



# Electric Power Grids Performance under Extreme Weather Events

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The University of Texas at Austin



- **Power Grids Vulnerabilities**
- **Performance during hurricanes**
- **Adaptation: proposed technological solutions**
- **Conclusions**

- **Availability**

## Conventional grids weaknesses:

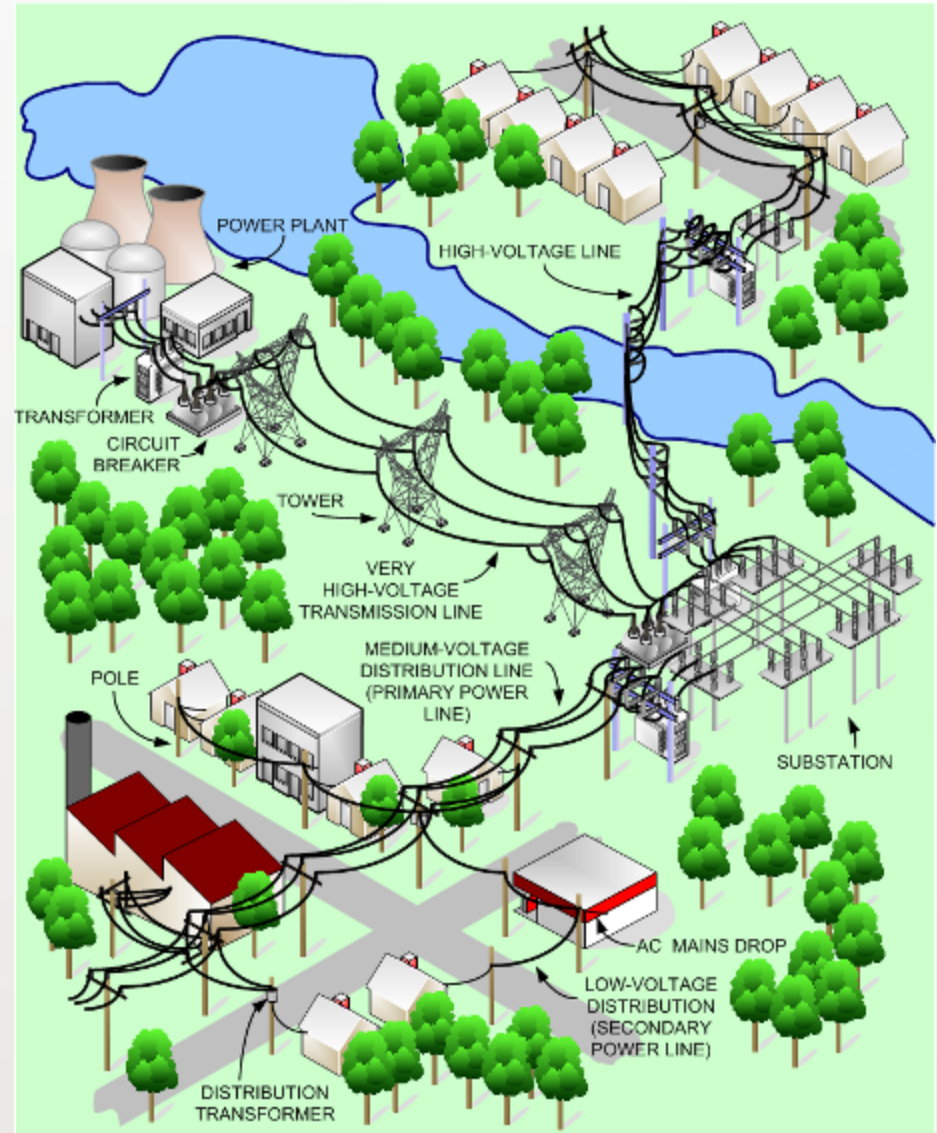
- Centralized architecture and control.
- Passive transmission and distribution.
- Very extensive network (long paths and many components).
- Lack of diversity.

- **Traditional grid availability:**

Is “up” approximately 99.9 % of the time

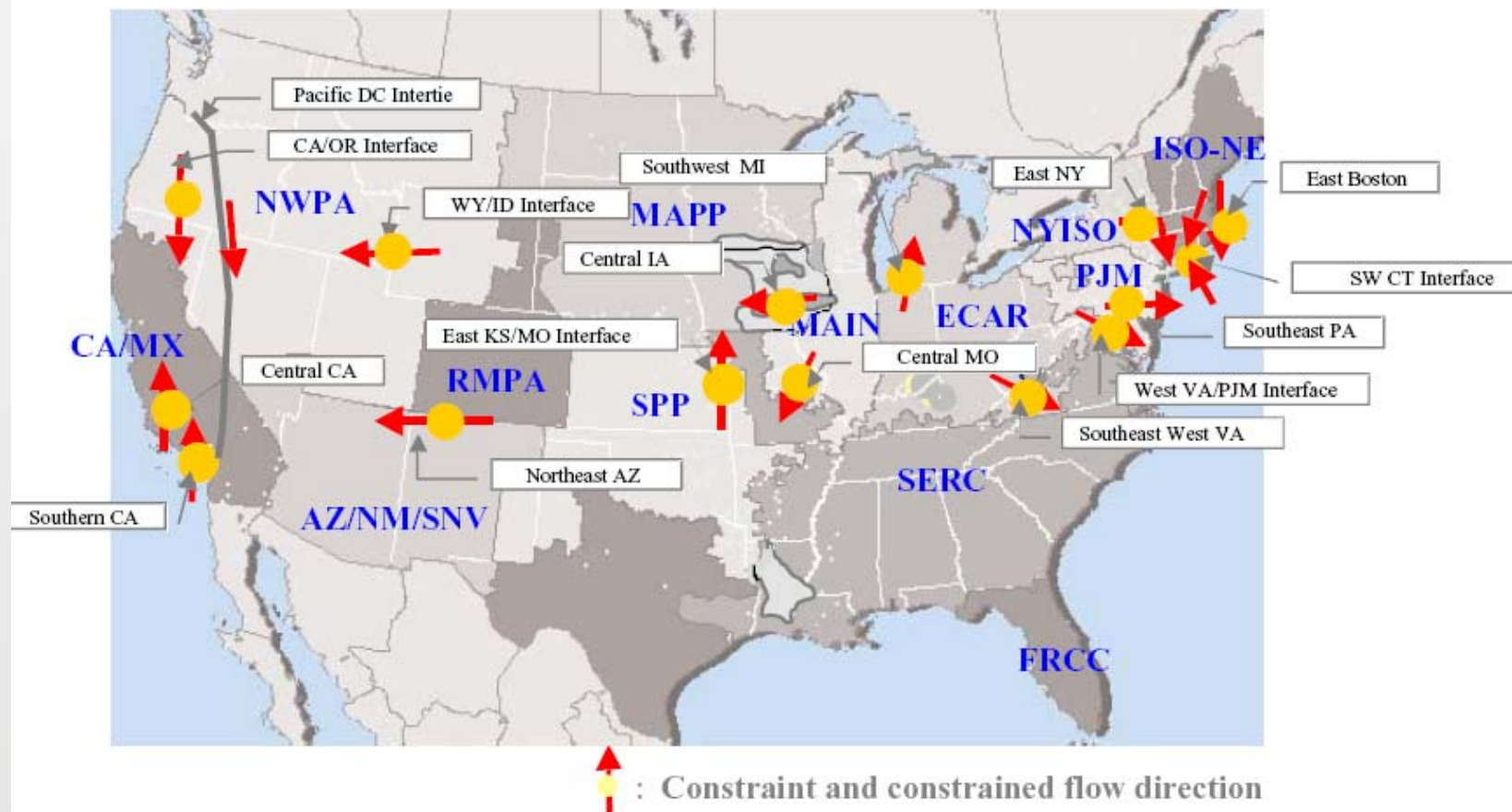
- **Availability required in critical applications:**

