.S. DEPARTMENT OF ENERGY

Contents

Agenda and Introduction

Agenda

8:30 – 9:00	Introduction and Welcome • FEMA Introduction • DOE Introduction • Sandia Introduction • Attendee introductions and areas of interest
9:00 – 10:30	Module 1 – Electric Power Systems and Energy Surety Module 2 – Microgrids and Energy Surety Benefits
10:30 – 11:00	Break
11:00 – 12:00	Module 3 – Energy Surety Design Methodology Module 5 – Critical Assets and Services Module 6 – Design Threats

13:15 – 13:30	Discussion of Identified Critical Assets and Design Threats (from coursebook Ex. 5 and 6)
13:30 – 14:45	Module 7 – Performance Goals Module 8 – Performance Risk Analysis Module 10 – Formulating Design Options
14:45 – 15:00	Break
15:00 – 16:00	Naval Postgraduate School overview of USVI activities
16:00 – 16:45	Tool Demos: • Microgrid Design • FASTMap • ReNCAT
16:45 – 17:00	Discussion and Wrap Up

About Sandia National Laboratories

ceptional service in the national interest

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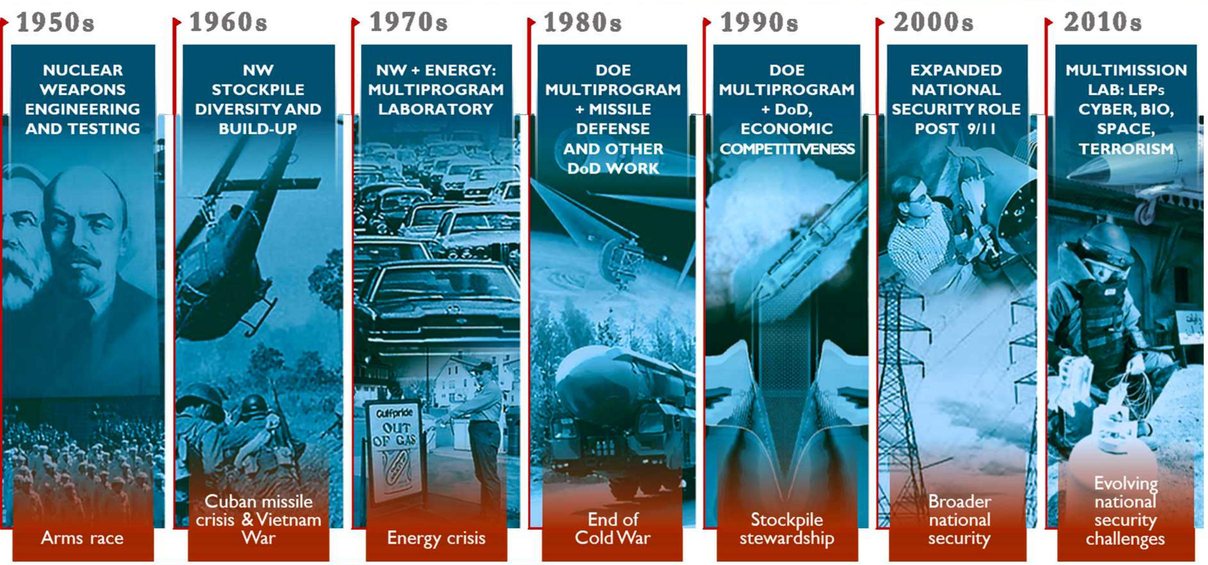
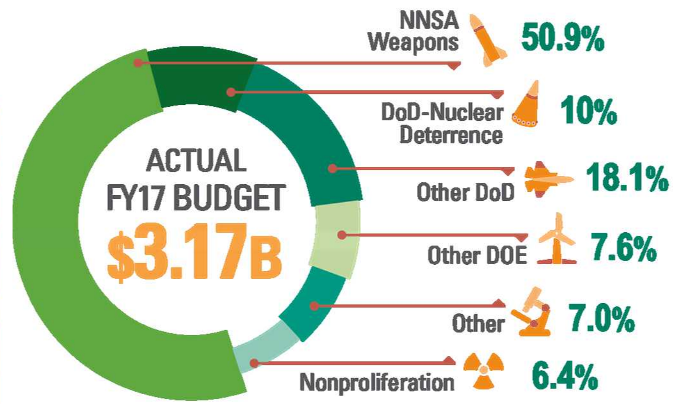
to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

Albuquerque, New Mexico (1949)

Livermore, California (1956)





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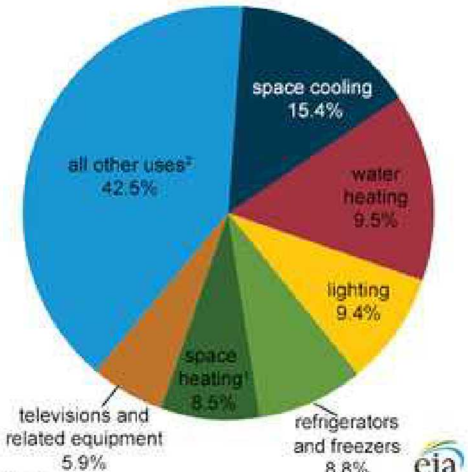
Need for Reliable Electric Power

- Our society is highly dependent on electric power
- Power outages have severe consequences:
    - Productivity:
        - Damage to equipment
        - Loss of perishables
        - Lost computing time
        - Unsafe work conditions
    - Daily Life
        - Communications challenges
        - Cooking difficulty
        - Entertainment unavailable
    - Health

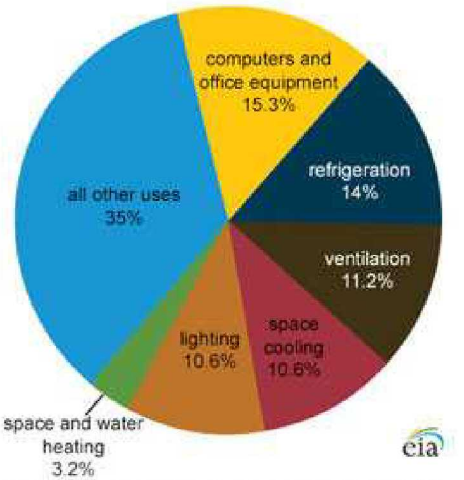
U.S. residential sector electricity consumption by major end uses, 2017



Notes:
[1]Includes consumption for heat and operating furnace fans and boiler pumps.
[2]Includes miscellaneous appliances, clothes washers and dryers, computers and related equipment, stoves, dishwashers, heating elements, and motors not included in other uses.

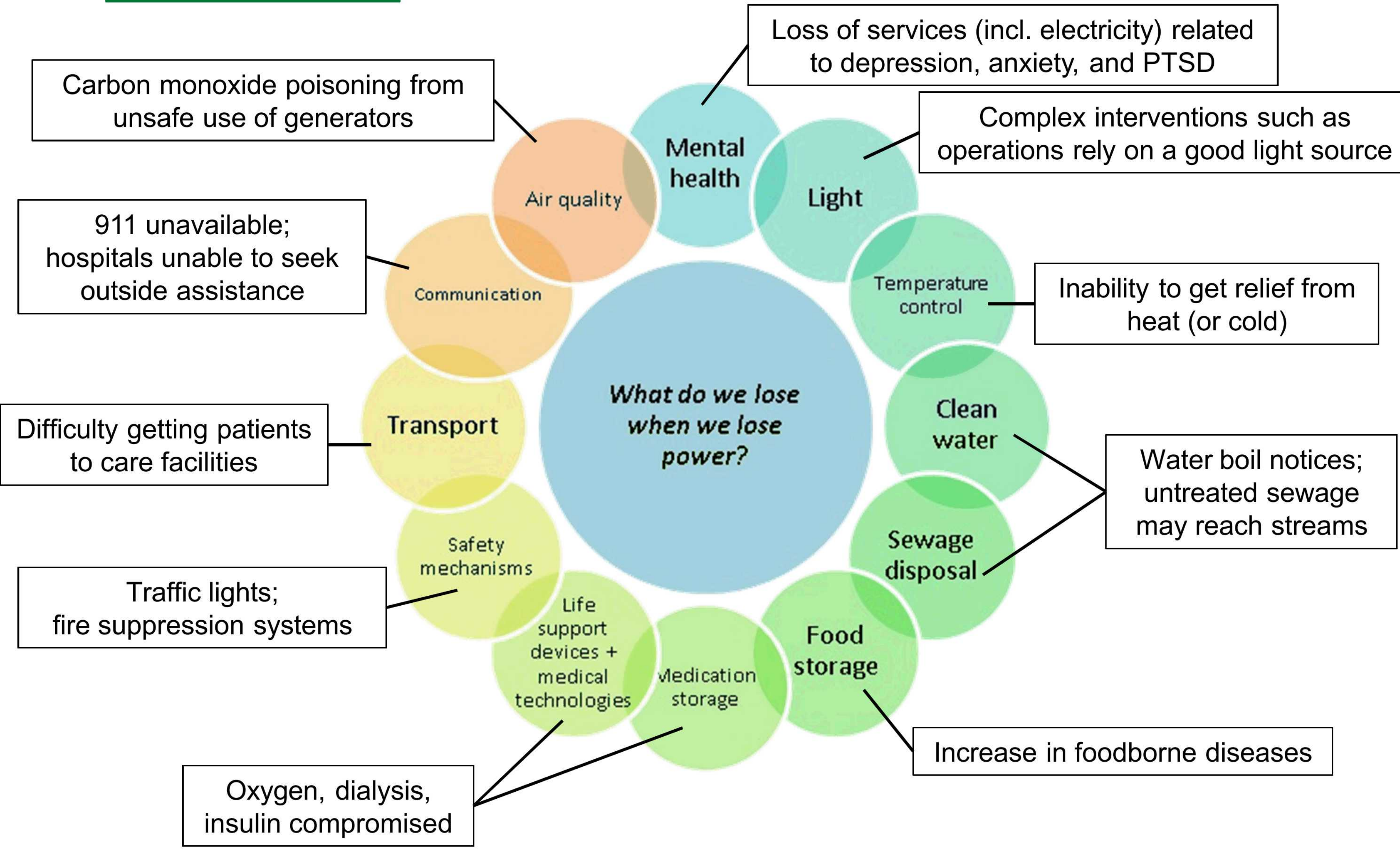
Source: U.S. Energy Information Administration, *Annual Energy Outlook 2018*, Table 4, February 2018

U.S. commercial sector electricity consumption by major end uses, 2017



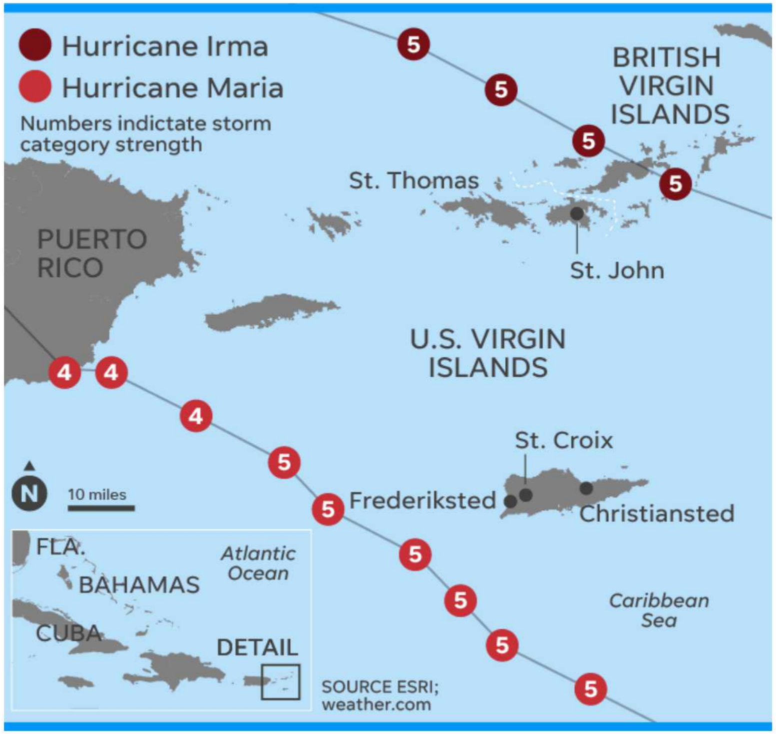
Source: U.S. Energy Information Administration, *Annual Energy Outlook 2018*, Table 5, February 2018

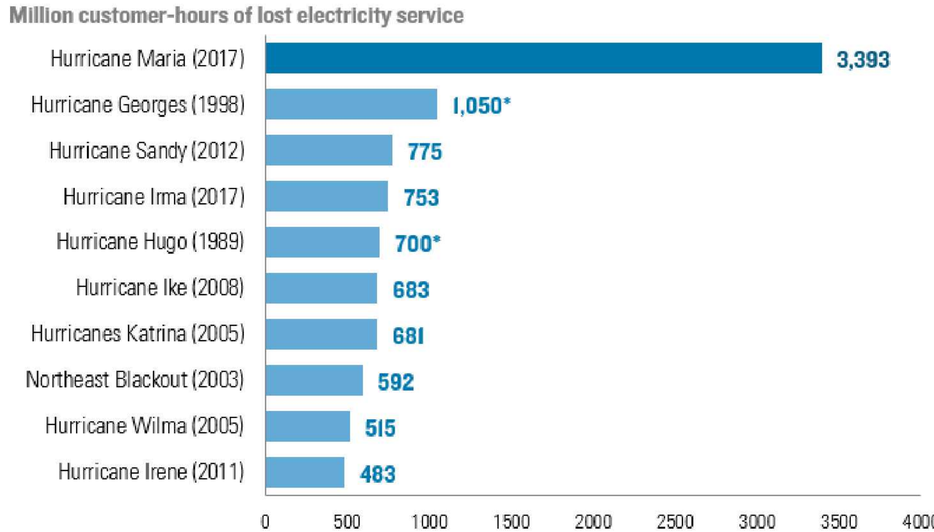
Electric Power and Health



From: “Power Outages, Extreme Events, and Health: a Systematic Review of the Literature from 2011-2012”

Power Outage Causes

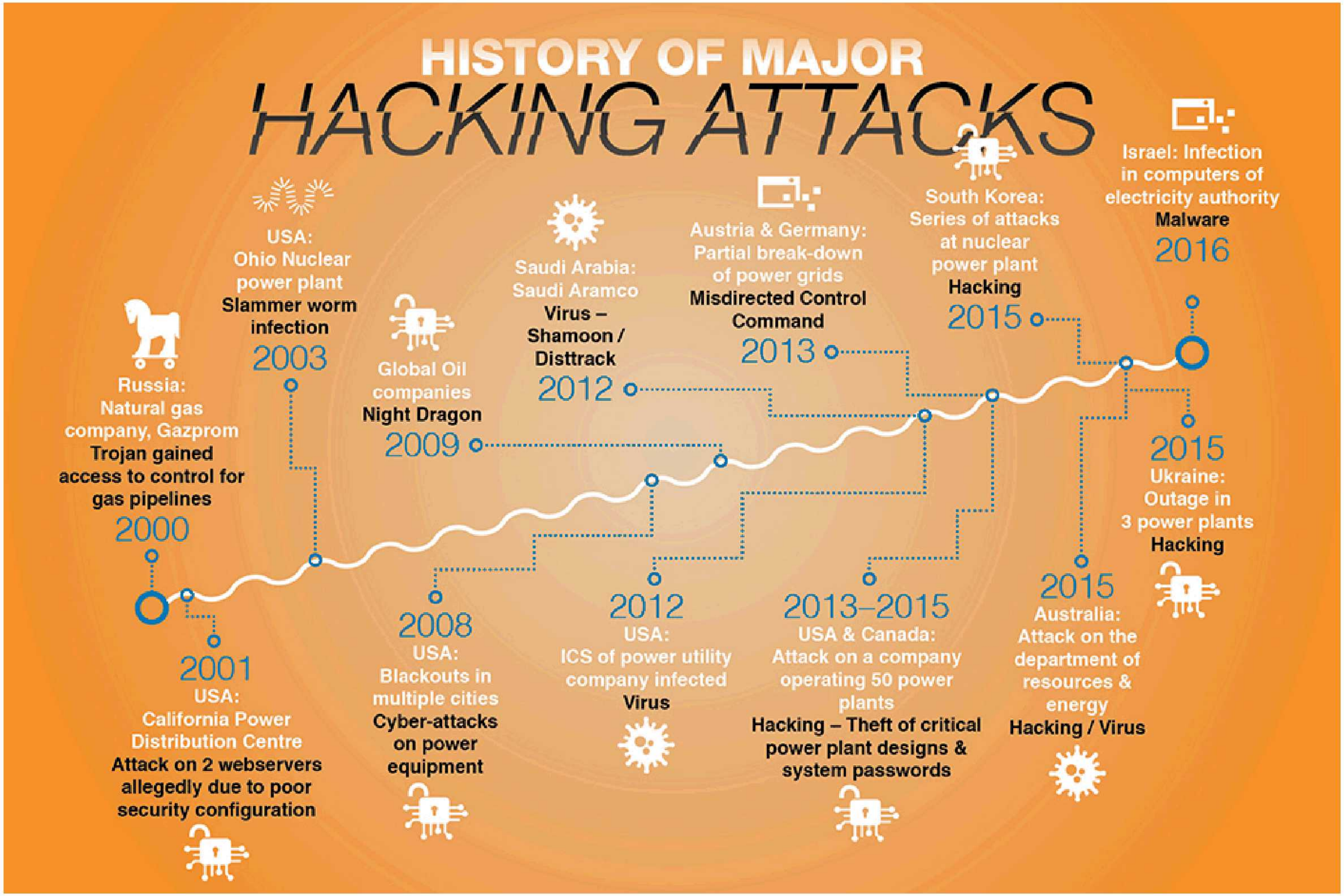




Source: DOE, National Academies, North American Electric Reliability Corporation (NERC), news reports and Rhodium estimates. We had a particularly difficult time estimating the impact of the 1938 New England hurricane. It may belong on the top 10 list, though we are confident it does not rival Maria for the top slot. Puerto Rico customer-hour estimates for Hurricane Maria from Nov 9-Dec 18, 2017, are based on use percent generation loss estimates from DOE. * Rough approximation based on available news reports.

Hurricane Maria caused largest blackout ever in US!

Power Outage Causes

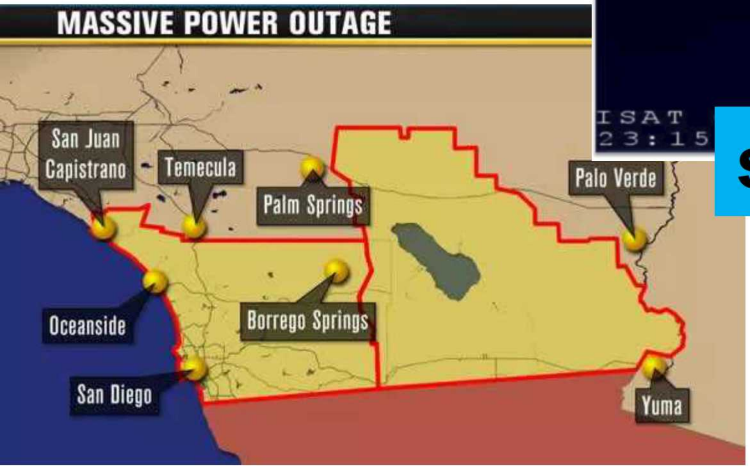


Power Outage Causes

human error

software bug

equipment failure



Energy Assurance

- **Practice of providing power security based on back-up generators was problematic**
  - *Frequently over-sized and under-maintained, low probability of start (<60%)*
  - *Dedicated to one building or facility*
  - *Operations for extended periods problematic*
- **Stating 9's of reliability – did not adequately factor in the erosion of critical mission capability for extended outages**
- **Safety requirements forced renewable energy technologies to go offline during a power outage**
- **Several large events highlighted that energy assurance was not impacted only by intentional events – Fires in the west with multi-state outages, large eastern multi-state outages due to weather**
- **Sandia started looking at advanced microgrids as an energy assurance solution**

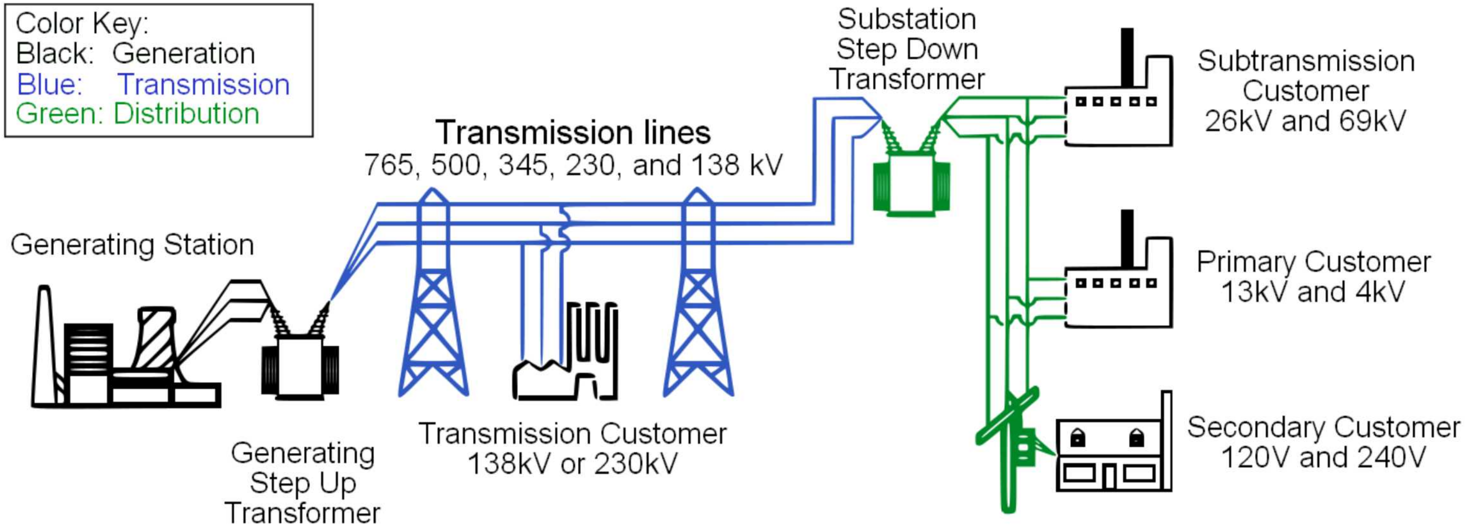
Module 1:
Electric Power Systems and Energy Surety

Module 1 – Electric Power Systems and Energy Surety

- **Topics will include**
  - Overview of the power grid (generation, transmission, distribution and loads)
  - Overview of distribution systems
    - Voltage levels
    - How distribution system grids connect to loads
    - Distribution system components
  - Energy surety considerations
    - Emerging electric power issues and challenges
    - Energy surety metrics
    - Common energy assurance approaches

Transmission and Distribution

- Transmission
  - Move bulk electricity from generation to load centers
  - Long distance (10s to 100s of miles), high capacity, high voltage
- Distribution
  - Distribute electricity to end users
  - Short distance (up to several miles), lower capacity, lower voltage



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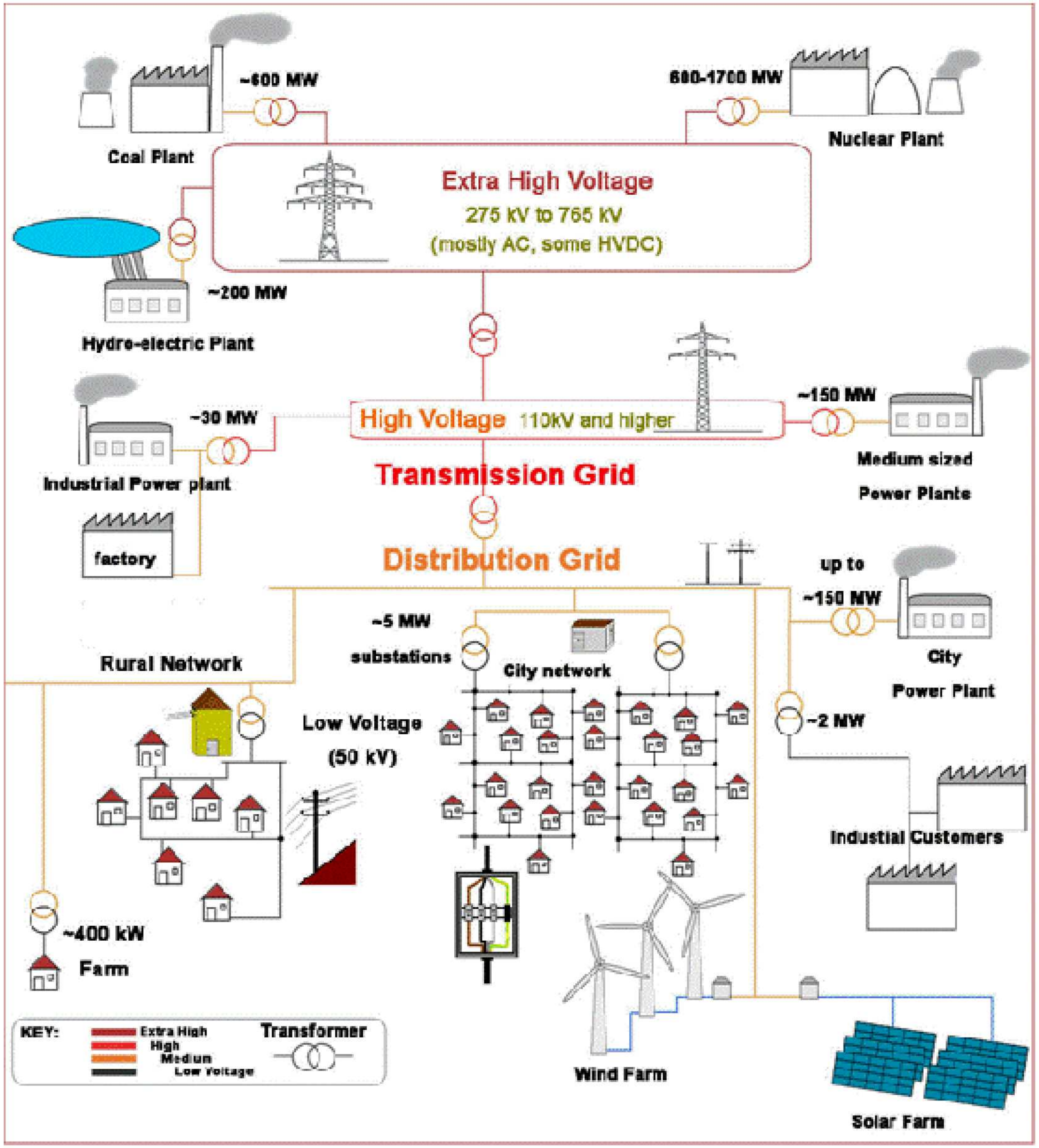
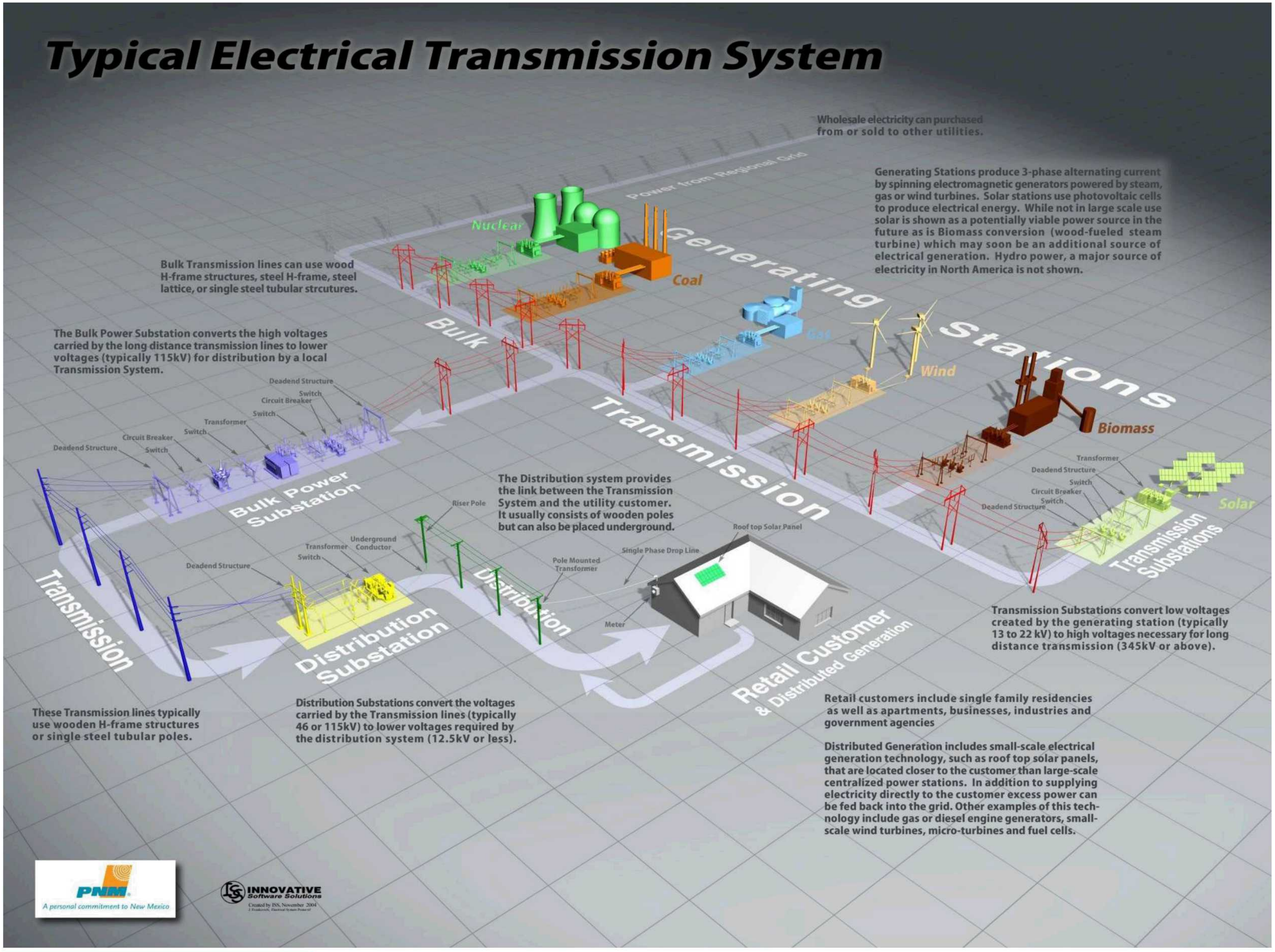
Transmission and Distribution

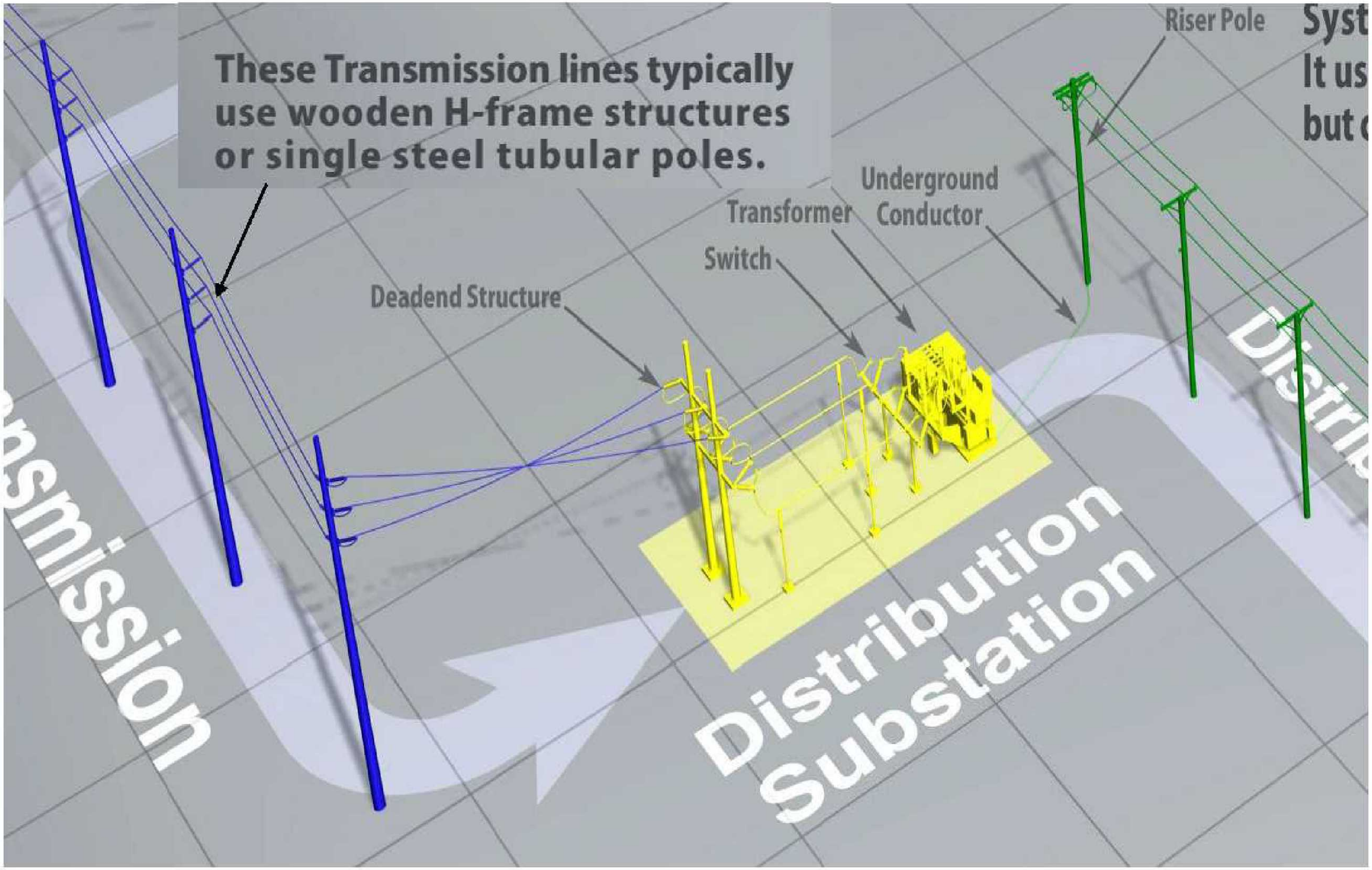


- **Transmission**
  - EHV: 345, 500, 765 kV
  - HV: 115, 138, 230 kV
  - Typically network
  - Long-distance
  - DC lines are used, too
- **Sub-Transmission**
  - 46, 69 kV
  - Network or long radial (e.g., rural feeders)
- **Distribution**
  - 4.16, 12.47 kV
  - Radial
  - Urban feeders

