Enhanced Power Supply Resiliency with dc Microgrids

Alexis Kwasinski, Ph.D.

R. K. Mellon Faculty Fellow in Energy

University of Pittsburgh, Swanson School of Engineering

Overview

- Motivation:
  - Performance of conventional power grids during past natural disasters
- Resilient microgrid design
- AC vs. DC microgrids for resilient power supply
- Conclusions

- This work was supported by NSF under award # 0845828

Introduction

Motivation

- The Presidential Policy Directive 21 identifies "energy and communications systems as uniquely critical due to the enabling functions they provide across all critical infrastructure sectors."

Resiliency (from PPD21):

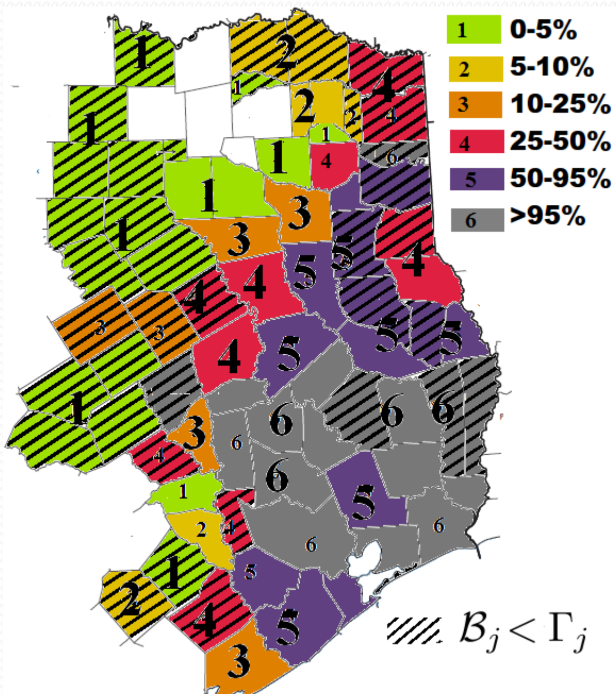
- The ability to **prepare** for and **adapt** to changing conditions and **withstand** and **recover rapidly** from disruptions.

Context:

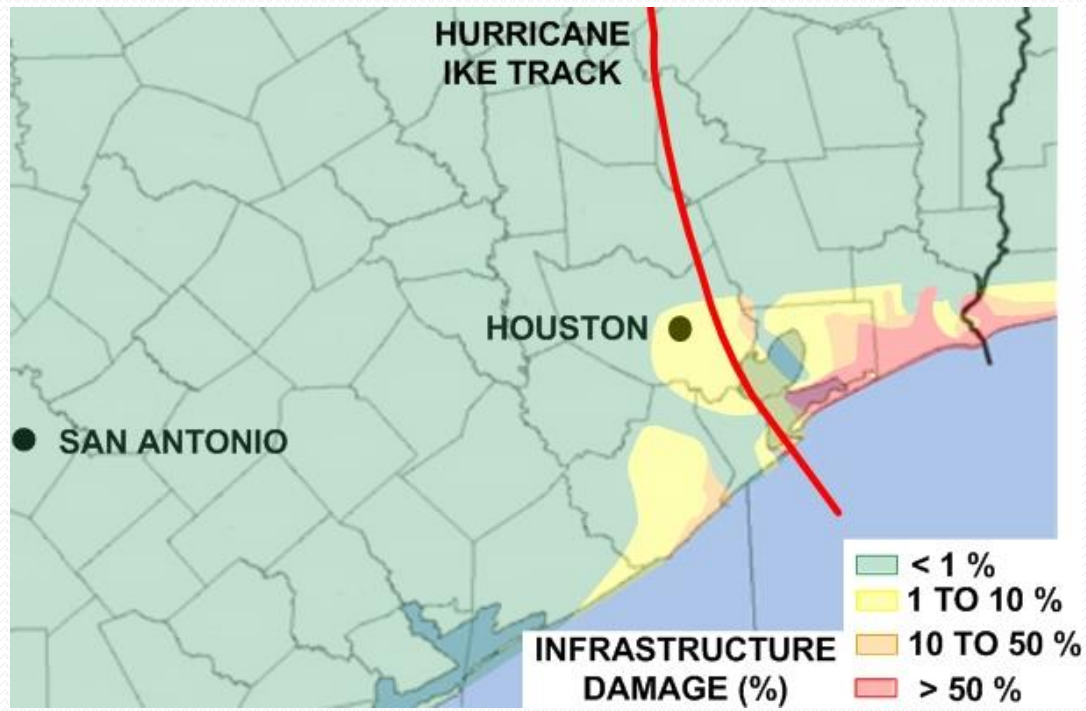
- Society demands more resilient power supply approaches.
- Conventional power grids were not necessarily designed for meeting current resiliency needs.
- Modern loads, local power generation sources and energy storage equipment are dc devices. Power electronics enable new designs.

Power grids performance during natural disasters

- Due to their predominately centralized control and power generation architectures, power grids are very fragile systems in which little damage may lead to extensive outages.