“Up” approximately 99.999% of the time



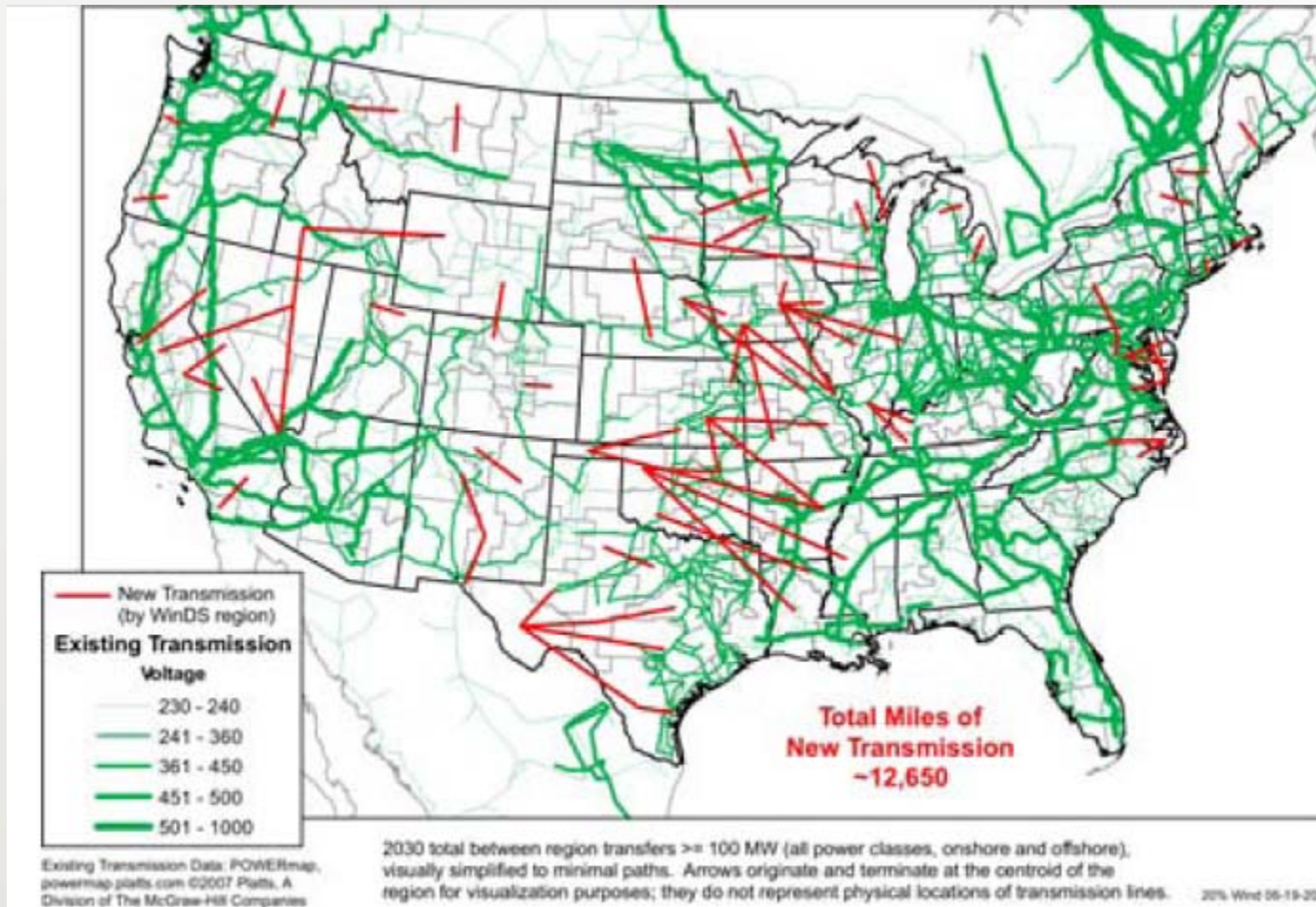
- **Availability issues**

- Non-seasonal transmission congestion points.





- **Security**
- Long transmission lines are easy targets for both intentional and unintentional attacks.