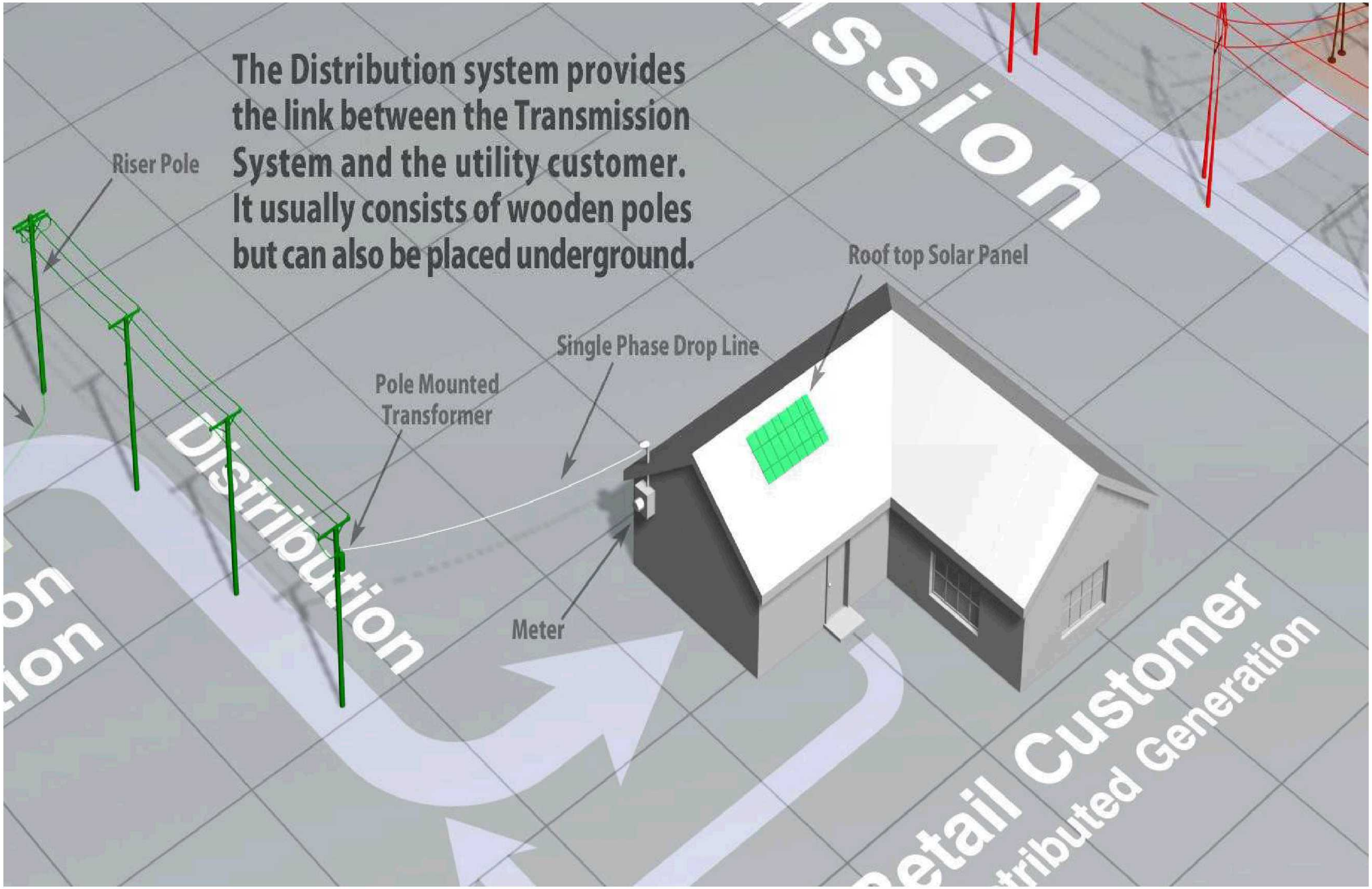
Transmisson



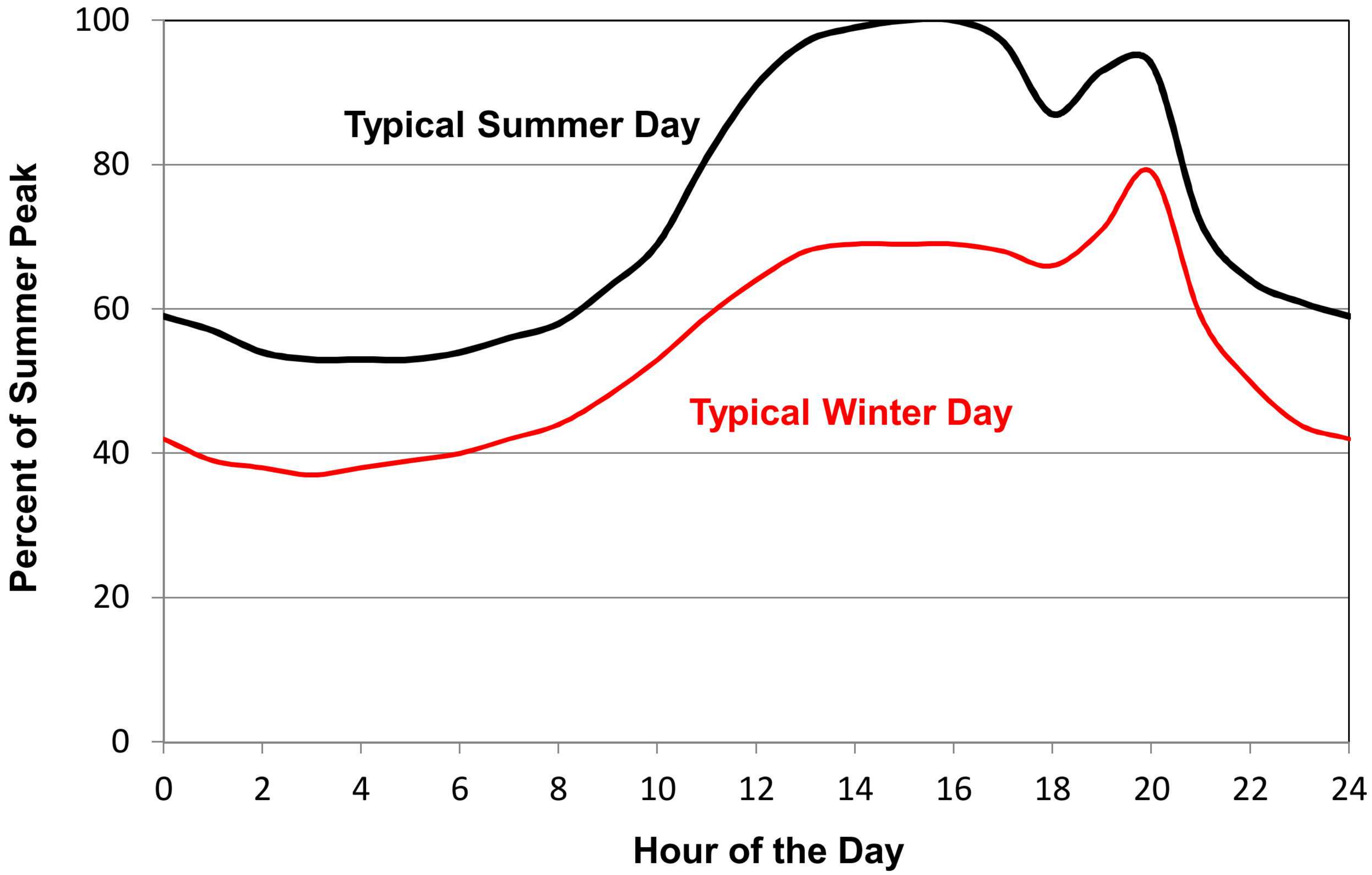
Distribution Substations



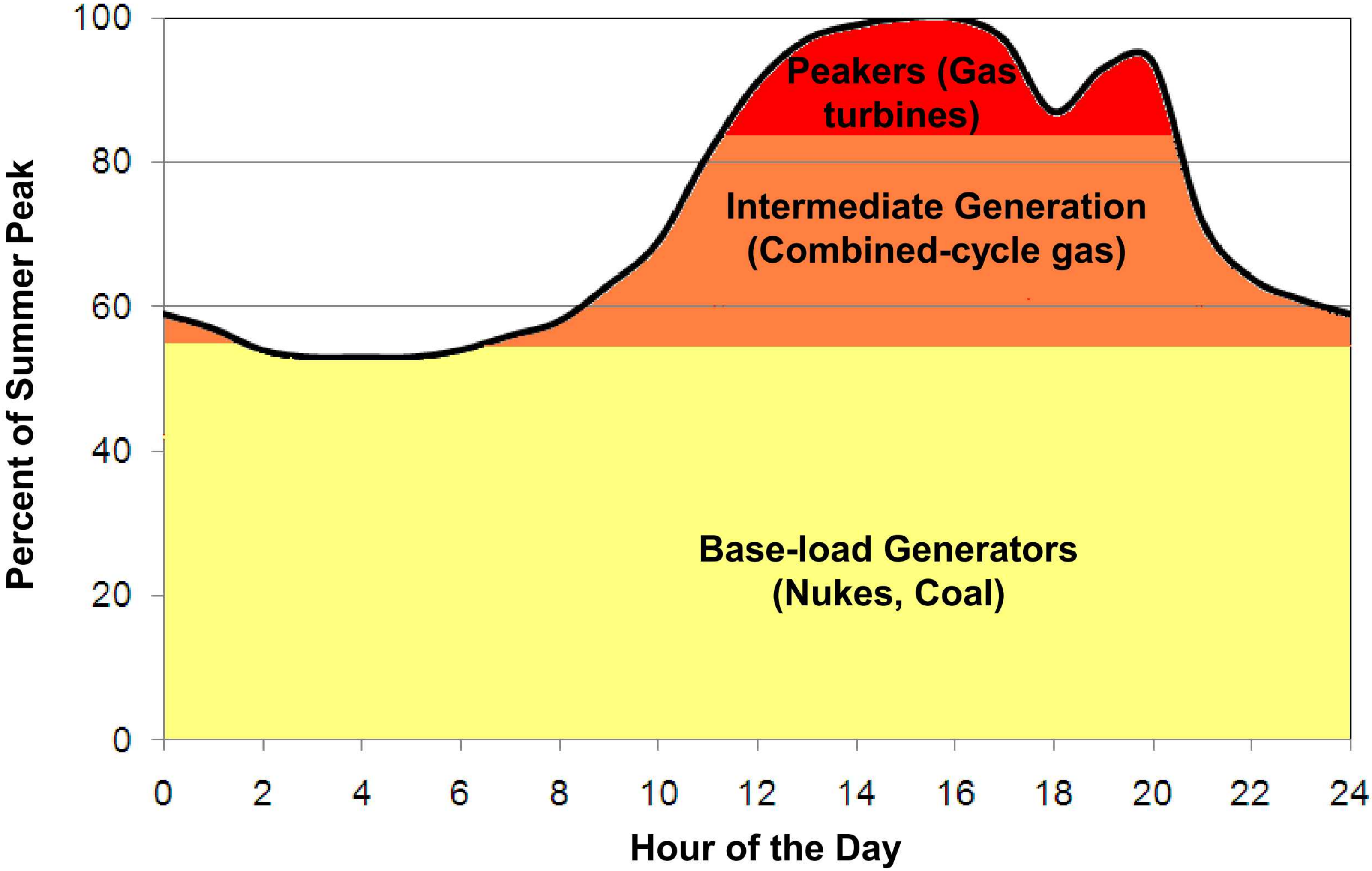
Delivery to Home



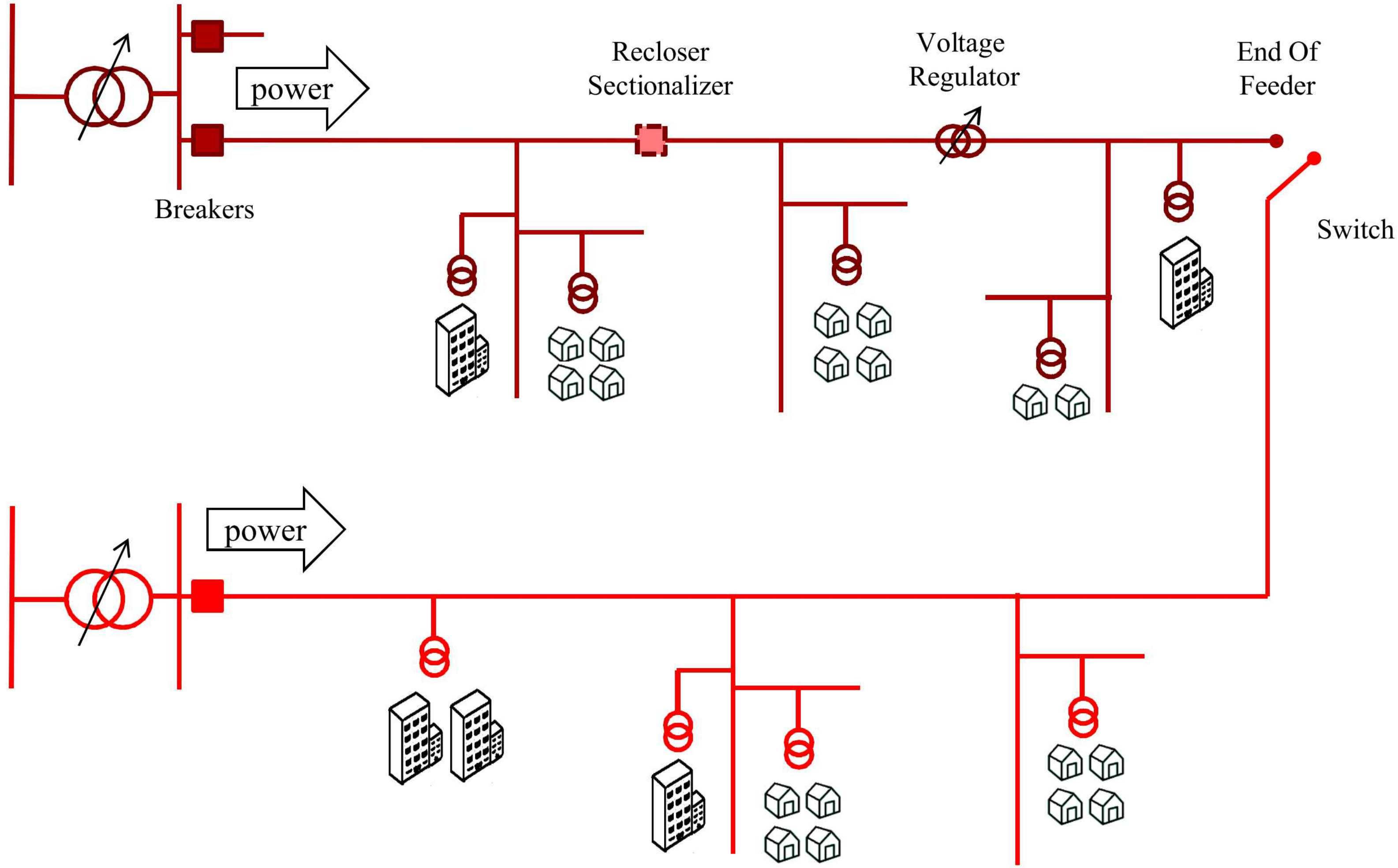
Electricity Demand



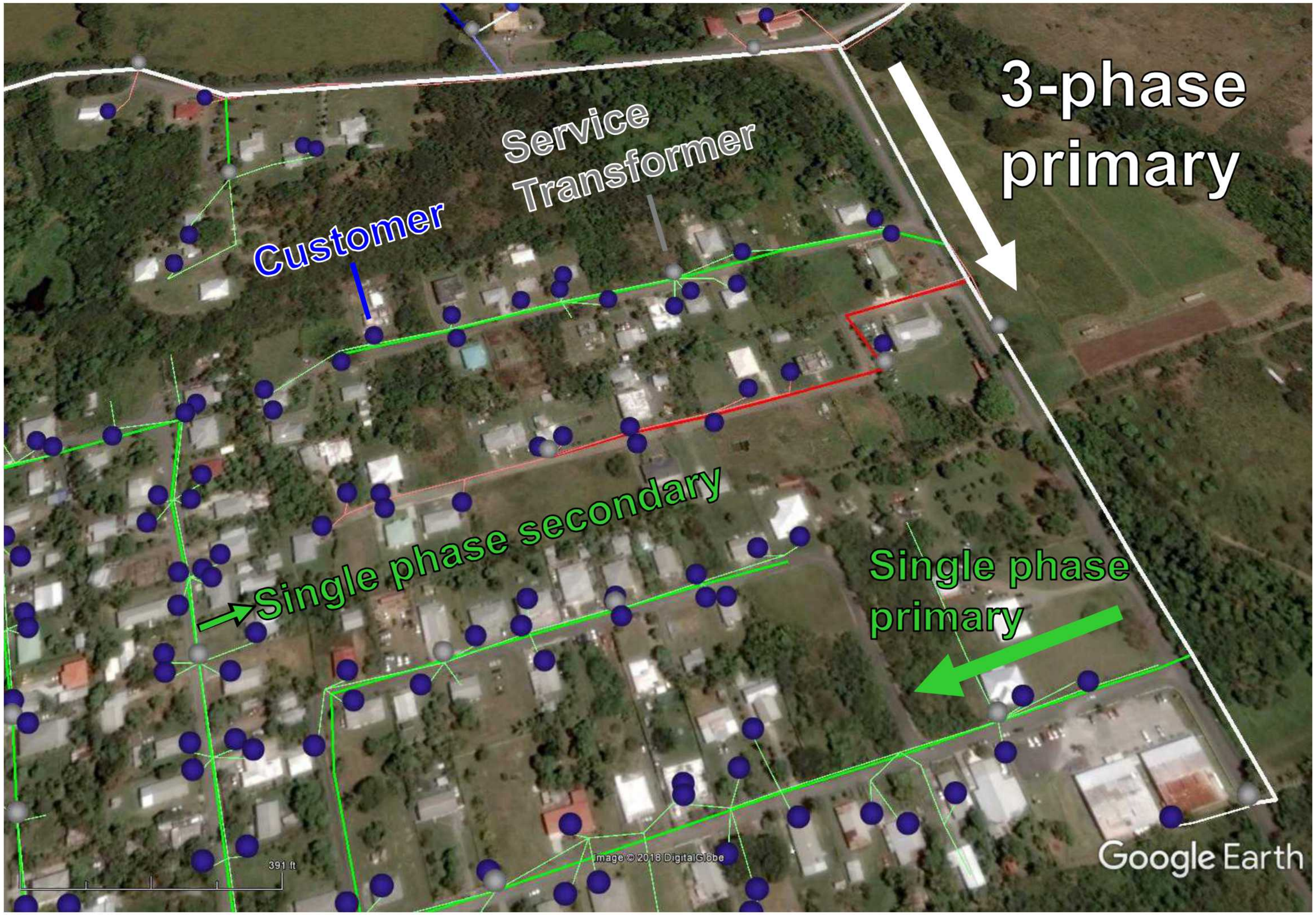
Electricity Supply



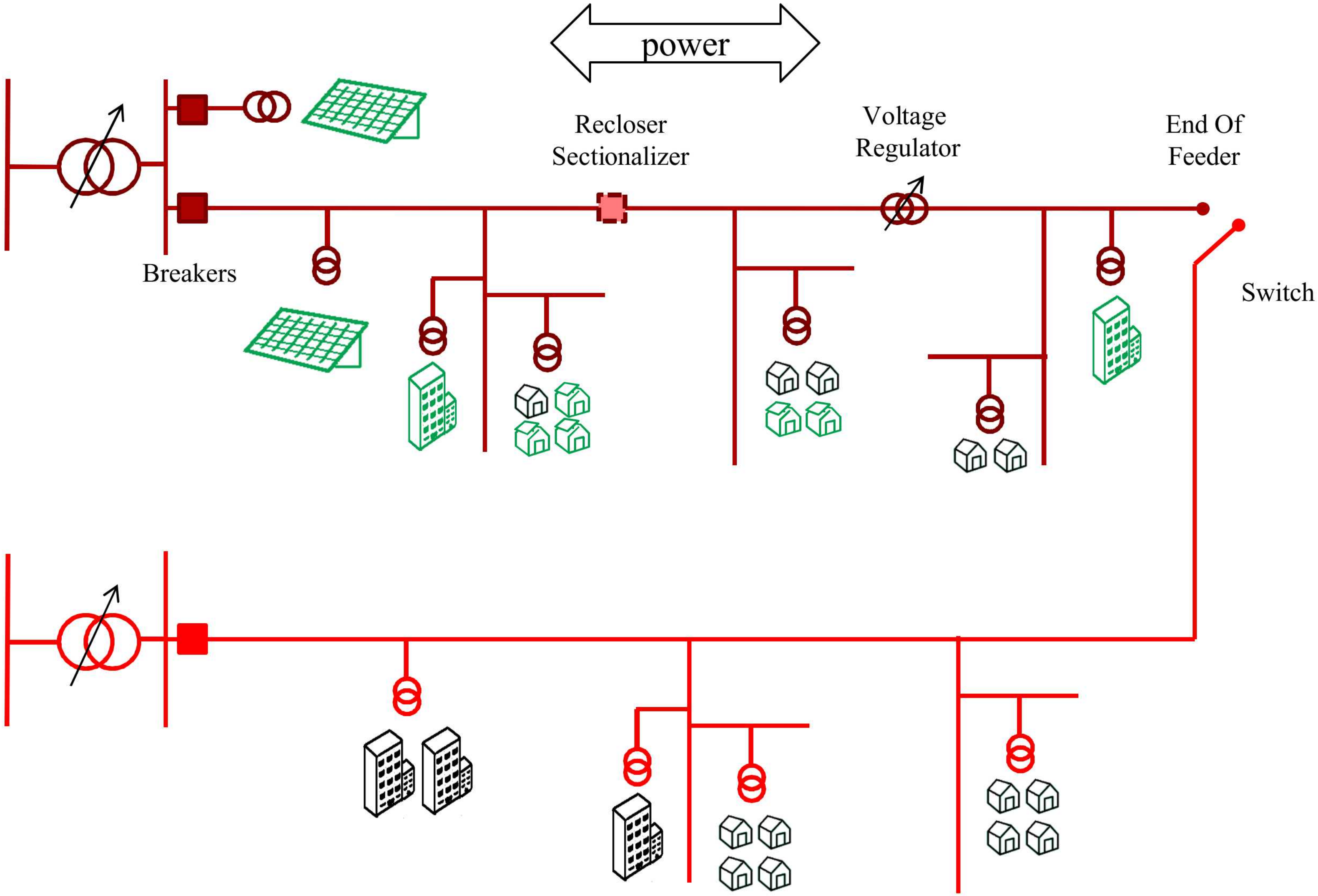
Distribution System



Typical Distribution Feeder

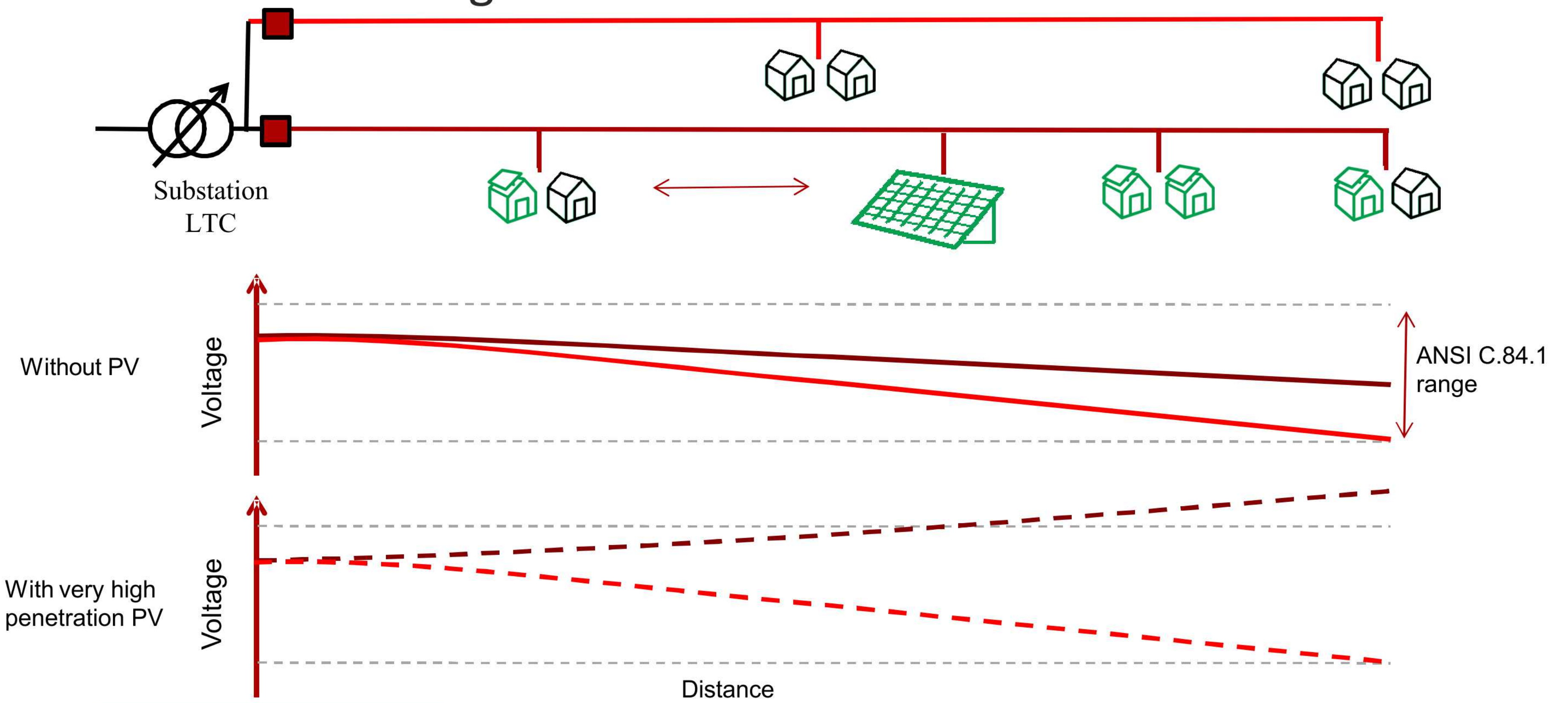


Distribution System with High Penetration PV



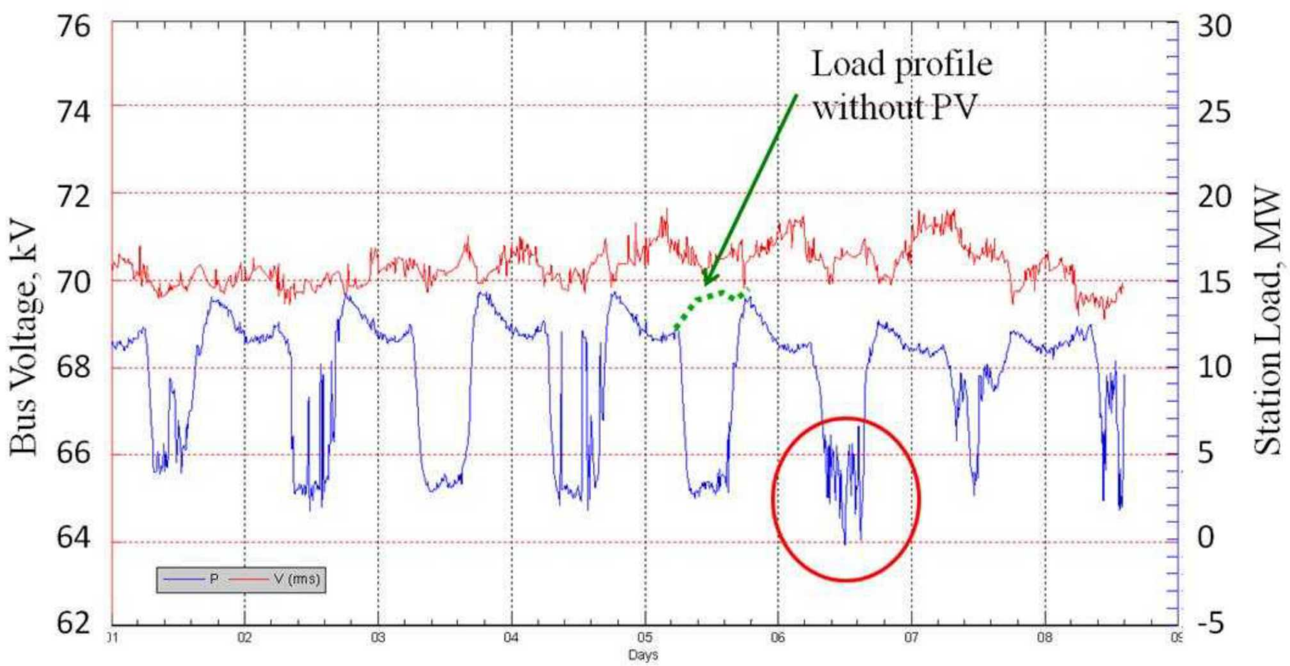
Voltage Regulation Issue

- High voltage at end of feeder
  - Most commonly encountered issue for high penetration PV
  - Worse on long feeders with PV at the end

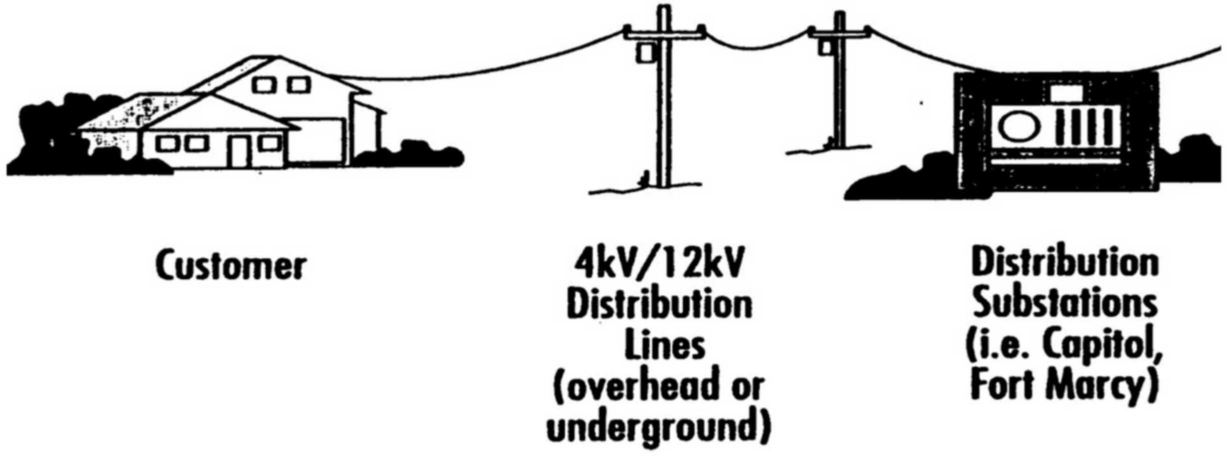


Voltage Regulation Issue

- High penetration does not always lead to voltage issues
  - Short urban feeder
  - PV connected close to the feeder head
- Example below: PV is connected next to strong urban feeder head, station voltage does not change



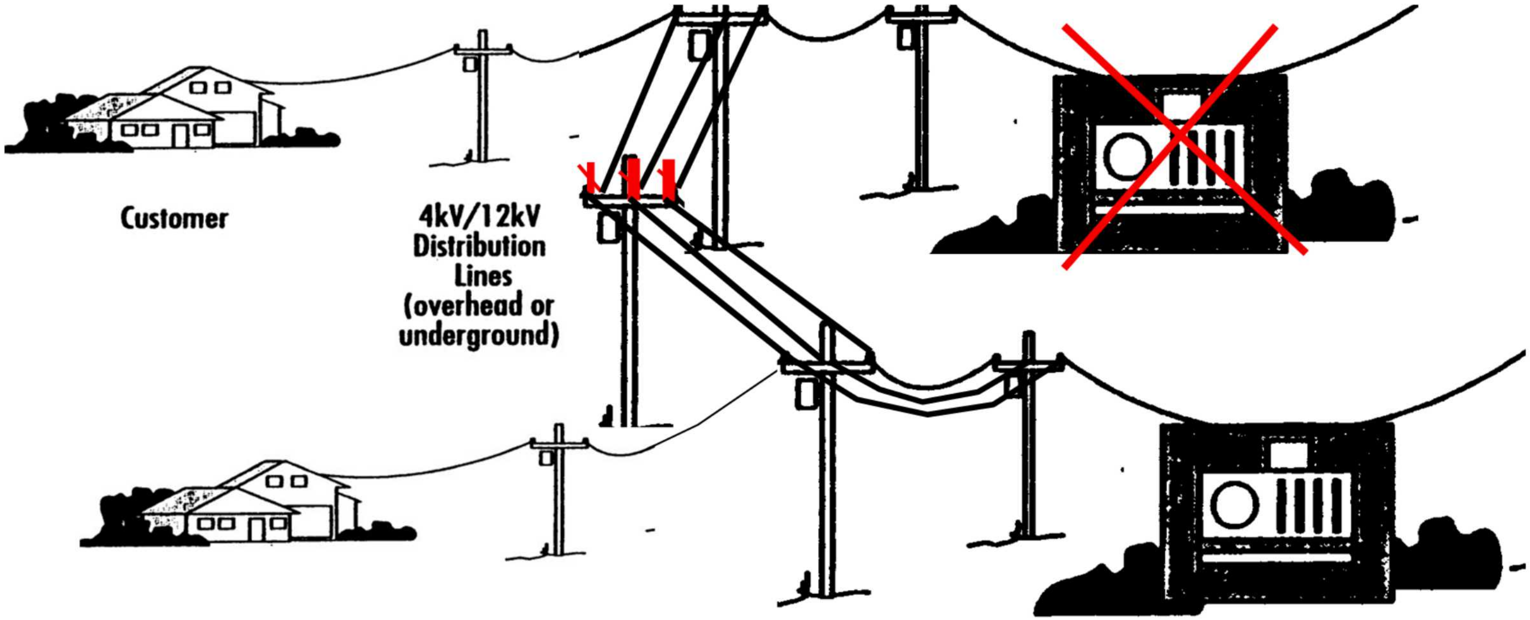
Distribution System Planning



Design Criteria

- PNM must maintain customer voltage at the meter between 126-114V, ANSI Range A, during normal operation per NMPRC regulations.
- Equipment and wire limits must not be exceeded during normal operation.
- Costs must be controlled to keep rates down per NMPRC regulations.

What to do when Equipment Fails?

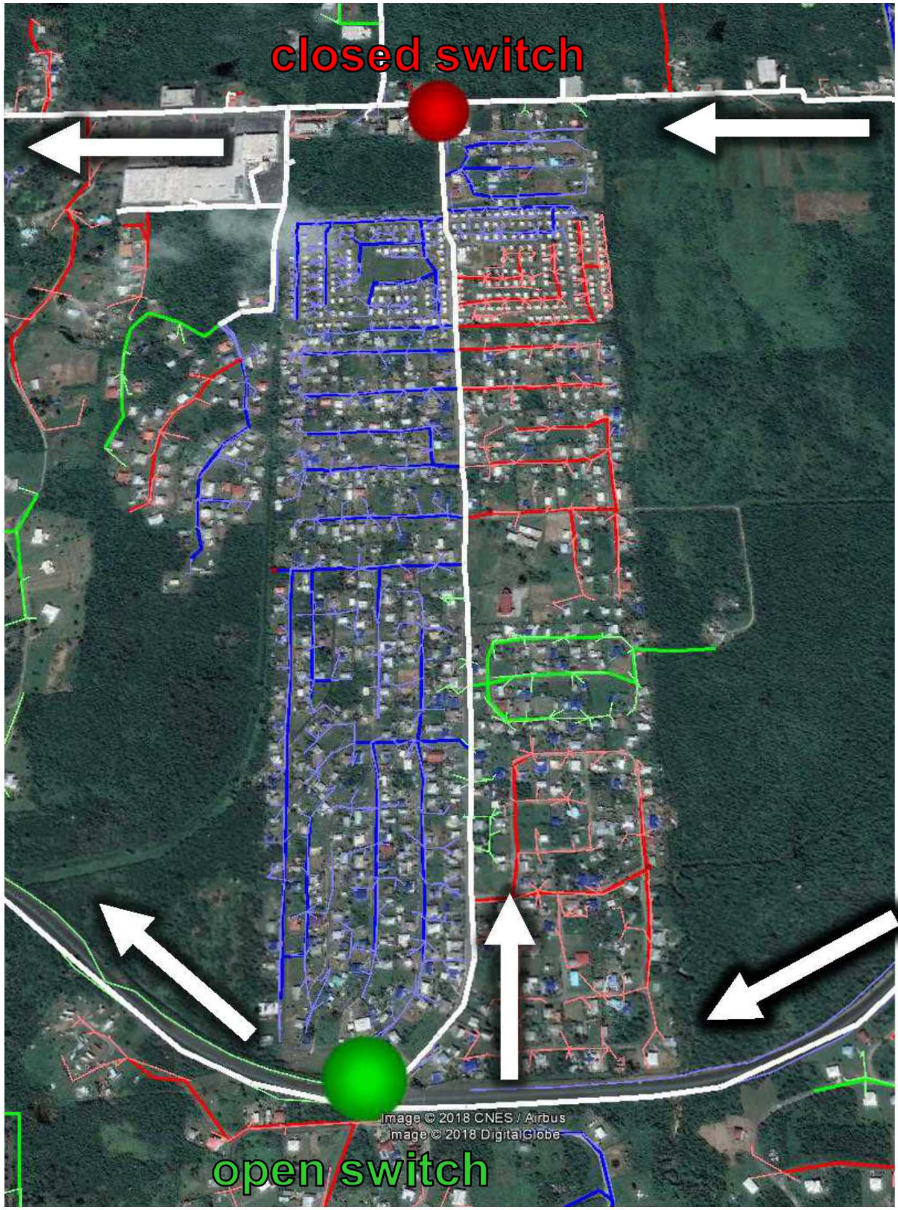


The primary source to an area is transferred to a surrounding area substation.

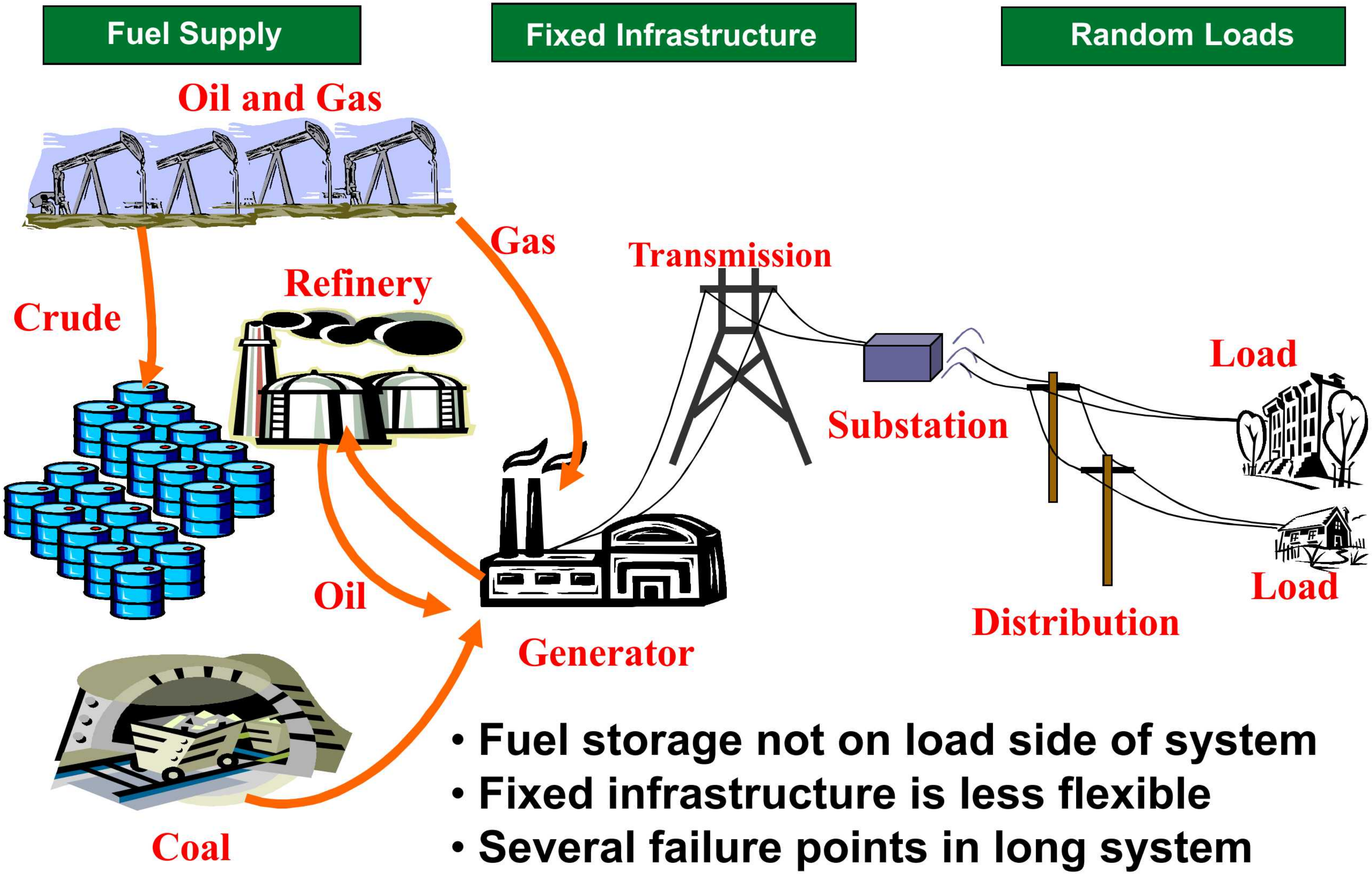
Technical Concerns

- Equipment and Conductors limits must not be exceeded
- Customer voltages at the meter do not fall below 110V (ANSI Range B)
- Transfer to other substation(s) should minimize loss of service to customers

Switches to Adjust Power Flow



Today's Power Grid is Limited in Ability to Meet Energy Assurance Requirements



- Fuel storage not on load side of system
- Fixed infrastructure is less flexible
- Several failure points in long system

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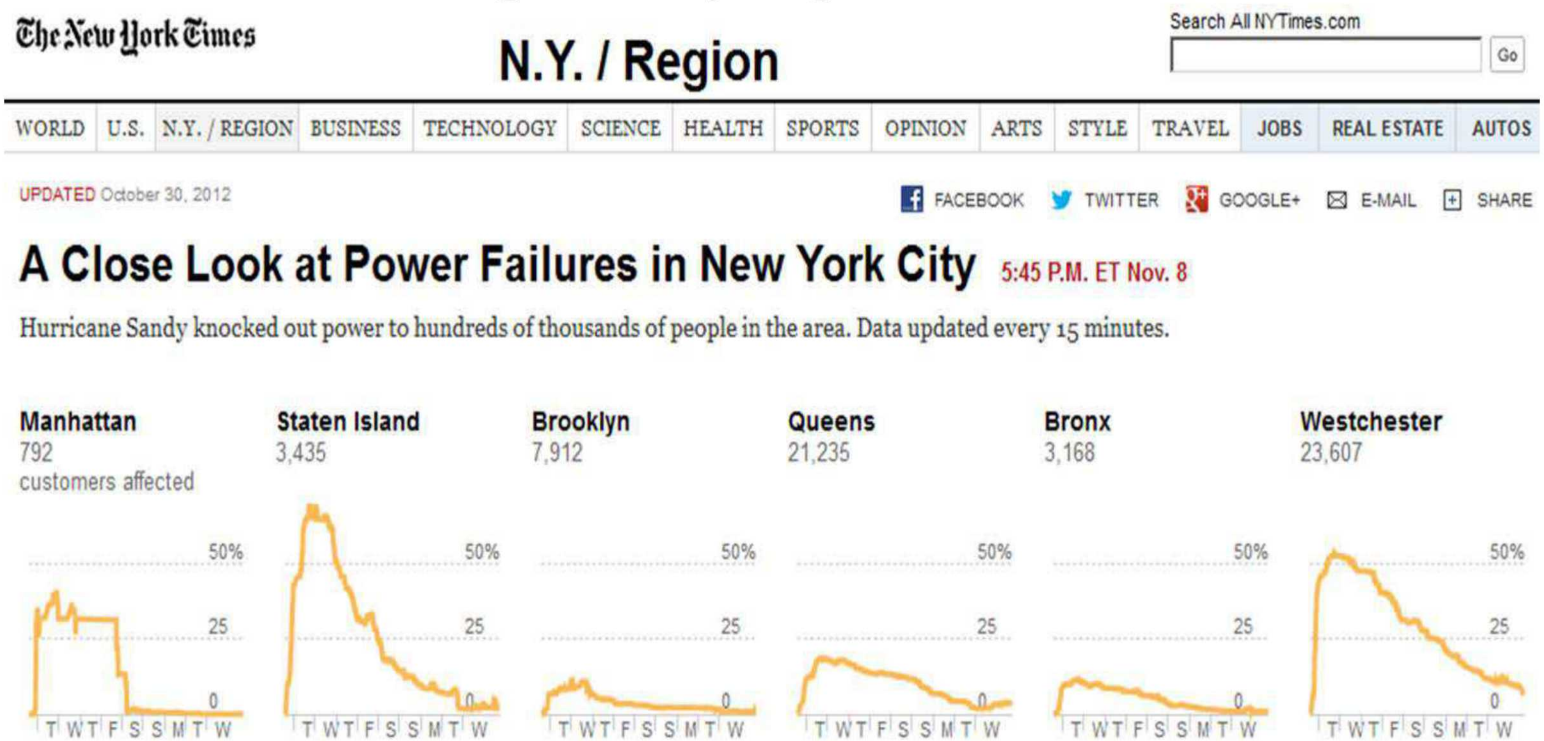
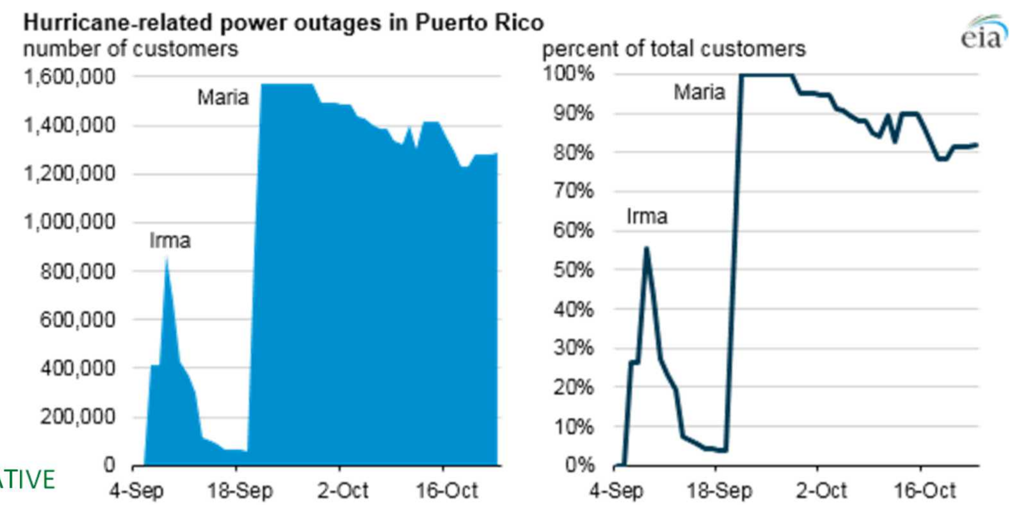
Power Outages Can be Regionally Significant



Major outages can last for many days, which must be considered in design of backup systems.