Peak power outage incidence after Ike (% customers w/o power)



Percentage of power grid damage after Ike

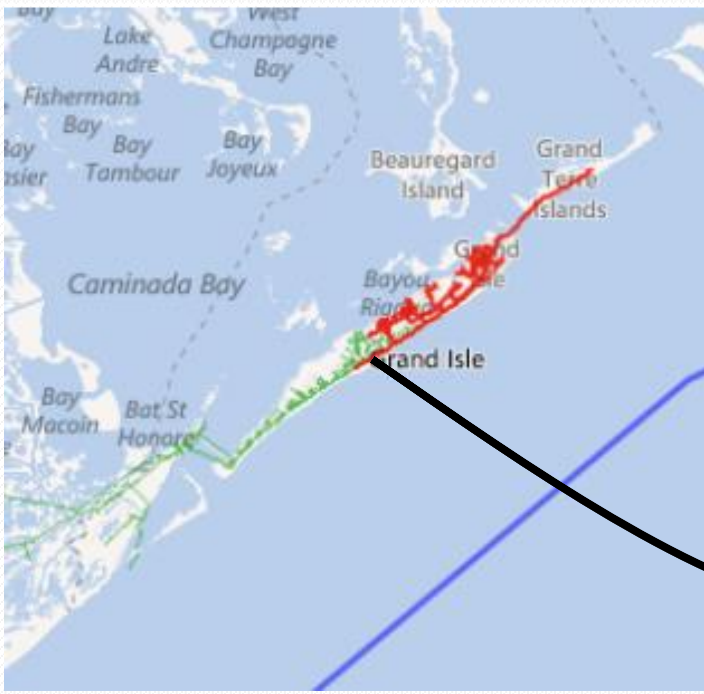
eLEAdERS @PITT

PITT SWANSON ENGINEERING ELECTRICAL & COMPUTER

Power grids performance during natural disasters

- Vulnerability: Sub-transmission and distribution portions of the grid lack redundancy. Most outages originate in distribution-level issues.

- E.g., Only one damaged pole among many undamaged causing most of Grand Isle to lose power.



Grand Isle, about 1 week after the hurricane

Entergy Louisiana

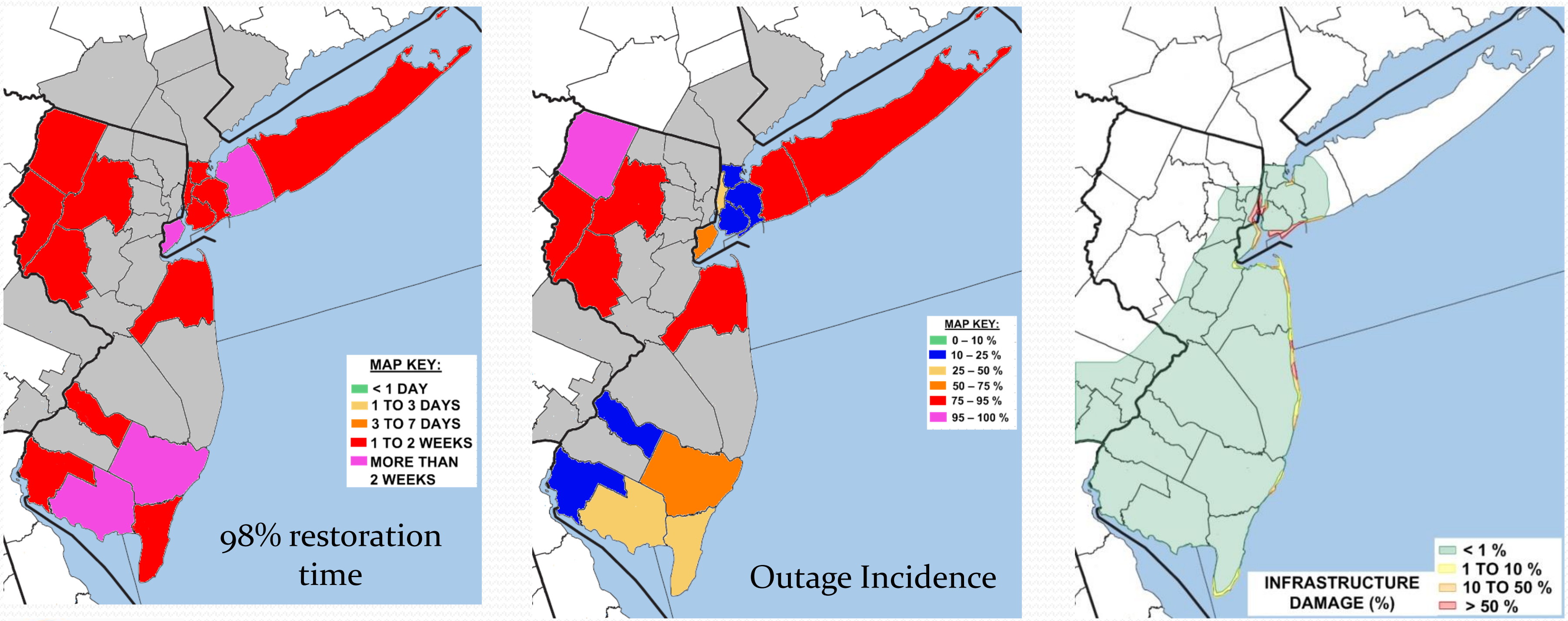
Power grids performance during natural disasters

- Severe damage is often limited to relatively small areas
- During disasters damage distribution is inhomogeneous (e.g. Ike).