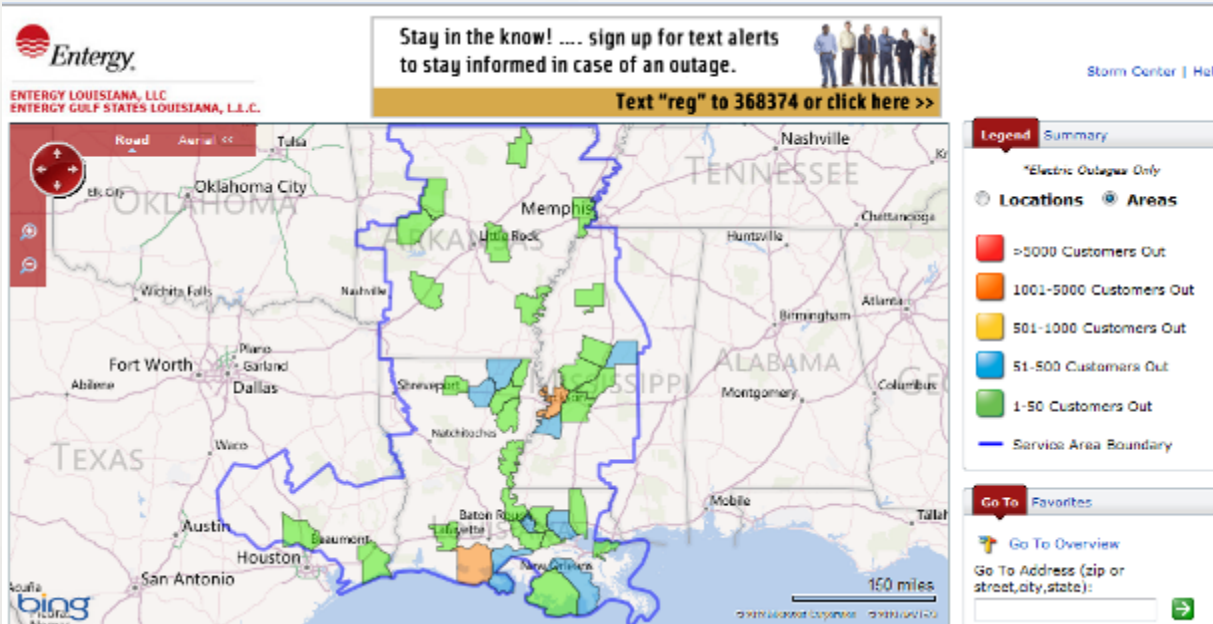




- **Operation and additional issues - Flexibility**

- Centralized integration of renewable energy may create generation profile unbalances that may create stability and other issues.
- Complicated stability control as more intermittent renewable energy sources are added.
- New loads (electric vehicles, dc loads) create power quality issues.
- Generation and consumption need to be continuously balanced. Energy cannot be stored in the grid, except in relatively small amounts.
- The grid's transmission and distribution portions lack operational flexibility because they are passive networks.
- The grid is old: it has the same 1880s structure. Power plants average age is > 30 years. Other components have been installed in average for over 40 years.

- Power outages



•The described weaknesses are prevalent throughout the grid. Hence, power outages are not too uncommon (they can happen even when there are no disasters).

- Natural disasters as real test-beds to evaluate power grids vulnerabilities
- Some relevant recent hurricanes: Katrina, Gustav, Ike, Irene (2011), and Isaac (2012).
- All of these hurricanes caused at least one million power outages.
- Power outages extended over large areas and lasted from several days to weeks.
- Extensive damage was mainly observed in part of the areas affected by the storm surge.



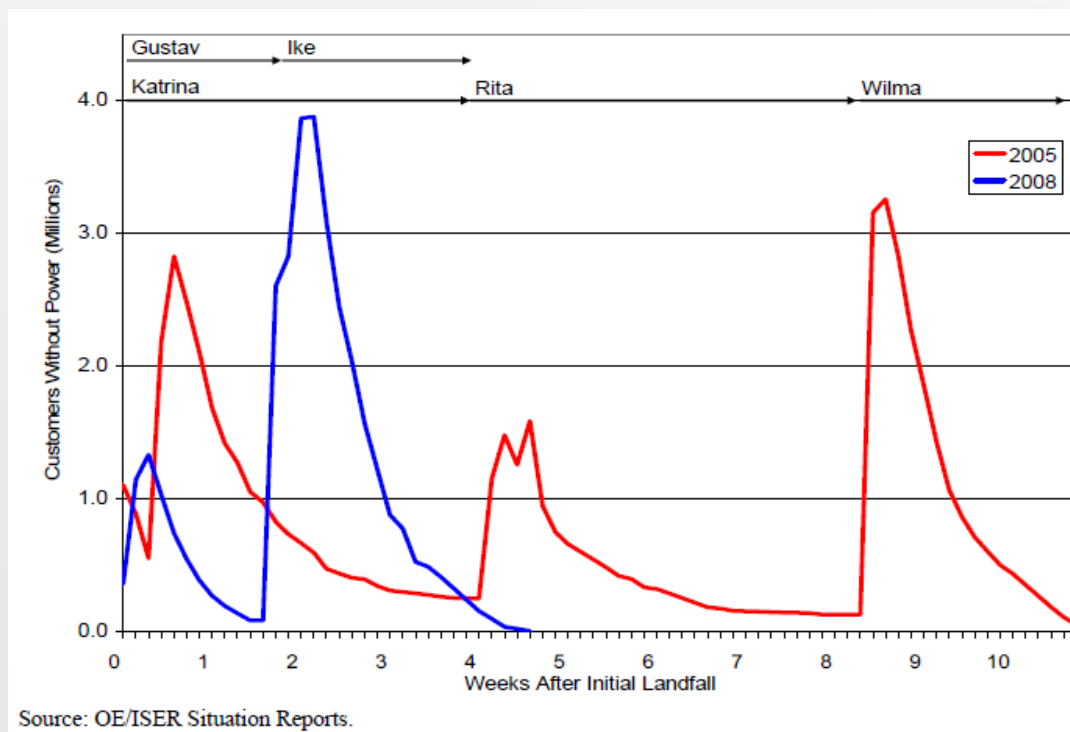


- Impact of recent hurricanes on electric power infrastructure

- Of all discussed relevant recent hurricanes (Katrina, Dolly (2008), Gustav, Ike, Irene (2011), and Isaac (2012)) only Katrina was a major hurricane when making landfall.
  - Katrina was a cat. 3 at landfall but only cat. 1 in New Orleans.
  - Gustav (cat. 2) caused more outages in Louisiana than Katrina (cat. 3). About 1,200K for Gustav vs. about 900K for Katrina.
  - Ike's outages extended from Texas to the Ohio River Valley.
  - Irene was mostly a tropical storm, yet it caused about 6M power outages.

- Impact of recent hurricanes on electric power infrastructure

- Of all discussed relevant recent hurricanes (Katrina, Dolly (2008), Gustav, Ike, Irene (2011), and Isaac (2012)) only Katrina was a major hurricane when making landfall.
  - Ike was a cat. 2 storm, yet.....