General Reliability Key Points

- Lightning, Trees, Cable Equipment, Bird, Vehicle, and Overhead Connector Causes are consistently top causes in PNM reliability stats
- 80% of all reliability statistics and events on PNM system pertain to overhead construction.
- Overhead vs Underground Construction Circuit Miles: PNM = 51% Overhead, 49% Underground
- Outage Events longer than 5 hours contribute
    - 18% of all SAIDI Minutes
    - 12% of all outage events
    - 4% of all customers affected.

Energy Assurance Strategy Concerns

- Army base served by two feeders
- Hurricane takes out both feeders
- **Base down for 16 hours**
  - Est. cost $3M
  - Loss of mission capability

- Semiconductor plant served by two feeders
- Forest fire takes out both feeders
- **Chip fab shuts down for 6 months**
  - High-value customers cancel orders due to delay
  - Economic loss forces plant to shut down permanently




Regional outages, slow repair, remote locations impact options and costs

Electric Grid Assurance Strategies

Component Hardening (Protection)	Increase Component Redundancy (Mitigation)	Accelerate Outage Response (Response & Recovery)	Distributed Resources (Mitigation, Recovery)
Harden substations – guards, guns, gates, barriers	Redundant transmission lines	Real-time monitoring of substations and transmission lines	Distribution switch gear improvements to more easily move power around
Harden substation equipment	Redundant substations	Fast response, fast reconstruction	Local energy generation
Harden transmission and distribution lines	Increase connectivity	Maintain spares, extra equipment, pre-planned work around	Renewables and/or alternative fuels
High costs, events beyond design basis	High costs, regional outage issues	High costs, regional outage issues	Medium costs, outage duration issues

Energy Surety Metrics

Energy Surety – Safe, secure, and reliable energy supply for sustained system operations and assured system and mission performance

Performance Characteristic	Definition and Metrics
Safety	Safely supplies energy to end user
Security	Protection of energy supply infrastructure
Reliability	Provide energy when and where needed
Sustainability	Can be maintained for long durations with minimal impact on resources
Cost Effective	Provided at affordable cost
Resiliency	Ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions

Module 2:
Introduction to Microgrids and Advanced Microgrids

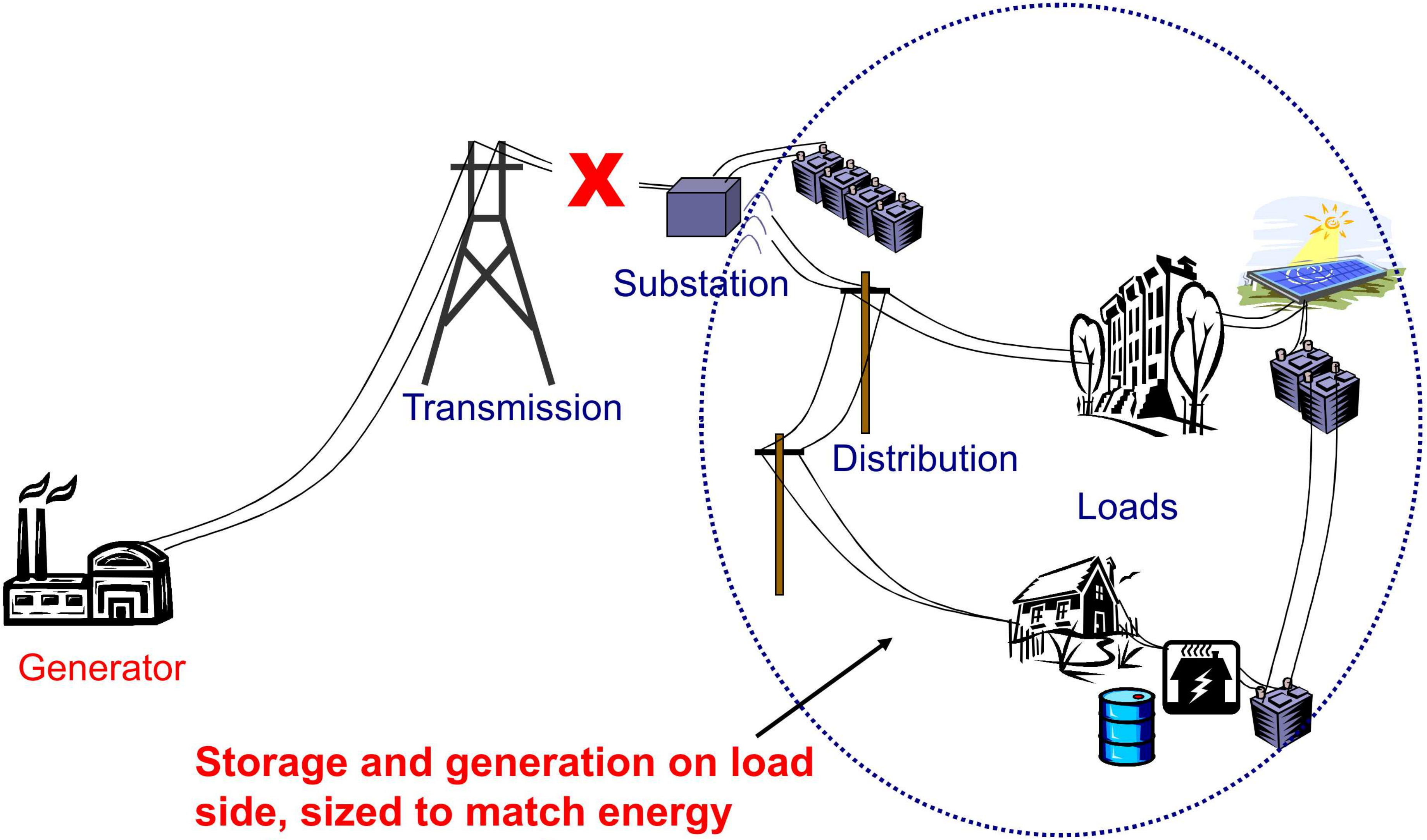
Module 2 – Introduction to Microgrids and Advanced Microgrids

- **Topics will include**
  - What is a microgrid?
  - Categories and functionality of microgrids
    - Standard
    - Advanced
  - Attributes of advanced microgrids
    - Safety, security, reliability, cost effectiveness, resilience, maintainability
  - Capabilities of advanced microgrids
    - Flexibility, redundancy, expandability
    - Peak shaving, load shedding, renewables integration, power quality management, energy efficiency
  - General operation of microgrids

Mathematically - What is a microgrid?

Grid Definition	Generation Size	Commonly Considered Size	Common Attributes
U.S. Grid	~1 Tera watt (1x 10^{12} watts)		High to medium voltage, 4 kVa- 700 kVa
Microgrid	1 x 10^{-6} (US Grid) 1 x 10^{6} watts ~1 MW	500 kW-20 MW	Medium voltage 4 kVa - 34 kVa, three-phase, 4-20 buildings
Nanogrid	1 x 10^{-9} (US Grid) 1 x 10^{3} watts ~1 kW	1-200 kW	Low voltage 120/480 V, often single phase, 1-2 houses or buildings

Microgrids are Generally Associated with the Energy Distribution System



Storage and generation on load side, sized to match energy <u>performance</u> needs

Functionality and Types of Microgrids

STANDARD MICROGRID	• Operates where there is no large grid or operates generally islanded from the larger grid • Often used with a central power plant or CCHP plant to balance power supplies and demand locally (universities, industries) • Minimal grid interaction or support
ADVANCED MICROGRID	• Can operate islanded or grid-tied • Can integrate distributed and renewable generation and manage and control power demand and distributed resource allocation • Supports optimal use of distributed energy resources during both power outages and for grid support
SMART GRID NODE	• Same functional capabilities as an advanced microgrid • Control capabilities to federate with other microgrids, if needed • Grid-tied operations are coordinated through the grid operator to support grid operations and performance, and provide ancillary benefits to the grid

Advanced microgrids are the building blocks for Smart Grid Nodes, which in turn are major power utility building blocks for a Smart Grid.

DOE Microgrid Exchange Group
Advanced Microgrid Attributes and Benefits

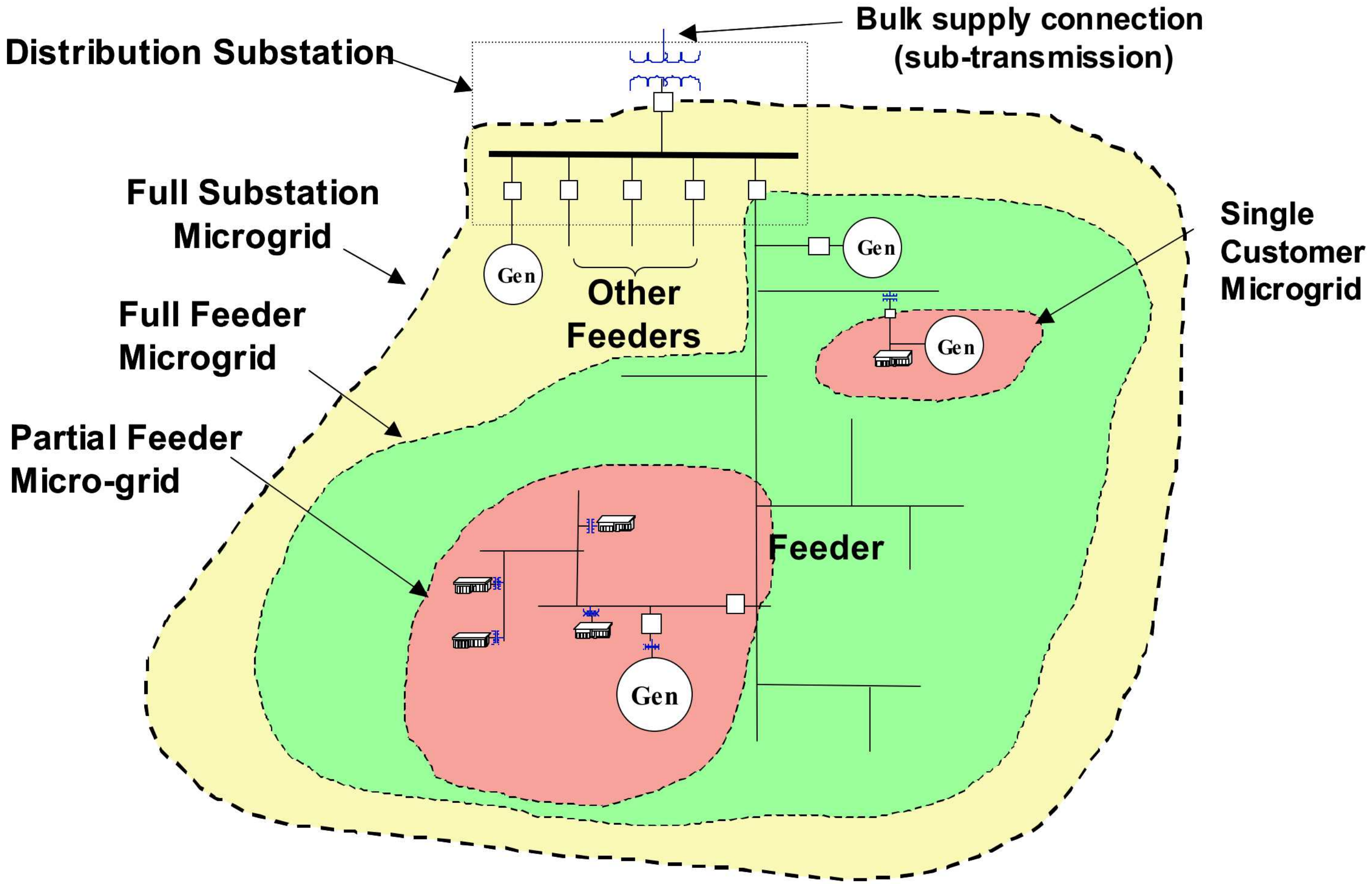
Advanced Microgrid Key Attributes

1. Interconnected loads and generation (multiple distributed energy resources)
2. Ability to operate in island mode or grid-connected mode
   a. Seamlessly connect and disconnect
   b. Maintain load and generation balance
3. Local control
   a. Acts as a single controllable entity to the grid
   b. Provides a point of common coupling for safety
   c. Utilities advanced communication/control technology with cyber security

Advanced Microgrid Benefits

1. Enhances the integration of distribute energy resources
2. Increased reliability
3. Promotes energy efficiency
4. Increased consumer participation
5. Locally controllable power quality and quantity
6. Enables Smart Grid technology integration

Microgrids Can Address Energy Surety Challenges



Applicable to small, large, and even regional scale energy infrastructure security and reliability

Microgrid Point of Common Coupling (PCC)

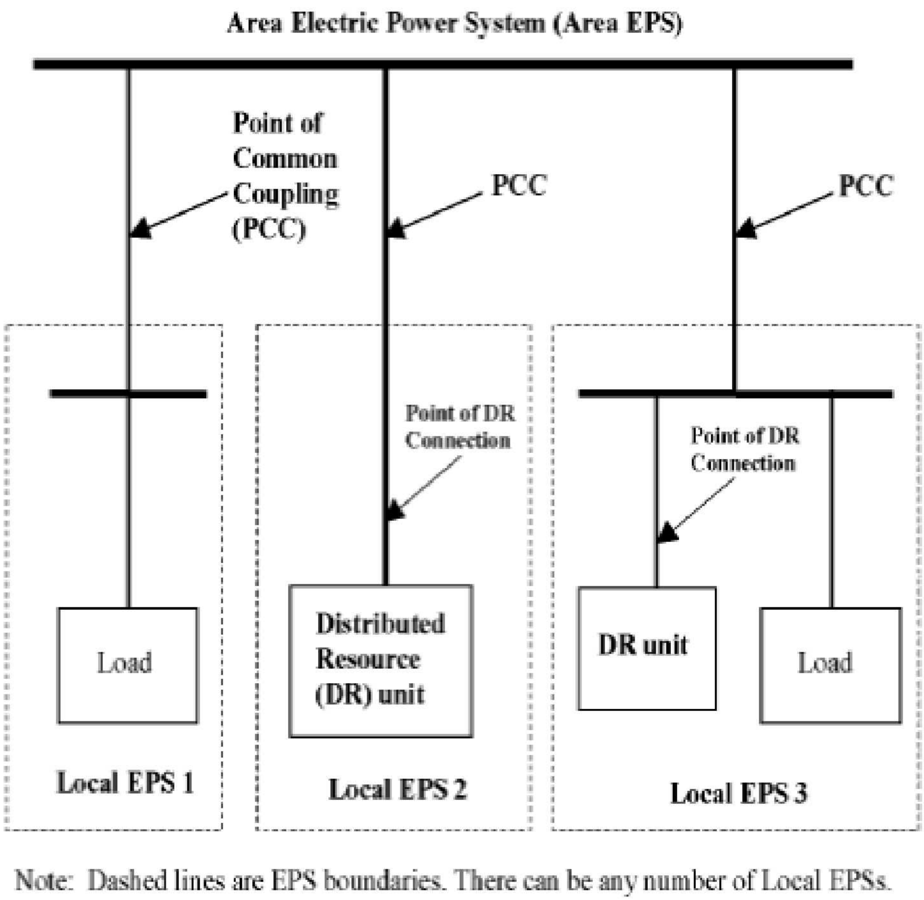


Figure 1—Relationship of interconnection terms

Reference: 1EEE Std. 1547

Unique Elements of Advanced Microgrids

- Point of Common Coupling (PCC) – One or more devices (breakers, switches) which island the microgrid from the utility power
- Power Lines – Overhead and/or underground distribution network - may or may not utilize existing utility distribution system
- Switching devices – Breakers, reclosers, load break switches, manual switches, automatic transfer switches, etc. involved in switching and isolating microgrid elements
- DERs – Local generation and storage units including renewables to supply power to the microgrid – can use exsiting resources
- Other elements –
  - Controls – Local and remote monitoring and controls
  - Protection – Relaying used to isolate system faults specific to microgrid
  - Cyber security – Implementations to secure microgrid controls and data

Capabilities and Benefits of Advanced Microgrids

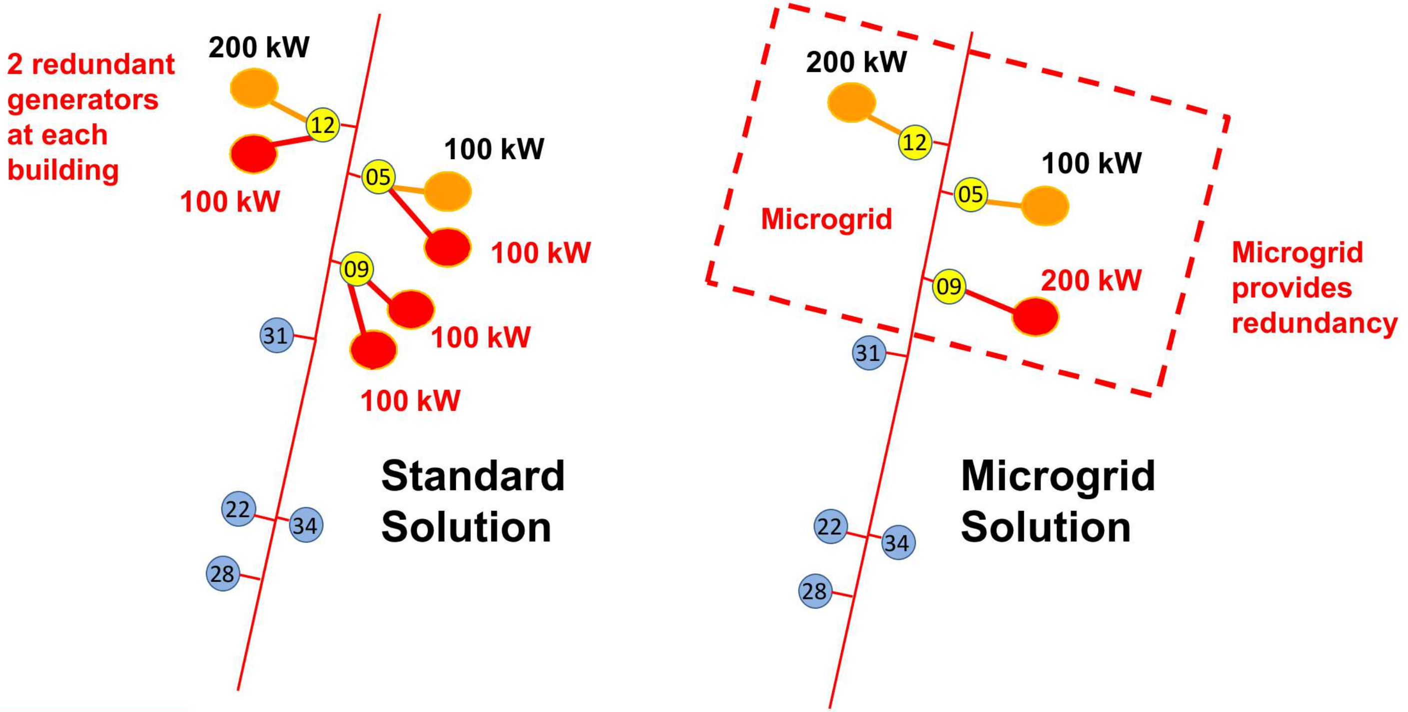
- Peak shaving – normally islanded microgrid can be paralleled with utility to reduce system peaks and lower energy costs
- Load shedding – less critical microgrid loads can be shed if microgrid generation is not available
- Enhanced renewable, storage and CHP integration – microgrid designed to allow use of renewables, energy storage and CHP resources more efficiently
- Power quality – Energy storage and other devices can be used to increase quality of microgrid power

Capabilities and Benefits of Advanced Microgrids

- Efficiency – Microgrid can be designed to integrate with building efficiency and load reduction control devices
- Transmission and Distribution Deferral – Microgrid can defer costs of transmission and distribution assets to meet critical load demand
- Demand Response – Microgrid can operate during peak demand periods offsetting utility demand charges
- Ancillary Services such as Voltage Regulation – Microgrid can supply additional generation to augment system voltage levels through system

Example - How do Microgrids Help

- A standard solution (left) would require installing a minimum of two redundant generators at each building for redundant backup power or four new (red) 100 kW generators, each only supporting one building
- A microgrid solution would require only one new (red) 200 kW generator at one of the buildings for redundant power
  - Loss of any of the three generators would still be able to supply the 300 kW load required for the 3 buildings
  - The combined resources in a microgrid can be used to support the grid



Generation Needs with and without a Microgrid

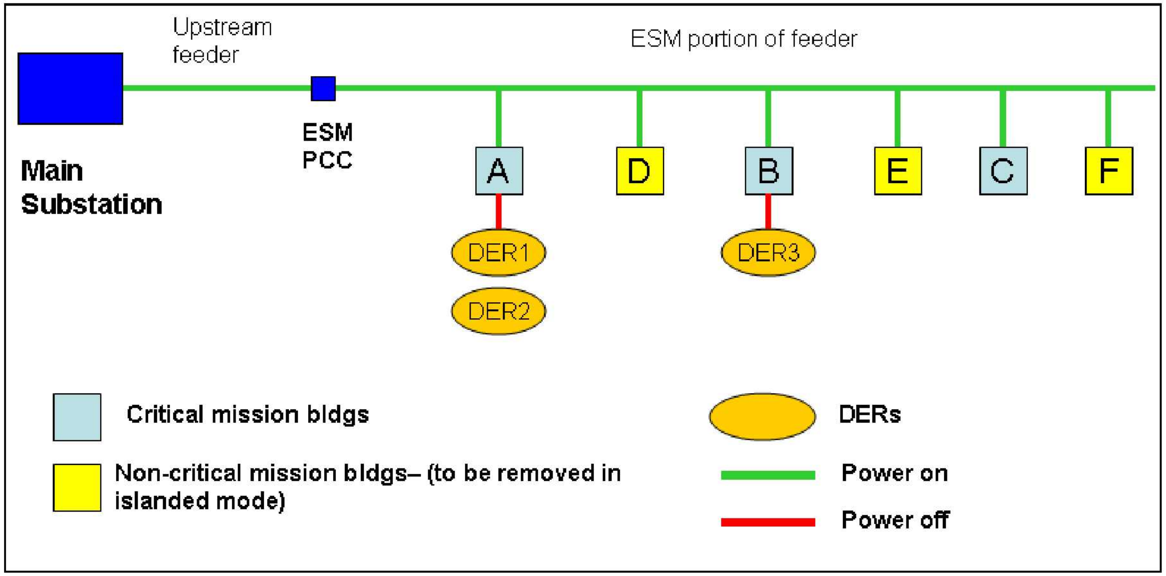
- **Generator reliability – 60%, 85%, and 95% (based on maintenance)**
- **Generators required for 99.5% energy reliability – (unavailability 0.005)**
  - 60% reliability - 6 generators
  - 85% reliability - 3 generators
  - 95% reliability - 2 generators
- **To serve 10 buildings at 99.5% reliability**
  - need 20 generators with good maintenance
  - need 30 generators at average maintenance
- **To serve those same 10 buildings in a microgrid**
  - 11-12 generators with good to average maintenance

NYC After Super Storm Sandy

Microgrid installed in financial district due to Y2k concerns.

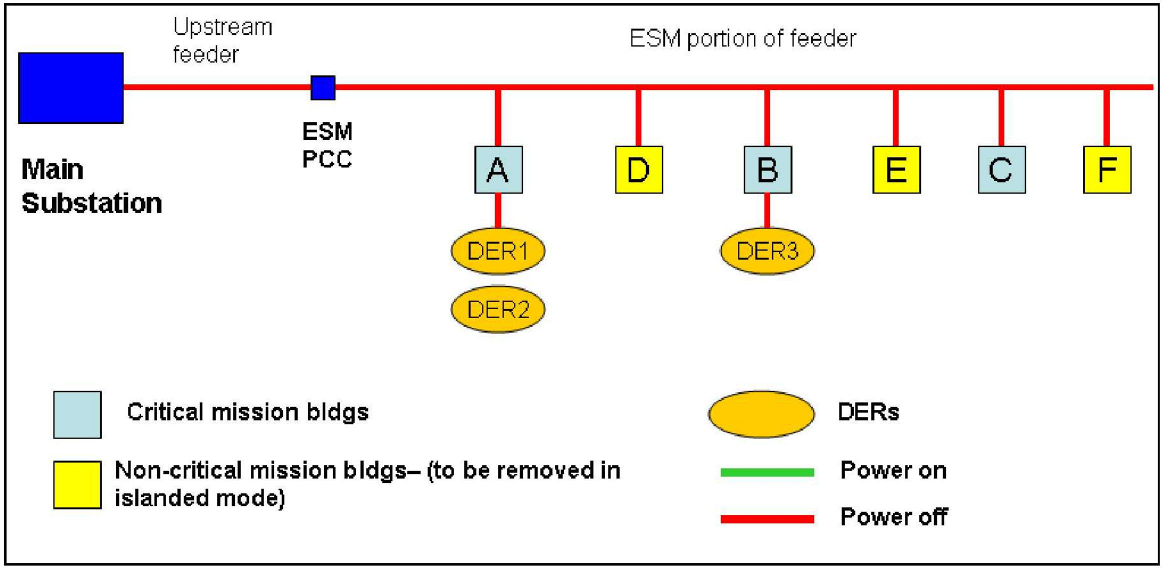
Energy assurance designs at work

Example Microgrid Operation



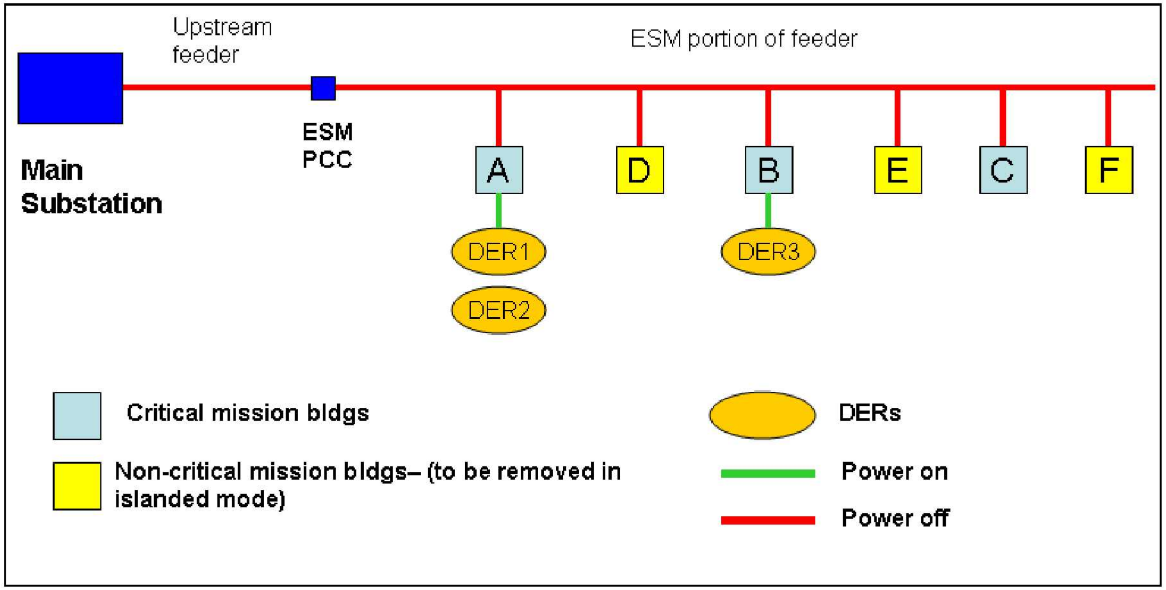
Step 1 – Feeder and microgrid are grid connected (DER – generation resource such as diesel or gas generator)

Example Microgrid Operation



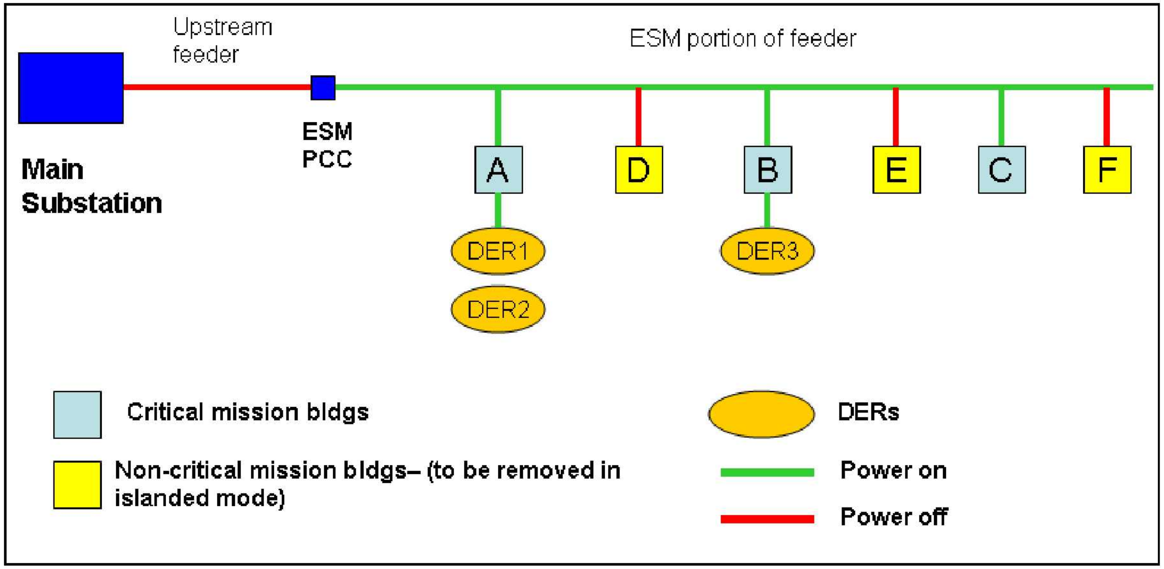
Step 2 - Loss of utility power to Feeder and microgrid (ESM)

Example Microgrid Operation



Step 3 – Generation resources (DERs) start up to pick up critical buildings; non-critical buildings are kept offline

Example Microgrid Operation



Step 4 – Generation resources sync together to form microgrid supporting critical buildings

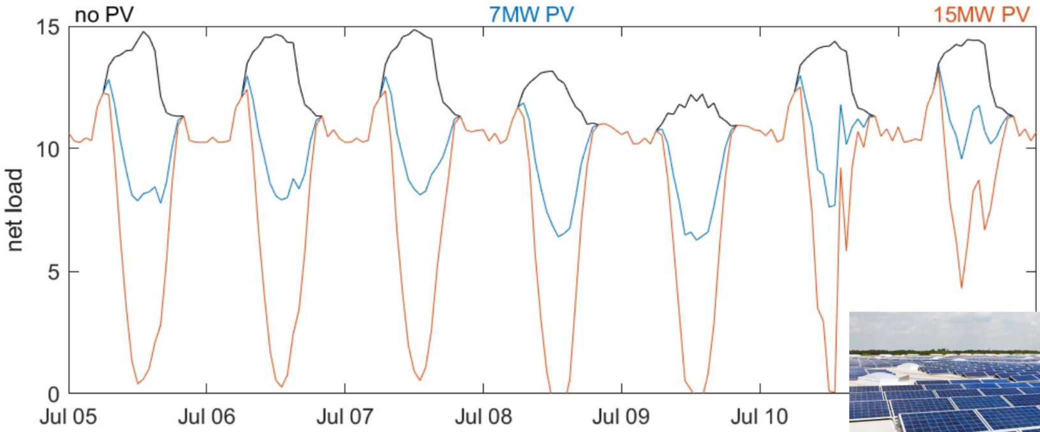
Advanced Microgrid Implementation Lessons Learned

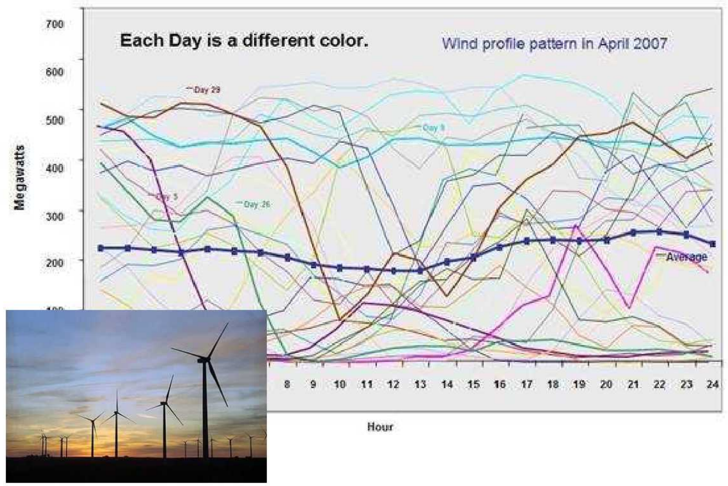
- **Ability to quickly shift between ‘grid tied’ and ‘islanded’ can add major safety, reliability, and resiliency benefits to customers**
  - And have positive externality – help stabilize grid
    - Serve as demand response by islanding to reduce load when needed
    - Provide power to grid or nearby critical services (e.g., water treatment) when needed
- **N+1 generation redundancy is simple with microgrids resulting in high reliability**
- **Full utilization of microgrid benefits for cost reduction require close coordination with utilities:**
  - Utilities are often limited in back-fed power and variable renewable generation they can easily accommodate
- **Critical loads often only 25% of total system load**
- **Technology is advancing – high renewable (70-100%) penetrations are on the horizon**

Challenge and Opportunity of Integrating Renewables

Challenge: solar and wind power output is variable

- May be production vs. load mismatch (e.g., nighttime)





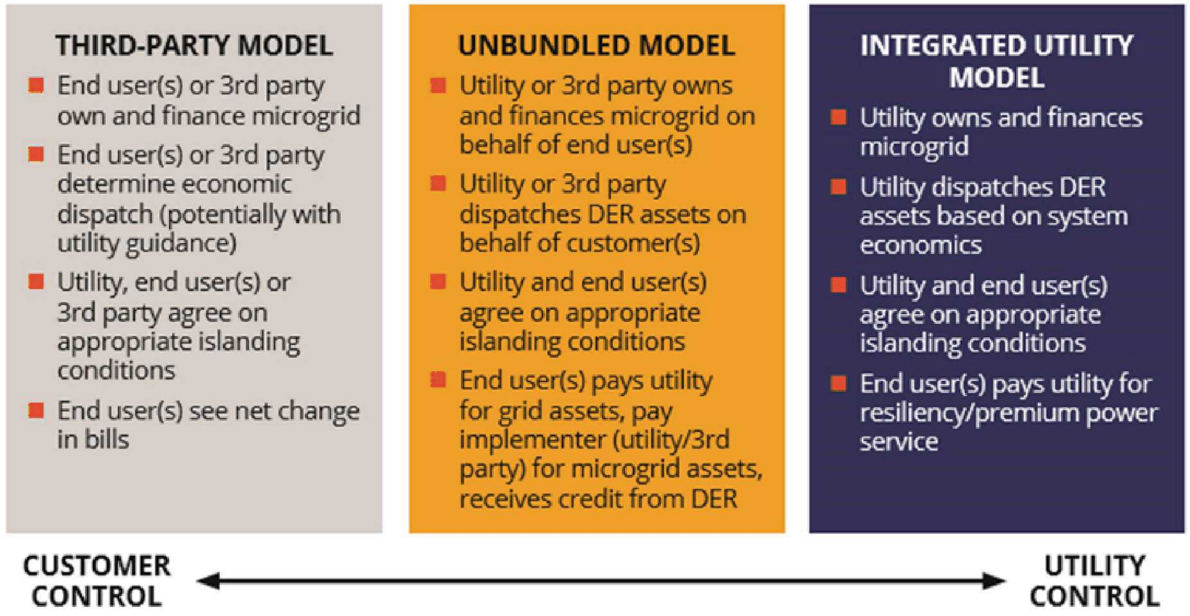
Opportunities

- Cost savings
  - Commercial PV: $0.08 to $0.19/kWh, add ~$0.04 for some storage (Lazard 2017 – LCOE 11)
  - Large-scale wind: $0.03 to $0.06/kWh (Lazard 2017 – LCOE 11)
- Integrate with charge controllers
  - Electric vehicles, pump wells, etc.
- Sustainability and Resilience
  - Operate with no emissions and no need for fuel delivery

Advanced Microgrid Observed Best Practices

- Simple controls and well trained and experienced operators increased microgrid utilization
- Enhanced energy metering at a site consistently increased microgrid use for utility support
- All sites have implemented many simple strategies - circuit-level UPS systems, VFDs, etc. – which has minimized large-scale energy storage requirements
- Renewable energy systems greater than 1 MW partitioned to support feeders or connected to substations, were more easily integrated and utilized
- Microgrids designed to consider longer-term outages and associated changes in critical missions provide greater energy resiliency

Emerging Microgrid Business Models



Microgrid business models are evolving along a continuum, from third-party projects to utility-initiated projects. In between, a hybrid, “unbundled” model based on public-private partnerships is emerging, which could offer more flexibility and opportunities for collaboration.

Assigning value to microgrids—and monetizing a project’s potential value streams—is complicated by the tangle of economic and industry factors involved. Clarity on price signals, rate structures, and regulations are needed for the sector to expand. Characterizing and having confidence in value streams for microgrids over time are likewise necessary for investment in these systems.

Current technical standards can provide guidance on microgrid development, but a more detailed and nuanced set of standards is needed to help ensure interoperable designs, communication and testing practices.