Power grids performance during natural disasters

- Case Study: Hurricane Sandy

- Relatively little damage to the power grid but outages were severe
- Longer restoration times than usual observed in areas with underground power facilities.



Power grids performance during natural disasters

- Case Study: Hurricane Sandy

- Often, damage to power grids is less severe than for residences.
- Storm surge damaged some substations in coastal areas

Resiliency Metrics

Resiliency (from PPD21):

- The ability to prepare for and adapt to changing conditions and **withstand** and **recover rapidly** from disruptions.

- "Withstand" refers to an "up" time
- Rapid recovery refers to a "down" time

- Inclusion of an up and a down time points towards an equivalence between the concept of base resiliency and that of availability

Resiliency Metrics

- Base resiliency:

$$R_B = \frac{\sum_{i=1}^{N} T_{U,i}}{NT} = \frac{\sum_{i=1}^{N} T_{U,i}}{\sum_{i=1}^{N}(T_{U,i} + T_{D,i})}$$

- N is the total number of customers in a given area, $T_{U,i}$ is the time when customer i receives electric power during the total measured time T.

- $T_{U,i}$ (withstanding characteristic) is mostly related with hardware issues.

- $T_{D,i}$ (recovery speed) is the down time, which is influenced by human processes and aspects, such as logistical management, as well as hardware-related issues.

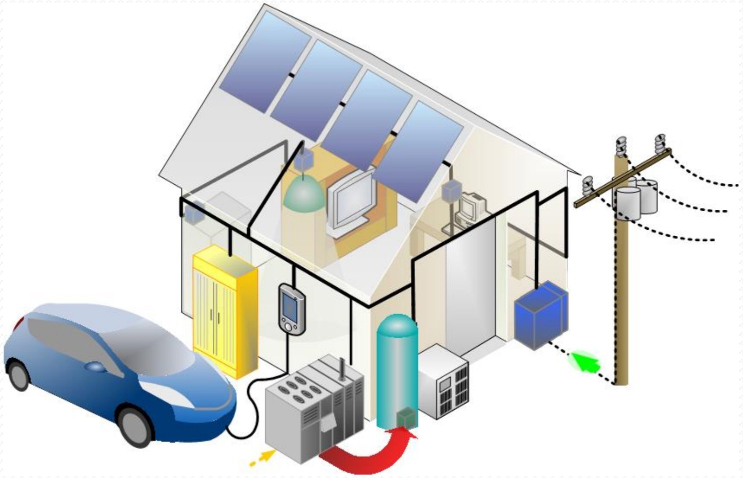
- Base resiliency is equivalent to the average service availability index (ASAI) or, more generally, to availability.

Solutions for Improved Resiliency

- Conventional approaches:
  - Limited effectiveness because power grids inherent vulnerabilities persist.
- Infrastructure hardening:
  - Tree trimming programs
  - Reinforced poles
  - Underground infrastructure
- Solutions to accelerate restoration times once outages occur:
  - Mobile transformers
  - Portable diesel generators

Solutions for Improved Resiliency

- Some **smart grid** technologies:
  - Community energy storage
  - Advanced distribution automation
  - Integrated communications
  - Smart meters
  - Phasor measurement units
  - Grid-tied residential photovoltaic (PV) systems



- These solutions are limited because they do not address inherent problems in power grids.
  - Grid-tied PV systems must be turned off when the grid is off.
  - Smart meters and other related smart grid technologies facilitate detecting an outage but they provide very limited improvement to avoid outages or to mitigate their effects.