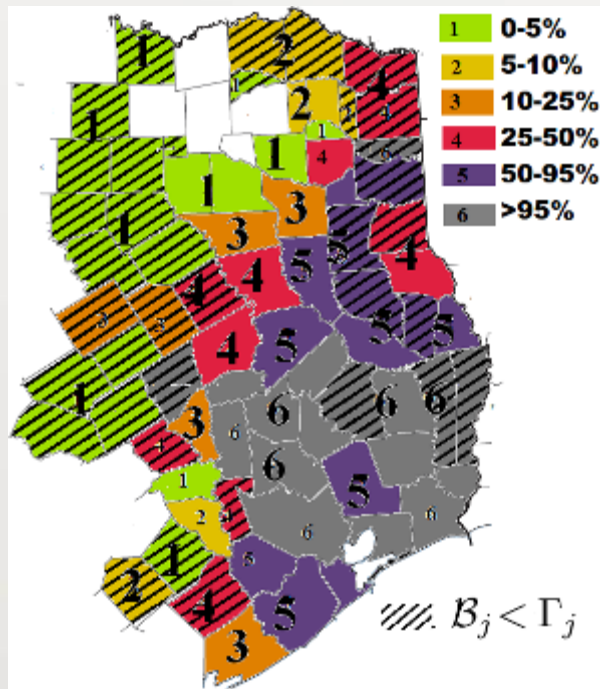
- Impact of recent hurricanes on electric power infrastructure
- Possible causes of mismatch between hurricane intensity measured on the Saffir-Simpson scale and impact on power grids:
  - More population
  - Power grids are extended over larger areas
  - More interdependent infrastructure
  - Intrinsic characteristics of the storms (larger storm surges, more intense rains, larger area) that are not correlating as well as expected with respect to maximum sustained wind speeds.

- **Availability during natural disasters**

- Most of the area affected by a large disaster shows little damage to the power grid, yet, power outages are significant and long.



Photo courtesy of NOAA



- **Availability during natural disasters**

- Severe damage is limited to relatively small areas.



< 10 % of the affected area

> 90 % of the affected area

- Bolivar Peninsula after Hurricane Ike

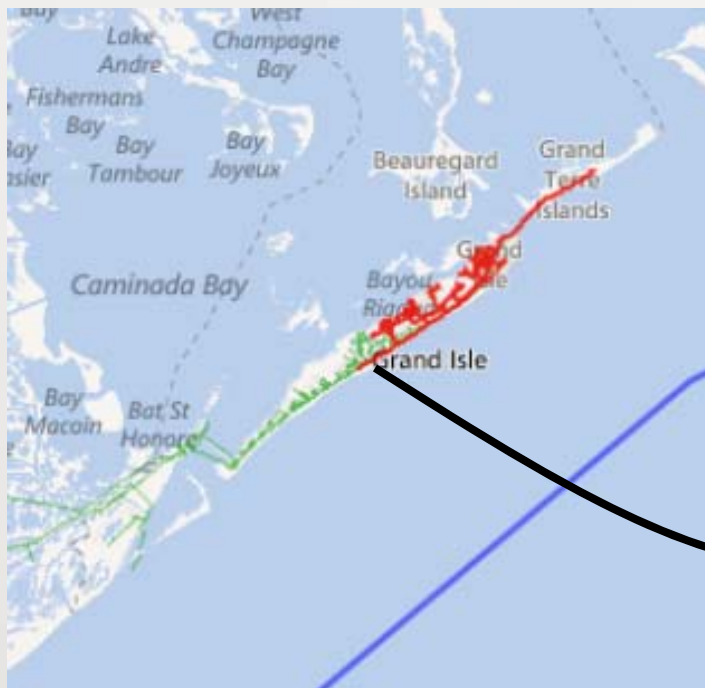
VS.

- Baton Rouge, Louisiana, after Hurricane Gustav  
(only 1 pole damaged among many undamaged)



- **E.g. Hurricane Isaac**

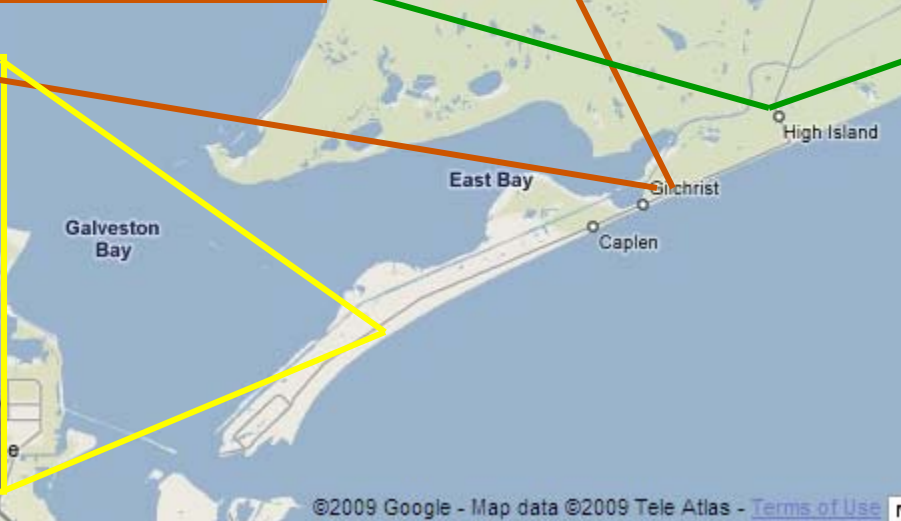
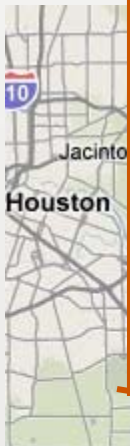
- Severe damage is limited to relatively small areas.
- Only one damaged pole among many undamaged causing most of the island to loose power.



Grand Isle, about 1 week after the hurricane

Entergy Louisiana

- **Availability observations**
- During disasters damage distribution is inhomogeneous