Module 3:
Energy Surety Design Methodology and Microgrids

Module 3 – Energy Surety Design Methodology and Microgrids

- **Topics will include**
  - Emerging energy system metrics and general considerations and needs
  - Energy surety conceptual design methodology
  - Steps involved in development of energy surety conceptual designs for microgrids
  - General process from conceptual design development, microgrid operational approaches, and microgrid installation

Introduction

The Energy Surety Design Methodology (ESDM) provides a systematic approach for engineers and researchers to create a preliminary electric grid design, establishing a means to preserve and quickly restore customer-specified critical loads.

- The ESDM enables users to identify and evaluate alternative design options, and generate design recommendations.
- The methodology includes both process recommendations and technical guidance, with references to useful tools and analytic approaches at each step of the process.

History

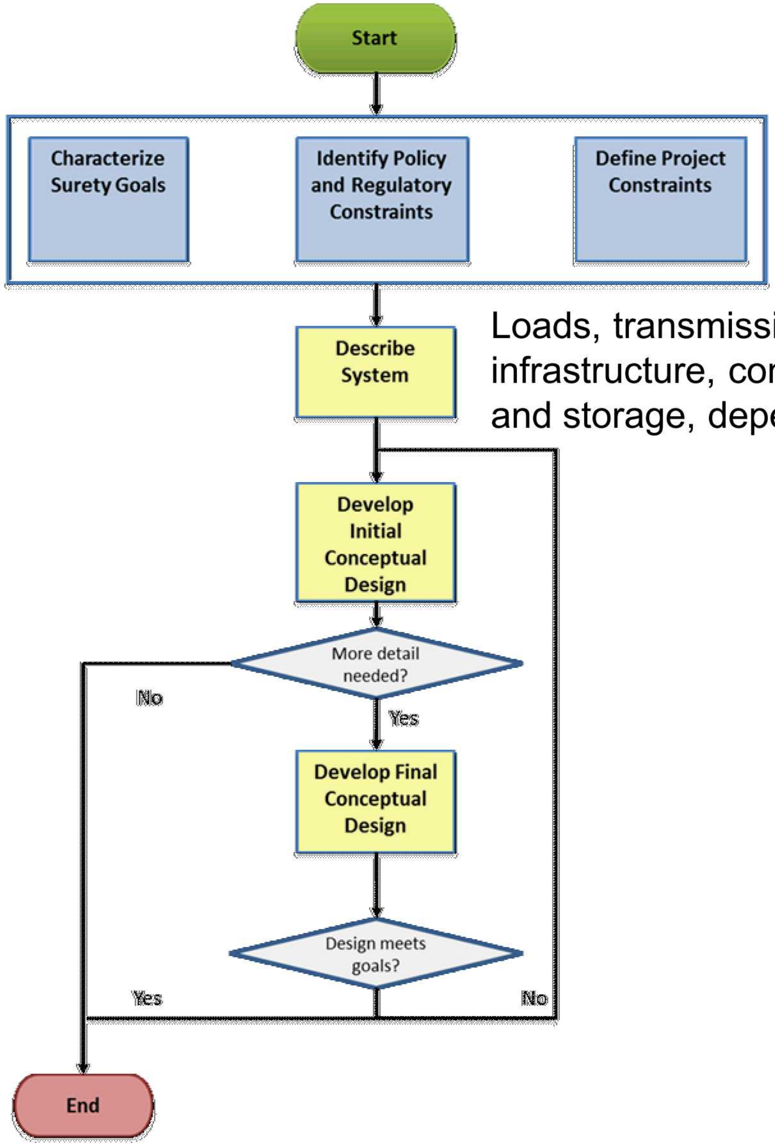
Over a decade ago, Sandia defined Energy Surety for applications with energy systems to include elements of reliability, security, safety, cost, and environmental impact.

Sandia has been employing design concepts of energy surety for over 20 military installations and their interaction to utility systems, including the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) Joint Capability Technology Demonstration (JCTD) project. In recent years, resilience has also been added as a key element of energy surety.

Structure

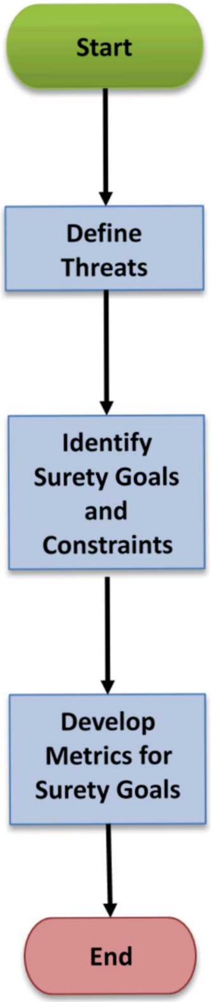
- Method describes:
  - High level methodology and sub-processes
  - Data requirements and resources for data collection
  - Recommended approaches for process steps and applicable tools
- The update methodology goes through two realistic use cases:
  - Military microgrid
  - Utility transmission system

High Level Overview



Loads, transmission and distribution infrastructure, controls, generation and storage, dependencies

Characterize Surety Goals



Define Threats

- Threat characterization is critical to understanding how capable the system must be to absorb and adapt to different types of attacks or natural events.
- When performing an analysis to evaluate surety under multiple hazards, it is important to gather information about 1) the likelihood of each possible threat scenario and 2) the capabilities or strength of each threat. This step of the process is often referred to as the “design basis threat.”

Energy Surety

- Reliability
  - the ability of the power system components to deliver electricity to all points of consumption, in the quantity and timeframe demanded by the customer
- Resilience
  - the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions
- Security
  - includes both physical and cyber
- Safety
- Cost
- Environmental Impact/ Sustainability

Energy Surety - Resilience

- Resilience refers to the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.
- Electric power system resilience is a risk-based attribute of a system. Risk-based means that the resilience of the system is an artifact of three things:
  - 1) a particular threat(s) (e.g., a hurricane or geomagnetic disturbance [GMD] event),
  - 2) the vulnerability of the system, which can be modeled as the ability of the system to deliver electricity to its points of consumption, and
  - 3) the critical operations or functions affected and social consequence(s) of the inability to deliver the quantity or timeliness of the electricity.

Energy Surety- Resilience

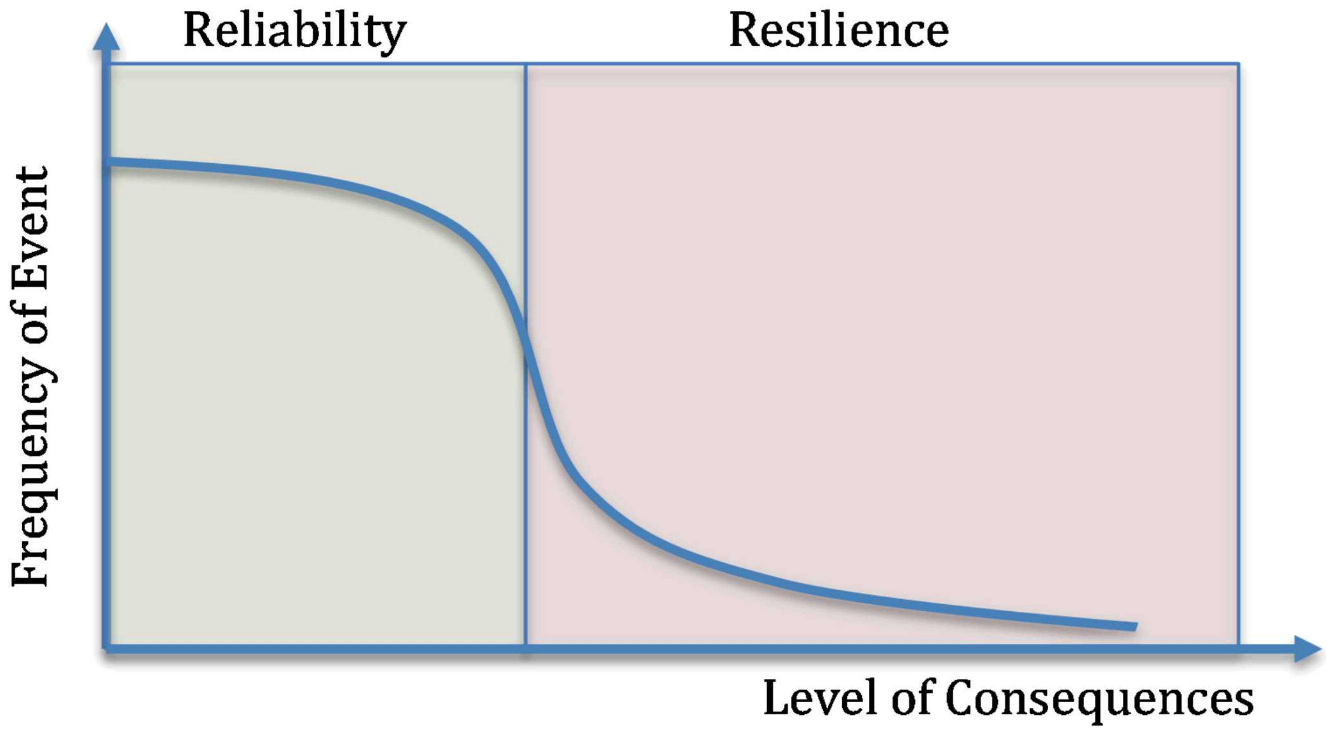
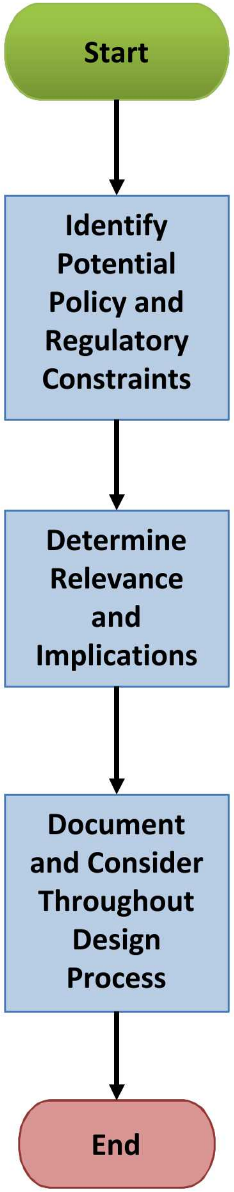


Illustration of Semantic Difference between Reliability and Resilience

Identify Policy and Regulatory Considerations



- Federal, regional, and state regulations, as well as private agreements and other policies, can significantly impact the design alternatives available for consideration.

- The relevant policies, regulations, standards, codes, and agreements should be identified and documented, and then their implications for the project should be determined.

Policy Considerations

Ownership

- Terms and Conditions for Systems with Multiple Owners and Political Jurisdictions
- Safety, Power Quality, and Ownership Liability

Planning

- Siting and Permitting
- Easements and Rights of Way

Operations

- Loads
- Distributed Generation
- Net Metering and Feed-In-Tariffs
- Storage

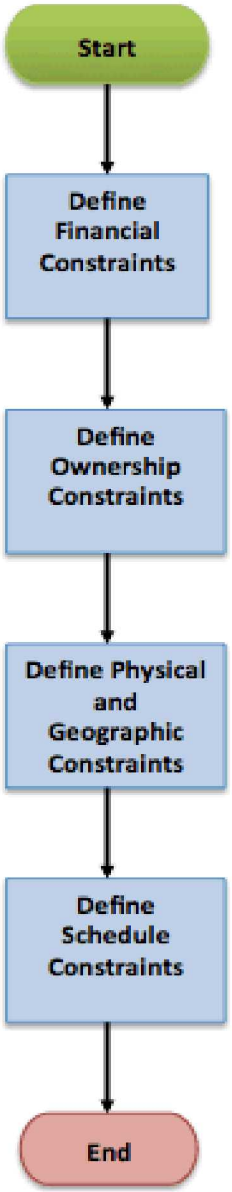
Economic Considerations

- Project Financing and Incentives
- Tariff and Pricing Structures

Define Project Constraints

- **Physical Constraints**
  - Geographic – identify physical boundaries for the power infrastructure
  - Infrastructure Placement – identify environmental constraints for power components (e.g., climate operating boundaries for renewables or storage, soil density for heavyweight components)

- **Financial Constraints**
  - Infrastructure – identify power system components and respective cost
  - Operations – identify operator skill requirements and shift details with cost
  - Maintenance – identify expected cost for maintenance of components and system
  - Marketplace – determine expected business model for financial gain (e.g., ability to participate in any market or need for system to 'pay for itself')
- **Ownership Constraints**
  - Ownership – identify single or multiple owners
  - Operations Responsibility – identify organization responsible for managing infrastructure
  - Maintenance Responsibility – identify organization responsible for maintaining infrastructure
  - Liability Responsibility – identify organization responsible for handling liability cases
- **Scheduling Constraints**



Define Existing System

1. ***Define Loads***
2. ***Define Transmission and Distribution Infrastructure***
3. ***Define Generation and Storage***
4. ***Define Controls***
5. ***Define Dependencies***

- ✓ Identify and document load characteristics for the existing system, including load criticality, location, and density.
- ✓ Identify and document generation characteristics for the existing system, including fuel types, energy output, capabilities, locations, and grid interface capabilities.
- ✓ Identify and document storage characteristics for the existing system, including response rate, capacity, and location.
- ✓ Identify and document controls for the existing system, including input and output signals, sensing equipment, modes of operation, and algorithms for each component.
- ✓ Identify and document dependencies with a broader system.

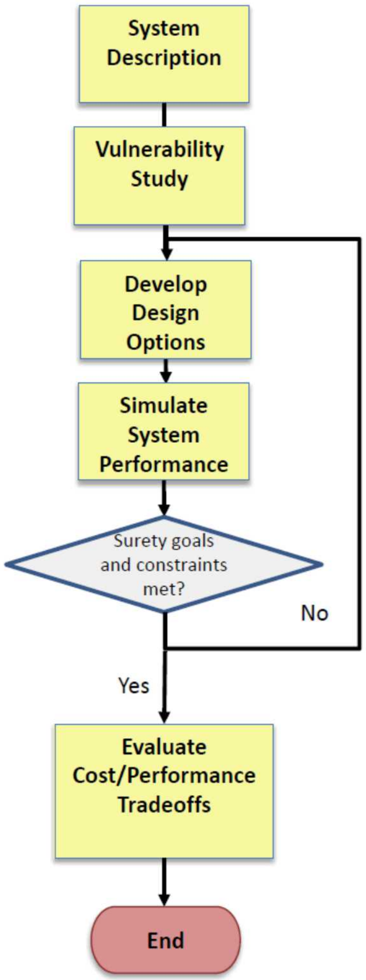
Initial Concept Design

The initial conceptual design phase (10-15% design) is focused on the development of an Engineering Project Definition that proposes an initial energy surety project scope, objectives, and requirements.

The initial conceptual design provides a general description of the major design and construction elements, best locations to enhance energy surety, and suggestions of the elements and operational scenarios to be included.

Once the design options are identified, quantitative evaluation of the system-level impact of the proposed design options must occur, typically through simulation or optimization. A more in-depth description of the process for developing a frontier of optimal design options is described in the Final Conceptual Design section.

Develop Initial Concept Design



The initial conceptual design sub-process begins with a vulnerability study to determine parts of the system most likely to be impacted by the events described in the Design Basis Threat.

For example, parts of the system that are especially vulnerable to flooding might be identified as possible locations to add flood hardening or redundancy.

The design options identified for consideration will represent a set of options that could potentially improve the surety of the system for the metrics that were identified early in the design process.

Study Area \ Data required	Network	Electrical network	Sensors	Protection	Contingency Procedures	Outage rates	Equipment Data	GIS Data	Facility One-lines
Steady state Power Flow		✓	✓				✓	✓	
Interconnection study (QSTS)		✓	✓	✓			✓	✓	
Reliability		✓			✓	✓			
Protection		✓	✓	✓			✓		✓
Controls		✓	✓						✓
Communications		✓	✓						✓
Resilience		✓	✓	✓	✓	✓	✓	✓	✓
Planning		✓	✓	✓	✓	✓	✓	✓	
Economic	✓								✓

Example of data requirements guidance for electric distribution system studies

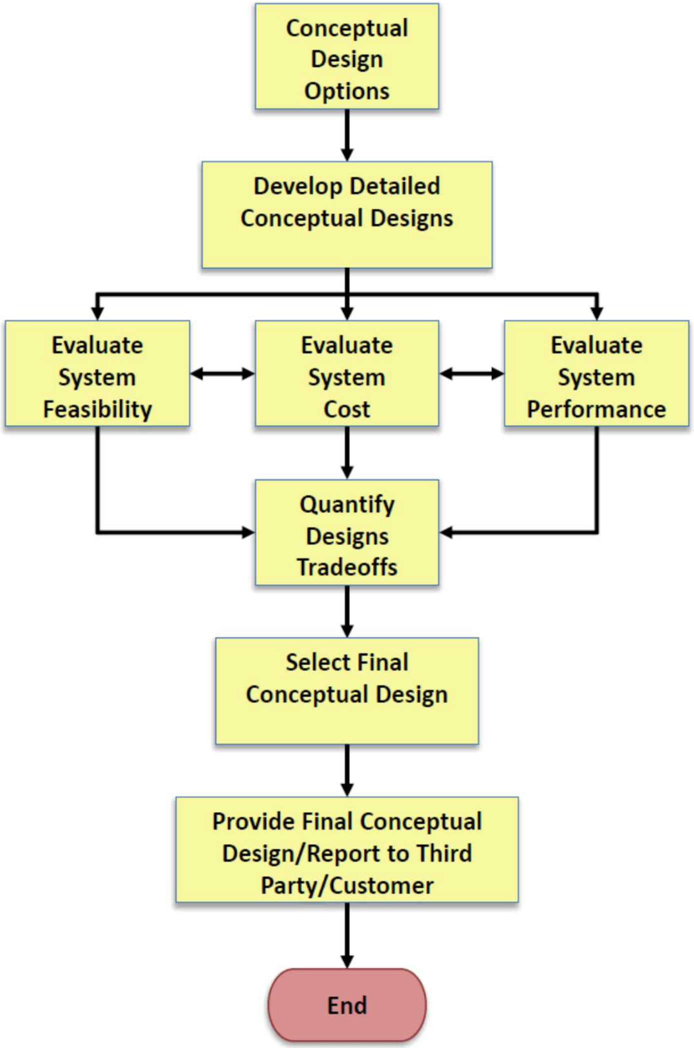
Develop Final Conceptual Design

Development of a final conceptual design (30% design) starts by taking inputs from the initial conceptual design process. The initial conceptual design renders several options for meeting the same set of surety goals by either using different technologies or deploying similar technologies in different manners.

The final conceptual design takes these initial conceptual designs, expands them using more accurate models/descriptions or fills in blanks that the initial conceptual design may have left, and performs detailed studies to determine which option should be implemented by an A&E firm or similar entity.

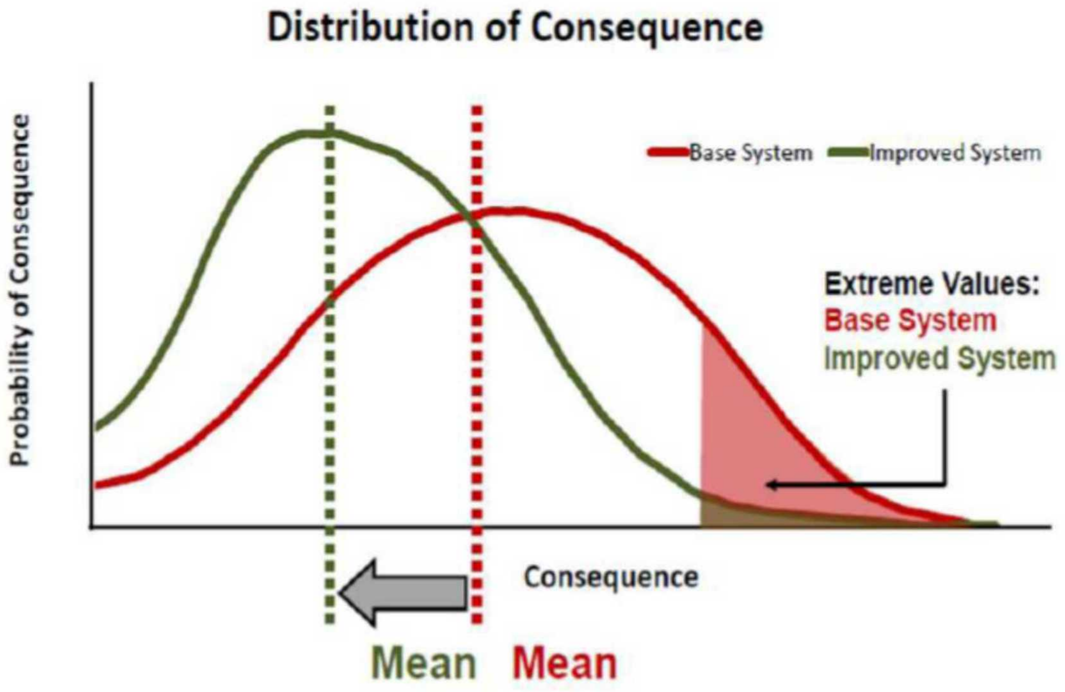
This value engineering is based on several factors such as feasibility, cost, and performance.

Develop Final Conceptual Design



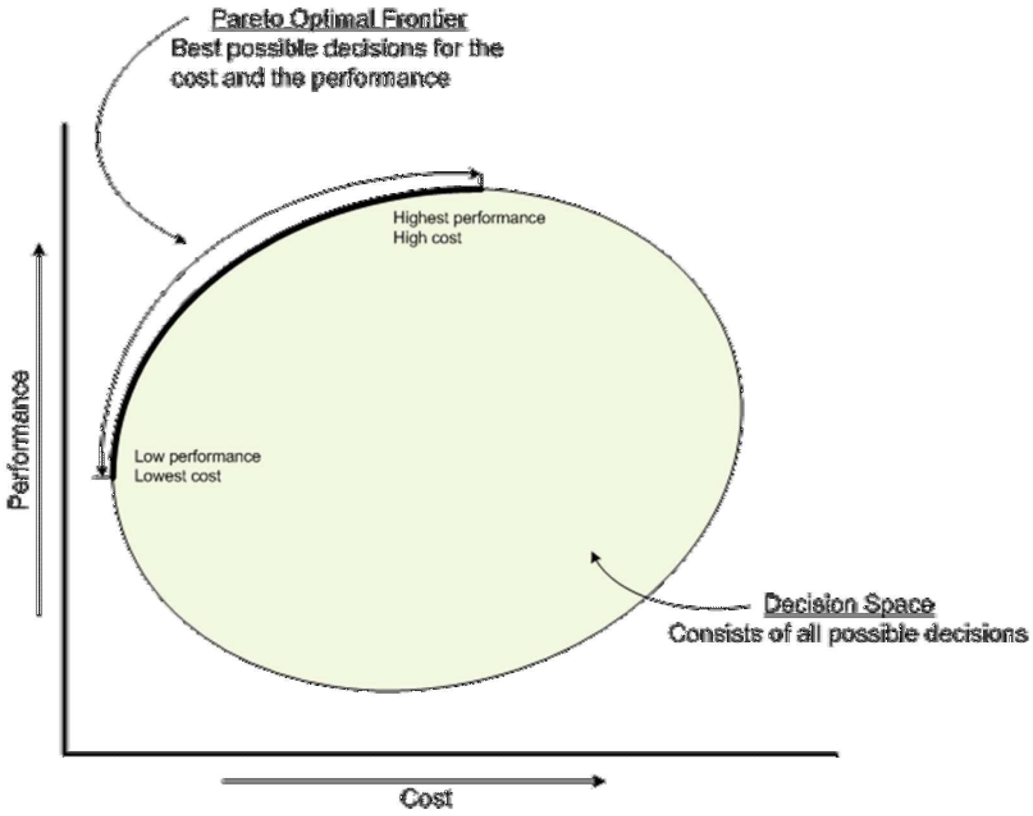
Develop Final Conceptual Design

A final conceptual design outlines the tradeoffs in cost and performance as related to varying potential designs of a system, and describes how the system will operate under each design to meet performance and cost requirements.



Develop Final Conceptual Design

Moving to the final conceptual design phase involves narrowing the design options to select a single design via evaluation against surety goals. Evaluation against surety goals typically involves development of a Pareto frontier of alternatives, which could potentially meet the goals and constraints identified early in the design process.

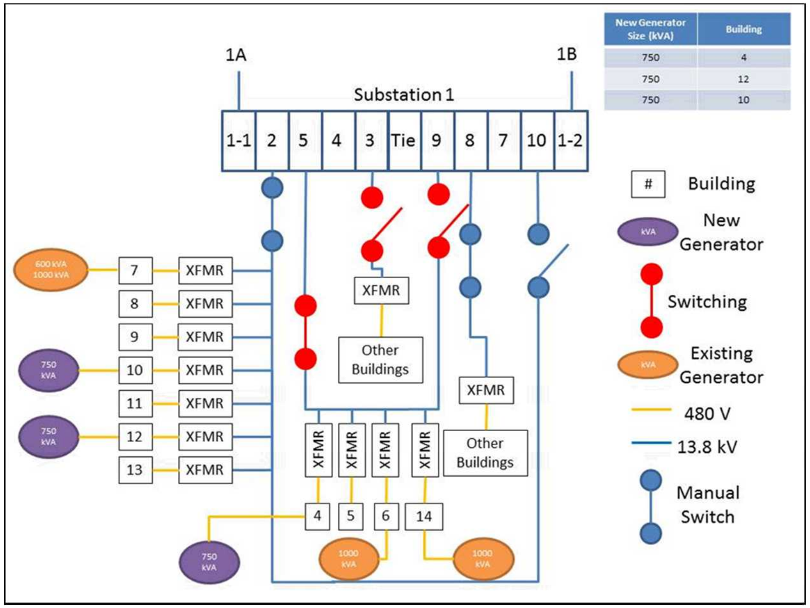


Each point in the decision space depicted in the figure represents a conceptual design option, and the best possible decisions are the ones along the Pareto frontier.

The Pareto frontier illustrates trade-offs between expected performance improvements from each proposed design alternative and cost of implementation. Selection of a specific design from this frontier is based on stakeholder priorities

Military Use Case

- Energy surety design for a base with a population of 15,000 military personnel in a desert environment
  - Threats include flooding, wind, heat (rolling brownouts). Stakeholders selected heavy summer rainstorms as the primary concern.
  - Stakeholder goals are to reduce energy cost and increase energy security while enhancing the existing reliability and reducing critical load not served



Initial energy surety design for Substation 1 (PSLF)

Configuration	FOI (% DBT)	Cond. EENS (kWh/h)	EIR	Cost ($M)	Modification
Option A	0.685	0.069	0.99985	$6.9	Included 1000kVA generator in Substation 1 and a 1200kVA and 560kVA generator to Substation 2. These generators are added to supplement the loss of any given generator when system is separated from the utility provider outside the base.
Option B	0.001	0.016	0.99999	$10.4	Modifications from Option A plus changing the manual transfer switches to automatic transfer switches and adding controls and monitoring on top of the switches.

Options on Pareto frontier from MDT analysis

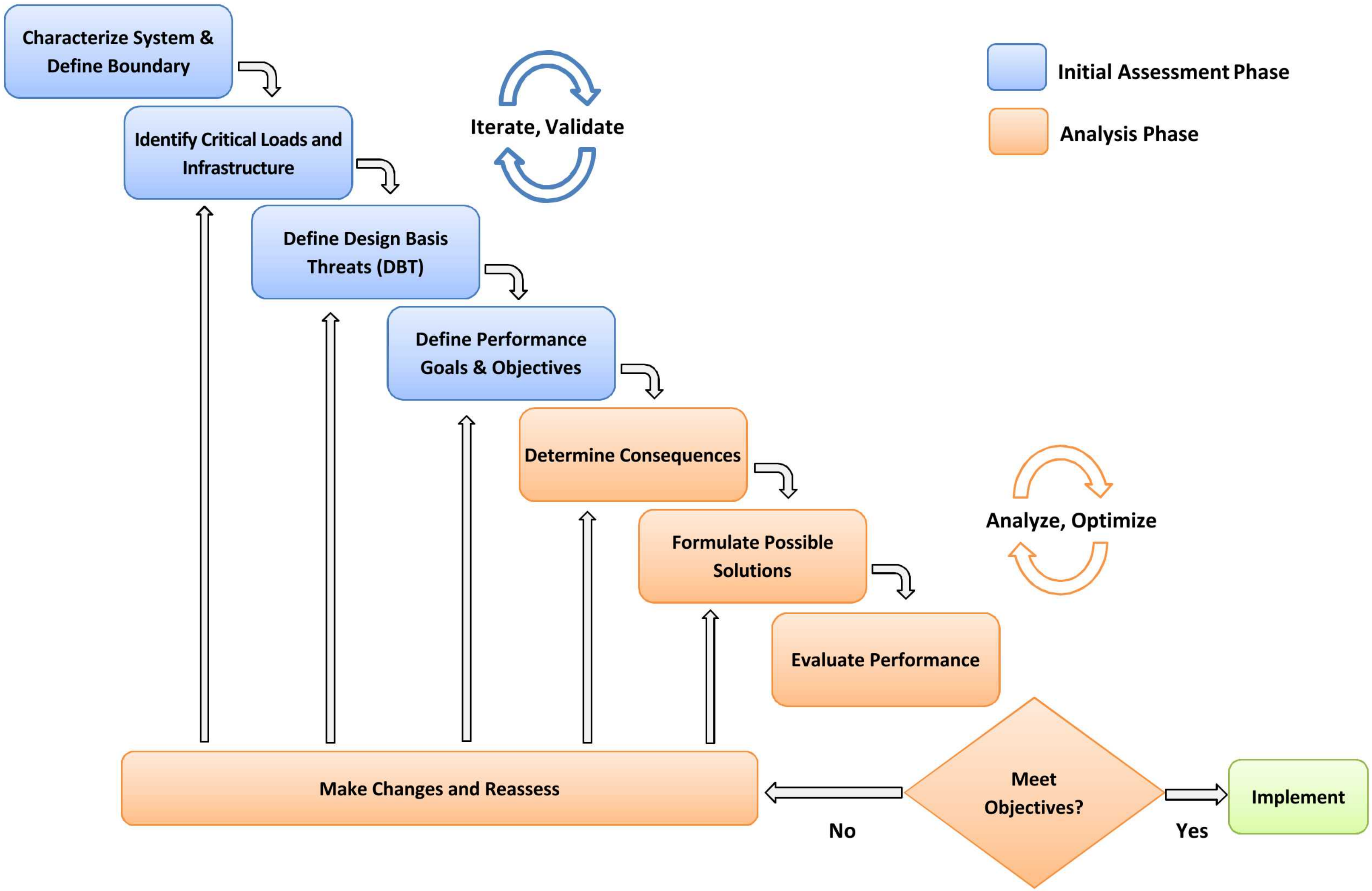
Utility Use Case

- Energy surety analysis for an electric utility in the northeast region of the United States with 25 GW of electric power generation, 6,500 miles of transmission lines, and 5 million customers
  - Surety goals are to increase resilience against geomagnetic disturbances using the existing infrastructure, minimizing operational cost impacts and maintaining the other surety characteristics at current levels
  - Main technical challenges are that the voltage stability margin is mathematically not well defined and the standard AC optimal power flow formulation is non-linear and difficult to solve

Design alternatives for evaluation		
Change generator set points	Install GIC blocking devices	Add voltage support devices

  - Resilient dispatch was selected, final Pareto frontier for stakeholder selection reflects trade-offs between cost of changing the generator set points and the reduction of voltage collapse occurrences.

Energy Surety Design Methodology



Summary

This methodology includes both process recommendations and technical guidance, with references to useful tools and analytic approaches at each step of the process.

The intent of this methodology is to provide enough information to allow the designer to develop a final conceptual design, which could then be handed off to an Architecture and Engineering (A&E) firm for detailed design and implementation.

The ESDM enables users to identify and evaluate alternative design options, and generate design recommendations. Examples of possible energy surety improvements to be studies with this methodology include building additional transmission and distribution systems to provide energy supply redundancy, hardening transmission and distribution systems to make them more resistant to storms or attacks, adding additional onsite energy generation and storage systems to protect critical buildings or services and critical mission functions, or the use of microgrids.

Module 4:
Defining Energy System Boundaries

Skipped – see coursebook

Module 5: Identify Critical Assets and Services

Module 5 –
Identify Critical Assets and Services

In this module we discuss the process of:

- First, meeting with key stakeholders to identify community services and critical infrastructure assets needed for normal as well as emergency operations
- Listing key facilities (assets) associated with the critical infrastructure services, including interdependencies
- Prioritizing critical services, and then relevant infrastructures and assets in terms of importance to stakeholders in tier groups
- Begin to think about what is needed to enhance resilience for each critical service in terms of performance goals aimed to address the design basis threat (DBT) considered

Community Services are Supplied by Critical Infrastructure Assets

Community Services		
Electric Power	Food	Evacuation
Drinking Water	Emergency Response	Medications
Dewatering	Communications	Safety
Sewerage	Finances	Security
Medical Services	Transportation	Shelter

Work with stakeholders to understand which assets contribute to each service.
The goal is to enable service availability by identifying the correct assets that contribute to that service.

Example: To enable an evacuation service requires multiple critical infrastructure assets including evacuation sites, operation centers, wire centers, rail stations, bus stations, police, emergency operations center, cell towers, etc. Each of these assets may have a different level of criticality to the service.

Hierarchy of Critical Infrastructure Assets for Microgrid Inclusion

The hierarchy implies priority for restoration or placement on a microgrid, but the individual assets cannot be considered in isolation. Consider each assets contribution to community services.

Example Hierarchy of Critical Infrastructure Assets		
Tier 1 • Public Safety Answering Points (911 centers) • Emergency Communication System • Emergency Operations Center • Water Pump Control Center • Hospitals	Tier 2 • Drainage Pumps • Shelters • Fuel Storage • Medical Centers • FM and AM Broadcasts • Sewer Pumps • Water Purification	Tier 3 • Evacuation Sites • Banks • Pharmacies • Gas Stations • Sewer Treatment • Grocery Stores • Fire Stations • Police Stations

Example: Wire centers enable evacuation, safety, security, finance, emergency logistics, and communication services. So the resilience benefit of including a wire center on a microgrid may be different than including a grocery store that contributes to food, water, and medication services. The right tradeoff depends on the service needs of the community in the area of study.

Example of Stakeholder Rankings of Critical Assets Needed for a 2-day and a 5-day Power Outage

Asset	Building or Asset Name	Group A	Group B	Group C
1	Public Works Garage			
2	Fire Department - HQ			
3	Police Department - HQ			
4	WTP + Low Lift Pump			
5	WWTP			
6	Radio Towers and System: Fire/Police			
7	High School (Emergency Shelter)			
8	WWTP Flood Control System			
9	Flood Control - Remote Sewer Pump System			
10	Municipal Building			
11	Food and Gas			
12	Fuel Company			
13	Cell Towers			

Building additions for a 5-day outage

Note: Stakeholders have different views, and some critical functions are missing

Module 5 Exercise

5.3 Module 5 Exercise

Assign the following general services and facilities high, medium, or low priorities. Assign each facility a category of service (e.g., grocery stores applies to the "Food" service) to help map facility priorities to service priorities.

	Service	Priorities (H, M, L)	#	Facilities	Priorities of Facilities (H, M, L)	Facility Category Service
1	Comm. (Radio and Phone)		1	City Hall		
2	Data Service/Internet		2	Public Works		
3	Emergency Response		3	Fire Station A		
4	Fire/Ambulance		4	Police Station A		
5	Road Clearing		5	City Radio Repeater		
6	Equipment Maintenance		6	Water Treatment		
7	Water Resource		7	Waste Water Treatment		
8	Waste Water		8	Pump Station A		
9	Flood Control		9	Pump Station B		
10	Temp. Housing		10	Senior Housing A		
11	Safety Systems		11	Affordable Housing A		
12	Police		12	Affordable Housing B		
13	Shelters		13	Hospital		
14	Hospital		14	Cell Tower		
15	Medical Supplies		15	Gas Station A		
16	Food		16	Gas Station B		
17	Fuel		17	Grocery A		
			18	Grocery B		
			19	Pharmacy A		
			20	School Shelter A		
			21	Church Shelter		
			22	Garage A		

Rank your specific facilities from highest to lowest priority. Higher-ranked facilities are critical loads that should be included in microgrid designs. Lower-ranked facilities may be non-critical loads that can be disconnected during a stress event (e.g., a grid outage), so may not need to be included in microgrid designs.