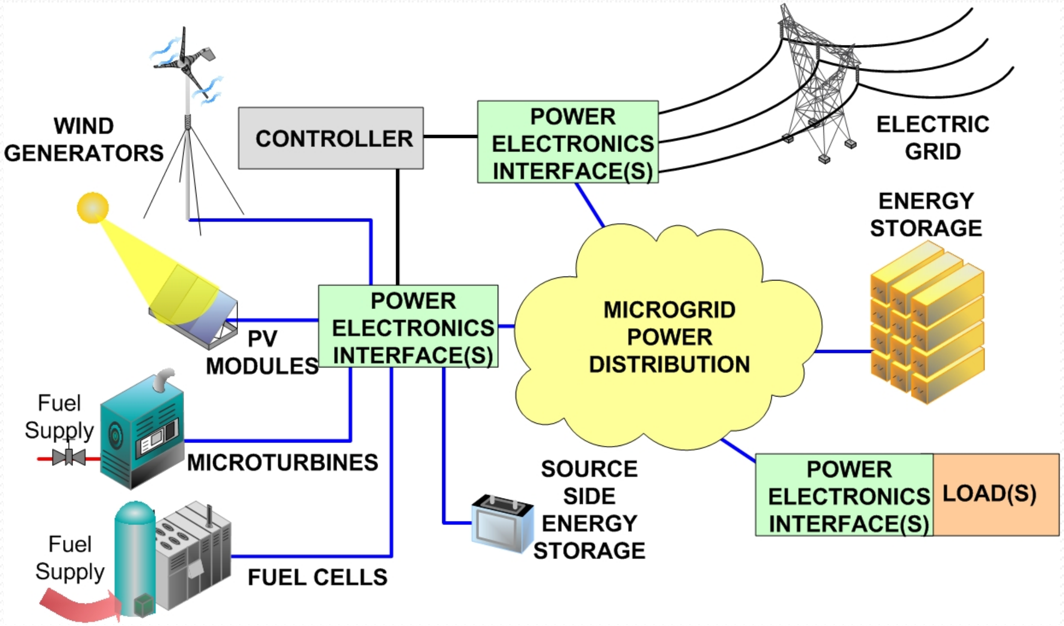
Solutions for Improved Resiliency

- "Customer side of the meter" solutions
- Standby power systems (i.e. systems that are brought into service after the power grid tie fails).
  - Power grid is the primary source of electric power.
  - Issues:
    - Inefficient use of capital
    - high failure to start probability for standby gensets
    - Gensets low availability for long operating times
- Microgrids
  - Local power generation units are the primary source of electric power

Cell site with a standby diesel genset after Hurricane Ike

Solutions for Improved Resiliency

- **Microgrids:**
  - are locally confined and independently controlled electric power grids in which a power distribution architecture integrates loads and distributed energy resources—i.e. local distributed generators and energy storage devices—which allow the microgrid to operate connected or isolated to a main grid.
- Well designed microgrids can achieve very high availability levels and provide a solution for resilient power supply when a disaster strikes
- Microgrids have operated satisfactorily after Irene, Sandy and the 2011 earthquake in Japan



Microgrids Resiliency

$$R_{MG} = A_{MG} = 1-(1-R_B)e^{-\left(\sum_{\mu_i \in M_{mcs}} (\mu_i T_{ES})\right)}$$

Total resiliency (availability)

Base resiliency (without batteries)

Repair rate – related to the inverse of the down time (Depends on **logistics**)

Local energy storage (e.g. batteries) autonomy

Heavily depends on unavailability of **power sources**

May depend on **lifeline performance** (if they are not renewable energy sources)

Local energy storage improves resiliency

- Two types of sources:
  - Those which depend on another infrastructure (lifeline).
  - Renewable sources

LEAdERS @PITT

PITT SWANSON ENGINEERING ELECTRICAL & COMPUTER

Microgrids Resiliency

- Lifeline-dependent power sources:
- Approaches to mitigate lifeline dependencies:
  - Use of **diverse power source technologies** (e.g. combine natural gas and diesel, or natural gas and renewable energy sources)
  - **Local energy storage** (e.g. diesel tank) – local energy storage serves to:
    - Quantify degree of functional dependence
    - Reduce lifeline dependencies

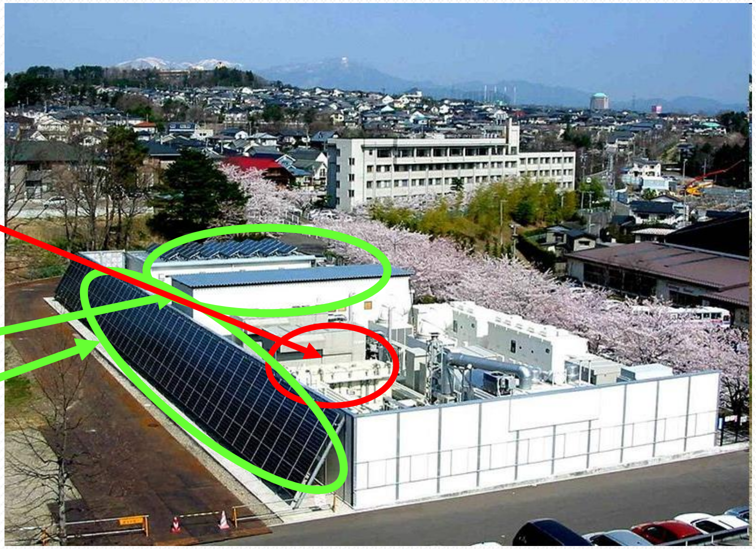
Microgrids Resiliency

- Power sources converting renewable energy:

- Most renewable energy sources do not require lifelines, but…..
- Issues with PV systems:
  - Large footprints
  - Variable output (part stochastic, part deterministic)
- Issues with wind generators in cities
  - wind profiles and aesthetics