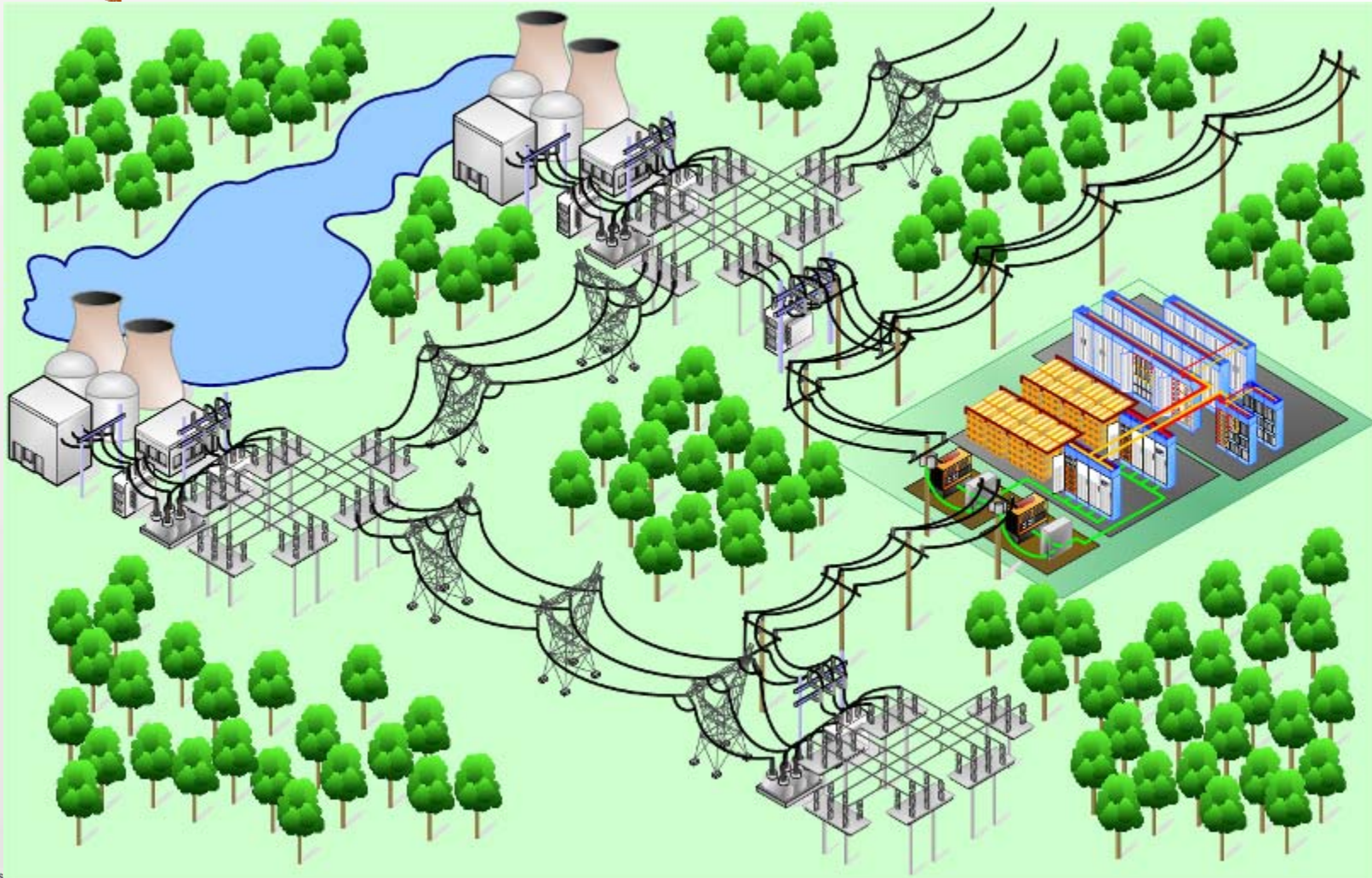
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- **Reliability issues**
- Sub-transmission and distribution portions of the grid lack redundancy

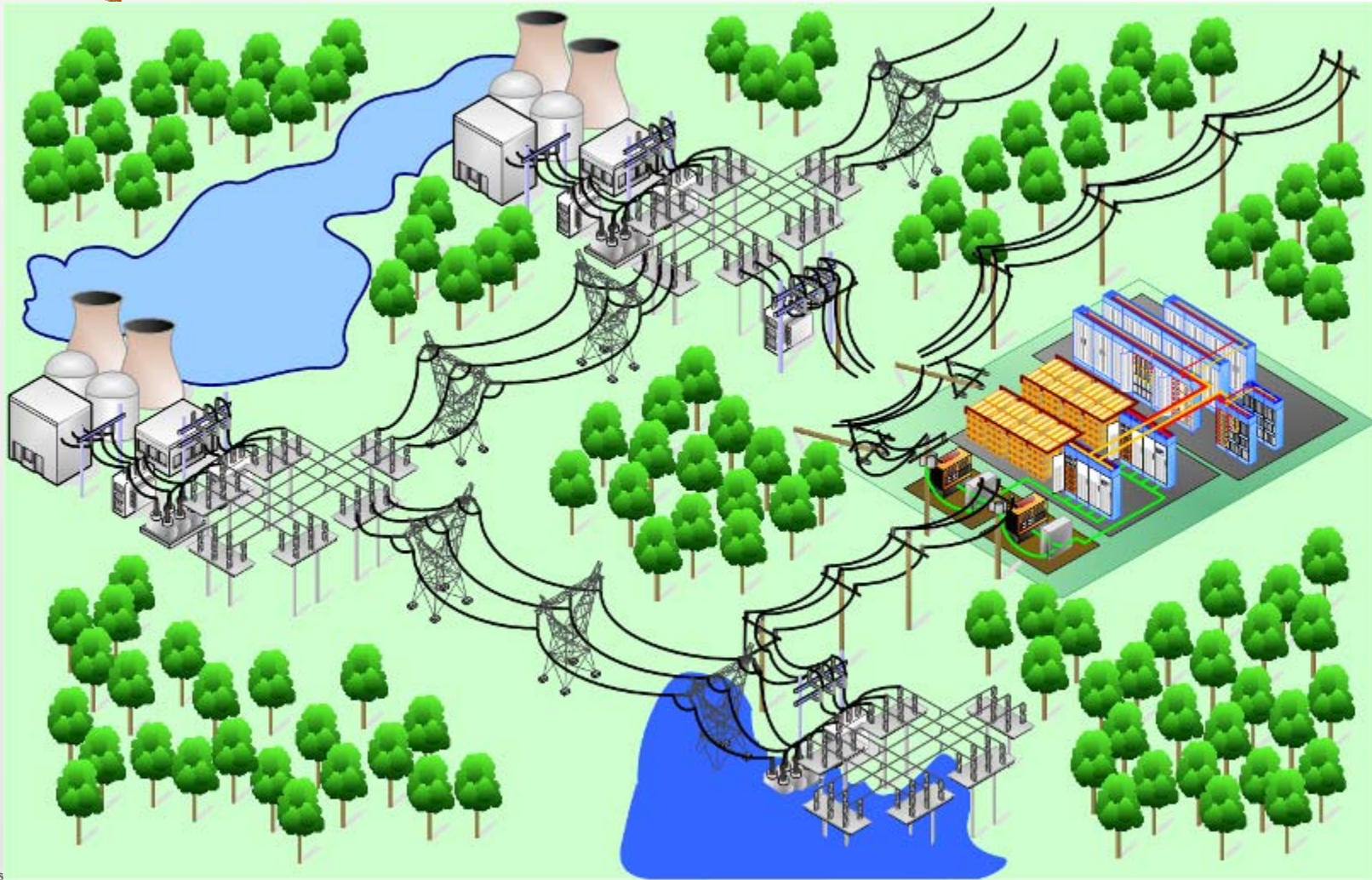




- **Reliability issues**
- Lack of diverse power supply



- **Reliability issues**
- Lack of diverse power supply



- **Cascading failures**

- Power outages is one of the main causes of communication sites failures. E.g. Hurricane Katrina