Facility	Service	Priority

Module 6:
Identification of Design Basis Threat (DBT)

Module 6 – Identification of Design Basis Threat (DBT)

- Design basis threat (DBT) used as a basis for performance objectives mapped to protecting critical assets
- DBTs can be natural or human oriented
- Categorize DBTs according to likelihood of occurrence and impacts
- Impacts can be in terms of direct costs, duration as well as mission availability
- Analyze and define the DBT(s) which will be used as basis of performance objectives

Design Basis Threats

Natural causes (High Impact)

- **Hurricanes** – rare, can carry winds up to 200 km/hr and storm surges >10 ft; floods, impacts are regional can take 1-2 wks to recede & restore power
- **Floods** – common, impacts vary from regional or local, usually restored within a few days
- **Tornado** – more common in some locations, local, but people can be displaced for long periods, wider area can be restored quickly in days
- **Earthquake** – rare but in active zones impacts can be over a wide regional area, can take days to weeks for restoration depending on the impact
- **Volcano** – rare, and localized only to certain areas, can devastate a local to regional area, can take weeks to months to restore power

One resource to characterize potential losses from earthquakes, floods, hurricanes, and tsunamis is HAZUS
https://www.fema.gov/hazus

HAZUS®
EARTHQUAKE • WIND • FLOOD • TSUNAMI

Design Basis Threats

Natural causes (Medium to Low Impact)

- **Explosion/fire** – usually localized and impacts for short durations, local power outages only for area where fire occurs
- **Fires** - rare, in susceptible areas, can entail evacuations of whole areas, and take weeks to restore power depending on the damage
- **Heat wave** – not uncommon, in susceptible areas, but people are generally mobile, at risk people do need support or shelter, don't usually entail large scale power outages
- **Ice Storms/Blizzards** – not uncommon, occur in susceptible areas, can take out local to small regions for days until storm clears and power can be restored often from tree damage to lines
- **Land Slide** - rare, particular areas, like explosions takes out local areas but doesn't cause widespread power outages

Design Basis Threats

Unintentional causes (High to Low Impact)

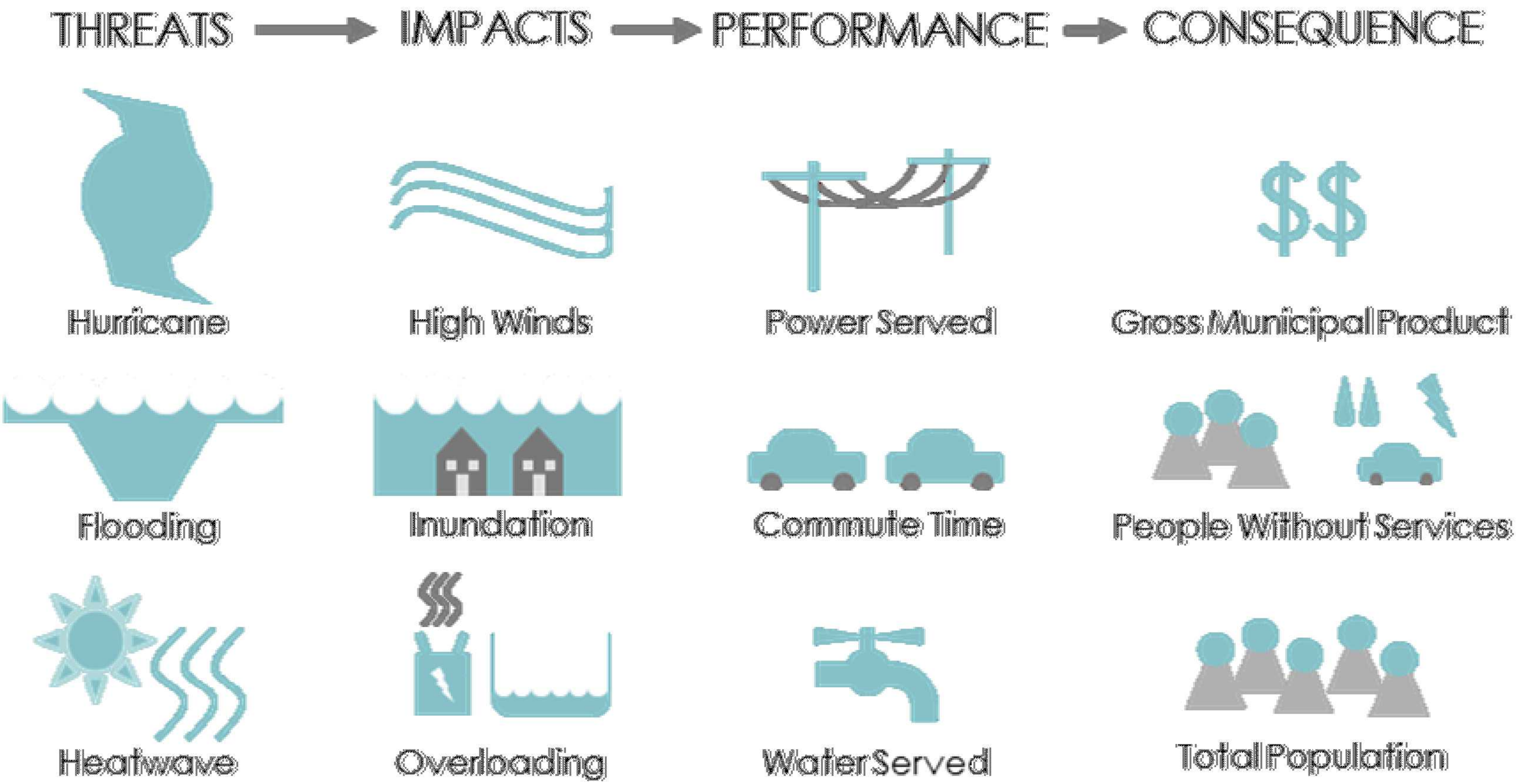
- **Blackouts** – rare, high impact over a wide region, depends on the overall security and adequacy of generation and transmission grid assets, main outage usually occurs over a few hours, but can take days to weeks to fully restore power to all areas
- **Brownouts** – less rare than blackouts, usually moderate impact over wide regions, more common in high demand periods like summer and winter, depend on generation and transmission availability, sometimes planned during high demand periods, take localized areas out in a rotating basis until overall demand decreases
- **Human Error** – rare, impact usually localized, takes out particular line, generator or equipment where error occurs, doesn't usually impact overall system
- **Equipment Failure** – rare, impact usually localized, takes out equipment which failed, system protection usually isolates the failure to localized areas impacted by failure

Design Basis Threats

Malevolent (High to Low Impact)

- **Cyber Attack** – rare, largely dependent on cyber protections and monitoring implemented, impact can be local to regional depending on the sophistication of the attack, restoration depends on mitigating the attack in order to restore the system
- **Physical Attack** – rare, dependent on physical protections, can cause human injury as well as an outage, impact depends on nature of physical attack

DBTs are linked to impacts on grid and consequences to drive development of performance objectives



Consider DBT and Expected Outage Duration

Normal Conditions

Tornado

Heat Wave

Snow Storm

Flood

Ice Storm

+

Distribution system outage

2, 5, 10, 21 days

Resources for DBTs, Hazard Identification, and Risk Assessments

- FEMA Hazard Identification and Risk Assessment
  https://www.fema.gov/hazard-identification-and-risk-assessment
- FEMA Comprehensive Preparedness Guide, Threat and Hazard Identification and Risk Assessment
  https://www.fema.gov/media-library/assets/documents/165308
- Ready.gov Risk Assessment
  https://www.ready.gov/risk-assessment
- Ready Business Risk Assessment Table – provides a methodology for scoring DBTs
  https://www.fema.gov/media-library-data/1389015304392-877968832e91898263514789026O624d/Business_RiskAssessmentTable_2014.pdf
- The World Bank, Urban Risk Assessments
  http://documents.worldbank.org/curated/en/659161468182066104/Urban-risk-assessments-understanding-disaster-and-climate-risk-in-cities

Module 6 Exercise

6.3 Module 6 Exercise

The city of Alphaville is considering options to improve the resiliency of their community, which has experienced 3–10 day power outages four times in the past decade due to flooding and heat waves. Additionally, there are rolling brownouts in peak summer seasons, during which portions of the city lose power for up to two hours per day (no blackouts, though increasing load demand may change this). Once, there was an ice storm that made services for senior and affordable housing impossible for a couple of days. This significantly impacted city services and public health because many people needed to be evacuated to shelters, but fuel supplies were limited, and city residents were unable to easily leave the region.

Alphaville

- Alphaville is a small city with a population of 30,000 residents
- It has its own city government, police, combined fire/ambulance services and a hospital
- It has a water treatment plant which is obtained from the river on the northeast corner of town, and processed by a wastewater treatment plant and discharged in the southwest corner of town
- The city is electrically served by a private utility with two substations and five feeders, both overhead (OH) and underground (UG)
- Most of the northern and central part of the city has gas services provided by a private utility

Using the following table, rank design basis threats to prioritize Alphaville's performance goals in addressing future threats.

Threats	Likelihood of event (H3, M2, L1)	Consequence of event (H3, M2, L 1)	System Resilience to event (H1, M2, L3)	Duration of event (Hours 1, Days 3, Weeks 5)	Overall rank scores (Total)

Module 7: Performance Goals and Objectives

Module 7 – Performance Goals and Objectives

- Based on mission requirements and DBT impacts:
  - Critical services to be maintained
  - Critical buildings supporting these services
  - Duration of DBT (2 day, 7 day, 2 week, etc.)

- Specify electrical and physical requirements necessary to meet DBT

- Requirements should be metric based

- Electrical requirements may include power availability metrics as well as power quality and redundancy necessary to meet DBT

Example Critical Services Prioritization

Grouping critical services and associated assets in terms of priorities of the needs of the community for the impacts of the DBT event helps define how resilience improvements can be targeted to needs and be cost-effective

Critical Services Hierarchy

Tier 1	Tier 2	Tier 3
• 911 • Emergency Communication Systems • Emergency Operations • Water Pump Control Center • Hospitals	• Drainage Pumps • Shelters • Fuel Storage • Other Medical Centers • FM and AM Broadcasts • Sewer Pumps • Water Purification	• Evacuation Sites • Banks • Pharmacies • Gas Stations • Sewer Treatment • Grocery Stores • Fire Stations • Police Stations

Example Performance Goals

- **Preliminary Design Basis Threat (DBT)**
  - **DBT– Specified hurricane with 100 year surge/inundation profiles and expected wind damage profiles**
  - **Defined Tier 1-3 critical service assets will be impacted to greater to lesser extent based on DBT, their location and elevation and current levels of hardening and backup power protection**

- **Critical service assets resilience improvement requirements**
  - **Resilience required for designated Tier 1-3 critical service assets necessary to be prepared for, withstand, adapt and quickly recover to DBT event as defined by performance goals**

- **Preliminary Performance Goals**
  - **Set of designated critical service assets defined (e.g. all major Tier 1 hospitals, at least once police station for a given region, etc.) that must maintain service during DBT**
  - **Period of performance of designated critical service assets is to maintain defined level of service (critical interruptible, non-interruptible, etc.) a minimum of 72 hours following the DBT event**
  - **Resilience options available to meet performance goals (e.g. microgrids, asset hardening, improvement of existing backup generation systems, etc.)**
  - **Metrics to determine if performance goals are met**
  - **Performance goals can include cost-effectiveness of resilience improvements of alternative options, availability of defined critical service assets for duration of DBT, overall system reliability improvement, as well as non-electric measures of improvement like adequate sheltering in place, emergency service availability etc, during the event**

Resilience Science at Sandia

Presidential Policy Directive 21:
The term "resilience" means 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.

Impact of Event

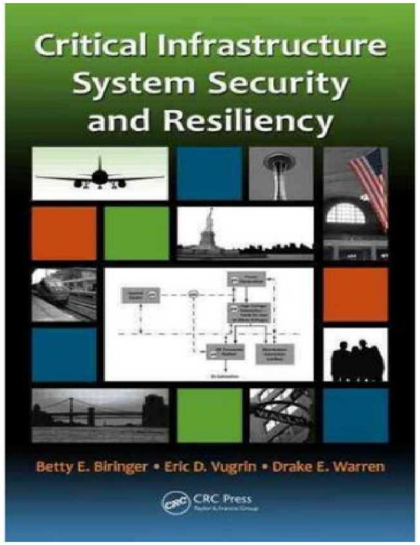
$$SI = \int_{t0}^{tf} \left[TSP(t) - SP(t) \right] dt.$$

Recovery

$$TRE = \int_{t0}^{tf} \left[RE(t) \right] dt.$$

SI = System Impact
SP = actual System Performance
TSP = Typical System Performance

RE = Recovery Effort
TRE = Total Recovery Effort



Resilience Science at Sandia

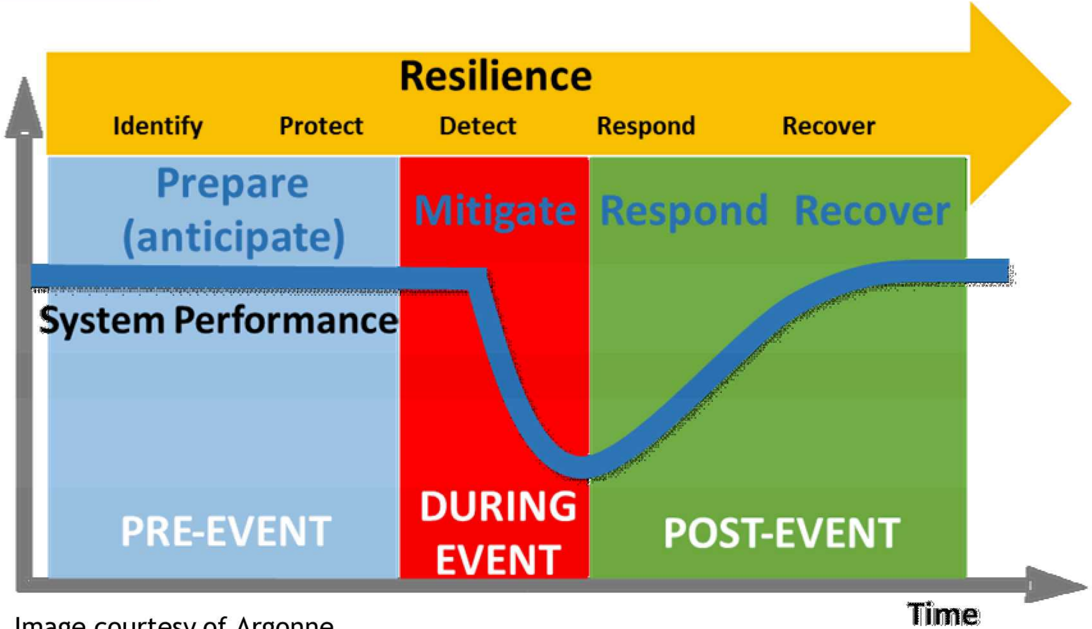
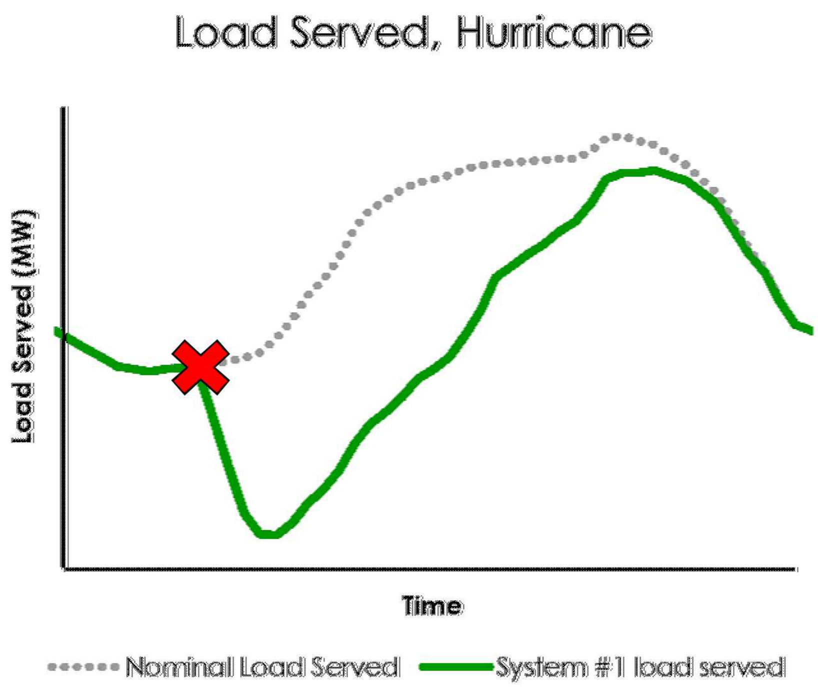


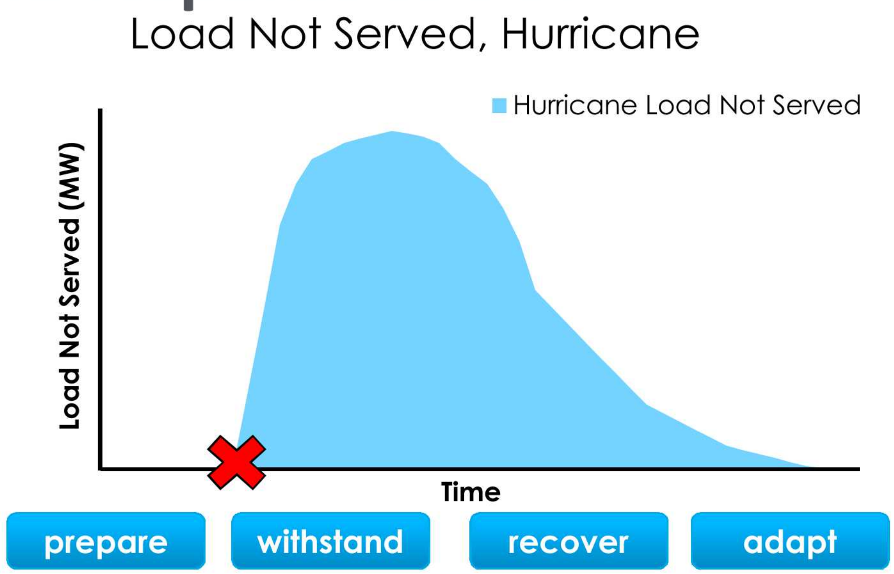
Image courtesy of Argonne National Laboratory

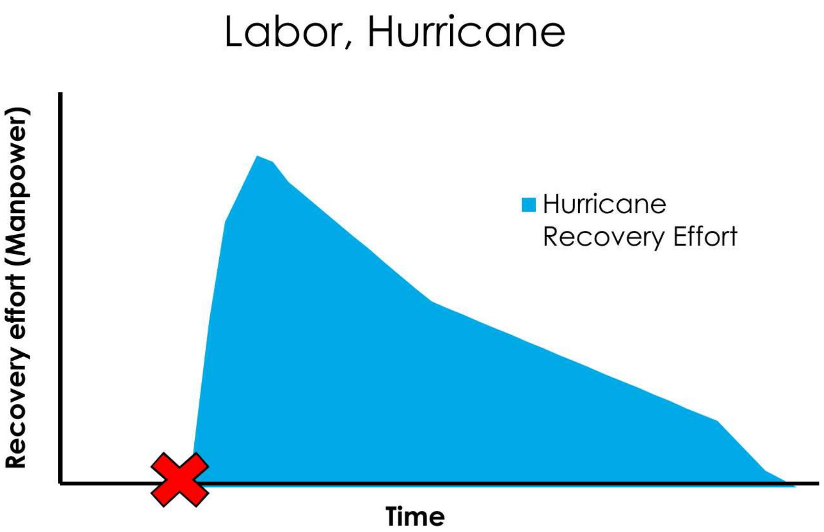
1. Resilience is contextual – defined in terms of threats or hazards
   - A system resilient to hurricanes may not be resilient to earthquakes
2. Includes hazards with low probability but potential for high consequence
   - Naturally fits within a risk-based planning approach…
   - …but difficult to capture this type of risk with high confidence

A resilient energy system <u>supports critical community functions</u> by preparing for, withstanding, adapting to, and recovering from disruptions

Resilience combines impact and response to DBT

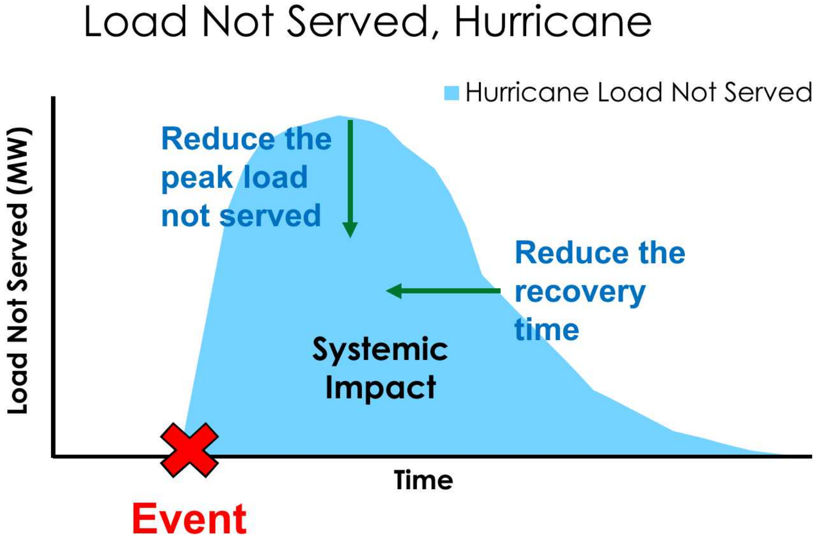


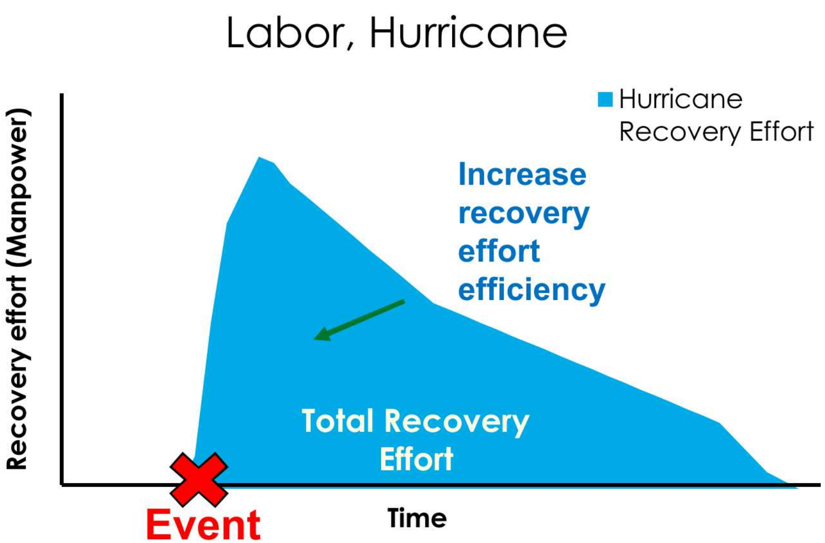




Resilience Index = Systemic Impact + Total Recovery Effort

Resilience enhancements aim to improve performance to expected DBT





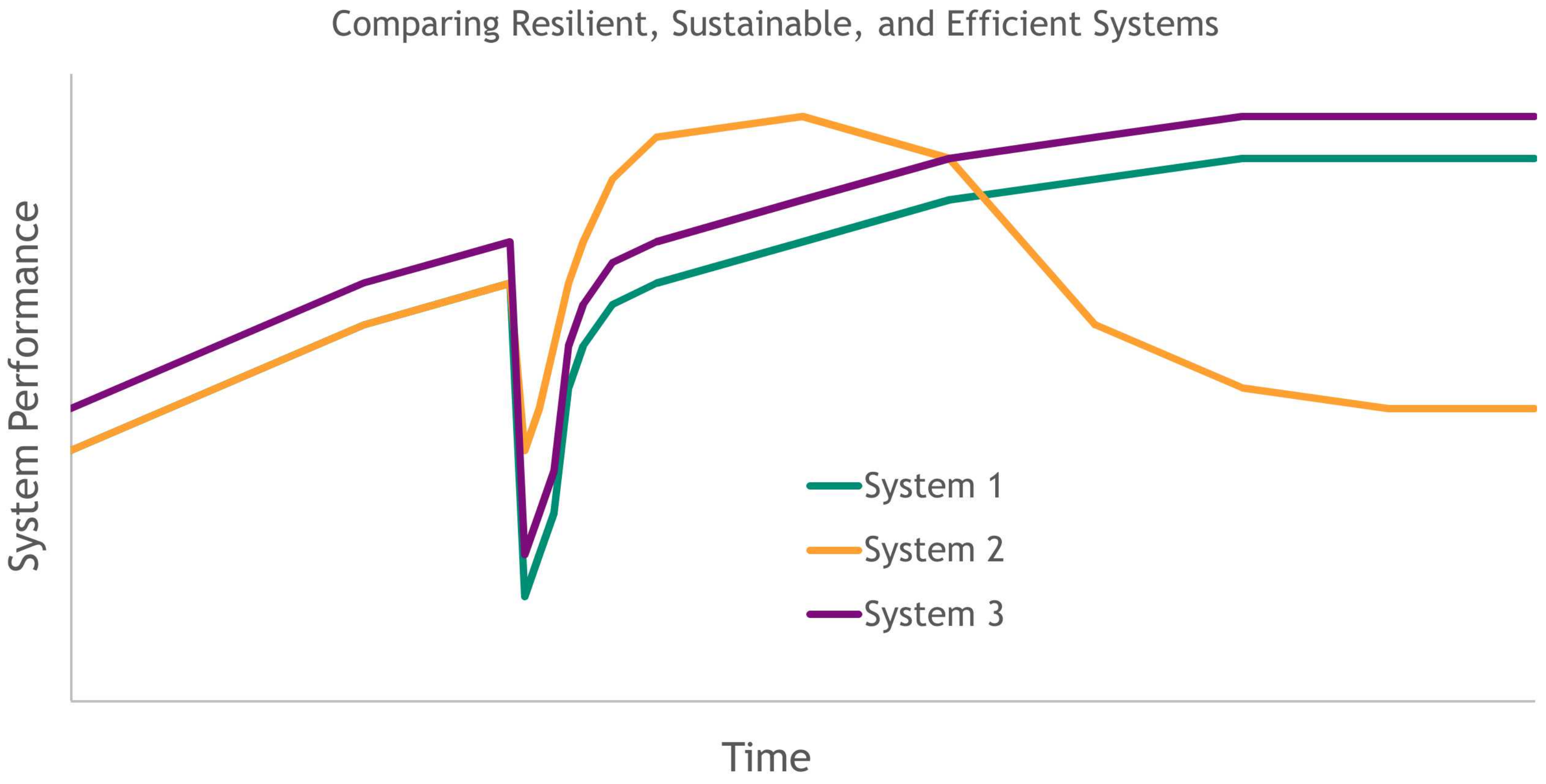
For a given DBT event

Resilience enhancements aims to both:

Minimize systemic impact
-reduce critical service and assets in terms of load impact, cost, and duration
-resilience improvements keep set of critical assets available during event

Maximize recovery effort speed
-Resilience improvements that make the system less susceptible to event
-Improvement of manpower response to event to speed up response

Tradeoffs – Resilience, Efficiency, Sustainability



Questions to consider in developing performance objectives

- **What are likely and worse case impacts to critical services and assets for the DBT event?**
  - Impact of services lost in terms of not only load, time, and cost but to human, social and emergency response during the event
- **How do we prioritize critical service and assets to both maximize the resilience improvements & minimize the service impacts**
- **How can the broad set of resilience options considered (distributed generation, renewables, storage, hardening, controls, etc.) both be compatible with the existing distribution and backup systems, and most efficiently improve resilience?**
- **For the resilience gained, what is the cost? How much enhanced resilience will be obtained over the existing system? How would the cost/benefit play out over short, medium, and long terms?**

Resiliency and Performance goals

High Level Resilience Performance Goals:

- Ability to prepare for, adapt to, and recover rapidly from changing, non-normal events defined by DBT
- Metrics quantify how critical services/assets impacts are improved in response to DBT
- Metrics also specify minimum time needed to provide critical services/assets during DBT (e.g. 2, 3, 7 days)
- Metrics can include environmental components like use of a minimal percentage of renewables in designs to reduce CO2 impacts
- As stated, metrics should specify impact of services lost in terms of not only load, time, and costs but also in terms of human, social and emergency responses during the DBT so resilience shows improvements to each of these
  - To the extent possible also take into consideration supply-chain impacts and interdependencies of infrastructures during evaluation
  - Example of supply chain is how types of fuel for generators can be obtained during a DBT event – consideration of local fuel storage needs, distribution carriers, access to remote suppliers, etc.

Further Considerations on Performance Goals

- Critical service/asset service requirements during DBT provide the basis for resilience improvements
  - Requirements include how many assets per critical service are needed to provide adequate resilience to the DBT
- Requirements for resilience may differ depending on the tier level of the asset
  - Some assets may require non-interruptible power and/or enhanced power quality to portions of loads
  - Some assets may require hardening to the event like relocating electrical equipment above the expected flood zone or improvements to wind damage
  - Depending on the location of the assets, resilience improvements may be deployed collectively across multiple local assets in terms of microgrids or individually through targeted improvements of local backup generation systems
- Assess existing backup systems for critical services/assets in terms of reliability, current maintenance, fuel storage, and supply chains to determine if they adequately meet needs for DBT or need improvements
- Goal is to produce the most cost effective sustainable set of targeted resilience improvements that address the critical service impacts expected by the DBT, in terms of costs, loss of load, as well as human and social impacts and includes any renewable penetration requirements

Module 8: Performance Risk Analysis

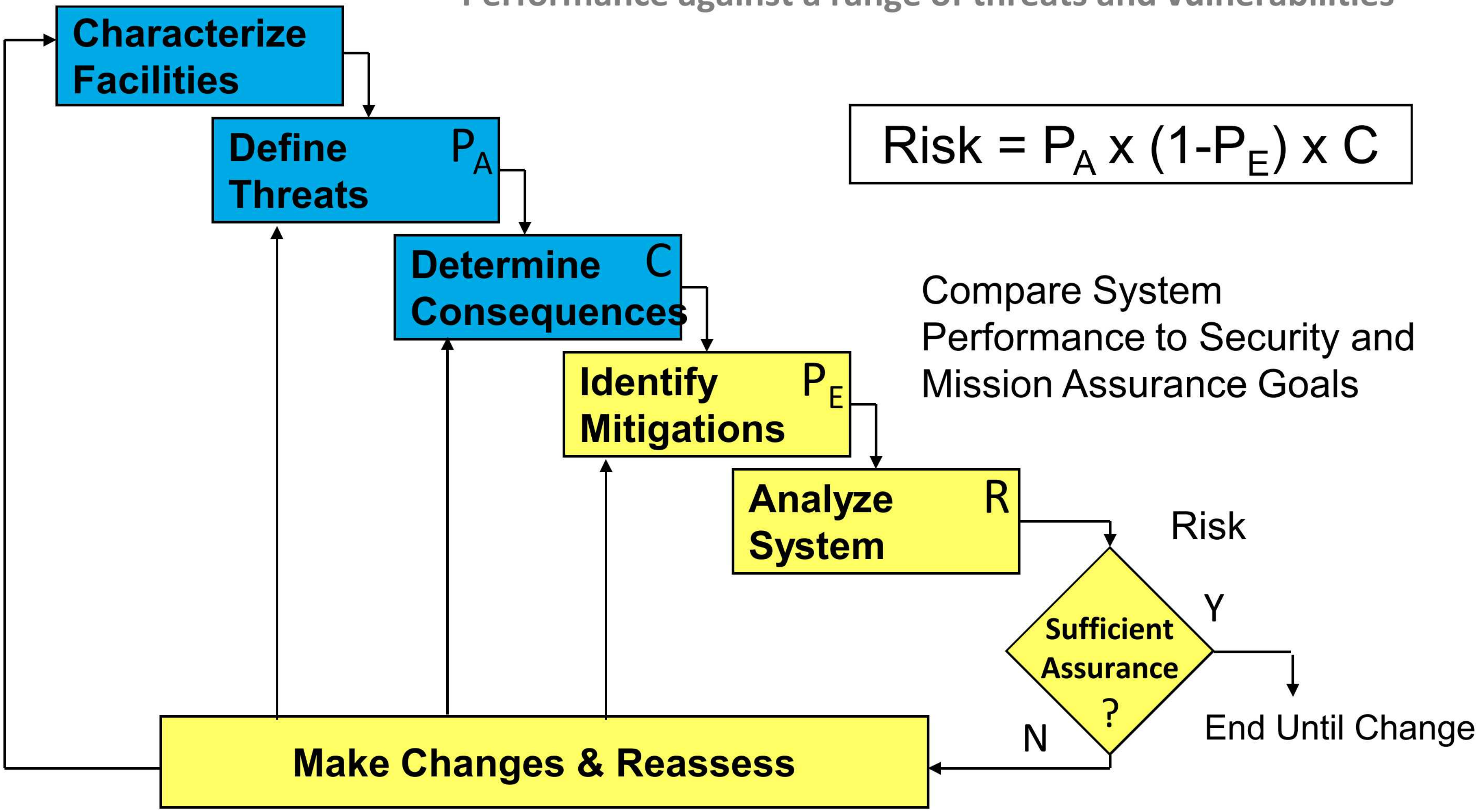
Module 8 – Performance Risk Analysis

- Performance Risk Analysis is a methodology to do a quick high level analysis of the resilience of a set of critical service assets to a particular DBT to understand the current level of resilience and help to formulate resilience improvements
  - This analysis presupposes that critical service assets required have been defined
  - This analysis is a metric that helps to determine if performance goals are met for the set of critical service assets by comparing the performance risk of the baseline system with a system with resilience improvements

- Basic Process
  - Calculate the baseline performance/risk of critical buildings covered by DBT's (can include evaluation of system availability as well)
  - Performance/risk calculates the system performance based upon the likelihood of the DBT occurring, consequence of occurrence, with existing backup systems taken into account
  - Performance risk is reassessed for every system resilience option considered to determine the level of improved resilience

Technical Basis for Risk Assessment Methodology – Energy (RAM-E)

A quantitative approach to assess energy system Performance against a range of threats and vulnerabilities



Performance/Risk Methodology

- CBS - Percent of critical buildings served – these are the percentage of critical assets with existing backup power systems or microgrids. If few of these buildings are served, then consequences and risks will be high since less services will be available.

- CLS – Percent of critical loads served – this is the amount of critical load served for the collection of critical assets, as a percentage of the load of all of the critical assets, to account for different sized critical asset loads. If minimal loads are covered, the consequences and risks will be high.

- RG - Reliability of generation – weights the existing maintenance program of backup generators. Poor or inadequate maintenance lowers reliability and the risks will be high.

- Da/Dn - Ratio of generator fuel availability versus outage duration - If the generator fuel tank is small, and/or the ability to refuel the generator is low, then the risks will increase with longer power outages. If the fuel tank supplies generation to the expected critical load for 3 days (Da) and the DBT is 5 days (Dn) then the ratio is 3/5 or 0.6 in this case.

Performance Risk Equation

Performance/risk metric defined:

- PR = 1-(CBS*CLS*RG*(Da/Dn)), *where:*

- PR = Performance Risk
- CBS = % Critical Buildings Served
- CLS = % Critical Loads Served
- RG = Reliability of generation system
- Da = Operational availability – up to outage period
- Dn = Operational duration needed (outage period)

Performance risk means essentially the level of risk of the system not providing adequate performance during the DBT event, so the lower the performance risk, the more resilient the system to the DBT.

Performance Risk Metric (0= best; 1=worst)

- Low Performance Risk – PR <.30
- Medium Performance Risk – PR = .30 to .50
- High Performance Risk – PR >.50

Example Performance/Risk Analysis (2 Day Outage)

Asset	Facility	Critical Building Served (CBS)	Generator Critical Load Served (CLS)	Generator Reliability (RG)	Existing Fuel Capacity
1	Public Works Garage	2/2	100%	.8	At least 2 days
2	Fire Department HQ	2/2	100%	.8	At least 2 days
3	Police Department HQ	1/1	100%	.8	At least 2 days
4	Water Treatment Plant	1/1	100%	.8	At least 2 days
5	Waste Water Treatment Plant	1/1	60%	.8	At least 2 days
6	Radio Repeaters/Police and Fire	2/2	100%	.8	At least 2 days
7	High School	2/2	75%	.8	At least 2 days
8	Flood Control	1/1	100%	.8	At least 2 days
	Total	100%	91.9%	80%	100%

Example Performance/Risk Analysis (2 Day Outage)

Performance/risk defined:

- **PR = 1-(CBS*CLS*RG*(Da/Dn)),** ***where:***

- **CBS = % Critical Buildings Served (all served = 1.0)**
- **CLS = % Critical Loads Served (based on which have generators = 0.91)**
- **RG = Reliability of generation system (0.8 – reliability of generator used for that not tested under load)**
- **Da = Operational availability – (2 days available)**
- **Dn = Operational duration needed (2 days needed)**
- **Da/Dn = 1**

Performance/risk

- **PR = 0.27 which is <.30 so Low Risk**
- **However if the DBT is 5 days, Da/Dn =0.4 then PR=0.71 so the system with have High Risk due to inadequate backup fuel for an extended outage**

Estimating Backup Generator Demand and Fuel Use

- **Generator demand determined by measured generator peak use (if available) or just Generator nameplate data**
  - Example – Generator A 350 kW; 235 kW measured demand so 235 kW used as peak demand
- **Generator fuel use is calculated by dividing the fuel tank size by the fuel demand**
  - Example – Generator A 235 kW demand translates to 420 gallons/day, so 500 gallon tank will last 1.2 days
- **Manufacturer specifications can be used to get information on generator fuel use in gallons/hour or gallons/day depending on the demand required which is converted to make calculations**
- **Analogous calculations can be used for gas generators or other distributed generators with different fuel types and storage mechanisms**

Example backup generator data used to estimate fuel supply adequacy

Critical Asset	Gen Capacity (KW)	Peak Measured Facility Load (KW)	Peak Use Relative to Rated Capacity (%)	Internal Tank Capacity (gallons)	External Tank Capacity (gallons)	Total Fuel Capacity (gallons)	Daily Fuel Use (gallons)	Total Supply (days)
A	350	235	67	-	500	500	420.8	1.2
B	400	169	42	1000	NA	1,000	320.8	3.1
C	7.5	0	0	20	NA	20	0	-
D	300	30	10	-	500	500	92.6	5.4
E	750	248	33	-	500	500	486.2	1.0
F	80	31	39	145	NA	145	79.0	1.8
G	150	38	25	850	NA	850	86.4	9.8
H	1750	410	23	1800	8,000	9,800	844.5	11.6
I	600	232	39	NA	5,000	5,000	449.4	11.1
J	1500	300	20	NA	10,000	10,000	653.9	15.3
K	125	0	0	154	NA	154	0	-

Estimating Fuel Storage Requirement for DBT

- **Backup diesel generator fuel storage calculations determine if storage adequate for performance requirements or if additional storage is needed**
- **Backup generator fuel storage also depends on existing centralized fuel storage for cities or bases**
  - For example – a 12,000 gallon centralized fuel storage tank that supplies 4,000 gallons/day to critical asset generators during an event can supply all the generators an additional three days beyond that provided by individual day tanks
- **Performance requirements should account for how often and when (e.g. ½ full) both bulk fuel storage and day tanks are replenished to adequately assess how much fuel is actually available for an event**
- **Performance requirements should also address fuel supply and delivery issues during a DBT event and what alternatives exist or can be arranged for to supply fuel to meet the or exceed the DBT requirements if fuel cannot be stored adequately for the DBT duration**
- **In some cases, types of diesel generators can be supplied by alternative fuels if they are designed for it, such as some types of jet fuels temporarily in lieu of available fuel.**

Characterization of Energy and Critical Infrastructures for Mission Assurance

It is necessary to visit the site and characterize the existing electrical and other critical infrastructures to provide sufficient information in order to develop conceptual design improvements

- Characterize electrical system infrastructure including building and feeder loads
- Characterize other critical infrastructures as applicable (gas, water, telecom) to mission assurance
- Characterize existing backup systems (generators, UPS systems, fuel storage etc.)