2x350 kW natural gas generators

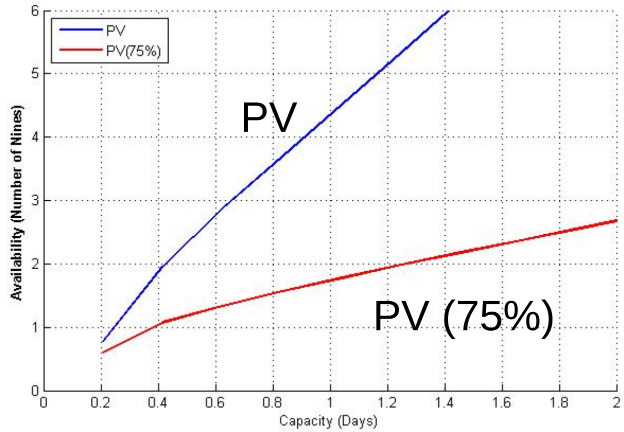
50 kW PV array

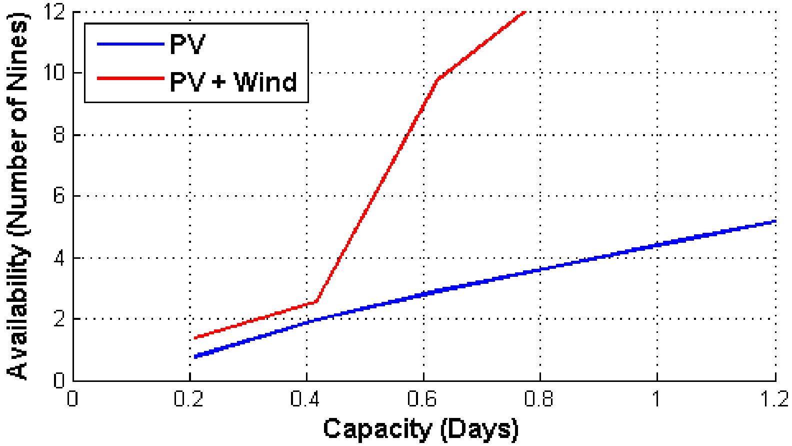


Microgrid in Sendai

Microgrids Resiliency

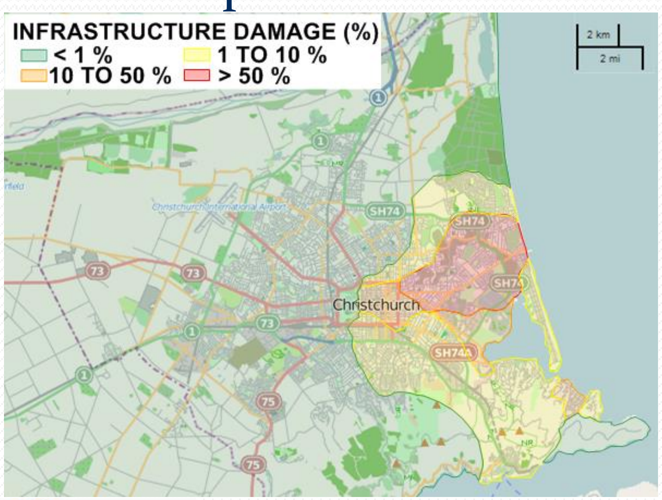
- Solutions to issues with renewable energy sources:
  - Combine them with local energy storage (e.g. batteries)
    - Very high availability requires significant stored energy
  - Diversify power sources (e.g. combine wind and PV)
    - Source diversification reduces energy storage capacity needs





Power Distribution Architecture

- Underground (buried) infrastructure.
- Issues:
  - It is not effective for earthquakes
  - With storms, it has lower failure probability but longer repair times.
  - Very costly (e.g. > 5x more than overhead).
  - A storm may never end up happening, but “normal” cable failures will surely happen (and will take longer to repair than with overhead lines).