Outage cause (PSTN)



Predominant cell sites condition after Katrina

- Proposed solutions
- Solutions domain:
  - Utility (e.g. mobile transformers, ADA): limited effectiveness
  - Users (e.g. microgrids): may be more flexible
- Users solutions:
  - Microgrids
  - Standby systems

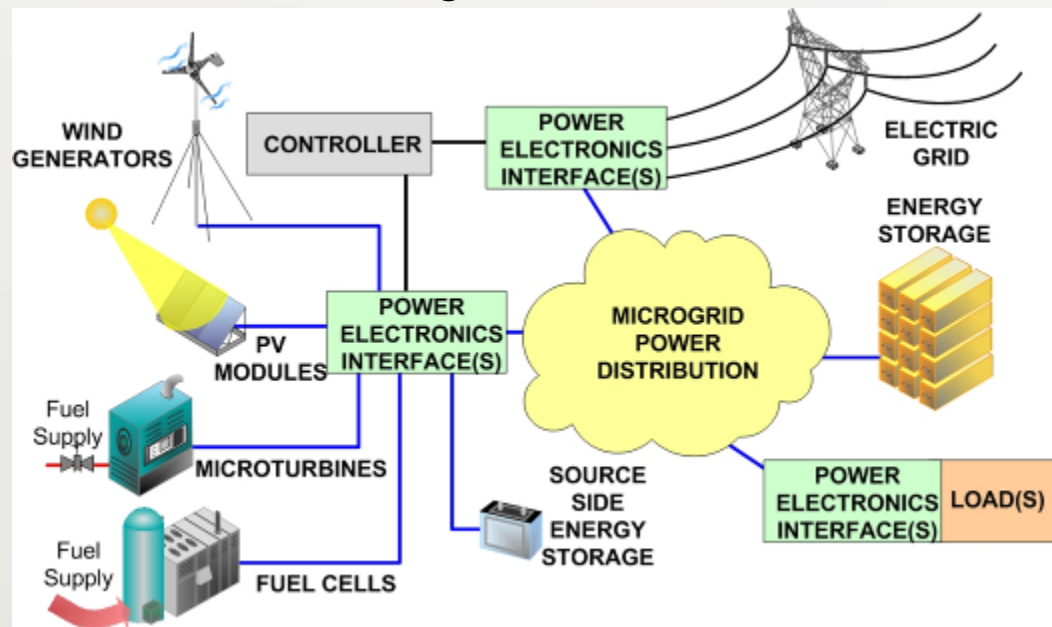


Fuel cell-based microgrid in Garden City, NY after Hurricane Irene

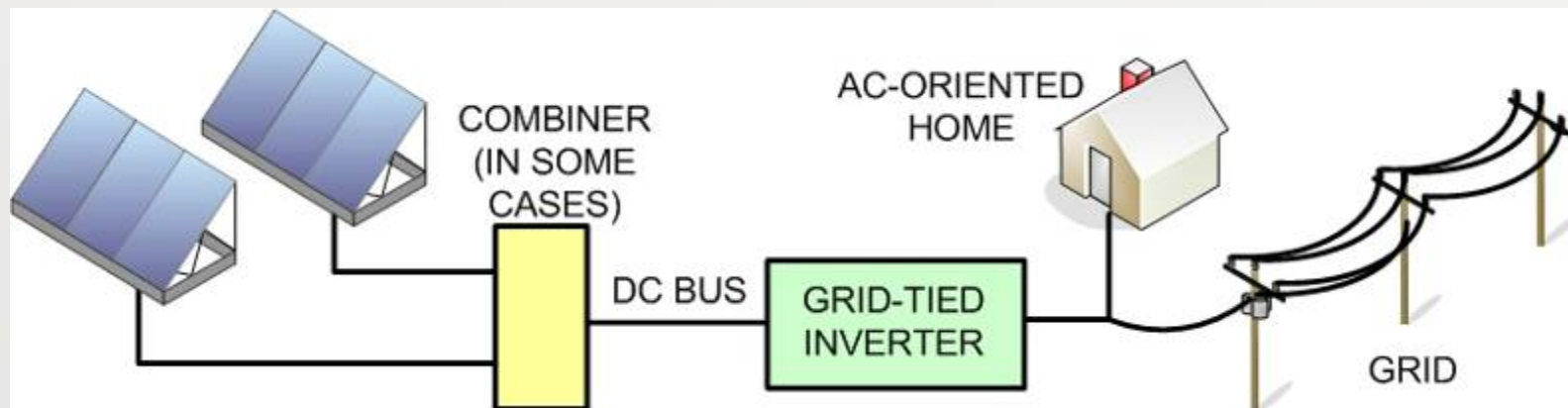


Cell site with a standby diesel genset after Hurricane Ike

- Solutions: microgrids
- What is a microgrid?
  - Microgrids are considered to be locally confined and independently controlled electric power grids in which a distribution architecture integrates loads and distributed energy resources—i.e. local distributed generators and energy storage devices—which allows the microgrid to operate connected or isolated to a main grid



- Adaptation realities
  - Conventional grid-tied system (utility centered) are not a microgrid.
  - Most widely used PV integration approach.
  - PV and home operation subject to grid operation: Due to IEEE Standard 1547, the inverter cannot power the home when the grid is not present.



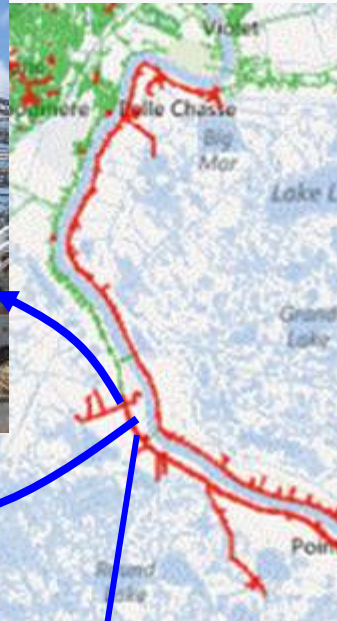
- Solutions: distributed generation (PV systems)
- E.g. Lower 9<sup>th</sup> Ward 4 days after Hurricane Isaac. The sun is shining but no grid = no power even with PV arrays.