Module 9:
Load Estimation Techniques

Skipped – see coursebook

Module 10: Formulating Design Options

Module 10 - Formulating Design Options

- Formulate conceptual design options based on performance objectives
- Utilize methods and tools to develop conceptual design options such as:
  - Reliability, efficiency, and cost analysis
  - Further engineering and consequence analysis
- Evaluate options
  - Performance/risk versus cost tradeoffs compared to baseline
  - Evaluate best set of conceptual design options

Design Option Tools

These are Sandia developed tools which can help develop various steps of developing design options

- **FASTMAP**
  - Utilizes GIS information to identify where critical service assets are in relationship to the utility distribution system
- **RenCAT**
  - Uses FASTMAP information and performance specifications such as critical service asset tier ranking to identify which set of critical assets are best candidates for microgrids
- **Microgrid Design Tool (MDT)**
  - Use system one-line diagrams and load data and microgrid design option inputs to characterize performance and costs of particular microgrid options identified by RenCAT to evaluate microgrid options

Conceptual Design Development

- Conceptual design development based upon performance objectives to meet DBT
- Conceptual designs can be:
  - Grid-tied or islanded microgrids
  - Hardening of buildings where microgrids aren't appropriate
  - Solutions with inclusion of CHP, renewables, and energy storage devices
  - Building energy efficiency improvements

Example of Clustered Assets for Candidate Microgrids

Facility/Description	Critical list?	Standby generators? kW	UPS	SS -- Feeder
Candidate Microgrid A				
Headquarters	Not listed	None		A – 1
Military Unit 1	Sensitive	None	Yes	A – 1
Military Unit 2	Sensitive	None	Yes	A – 1
Fire Station	Not listed			A – 1
Hospital	Not listed	None		A– 1
Candidate Microgrid B				
Command Center	Critical	Yes, 100 & 300	yes	B – 4
Police Station	Not listed	Yes, 100		B – 4
Control Tower	Sensitive	Yes, 365		B – 4
Armory	Critical	Yes, 200	yes	B – 4
Airfield Lights	Not listed	Yes, 2 x 200		B – 4

Types of Resilient Improvement Options

- **Microgrid options**
  - Utilizing an existing medium voltage feeder to build a microgrid capable of serving critical assets through DBT event
  - Alternatively building a dedicated medium voltage microgrid feeder to supply identified critical facilities during emergency situations serving critical assets through DBT event
  - Or developing microgrids at low voltage levels (600V or below) instead of at medium voltage if some critical assets are close enough to make lower voltage microgrids feasible

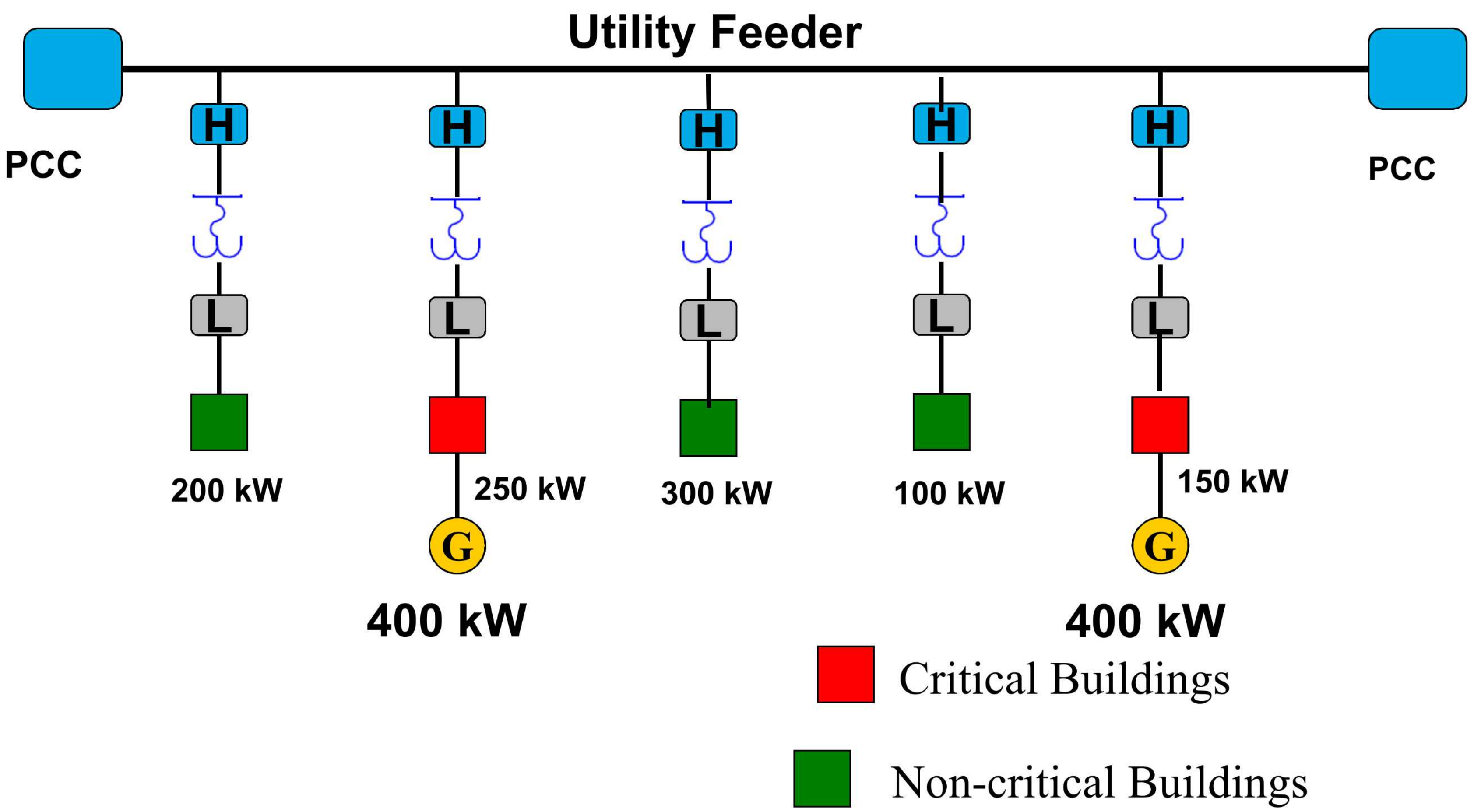
- **Non-microgrid options**
  - Add or enhance existing backup generators to make set of critical assets resilient to DBT event if microgrids inclusion isn't a good option
  - Make provisions for critical assets to quickly be able to connected to a backup generator if a DBT event occurs

Option – Grid-tied Microgrid with existing feeders

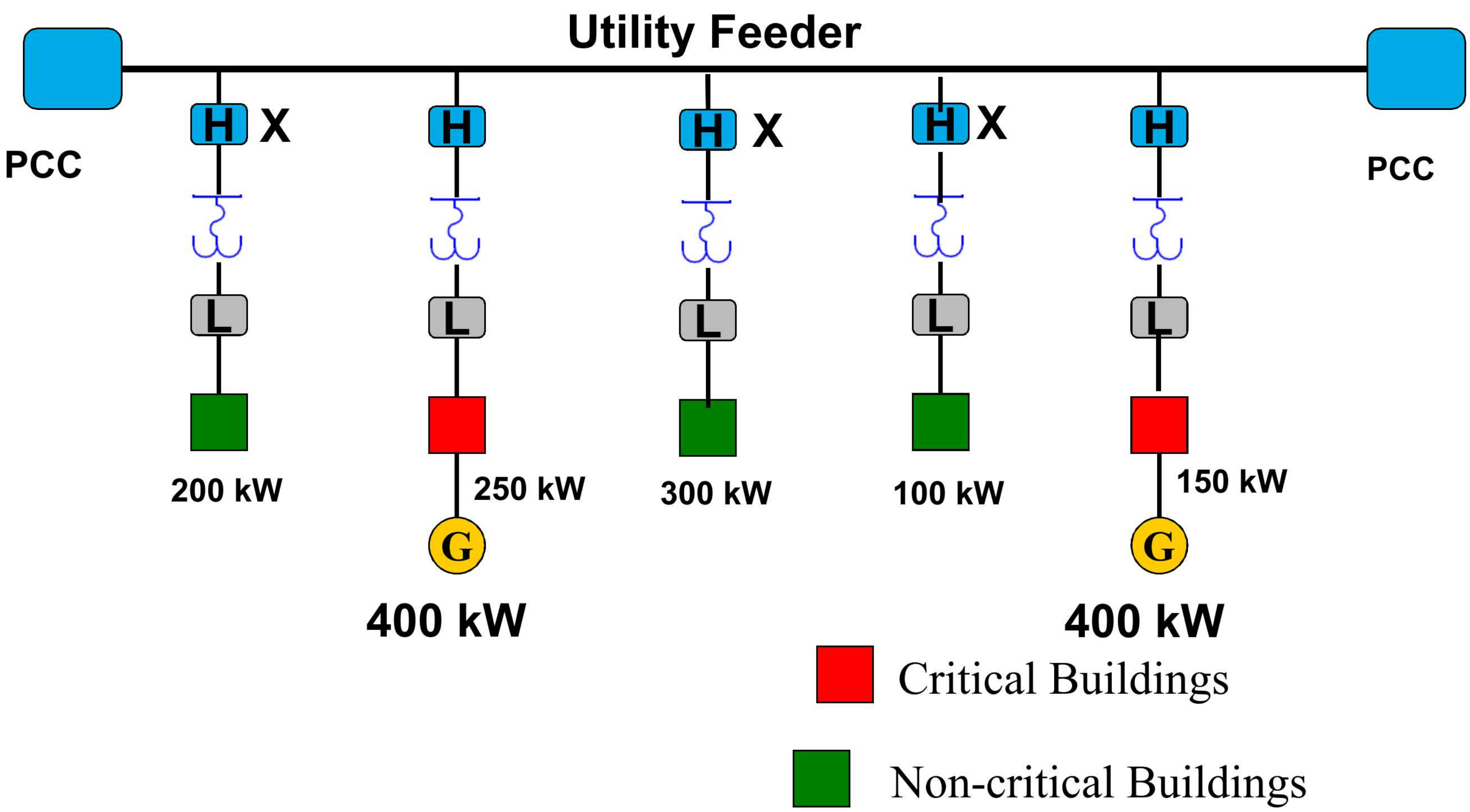
- **Requirements:**
  - Ability to utilize utility system to form microgrid
  - Can be manual or automatic
  - Attractive sites must be found which satisfy building needs and utility requirements for operation
- **Pros**
  - Less costly than MV microgrids independent of utility
  - Microgrid provides more resilience than individual backup generator through redundancy & serves multiple critical assets
  - Load shedding can be employed to reduce generation costs for microgrid
- **Cons**

  May alter automated/manual sectionalizing schemes
- **Issues, Risks and "Show Stoppers"**
  - Who owns, operates microgrid and how does it interface with utility
  - Regulatory, permitting, right of way (ROW), private business issues
  - Should we consider only emergency or also grid tied with possibility of wheeling

Microgrid using Utility Grid



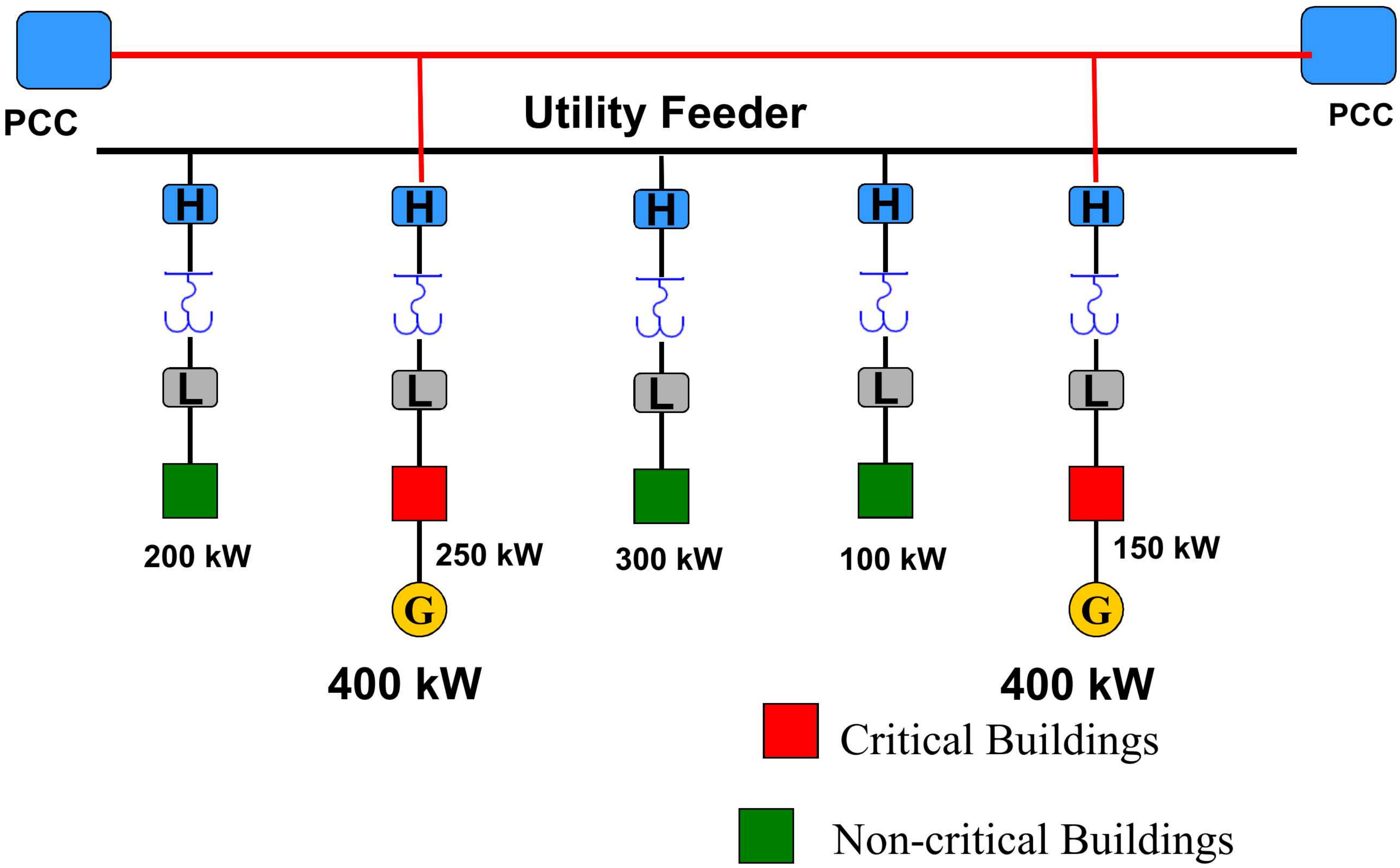
Load Shed Non-Critical Loads (High Side)



Option – Microgrid with dedicated feeder

- **Requirements:**
  - May require some right of way of utility lines to form microgrid or installed with underground feeders
  - Can be manual or automatic
- **Pros**
  - More flexibility in designing which facilities to include
  - Microgrid provides more reliability than individual backup generator through redundancy & can serve multiple critical assets
  - Except utilization of ROW, doesn't interfere with utility
  - Load shedding unnecessary since only critical assets connected
- **Cons**
  - More costly than using utility since new feeders must be installed
  - May be difficult to locate corridors to install system
- **Issues, Risks and "Show Stoppers"**
  - Who owns, operates microgrid and would it need to interface with utility
  - Regulatory, permitting, right of way, private business issues
  - Microgrid PCCs still may be connected to utility so how is this controlled and monitored in sync with existing distribution system

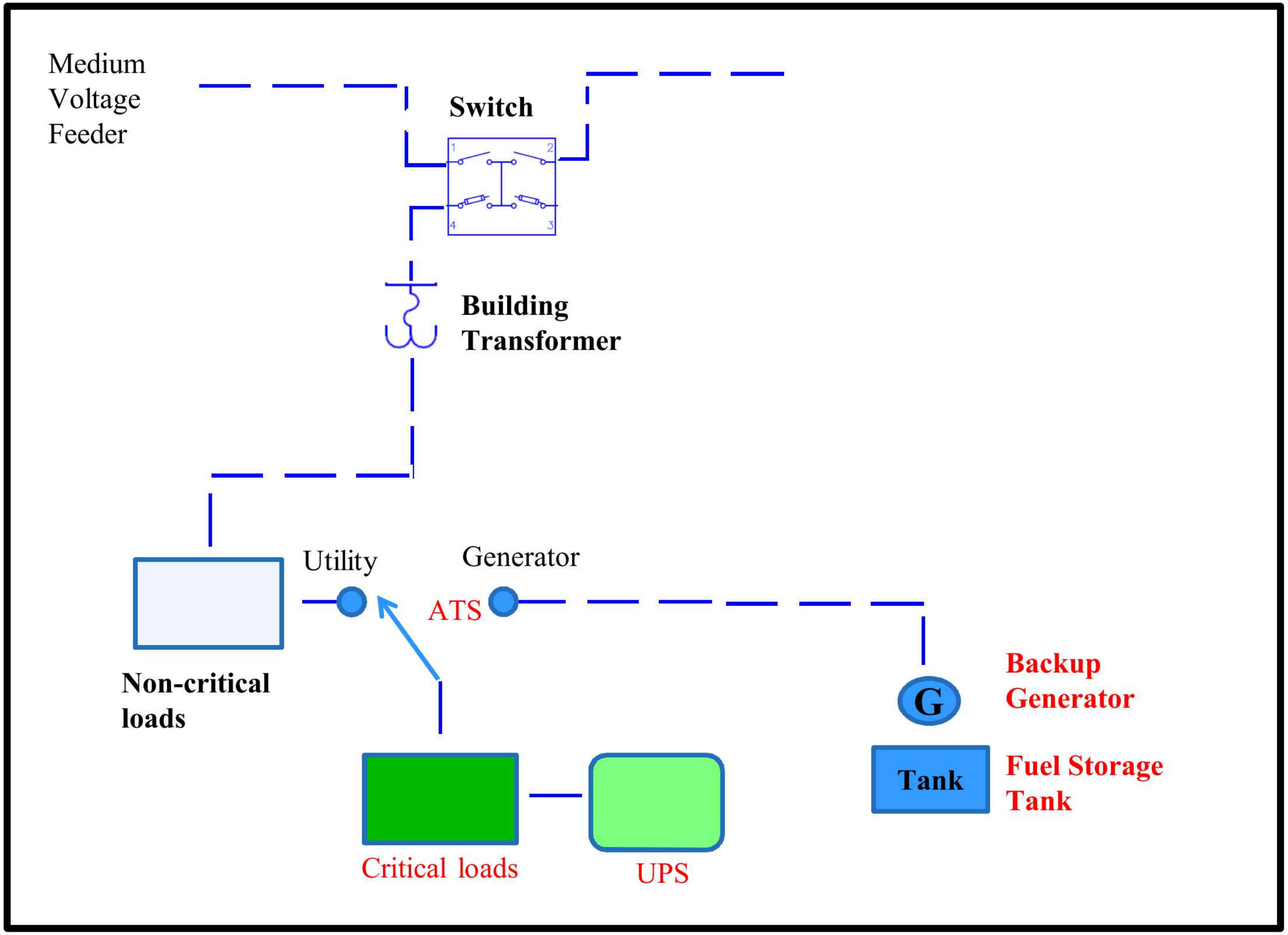
Dedicated Microgrid Feeder



Non-Microgrid Option – Add or Enhance Backup Generator System to Building

- **Requirements:**
  - Sizing and locating Backup generator to entire facility load or select critical loads
  - Adding ATS and necessary rewiring for installation
- **Pros**
  - Independent of utility so no technical/operational issues with existing system
  - Less expensive than a microgrid
- **Cons**
  - No redundancy so less resilient and efficient than if it were included in a microgrid
- **Issues, Risks and "Show Stoppers"**
  - Must obtain permitting to run as emergency unit, but same requirements for generators in microgrids
  - If required for private business needed for community emergency services, such as grocery or gas station, who pays and operates

Option – Backup Generators



Non-Microgrid Option – Make Additional Provisions for Backup Generators

- **Requirements:**
  - Refers to provisions to allow backup generator to be hooked up to facility during emergencies
  - Sizing to required generator for facility load or critical load
  - Adding cabling and/or ATS to be able to connect portable generator
  - Relies on a pool of portable generators to quickly get to building
- **Pros**
  - Less costly than backup generators
  - Faster and easier to connect a portable backup generator with system in place
- **Cons**
  - There is a delay until backup generator is wheeled to site
  - Buildings with provisions must be prioritized for service
- **Issues, Risks and "Show Stoppers"**
  - Ability to get to location during emergency and prioritizing
  - If required for private business and needed for emergency services, who pays and operates during emergencies

Example Conceptual Design Performance/Risk Calculations

Option	Primary Upgrade	P/R	Critical Asset Availability	Fuel Supplies Needed	Estimated Cost	Benefits
1	Pin and Sleeve at all facilities, some rewiring, and purchase additional portable generators	0.06	.9963	1700 gallons	$745K	Allows each building to be provided with a portable generator if needed. Minimizes redundant generators
2	Redundant generators at each building, some rewiring	0.05	.9975	800 gallons	$1190K	Redundant generator at each building, has its own fuel supply so less refueling needed
3	Pin and sleeve with PV integrated at 5 buildings	0.05	.9964	1500 gallons	$1450K	Option 1 with renewable energy at several critical builidngs
4	Pin and sleeve with PV	0.05	.9964	1500 gallons	$1000K	Option 3 but using PPA for PV

Module 11:
Cost Estimation

Skipped – see coursebook

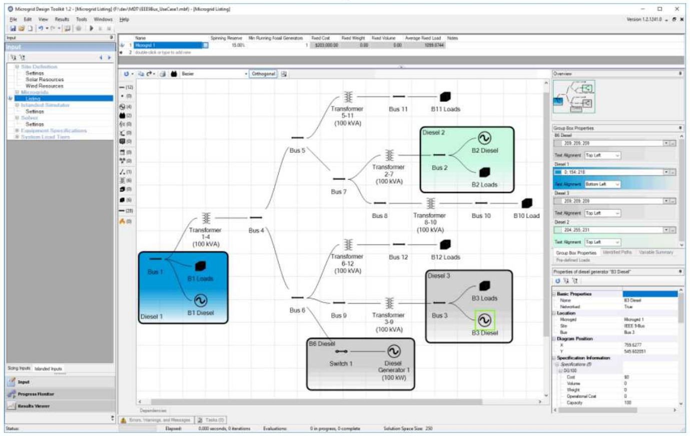
Module 12: System Reliability and Availability

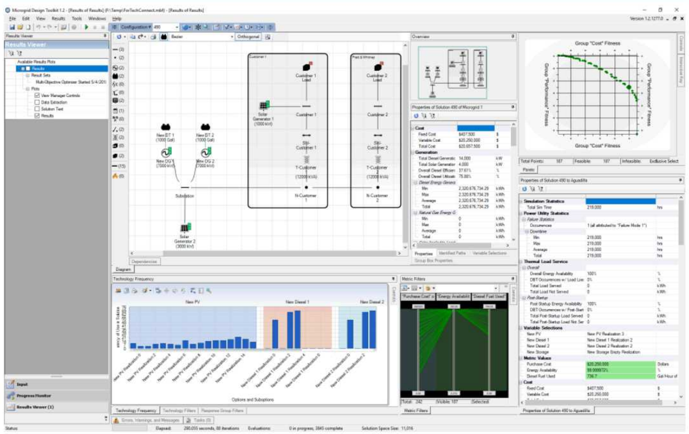
Skipped – see coursebook

Tool Overviews and Demonstrations

What is the Microgrid Design Toolkit (MDT)?

- MDT is a visual design and trade-space optimization capability for microgrids.
- A multi-objective optimization algorithm executes a discrete event Monte-Carlo simulation to characterize performance and reliability of candidate microgrid designs.
- Produces a Pareto frontier of efficient alternative Microgrid designs and visualizations to help a designer understand the trade-offs.





History

- SPIDERS (2011)
- DOE OE Funding (2014)
- v1.0 Publicly Released (2016)
- USMC SYSCOM Funding (2016)
- Use for GMLC and Others (2017-*)
- R&D 100 Award (2017)

Uses

The US Marine Corps Expeditionary Energy Office (E2O) used the MDT to assess microgrid power systems and *Mobile Electric Hybrid Power Sources (MEHPS)* for expeditionary units and brigades.

Over 50 microgrid models were developed in the MDT and used to provide design support for these islanded power systems.

The SPIDERS Program used a predecessor to the MDT to develop the preliminary microgrid designs for 3 military bases.

- Joint Base Pearl Harbor–Hickam
- Fort Carson
- Camp Smith

These microgrids are currently in operation on these installations

The City of Hoboken, NJ used a predecessor to the MDT to develop the preliminary microgrid design for backup power in response to Hurricane Sandy.

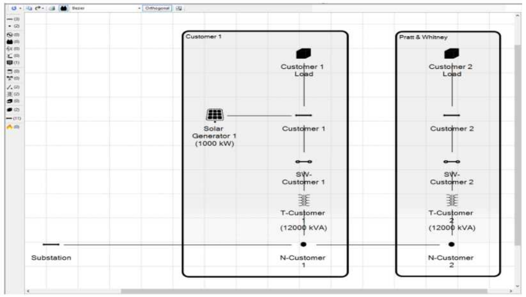
The primary goals of this design effort were to mitigate the impacts of extreme flooding on the distribution systems and electricity service throughout the city.

Other Past and Current uses of the MDT include:

- Remote community power system assessments for villages in Alaska (Shungnak, Cordova).
- A backup power system assessment and Microgrid Design of the UPS Worldport facility in Louisville, KY.
- A backup power system assessment and Microgrid Design of the city of New Orleans, LA.

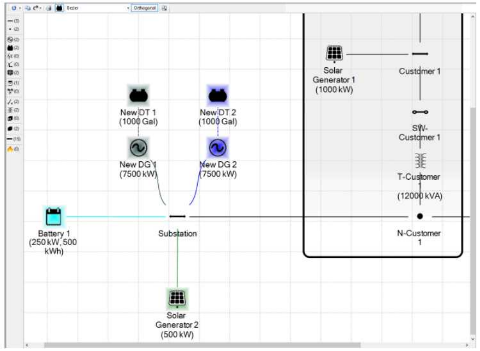
MDT Process

Define Baseline System



Investigate Results

Specify Design Options



Define Design Objectives

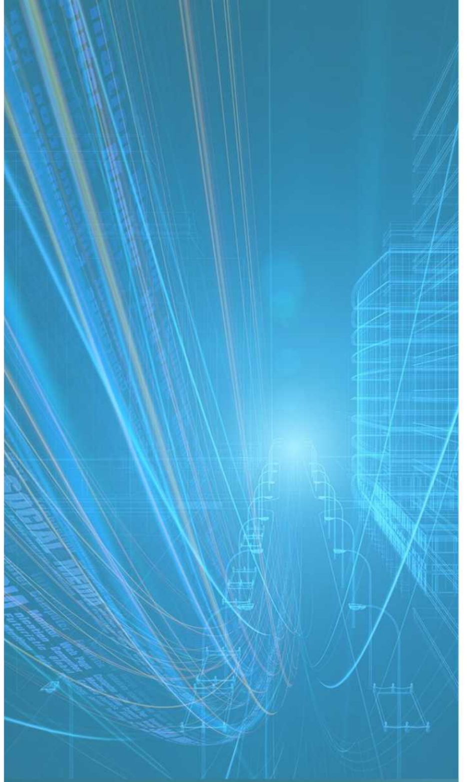
Metric	Limit	Objective
Energy Availability	98%	99.999%
Fuel Burn Rate	100 Gal/hr	65 Gal/hr
Renewable Penetration	25%	60%

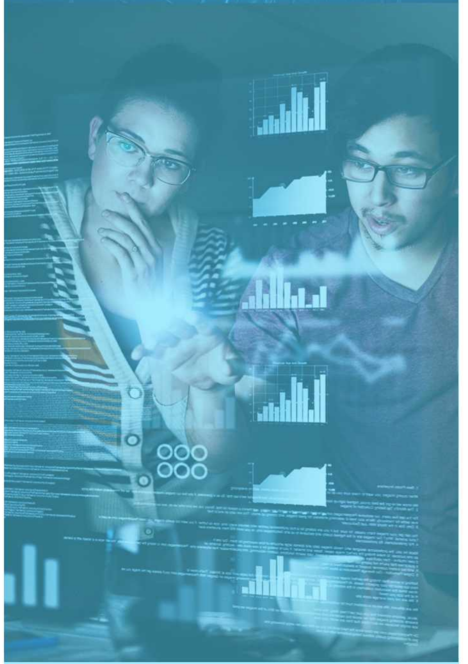
Optimize

Value Propostion

Using the MDT, a designer can:

- Effectively search through very large design spaces for efficient alternatives
- Investigate the simultaneous impacts of several design decisions
- Have defensible, quantitative evidence to support decisions
- Gain a quantitative understanding of the trade off relationships between design objectives (cost and performance for example).
- Gain a quantitative understanding of the trade-offs associated with alternate design decisions
- Identify “no brainer” choices to reduce the number of design considerations
- Perform what-if analysis by altering the input without loss of information to include or not include certain features in a run of the solver
- Perform hypothesis testing by manually generating solutions and comparing to the solutions found by the MDT





Differentiating Capability

The MDT represents an innovative capability not available elsewhere. It's ability to:

- **Perform mid-level topology optimization**
- **Account for both grid connected and islanded performance**
- **Account for power and component reliability in islanded mode**
- **Account for dozens of metrics when performing the trade space search**
- **Present a user with an entire trade space of information from which to draw conclusions**

Make it a significant advancement over anything available to designers today.

Acknowledgements and Contacts

Development of the MDT has been funded primarily by the Department of Energy Office of Electricity Delivery & Energy Reliability. Other sources include the USMC, GMLC, DoD, and Sandia.

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Download Link

http://www.energy.gov/oe/services/technology-development/smart-grid/role-microgrids-helping-advance-nation-s-energy-syst-0

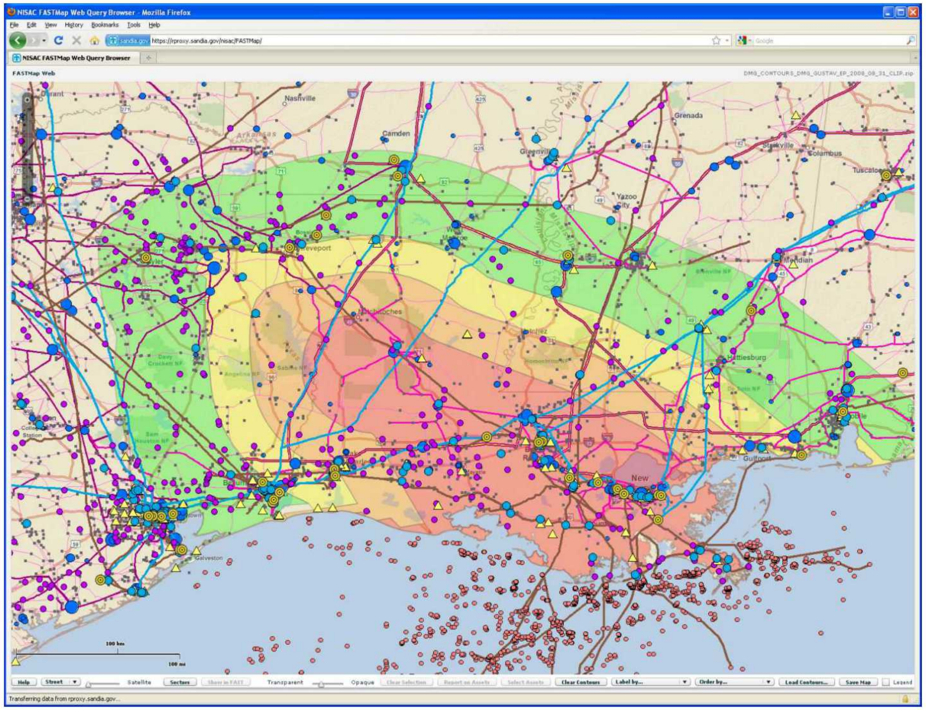
FASTMap

Situational Awareness
Infrastructure Analysis
Channel-Based Broadcast & Collaboration Environment

Leo Bynum
Sandia National Laboratories
Albuquerque, NM

FASTMap

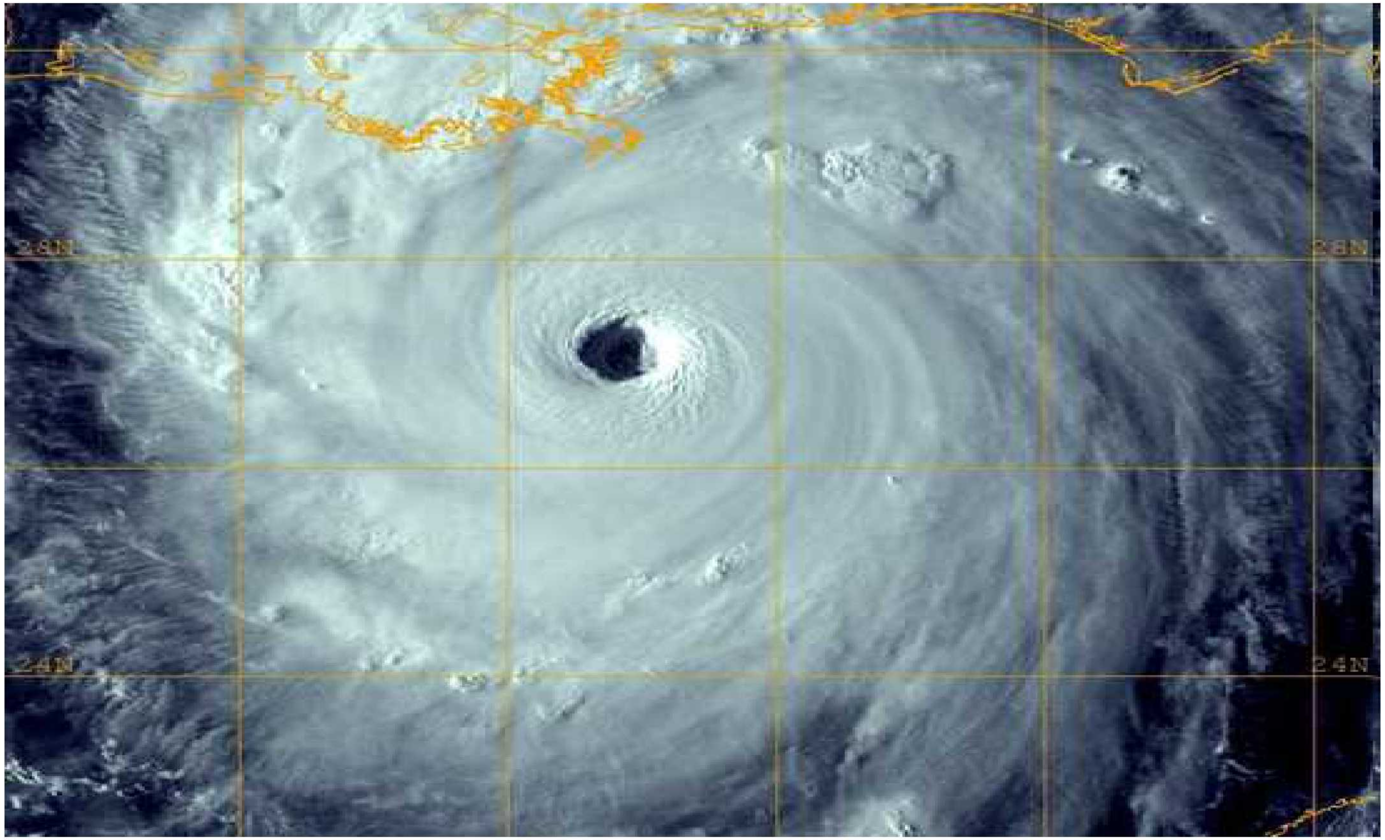
Web and Mobile Based Infrastructure Tool



- Built for Analysts
- Variety of Data Sources
- Instant Situational Awareness
- Rapid Publication-Quality Output
- Collaborative Geospatial Environment

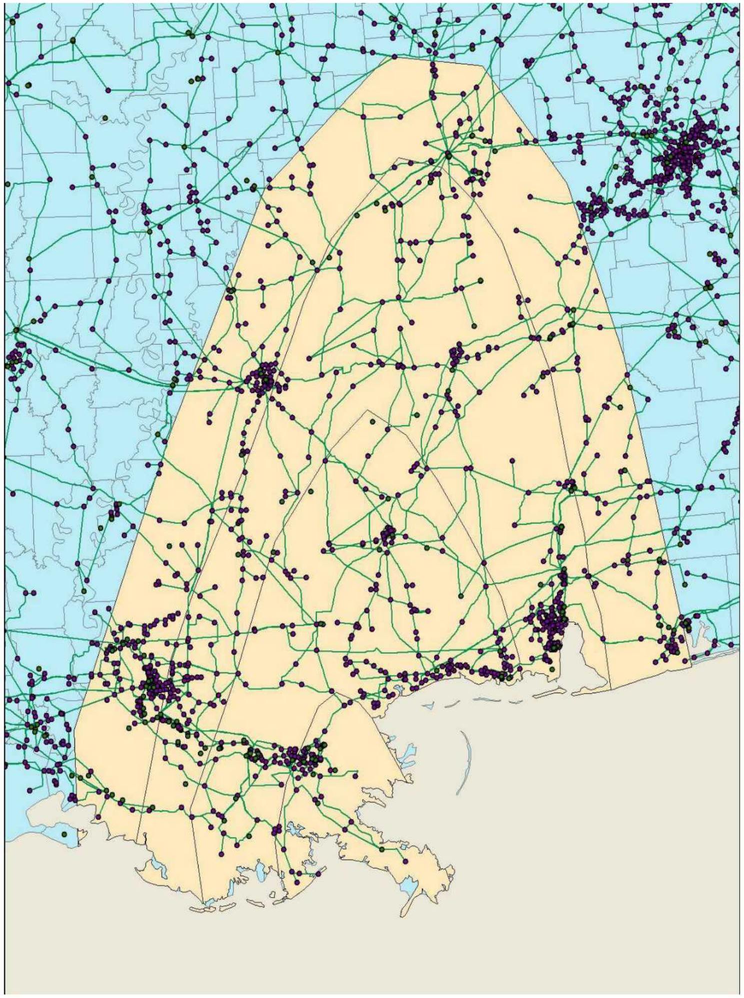
Katrina 2005

Need for Pre-staged Data, Map Templates, and Geospatial Analysis was Identified



Map Generation

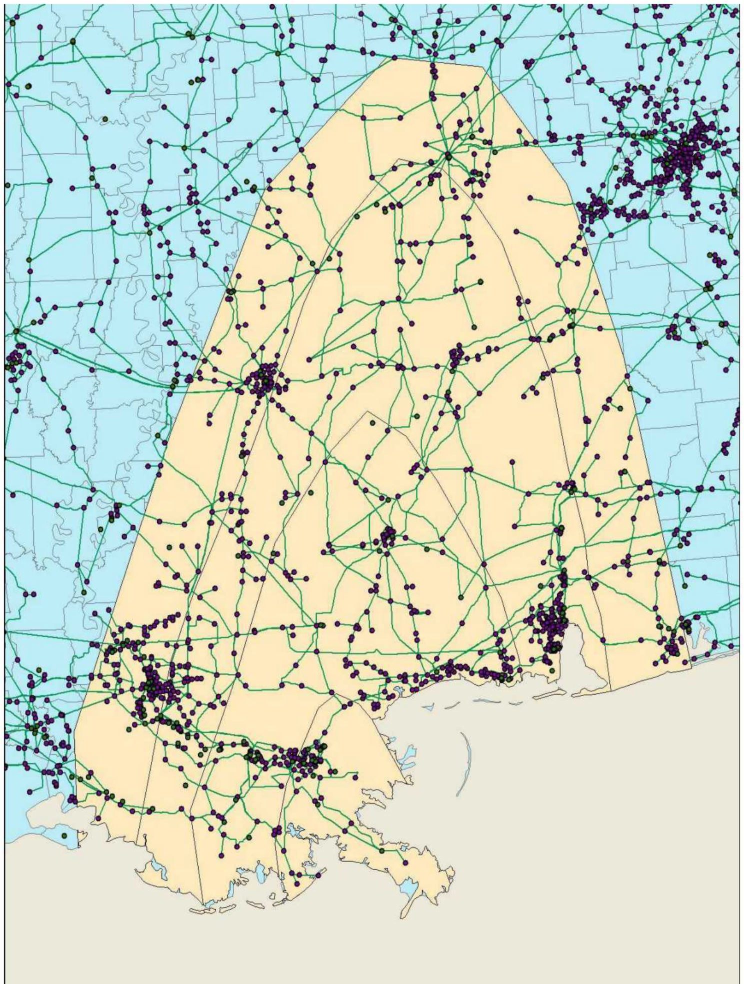
New Orleans Area Electric Power Facilities

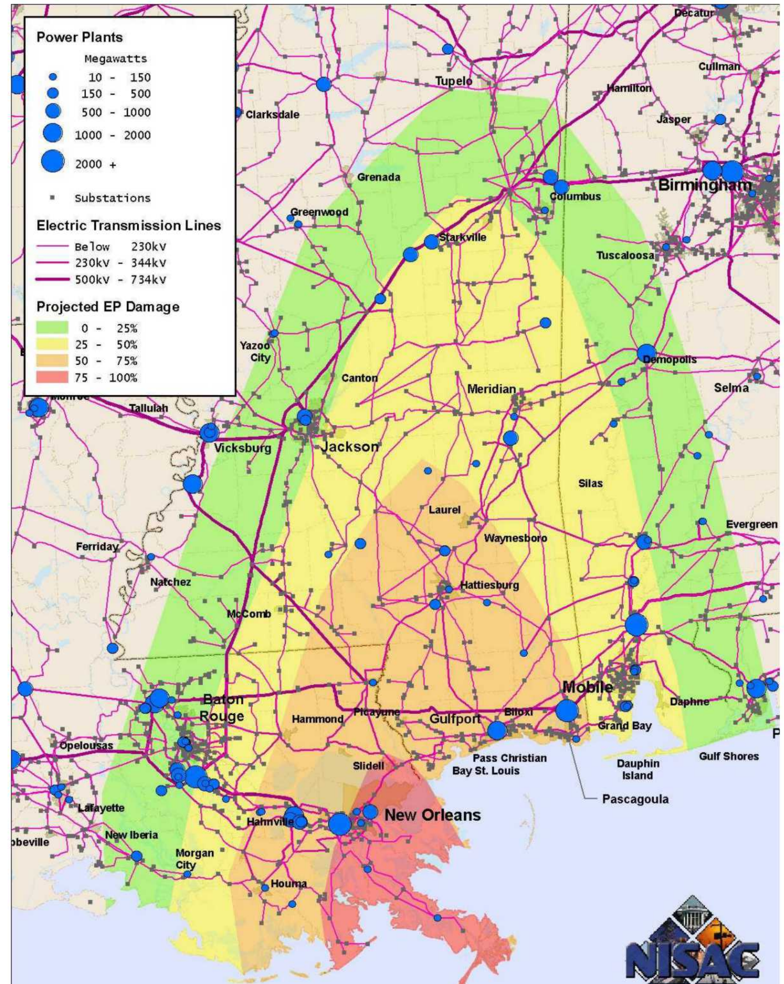


- Power Generation Stations
- Substations
- Transmission Lines

Map Generation

New Orleans Area Electric Power Facilities





FASTMap Foundations

- Data
  Pre-loaded and seamless nationwide and ready for instant situational awareness