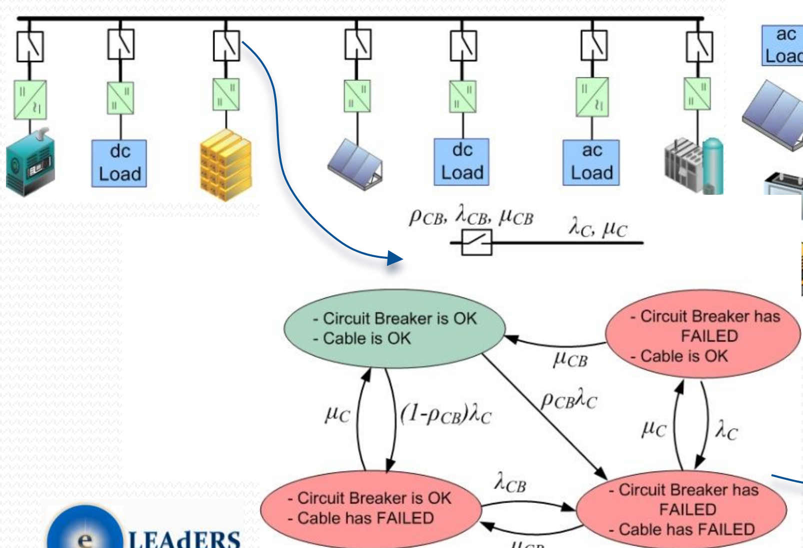


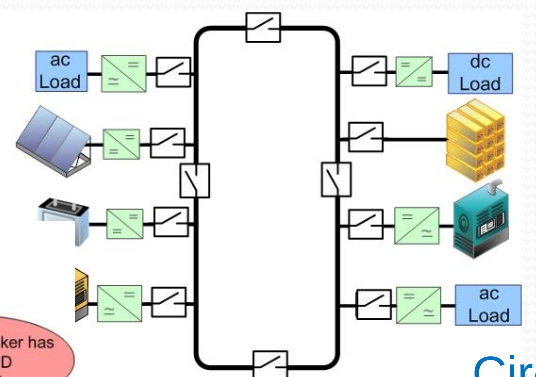
Christchurch, NZ

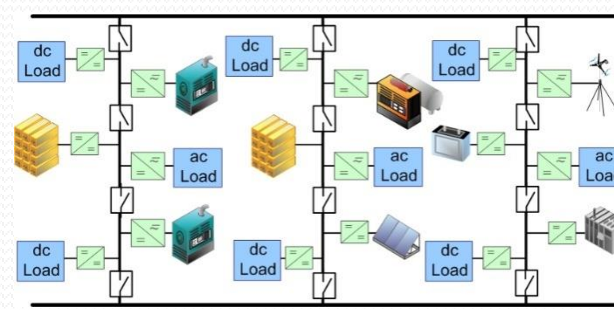
Power Distribution Architecture

- Redundant/geographically dispersed power paths
- Issues with conventional protection devices :
    - Reliability (particularly with dc)
    - Selectivity planning
    - Series (high-impedance) fault detection, particularly with power electronics circuits