- Adoption realities for microgrids and standby systems
  - Except for diesel generators, all other local power solutions tend to be costly (some more expensive than others).
  - Issues with PV systems: large footprints
  - Renewable energy sources have, typically, variable output power.
  - Most local generators depend on other infrastructures, called lifelines (e.g. natural gas distribution networks or roads)
  - But lifelines can be affected by the natural disaster like conventional grids.
  - Approaches to address lifeline dependencies or output variability:
    - Diverse power source technologies
    - Local Energy Storage



- Lifeline dependency. E.g. Hurricane Isaac



Port Sulfur,  
Oct. 2010



- Flooded loads makes impossible to deliver fuel for permanent diesel gensets

- In practice, new technologies are not yet fully adopted.
- Main issues with PV systems: large footprint and need for significant energy storage to address variable output.. Main advantage: no lifelines.
- Still, standby diesel generators (permanent or portable ones) are chosen over other options, probably because it is easier to obtain diesel than other options and because it is the best known option by restoration crews.



Site with a fuel cell powered by a diesel genset



Site with a natural gas generator powered by a diesel genset

- The same solutions that are sought for improving power supply availability during disasters can be used to support economic development anywhere in the world.
- Distributed generation may support economic development.
- E.g. Isolated microgrids for villages in Alaska.
- Wind power is used to supplement diesel generators (diesel is difficult to transport in Alaska)
- The same idea of using renewable energy sources to supplement conventional sources could be used in order to address footprint issues with PV power generation, particularly after disasters.



- **Toksook Bay**
- Current Population: 590
- # of Consumers: 175
- Total Generating Capacity (kw): 2,018
  - 1,618 kW diesel
  - 400 kW wind
  - (tieline to Tununak and Nightmute)

<http://avec.securesites.net/images/communities/Toksook%20Wind%20Tower%20Bulk%20Fuel%20and%20Power%20Plant.JPG>

- Final thoughts

- Power grids has been experiencing significant power outages even with tropical storms or hurricanes of moderate intensity.
- Hurricanes show that conventional power grids—one of the basis of modern societies—are extremely fragile systems.
- Solutions have been proposed as part of so called “smart grids”. However, **power grids may not seem to be adapting well to increased impact of weather events:**
  - Microgrids are not yet widely adopted.
  - Conventional residential PV systems do not operate during power outages.
  - In the future, electric vehicles may add challenges for operation under the effect of extreme weather events.

- Resources from Prof. Kwasinski's research group.
- akwasins@mail.utexas.edu

- Main website: <http://users.ece.utexas.edu/~kwasinski/>
- Research webpage:  
<http://users.ece.utexas.edu/~kwasinski/research.html>

Prof. Alexis Kwasinski  
Research

I am currently doing research in the broad area of local area power and energy systems (i.e., distributed generation or micro-grids) both at a component level studying power electronics interfaces, and at a system level through controls analysis, and improvements in terms of reliability and efficiency.

Some of my current research topics are:

- Local area power and energy system architectures and control.
- Power infrastructure in natural disasters (click on any of the disaster logos below to see pictures from my damage assessments). [NSF CAREER award #0845828](#)
- Interactions between micro-grids and the power grid with focus on "smart-grid" applications. Please check [Pecan Street, Inc](#) site for information about Austin's participation in the development of the future power grid
- Multiple input dc-dc converters.
- Datacenters and telecom power infrastructure.
- Constant-power loads control
- Interfaces and controls for photovoltaic systems.
- Electric vehicles

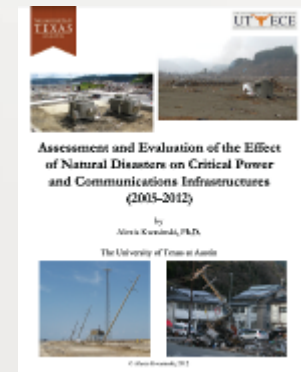
KATRINA DOLLY GUSTAV IKE M. R. R. MOULLE CHIE (2010)  
M. R. I. NEW ZEALAND (2011) M. S. D. TOHOKU JAPAN (2011) IRENE ISAAC OTHER EVENTS

For publications information please click [here](#). A compendium of my publications about the impact of natural disasters on power and communications infrastructures since 2005 can be downloaded from [here \(80 MB pdf file\)](#). For additional research information please click [here](#) and the my [research group page here](#). Also, follow my blog [here](#).

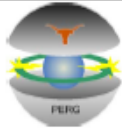
Click here to access information and photos from damage assessments after each of these events

Click here to access a compendium of publications about research related with natural disasters (80 MB file)

<https://webpace.utexas.edu/~ak9439/disasters/disasters%20comp.pdf>




- Resources from Prof. Kwasinski's research group.
- Posters from <http://users.ece.utexas.edu/~kwasinski/RG.html>




PEPG

The University of Texas at Austin, Power Electronics Research Group  
**Natural Disasters Hardened Power Supply through Microgrids**  
Alexis Kwasinski  
Work supported by NSF under CAREER award #0845828 and NEC Labs

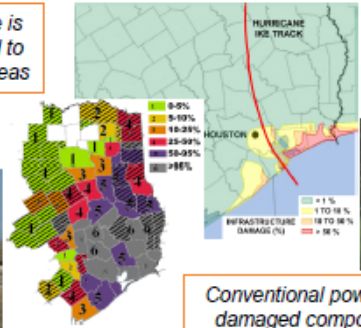


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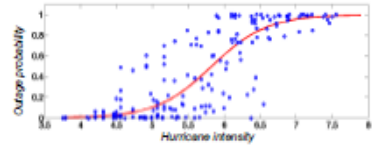
*Extreme damage is typically confined to relatively small areas*



HURRICANE IKE TRACK  
HOUSTON

INFRASTRUCTURE DAMAGE (%)

- 0-5%
- 5-10%
- 10-25%
- 25-50%
- 50-75%
- 75-95%
- 95-100%




Outage probability

Hurricane intensity


**Power grids performance during natural disasters**

*Conventional power grids are very fragile systems: less than 1 % of damaged components may still cause 100 % of outage incidence*


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*Lifelines performance influences microgrid availability*



*Lifeline dependencies can be decoupled using energy storage*

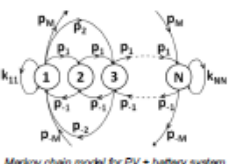


*Successful microgrids in disaster areas*


**Enhanced power availability through microgrids**

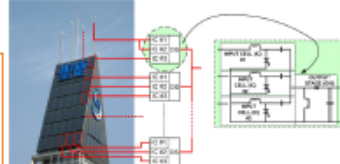
Microgrid unavailability:  $U_{MG,T} \cong \sum_{j=1}^{M_C} \prod_{l=1}^{C_j} u_{l,j} e^{-\beta_{FW} T_{BAT}}$

*Renewable energy sources do not have lifelines but their output is variable and their footprint is large*