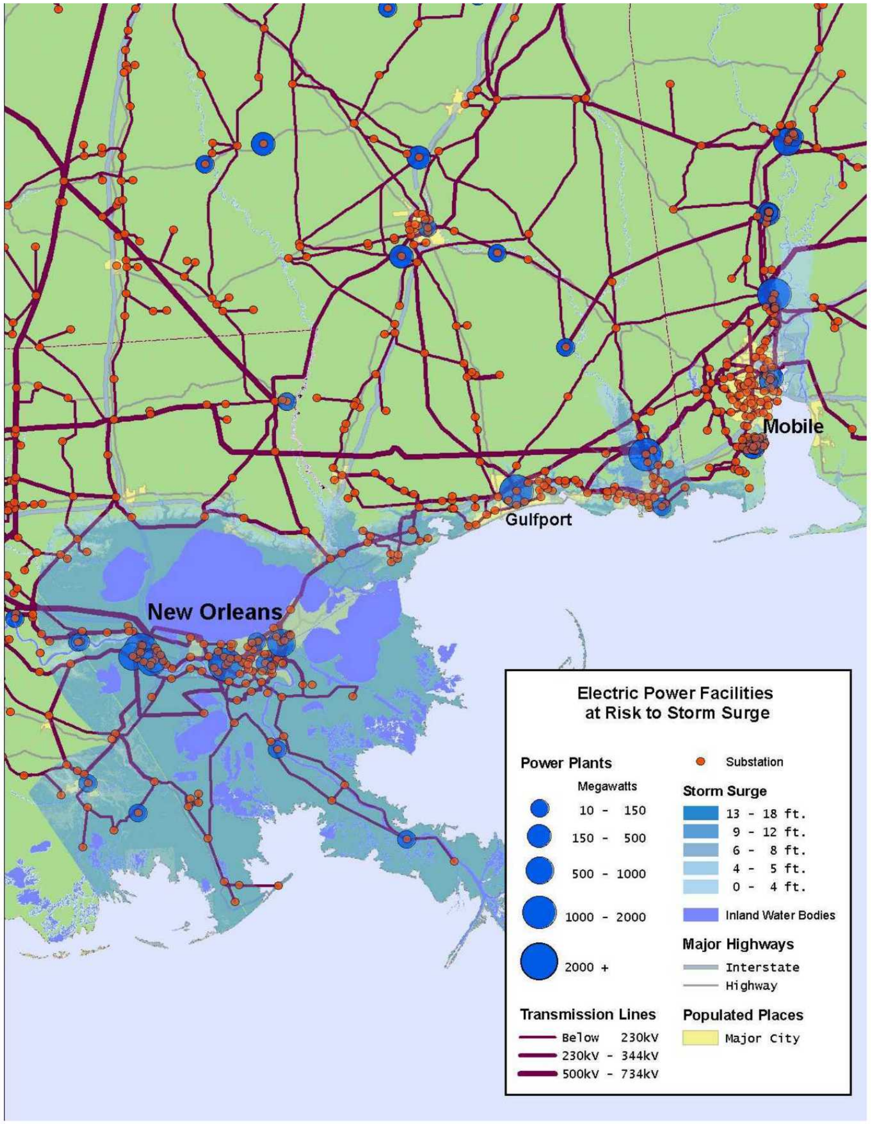
- Geospatial Analysis
  Pre-configured algorithms to identify infrastructure at risk

- Maps
  Pre-symbolized publication quality maps provide information in intuitive form

- Reports
  Pre-formatted output for consistent presentation in FAST reports

- Sharing
  The FASTMAP Channel supports discrete broadcast and collaborative sharing of maps and data

Pre-Formatted Output

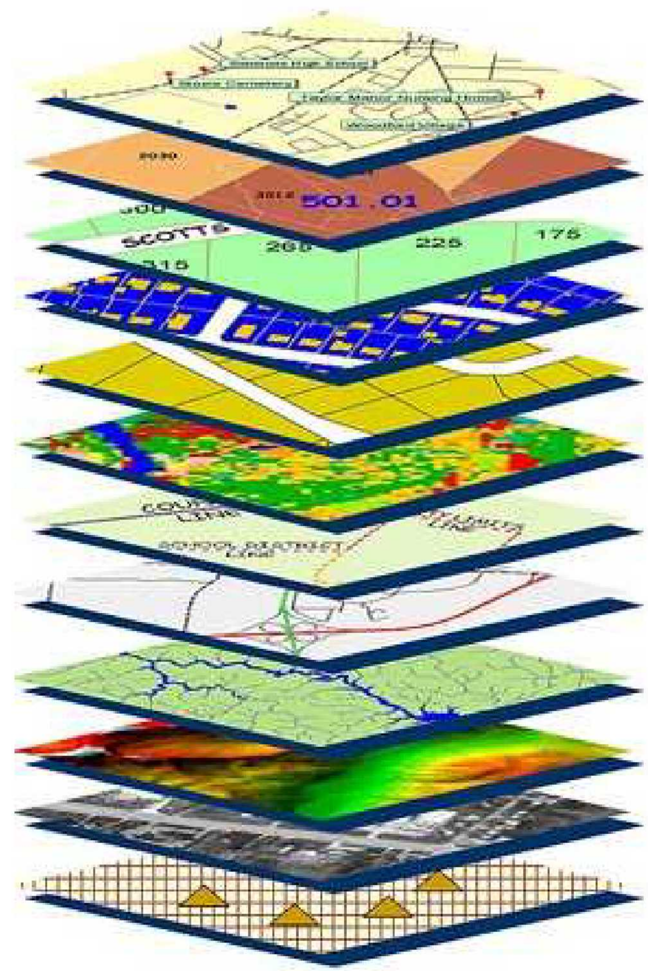


Substation Name	Max Voltage (kV)	Surge Depth (ft)	Generation Capacity (MW)
9MILE	230	11	--
AB Paterson Power Plant	115	30	143
ALMON	230	20	--
ARABI	230	23	--
AVNDAL	230	20	--
BARRYC1	230	2	--
BARRYC2	230	3	--
BAYSTL	230	11	--
BERMAN	230	30	--
BLPNT	230	23	--
CHEVCOG	115	17	--
Chevron Oil Power Plant	115	17	127
CHICK	230	4	--
CONVNT	230	14	--
CURRN	230	30	--
DERBI	230	20	--
DSTRHN	230	20	--
DUTBYU	230	20	--
ESTELL	230	20	--
FAIRVW	230	23	--
FRISCO	230	23	--
FRNBRA	230	20	--
FRNSTL	230	8	--
FRONTST6	230	17	--

Supported Infrastructure Sectors

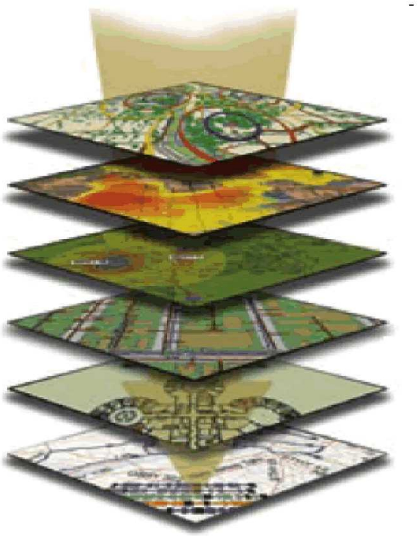
Airports
Banking
Broadcast
Chemical
Dams
Electric Power
Fire Stations
Government
Highways and Bridges
Hospitals
Intermodal Terminals

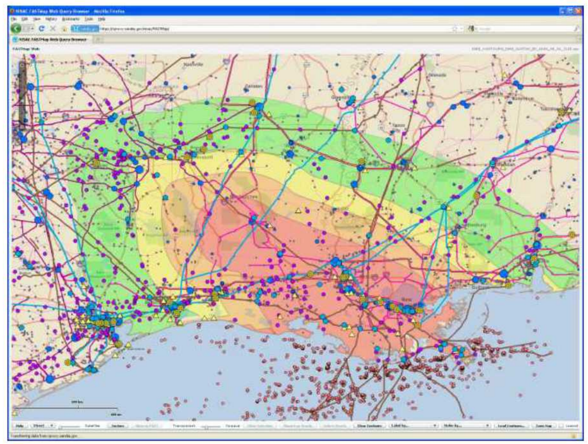
National Icons
Natural Gas
Nuclear Power
Petroleum
Police Stations
Population
Ports
Rail
Telco - Internet
Telco - Wireless
Telco - Wireline

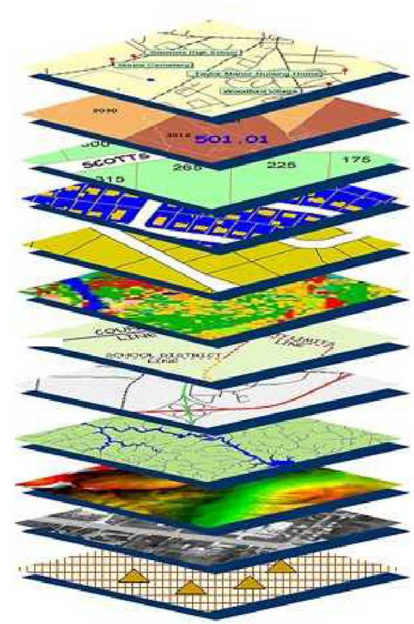


Data Can Come from Anywhere

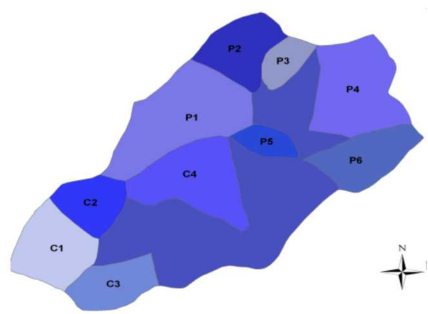
FASTMap







External Internet
Mapping Services



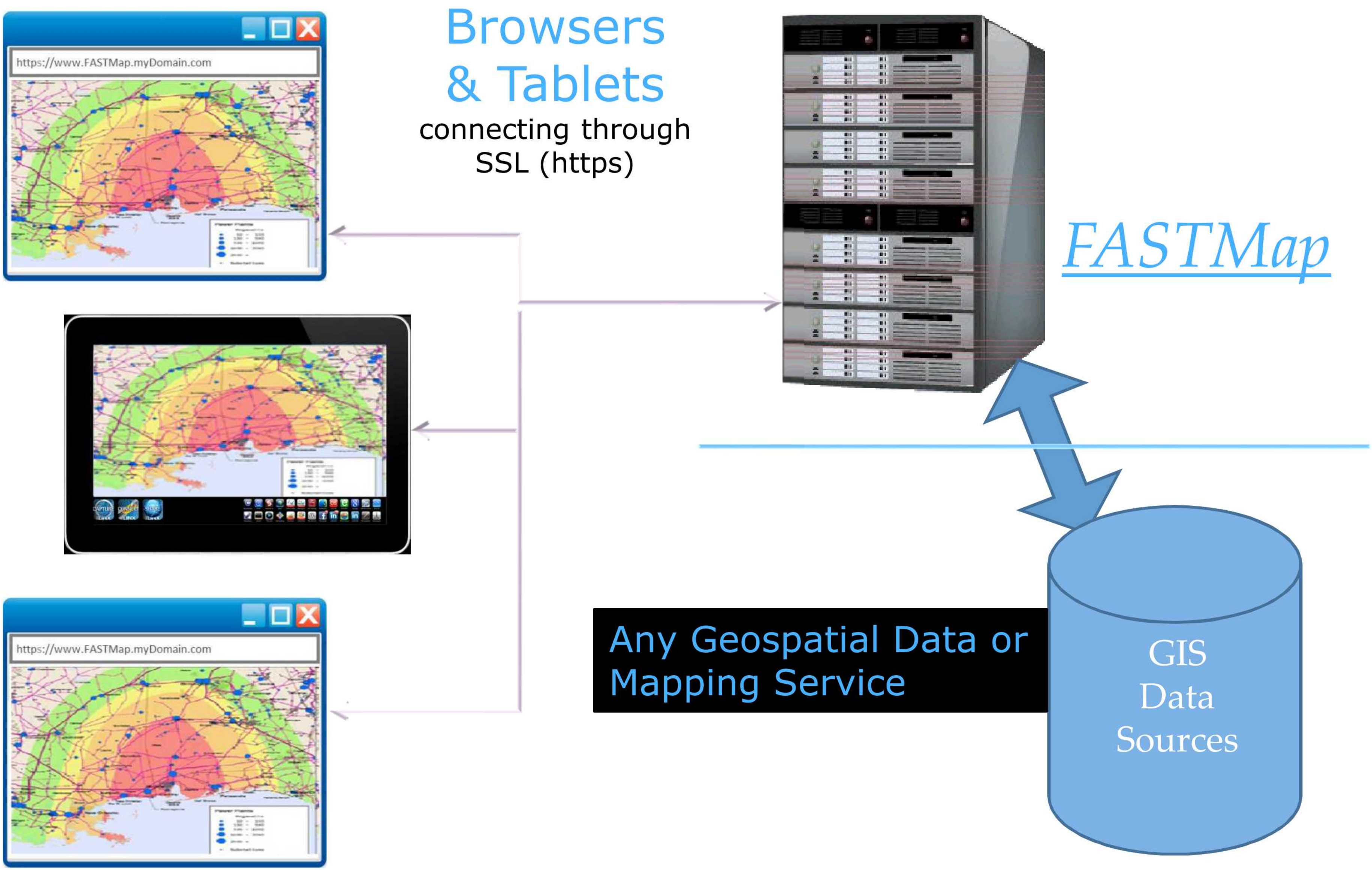
Intranet Mapping Services
Business Data
Application Services

Open Internet

Local Data
Data on *<u>your</u>* computer!

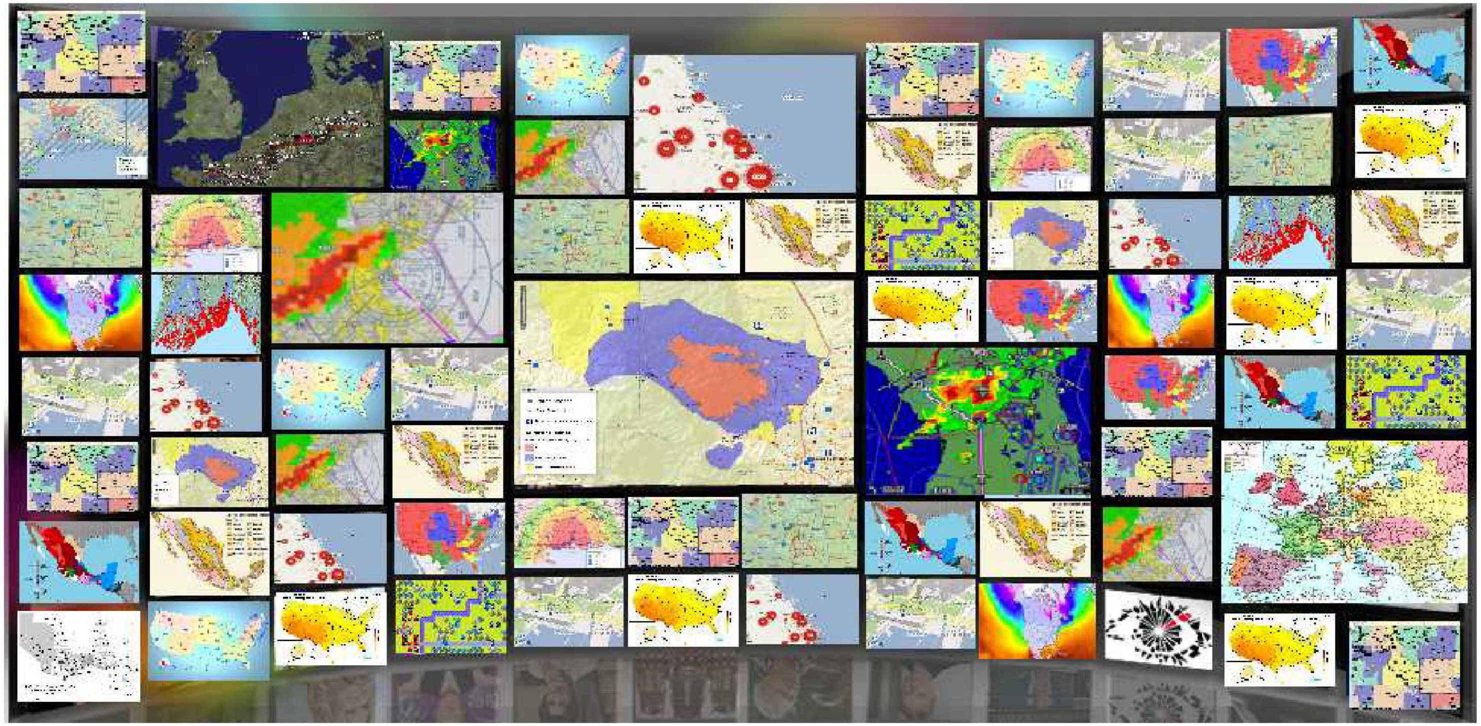
Inside Secure Networks

FASTMap Architecture



FASTMap Channel

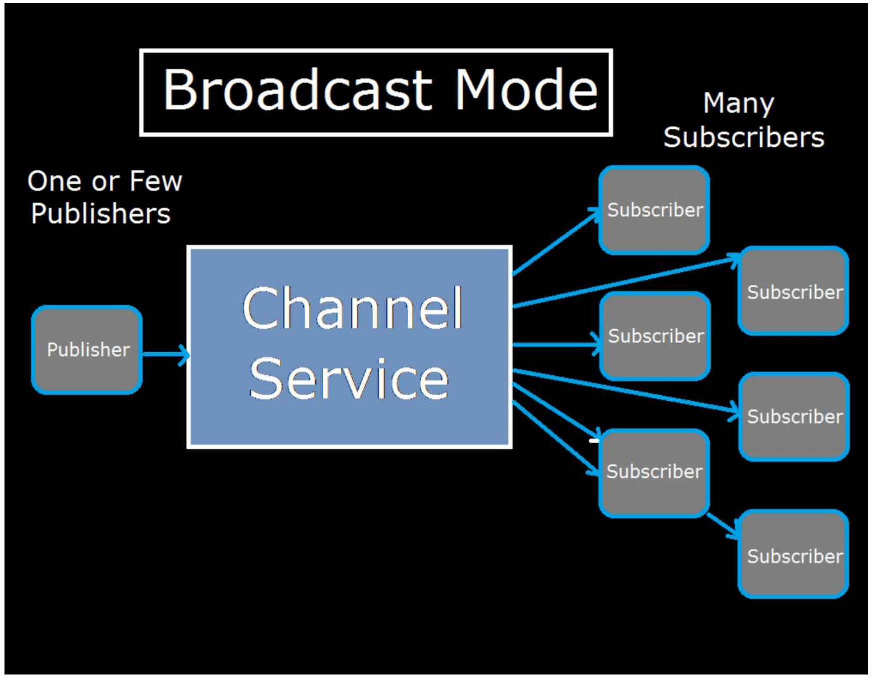
Infinite Number of Named Channels
Publish and or Monitor Capabilities
Authentication and Access Roles
Historical Browsing
Instantly Updated Anywhere Worldwide

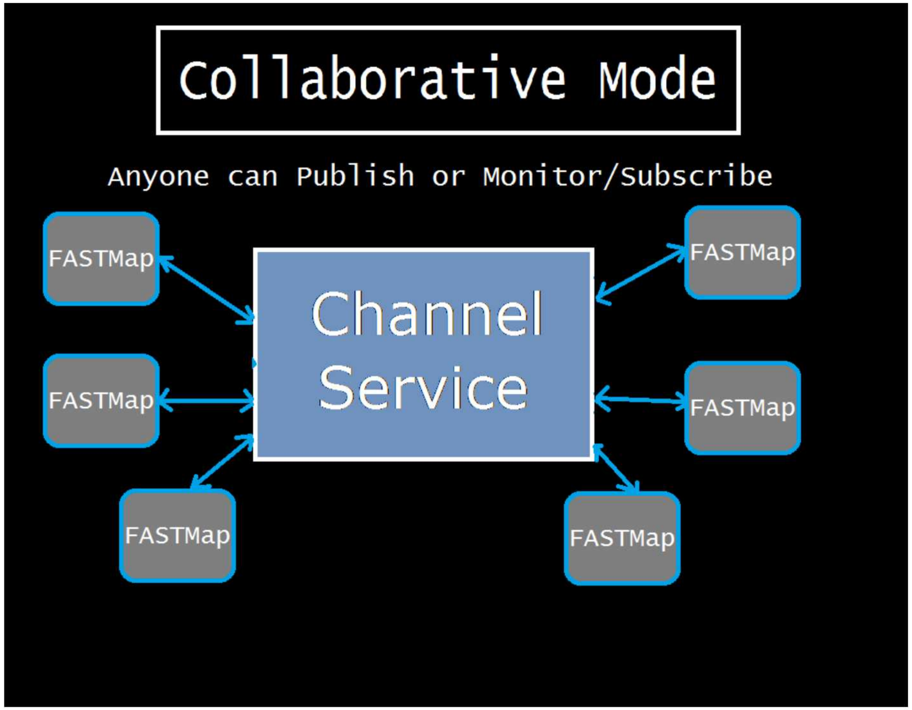


FASTMap Channel

Broadcast Mode
Few Publishers, Many Subscribers

Collaborative Mode
Anyone can Post or Repost



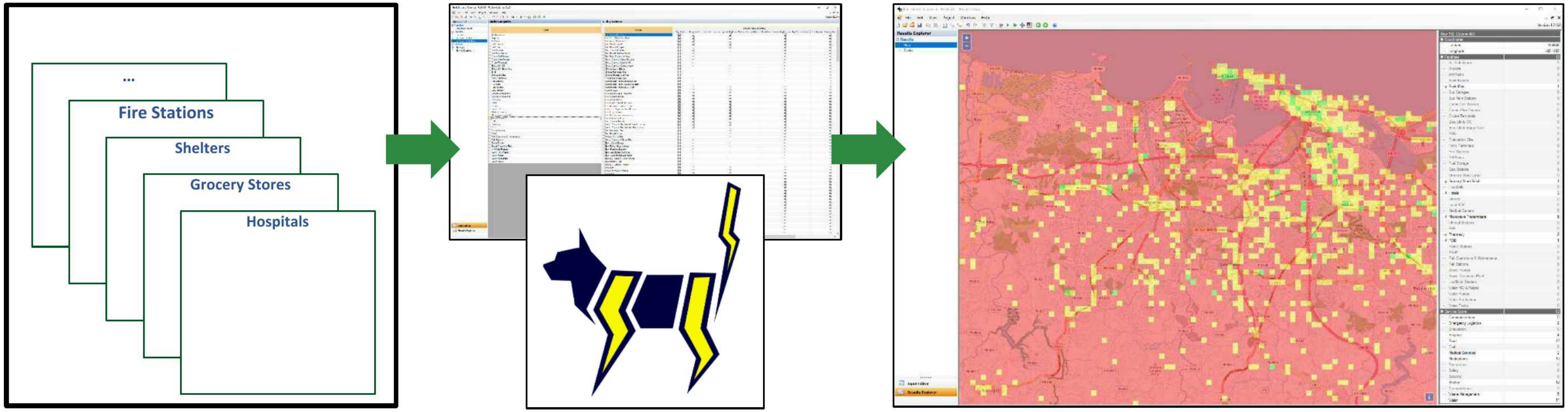


FASTMap

- Instant Situational Awareness
- Any GIS Data
- Rapid Publication-Quality Output
- Collaborative Geospatial Environment

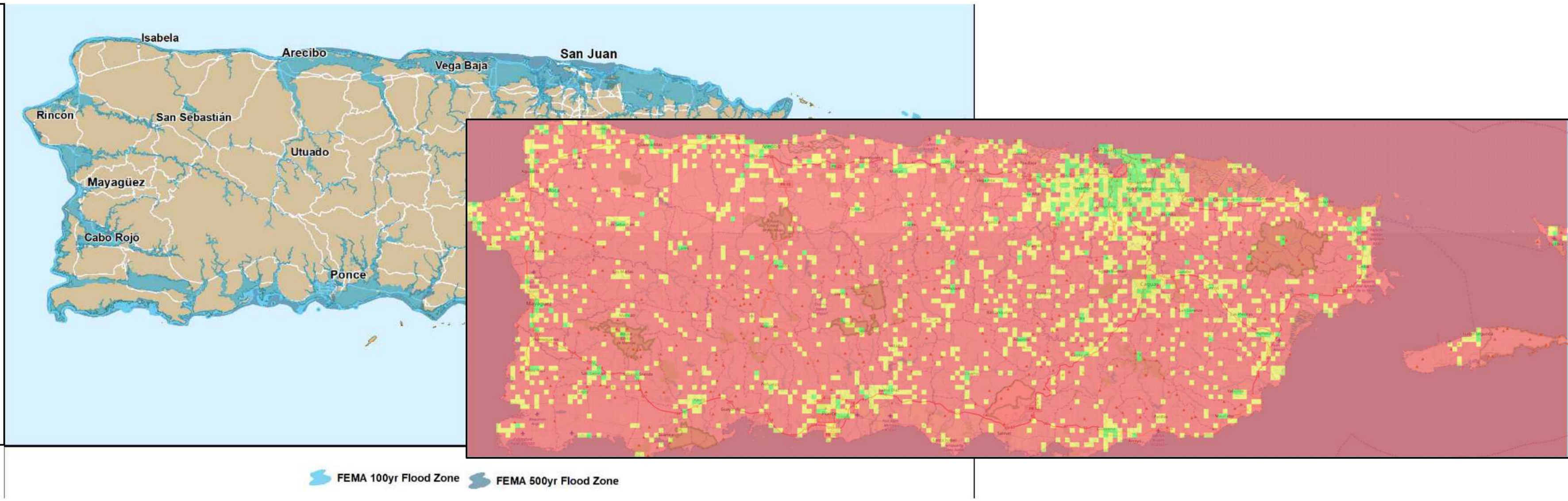
ReNCAT

- Uses information on infrastructure and critical service rankings to identify locations that have high levels of services available
  - Candidate locations for microgrids
- Can consider different design basis threats

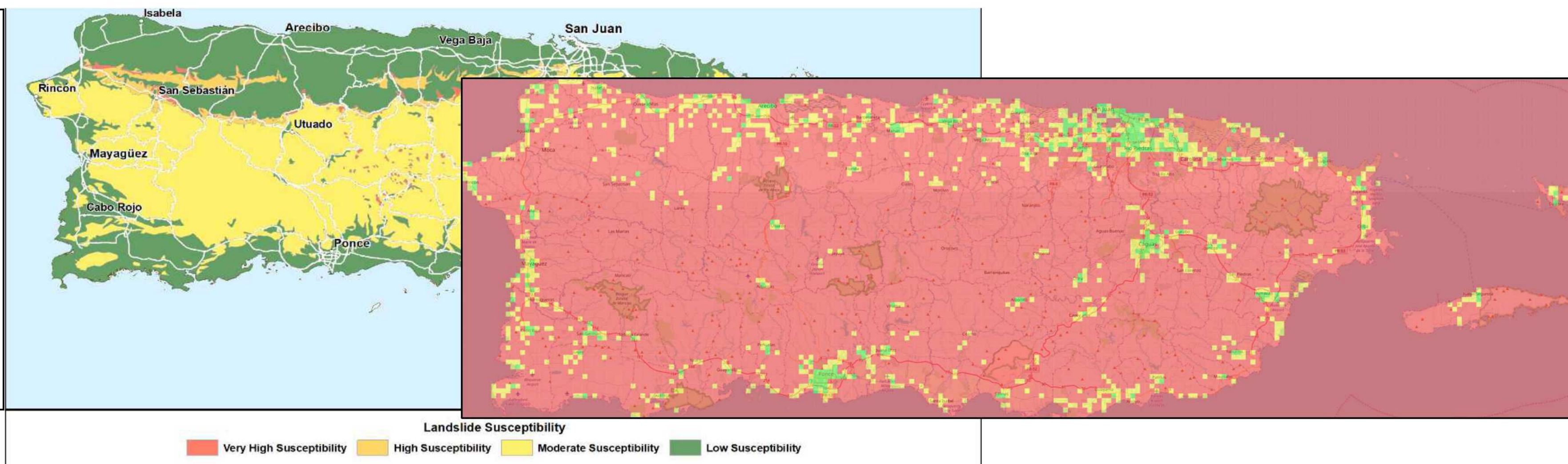


Threat Exclusion Profiles Show Different Results

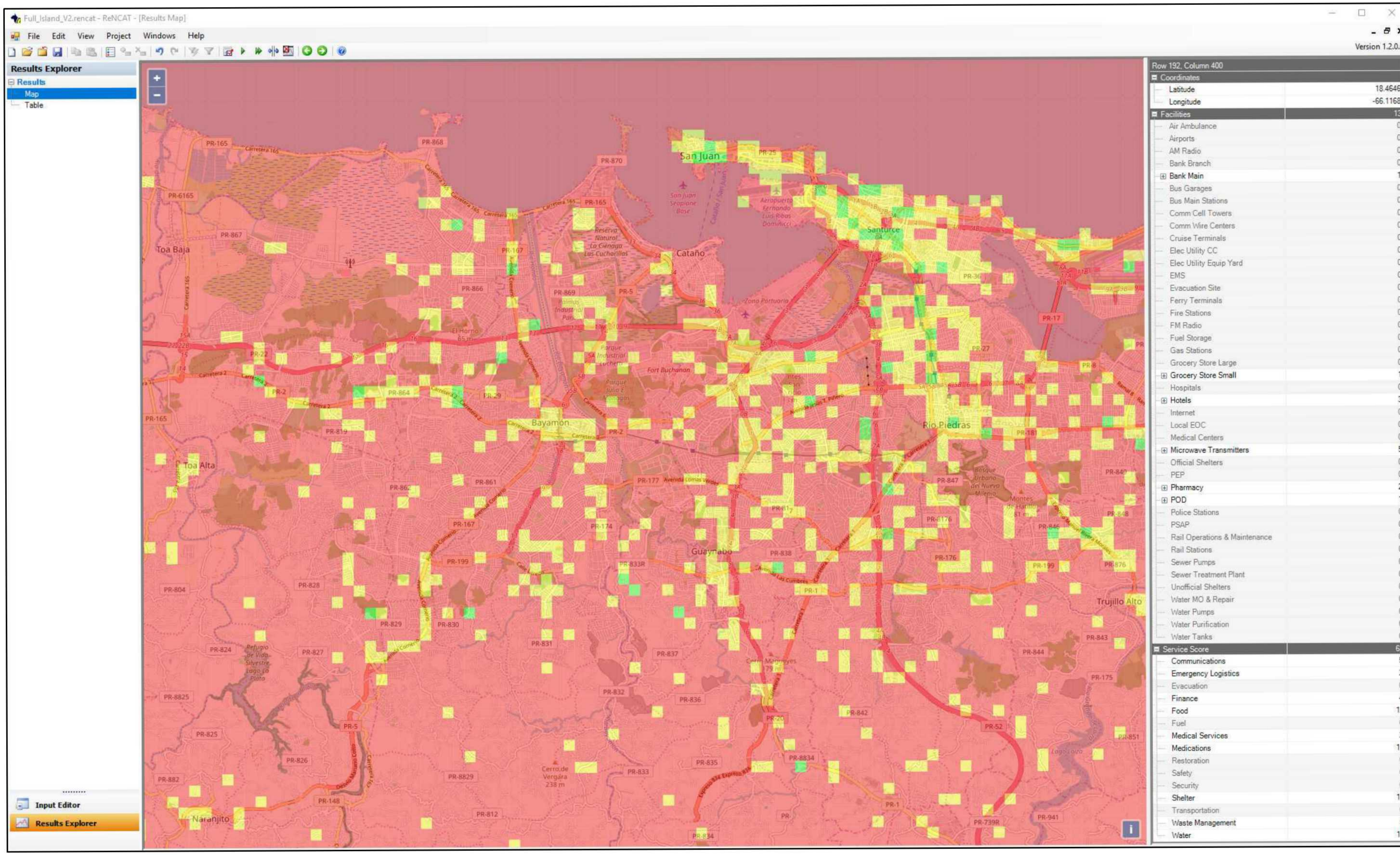
100-yr Flood



Landslide Med

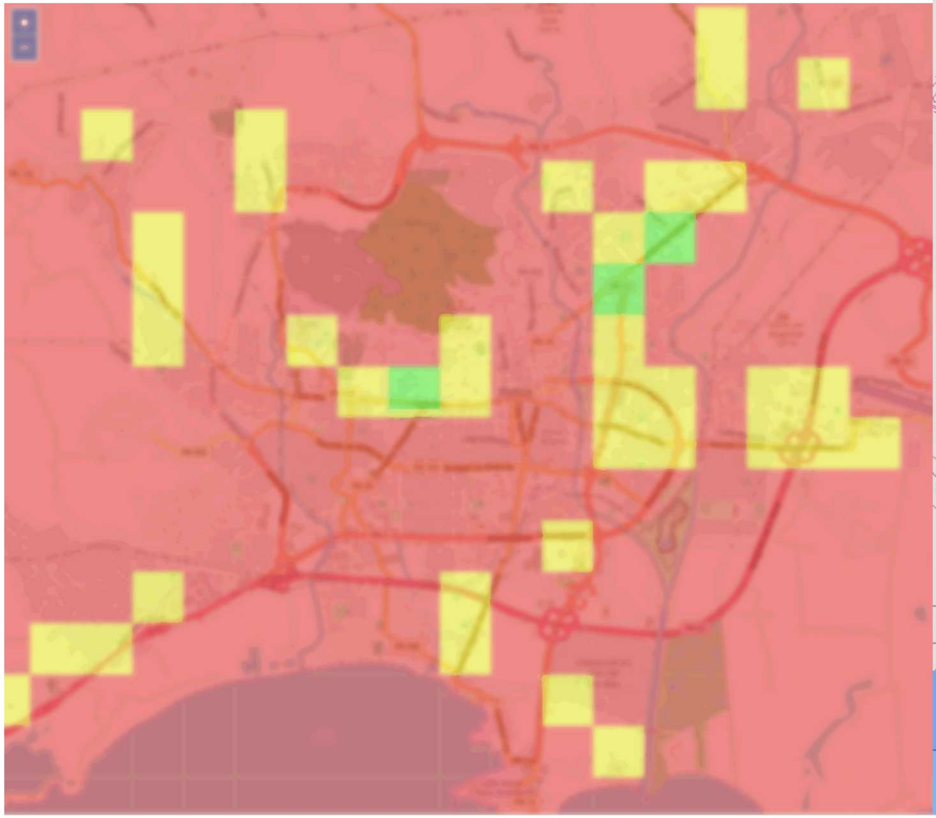


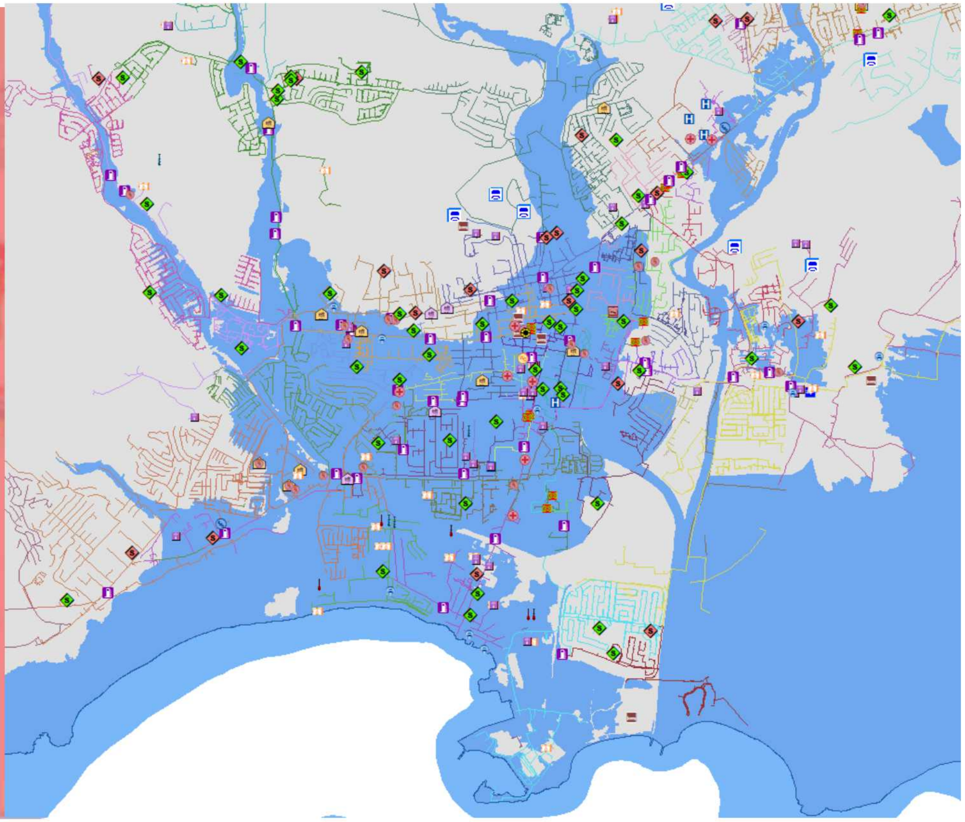
ReNCAT Tool Suggests Locations with High Service Levels



ReNCAT to Microgrids: Ponce Example

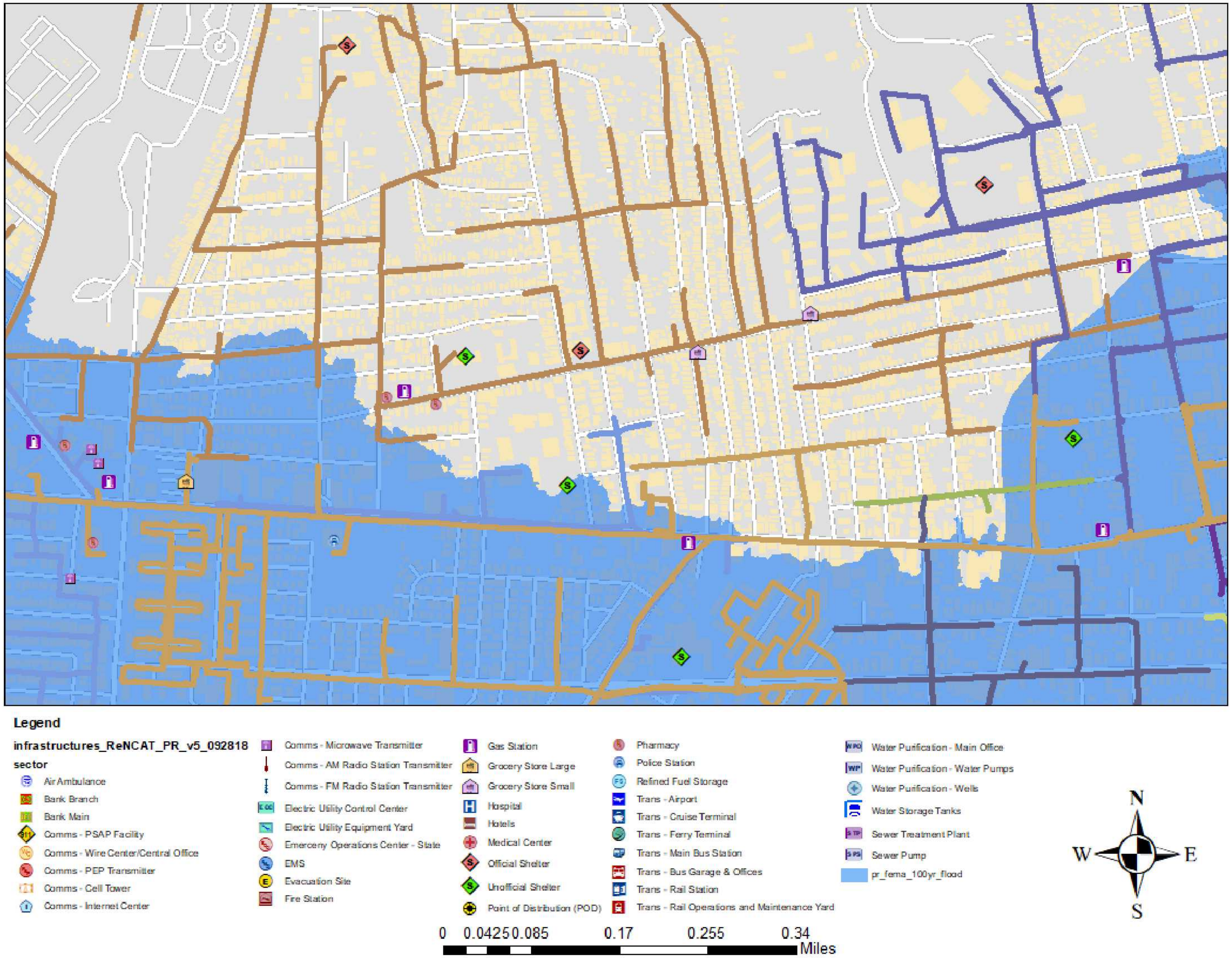
Explore the green squares – find high concentration of services outside the hazard zones