Increasing resiliency





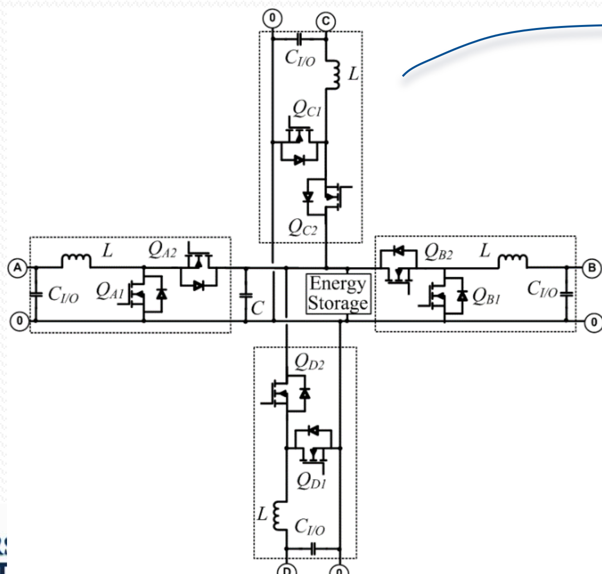


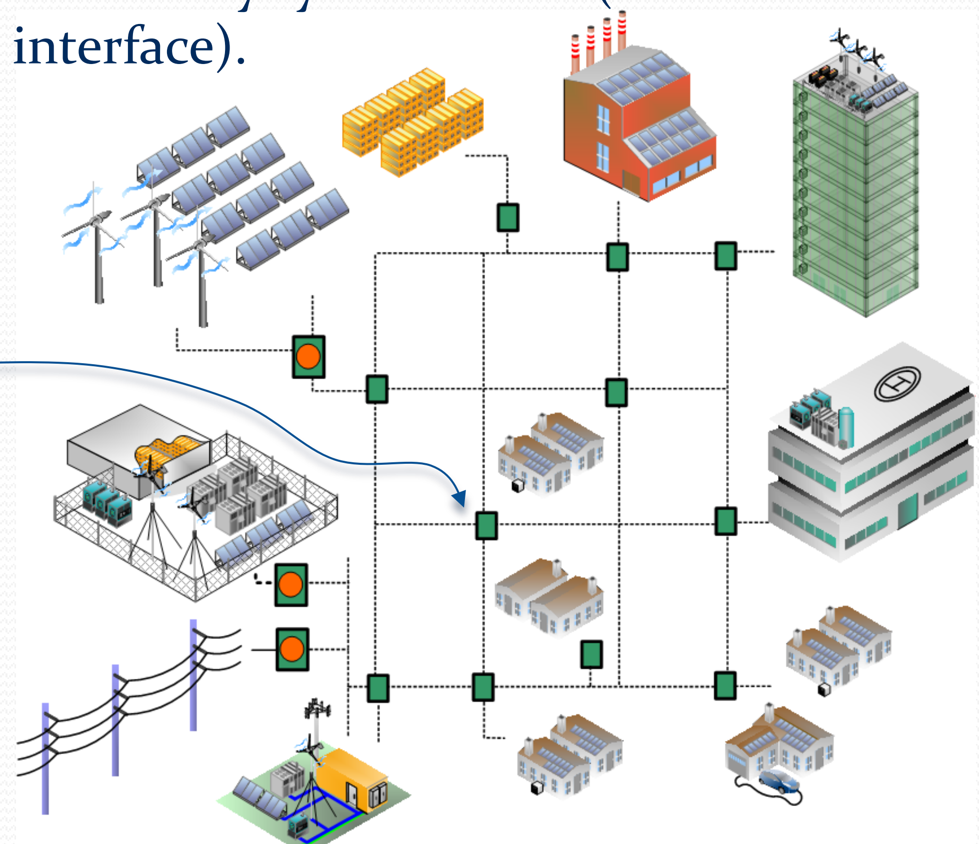
Circuit breaker availability model

$$1 - A_{CB-C} = \frac{\lambda_C(\lambda_{CB}+\rho_{CB}\mu_C)}{\mu_C(\mu_C+\mu_{CB})}$$

Power Distribution Architecture

- Power electronic circuits realizing active power distribution nodes (APDN)
- Concept: Place power electronic circuits in key system nodes (could be integrated as part of a source or load interface).
- APDNs can independently control power flow in its input and output ports and may include energy storage (e.g. batteries).





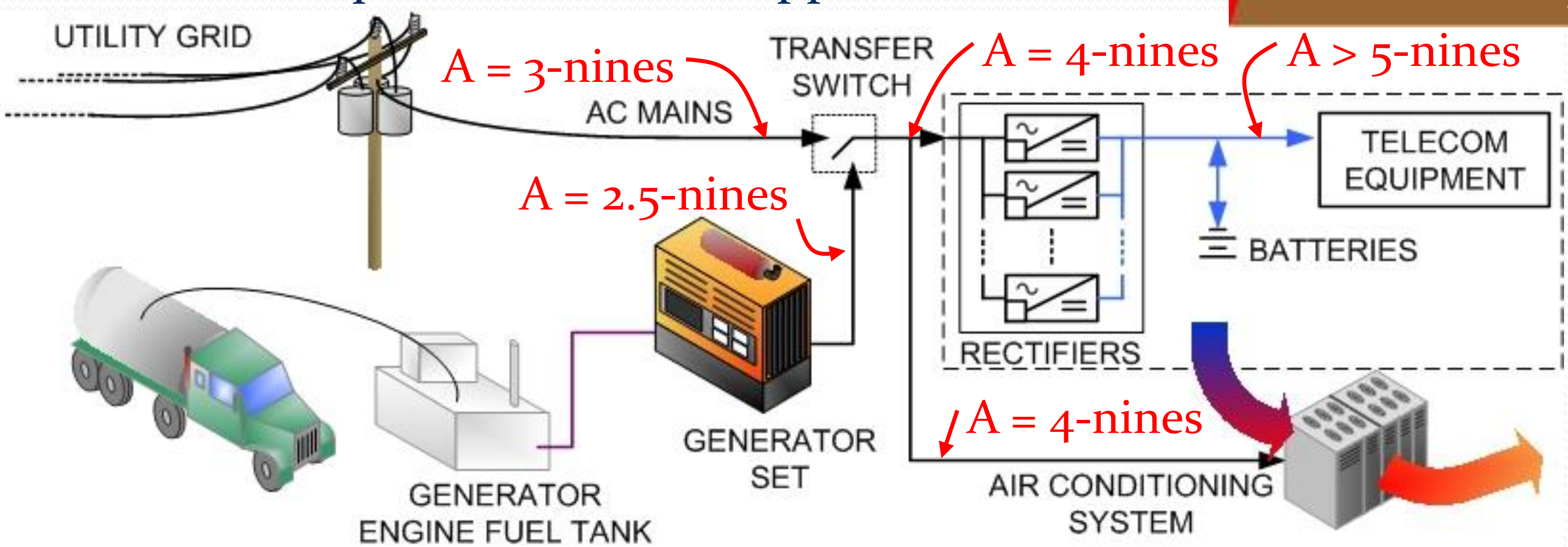
AC vs. DC

- Design needs favoring dc over ac power architectures:
  - Inclusion of energy storage
  - Power source technology diversification and redundant source arrangements imply the need for simple paralleling.
  - Complex power distribution architectures.
  - Increased use of power electronic circuits, even at the distribution level.
  - Preferred use of renewable energy sources

- Other advantages of dc over ac: simpler control, more flexible power distribution architectures, and potential for higher efficiency. Also, most modern loads are inherently dc.