Markov chain model for PV + battery system






*Source diversity with multiple-input converters*


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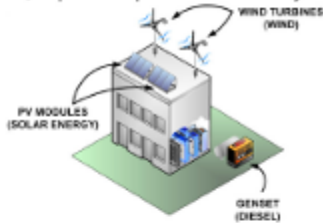
**The University of Texas at Austin**  
**Power Electronics Research Group (PERG)**  
Prof. Alexis Kwasinski  
Leading Investigator



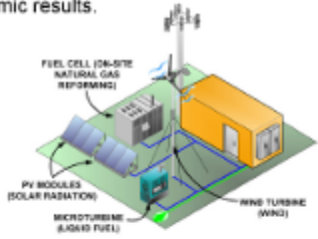
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**Reduced Power Supply Vulnerability to Natural Disasters**

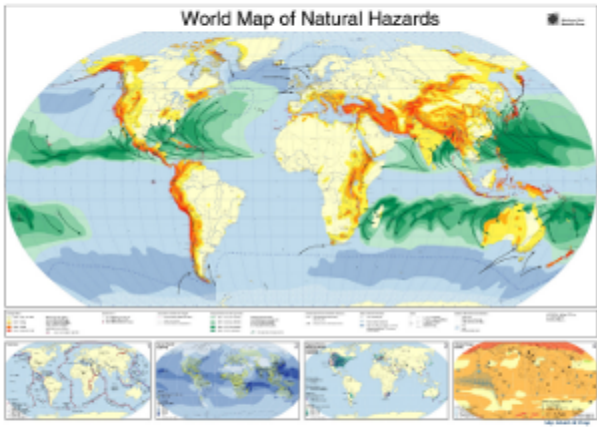
- Large world's regions are at risk of natural disasters.
- The active of every telecommunications system site acts a single-point of failure.
- Power outages are an important cause of communications loss of service during natural disasters.
- Telecom power systems lack power input diversity, not redundancy.
- Use of distributed generation technologies provides input diversity and, at the same time, improves operational flexibility and economic results.



PV MODULES (SOLAR ENERGY)  
WIND TURBINES (WIND)  
GENSET (DIESEL)




FUEL CELL (ON-SITE NATURAL GAS REFORMING)  
PV MODULES (SOLAR RADIATION)  
WIND TURBINE (WIND)  
MICROTURBINE (LIQUID FUEL)




World Map of Natural Hazards

**Example: Effect of Hurricane Katrina on Telecommunications Power Infrastructure**




Destroyed communications center




Very long power outages

Outage severity




■ MORE THAN 2 WEEKS  
■ 1 WEEK TO 2 WEEKS

Outage causes




■ DESTROYED CO  
■ FLOODING POWER-RELATED OUTAGE  
■ ENGINE FUEL STABILIZATION POWER-RELATED OUTAGE  
■ POWER-RELATED OUTAGE ACCOMPANIED BY PARTIAL SERVICE RESTORE


Inadequate Restoration Means




Power outages: Gensets



Multiple gensets at each cell-site




Central offices and feeders: Digital loop carrier systems




Digital loop carrier with genset

- Resources from Prof. Kwasinski's research group.
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Leading Investigator




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**Effects of 2008 hurricanes Dolly, Gustav and Ike on critical power infrastructures**

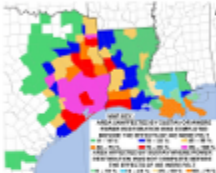
**Effects on the power grid**




Severe damage caused by Ike




Infrastructure hardening option:  
Gullied poles



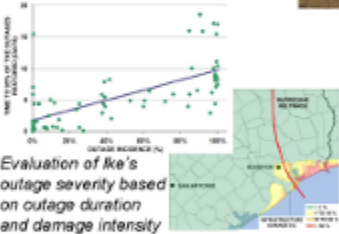
Ike's outage incidence




Grid restoration activities and technologies




Damage caused by Gustav



Evaluation of Ike's outage severity based on outage duration and damage intensity




Pole failure mode #1: Broken pole due to high winds




Pole failure mode #1: Extreme wet soil

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**Effects on Telecommunications Power Infrastructure**




Central Office  
Damaged infrastructure



DLC

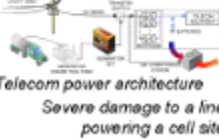


Cell site




Cell site

Dependency on reliable power




Telecom power architecture  
Severe damage to a line powering a cell site




Hut  
Power-related outages


Camping genset on pole (inadequate)




Restoration strategies



Portable Genset



COW




Portable Genset for DLC


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Center for ElectroMechanics




Pecan Street Inc.

**Smart Grid Research**






Cockrell School of Engineering



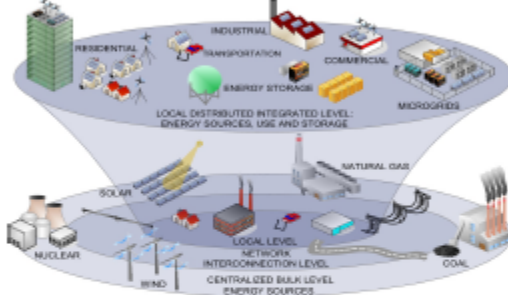
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**- Selected technologies and studies:**

- Disaggregated power consumption data from 1000 homes at 15 second intervals.
- 25 % PV power penetration.
- More than 100 electric vehicles within 1 sq. mile.
- Residential and community level energy storage.

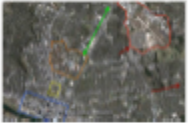





**PECAN STREET: A CUSTOMER-CENTRIC VIEW OF A SMART GRID**




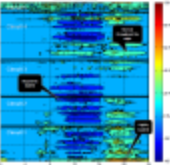
**- Pecan Street Mueller area smart grid demonstration project:**

- A real-life test bed within 2 miles from The University of Texas at Austin main campus.

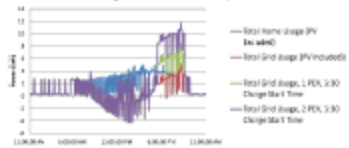



**- Modeling efforts:**

- Effect of EV charging on distribution transformers.
- Effect of high PV and EV penetration on electric grid.
- Relationship between diverse PV deployment and energy storage.


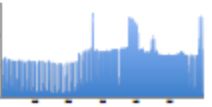



**Single Home Power Consumption**



**- Residential-level research**

- EV charge management.
- Data time resolution
- Interoperability.
- HEMS operation - energy management strategies
- Pricing strategies.
- Load pattern recognition
- Optimal PV orientation.

**- Data storage, processing and analysis**