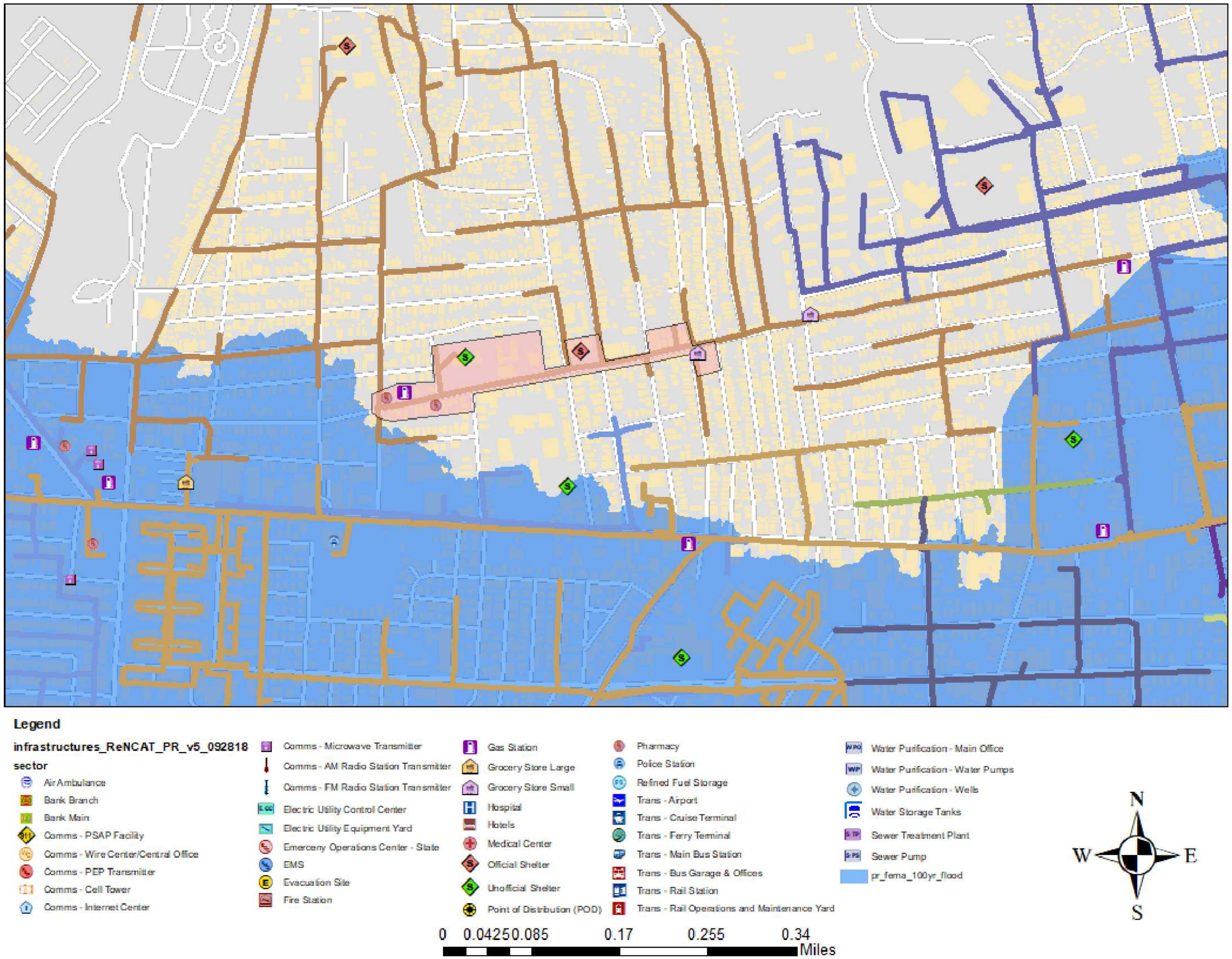
ReNCAT to Microgrids: Example

Find clusters of assets – ideally all on the same feeder - and minimize non-critical load



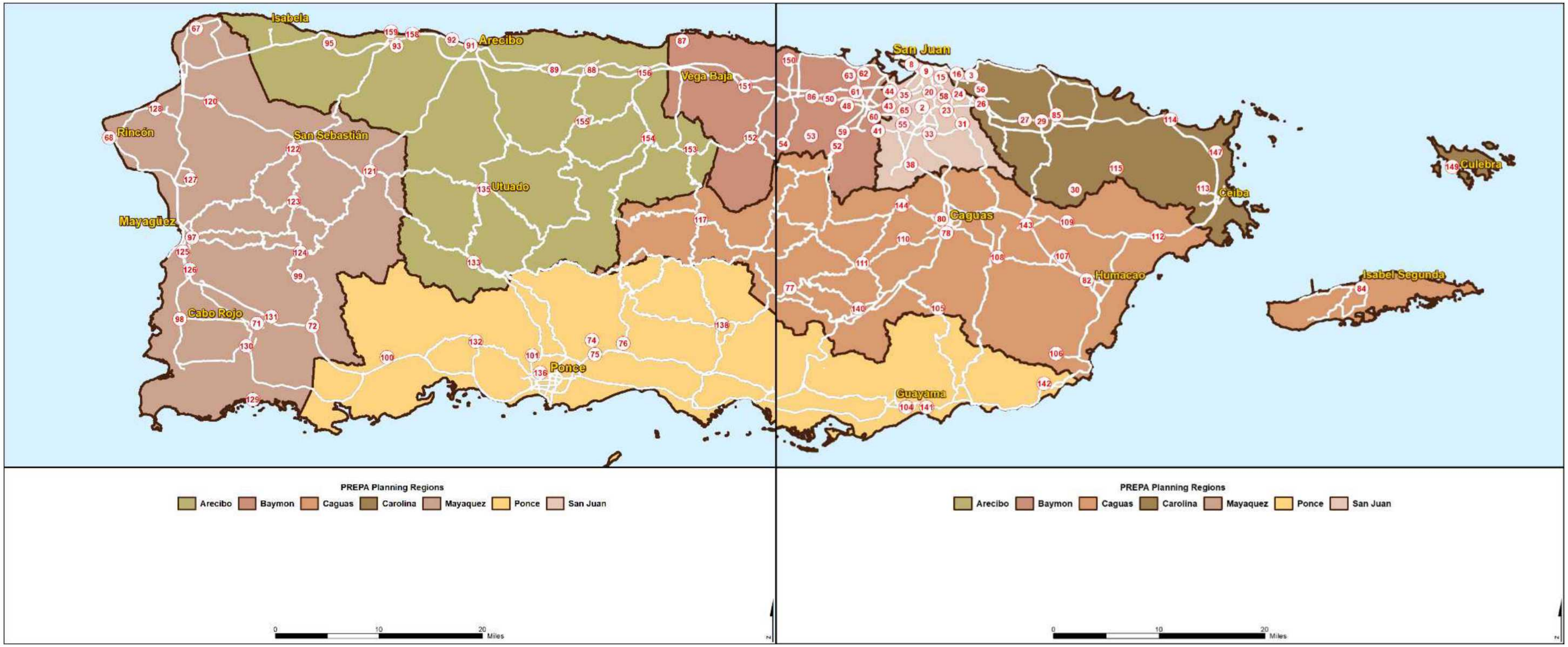
ReNCAT to Microgrids: Example

Draw microgrid polygon to balance use of isolation switches vs. acceptance of non-critical load



Suggested Microgrid Locations

159 locations in total



17 microgrids dominated by communications assets (cell towers, microwave transmitters, AM/FM Radio Transmitters):

115, 113, 105, 99, 93, 89, 88, 87, 86, 85, 53, 51, 44, 41, 40, 30, 29

Appendix A: Distributed Energy Generation and Storage

Types of Distributed Energy Resources

- **Conventional generation**
  - Diesel generators
  - Gas generators
  - Microturbines
  - Fuel Cells
- **Renewables**
  - PV
  - Wind
  - Others (geothermal, biomass,…)
- **Energy Storage**
  - UPS
  - Batteries
  - Others

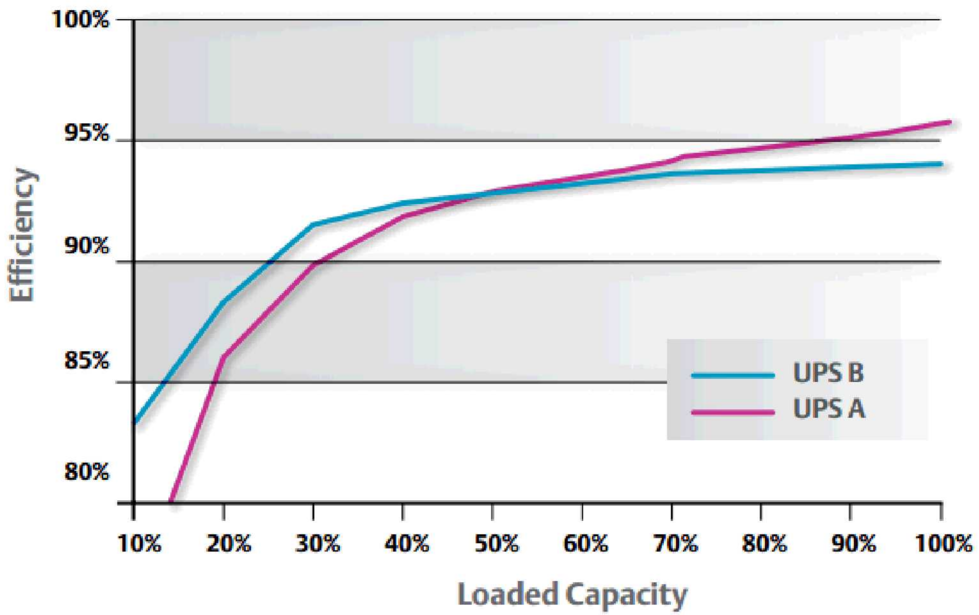
Diesel Generators

- 26% - 33% Energy Efficient
- Most Common DER used for back up power
- Power ratings are from the kW up to MW
- Standby, Prime Power, Continuous
- Cost range ($0.25 - $1)/Watt

Gas Generators

- 24% - 30% Energy Efficient
- Combined Cold and Heat Power (CCHP)
- Lower Emissions
- Power ratings are from the kW up to MW
- Cost range ($0.60 - $1.20)/Watt – 1.2-2X costs of equivalent diesel generator

Uninterruptible Power Supply (UPS)

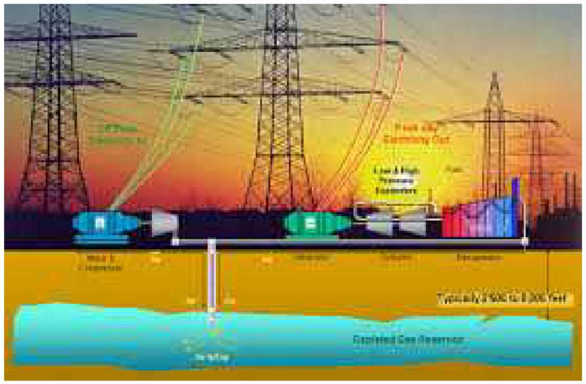


- Commonly put in series of a critical load
- Voltage and power disturbance ride through is typically 5-20 minutes
- Increases reliability and power quality for the load it is connected to

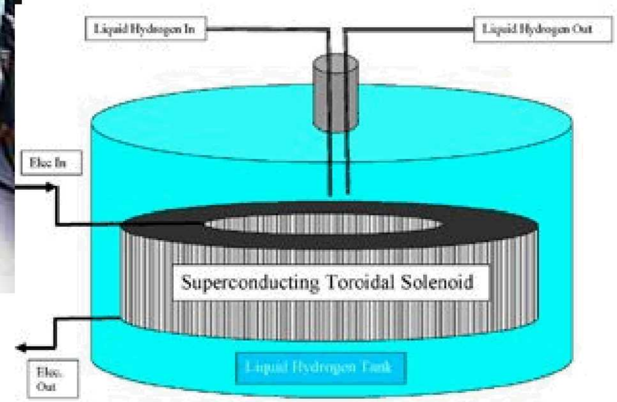
Batteries

- Various technologies, effective for different operations
  - Fast discharge
  - Long-term storage
  - High performance over many cycles
- Sizes range from Wh to MWh

Other Energy Storage



- Pumped hydro
- Compressed air energy storage (CAES)
- Flywheel
- Capacitors
- Superconducting magnetic energy storage (SMES)



Photovoltaics

- Power ratings from W to MW
- 10-30% energy efficient,
- Costs have decreased rapidly:
  - Commercial PV (~200kW): $1.85/W in 2017 (NREL)
  - Less for larger installations
- Fuel (sunlight) is free

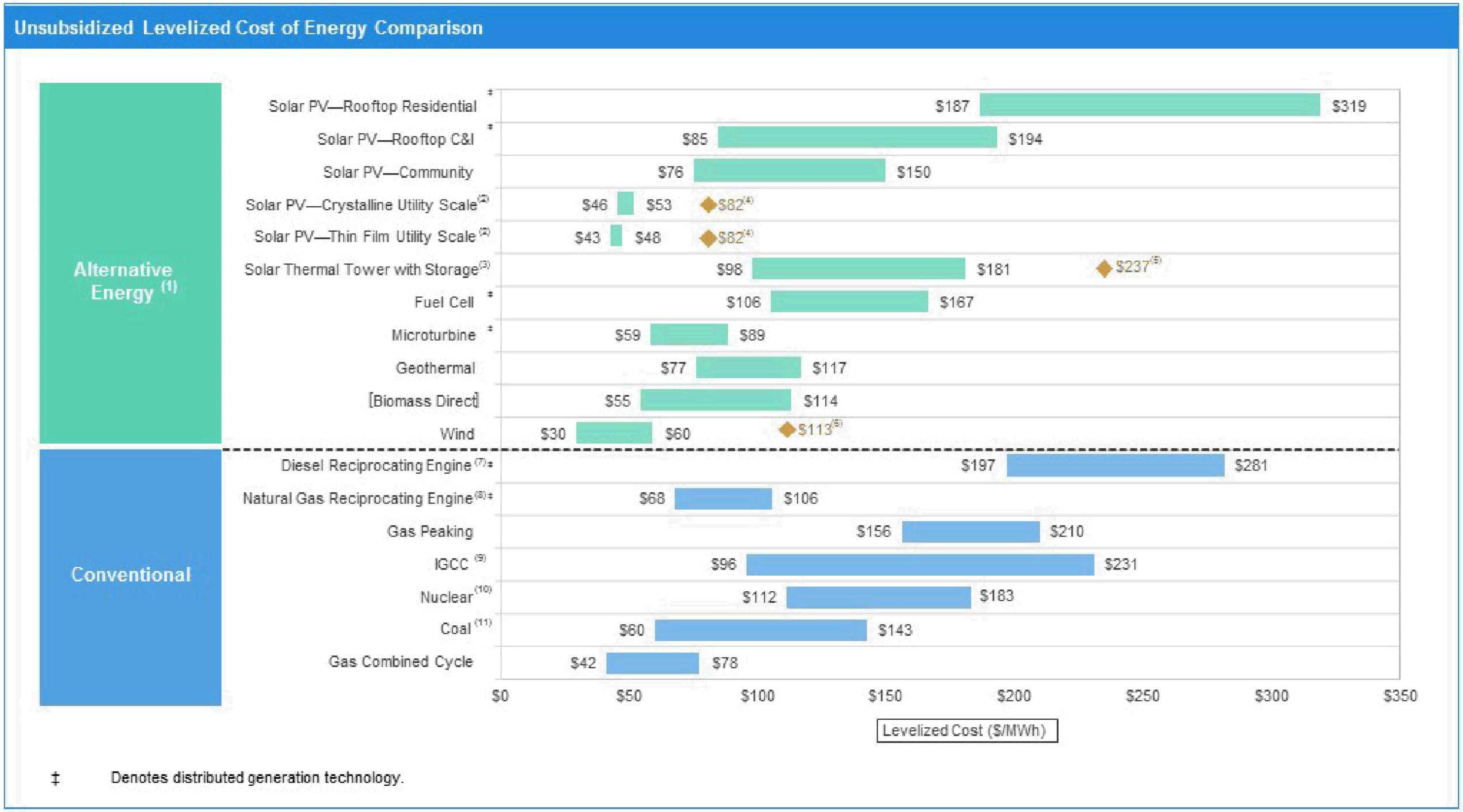
Wind Turbines

- Power ratings from kW to MW
- 75% energy efficient
- Costs are decreasing:
  - Median cost of $1.60/W in 2017 (REN21)
- Fuel (wind) is free

LCOE Cost Comparison

Levelized Cost of Energy (LCOE) – total cost to build and operate generation over its lifetime divided by total energy output

- Accounts for both capital costs and fuel costs



https://www.lazard.com/perspective/levelized-cost-of-energy-2017/, **November 2017**

Appendix B: Advanced Engineering Analysis

Appendix B- Advanced Engineering Analysis

- This appendix discusses advanced engineering analysis which can be performed to augment the microgrid conceptual design process in order to obtain more optimal microgrid conceptual designs that match performance goals

- The engineering analysis includes:
  - Power flow analysis
  - Consequence analysis
  - PRM and TMO analysis

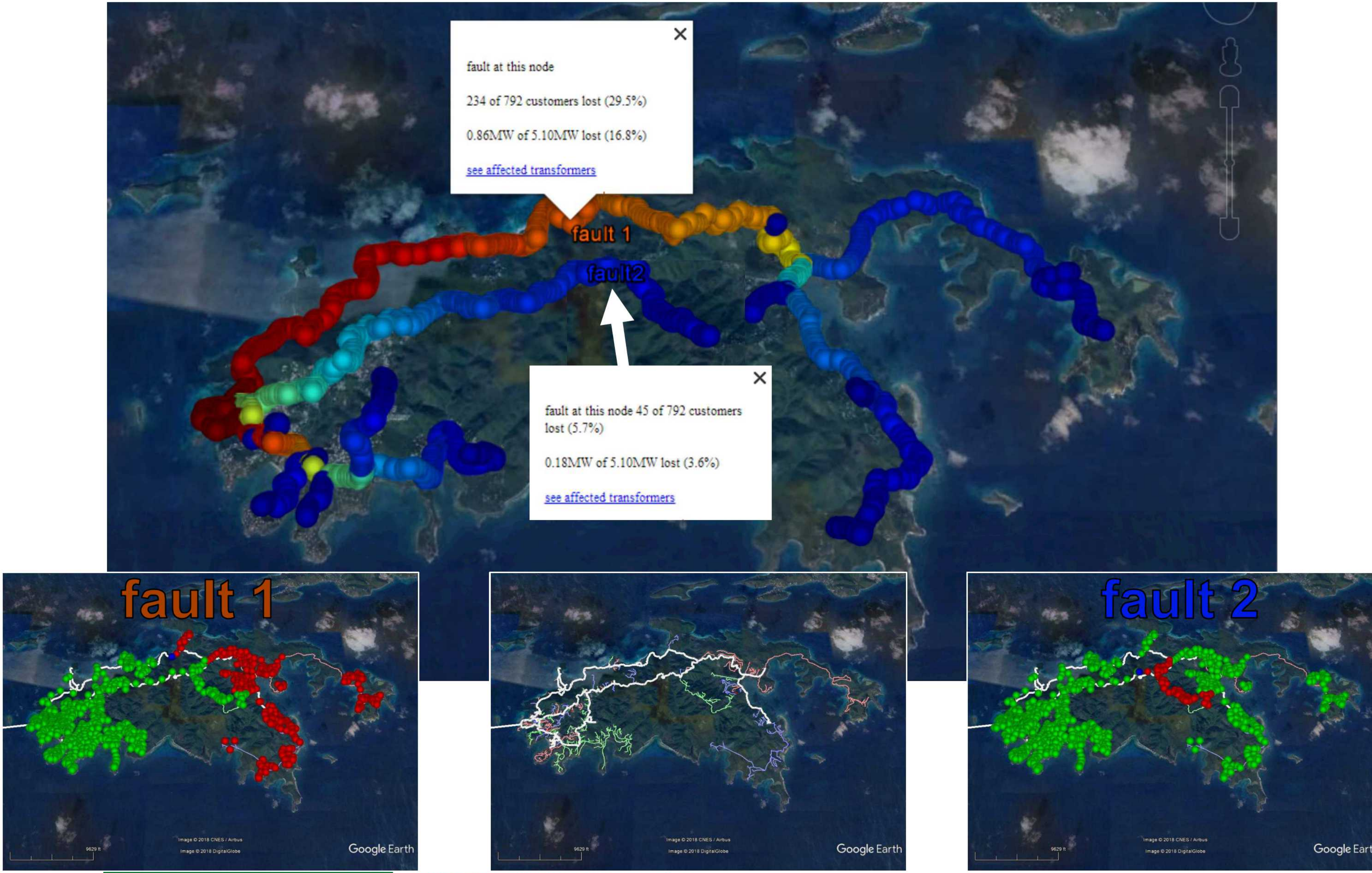
Power Flow Analysis

- Analysis to determine potential problematic microgrid behavior
  - Power quality, voltage sags, frequency regulation, transformer inrush, cold load pickup, etc.

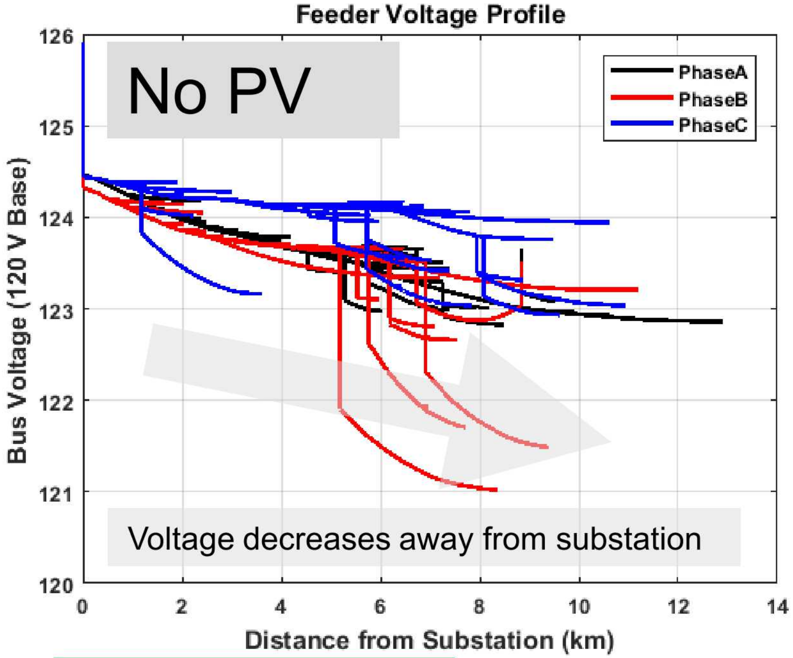
- Development of a notional microgrid one-line diagram
  - Determination of switching to form the microgrid MV backbone
  - Designation of PCCs
  - Designation of generators
  - Prioritization of buildings load served in microgrid (critical, priority, nice to have, etc.)

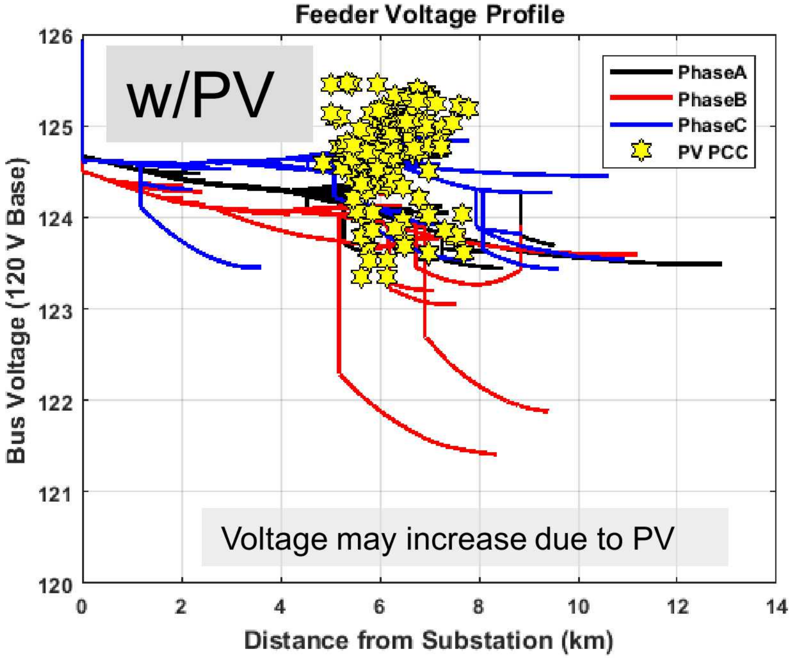
Example Power Flow Model

Locational Fault Analysis

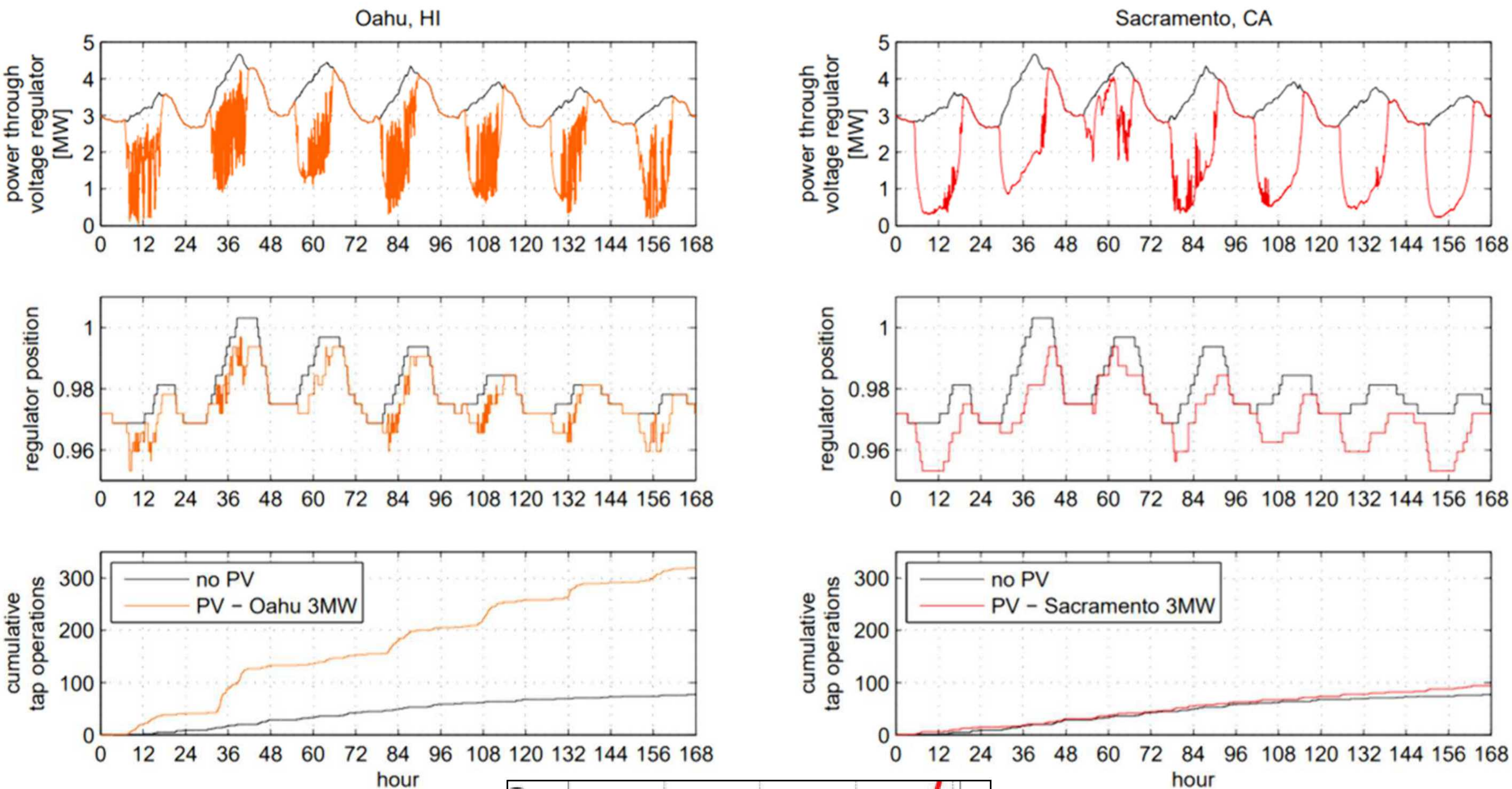


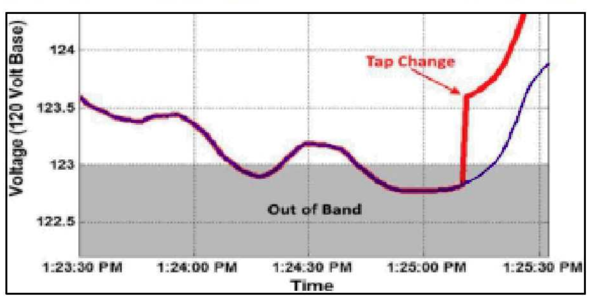
Voltage Profile





Timeseries analysis

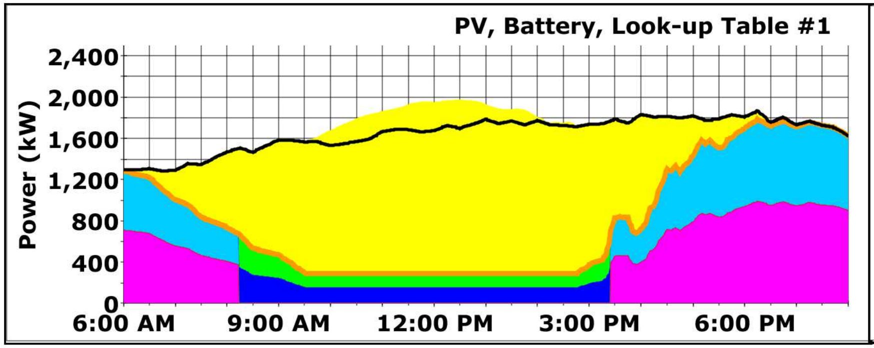


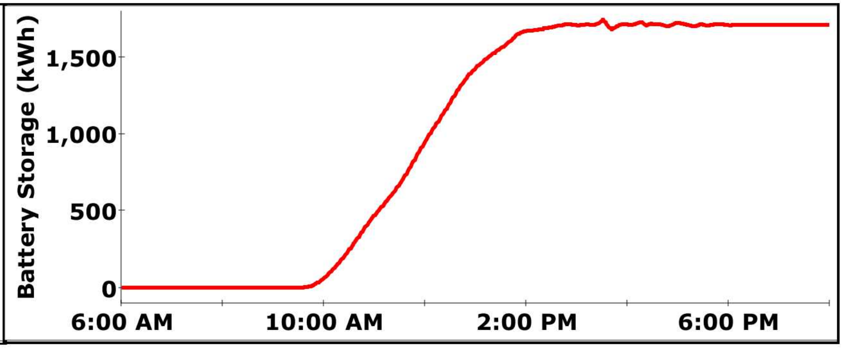


Consequence Analysis

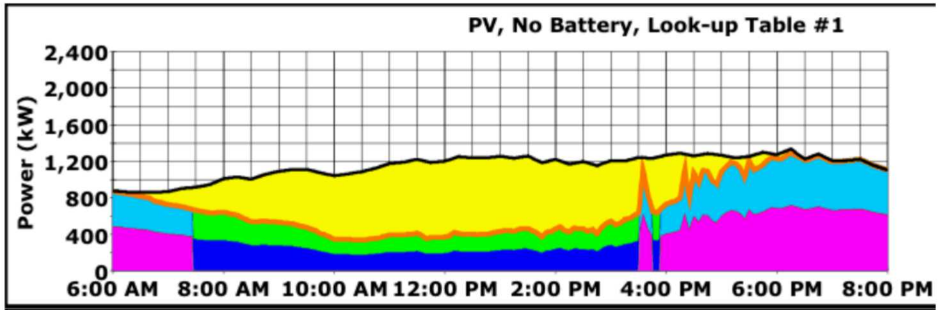
- Defining problems using a system dynamics approach, characterizing the significant dynamics of a system related to power system applications .
- Defining a system as continuous quantities interconnected in loops of information feedback and circular causality.
- Identifying independent stocks or accumulations (levels) in the system and their inflows and outflows (rates).
- Formulating a behavioral model capable of reproducing, by itself, the dynamic situation being modeled. The model is usually a computer simulation model expressed in nonlinear equations, but is occasionally left unquantified as a diagram capturing the stock-and flow/causal feedback structure of the system.
- Deriving understandings and applicable policy insights from the resulting model.
- Implementing changes resulting from model-based understandings and insights.

Example of Consequence Modeling

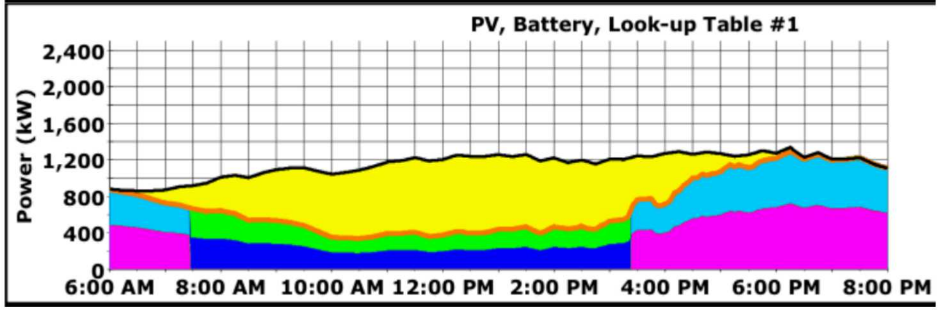




This system has too much PV energy and would require expensive amounts of energy storage.



With less PV, adding appropriate amounts of storage reduces renewable energy intermittency issues. More load would reduce the PV penetration levels.



Optimizing use of energy storage, PV, and diesel generators.

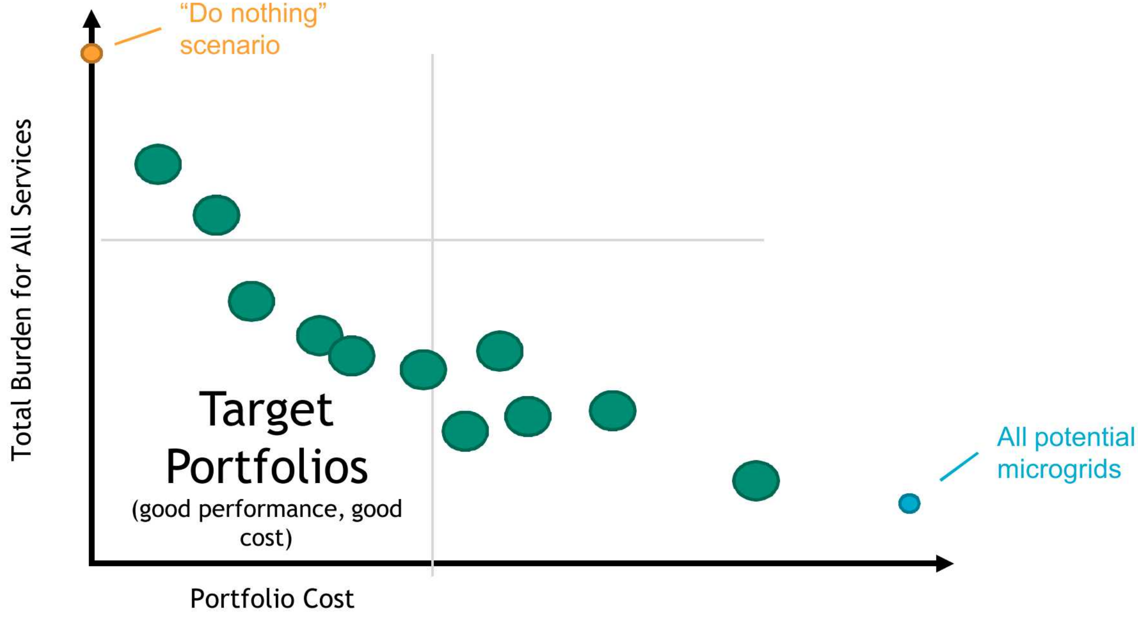
Performance/Reliability Model (PRM)

- The purpose of the PRM is to statistically quantify the behavior of a candidate microgrid design in terms of performance and reliability
- This information is used by TMO to tune the design according to the design options in order to maximize performance and reliability while minimizing cost
- PRM operation:
  - Samples utility outages according to a distribution (e.g., at a rate of ~4/year) for thousands of years
  - Microgrid is simulated during each outage and statistics are collected
  - Uses an event-driven simulation for better calculation efficiency
  - Once the standard error of the mean (SEM) of the primary statistic is below the desired threshold, the simulation stops and returns the analysis
- Required information:
  - Electrical layout, including transmission/distribution line data
  - MTTF and MTTR for grid elements, transmission lines, and other relevant equipment
  - Generator efficiency curves and other data
  - Load profiles (both critical and priority)
  - PV and wind profiles, etc.

Evaluate Options

- Compare performance/risk and cost estimates for each option
- A spreadsheet or Pareto chart representation can assist evaluation of options
- Performance risk modeling can be assisted with tools like the Sandia Performance Reliability Model (PRM) for grid dynamic analysis
- Pareto chart representation can be developed with tools like the Sandia Technology Management Optimization (TMO) to evaluate options

Cost vs. Performance



Technology Management Optimization (TMO)

- Software that computes planning roadmaps
- Tradeoffs are treated objectively and defensibly
- Solves user-defined problems: timeframe, objectives/constraints, options/suboptions are all user-defined
- Microgrid optimization

Performance/Risk and Cost Analysis

- Performance/risk
  - Determination of performance/risk for each option
  - Comparison of options with baseline system
  - More detailed performance/risk can be done by examining component and system reliability and availability and using engineering tools to perform more detailed calculations

- Cost
  - Estimation of microgrid component costs for each option
  - Include additional costs associated with additional design, engineering, and installation of microgrids

Optimizing Microgrid Design Performance

TMO

- Calculates fitness of design based on statistics from PRM
- Keeps track of the solutions (sets of design parameters) with the greatest overall fitness
- TMO develops the set of Pareto optimal points (multi-objective solution)

Design parameters from TMO to PRM

Reliability/Performance Model (PRM)

- Event-based simulation
- Calculates statistics of interest based on candidate design parameters from TMO

Statistics of interest from PRM to TMO

Evaluate Best Set of Conceptual Design Options

- Determine options which meet DBT according to specified performance objectives
- If best performing options are cost prohibitive, determine which options will most closely align with performance objectives at least cost
- Consider other factors in the evaluation, such as the time necessary for design and installation of the options as well as the feasibility in obtaining stakeholder support for each option