Application

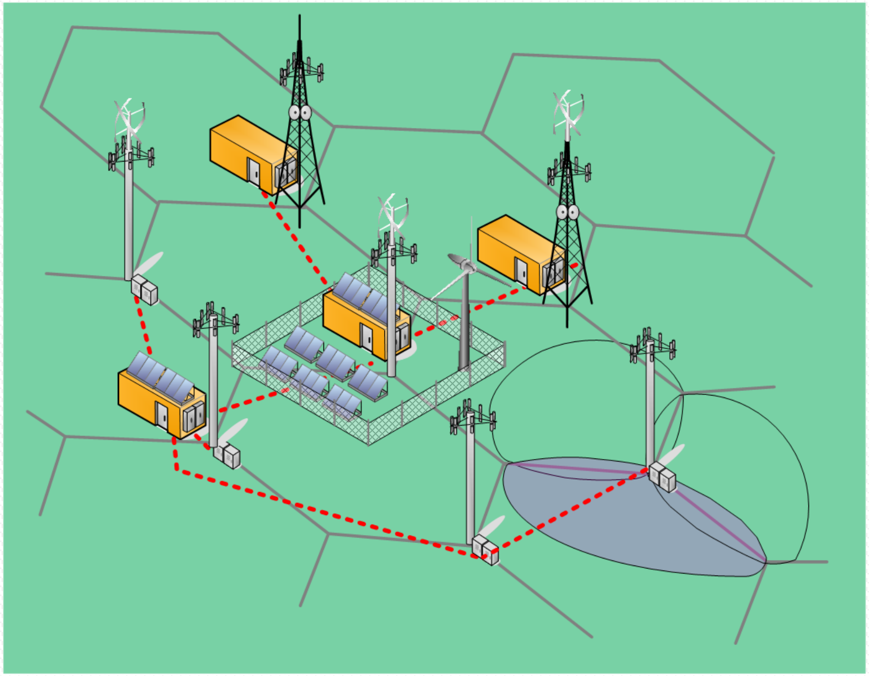
- DC system have been operating in telecom applications
- Telecom power plants are needed in order to overcome grid's low availability (resilience).
- Battery energy storage is essential in order to reach telecom-grade availability levels. Still, Power availability for air conditioners is below the minimum required in telecom applications



Typical availability in normal conditions

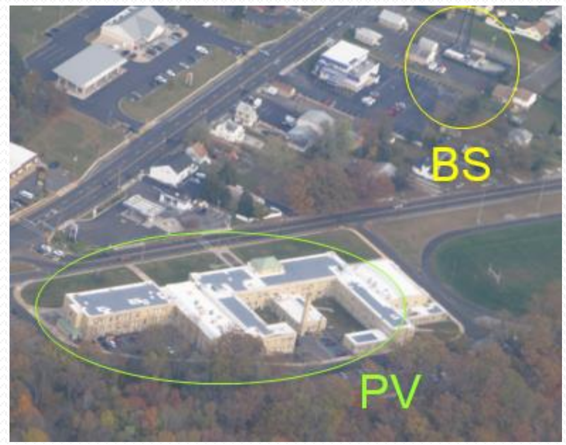
Application

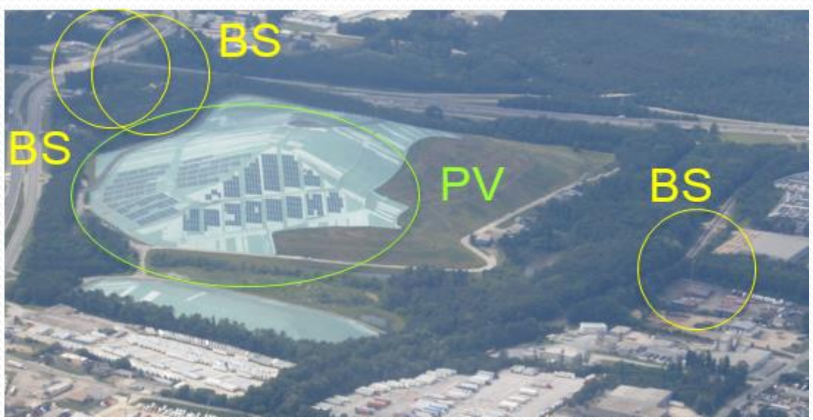
- Sustainable wireless area (SWA). Concept:
- SWAs are dc (e.g. 380V) microgrids created by interconnecting a few (e.g. 7) base stations with, possibly, an advanced power distribution architecture.
- Renewable energy sources are placed in base stations or nearby locations where there is sufficient space.
- Resources (power generation and energy storage) are shared among all base stations within the SWA.
- Traffic and electric energy management is integrated. I.e., traffic is regulated (or shaped) based on local energy resources availability and forecast.



Application

- Potential implementation in urban areas of SWAs





LEAdERS @PITT

PITT SWANSON ENGINEERING ELECTRICAL & COMPUTER

Conclusion

- Power grids are fragile systems with an original design that limits improvements in their resiliency performance.
- Microgrids may provide a better alternative for enhanced resiliency but only if they are well design:
  - Power generation sources diversification.
  - Use of energy storage.
  - Advanced power distribution architectures, likely requiring the use of APDNs.
  - Preferred use of renewable energy sources.
- Requirements for enhanced resiliency favors dc over ac microgrids. Additionally most modern loads are dc.

Thank you very much

Questions?

Alexis Kwasinski (akwasins@pitt.edu)