Power Electronics and The Smart Grid

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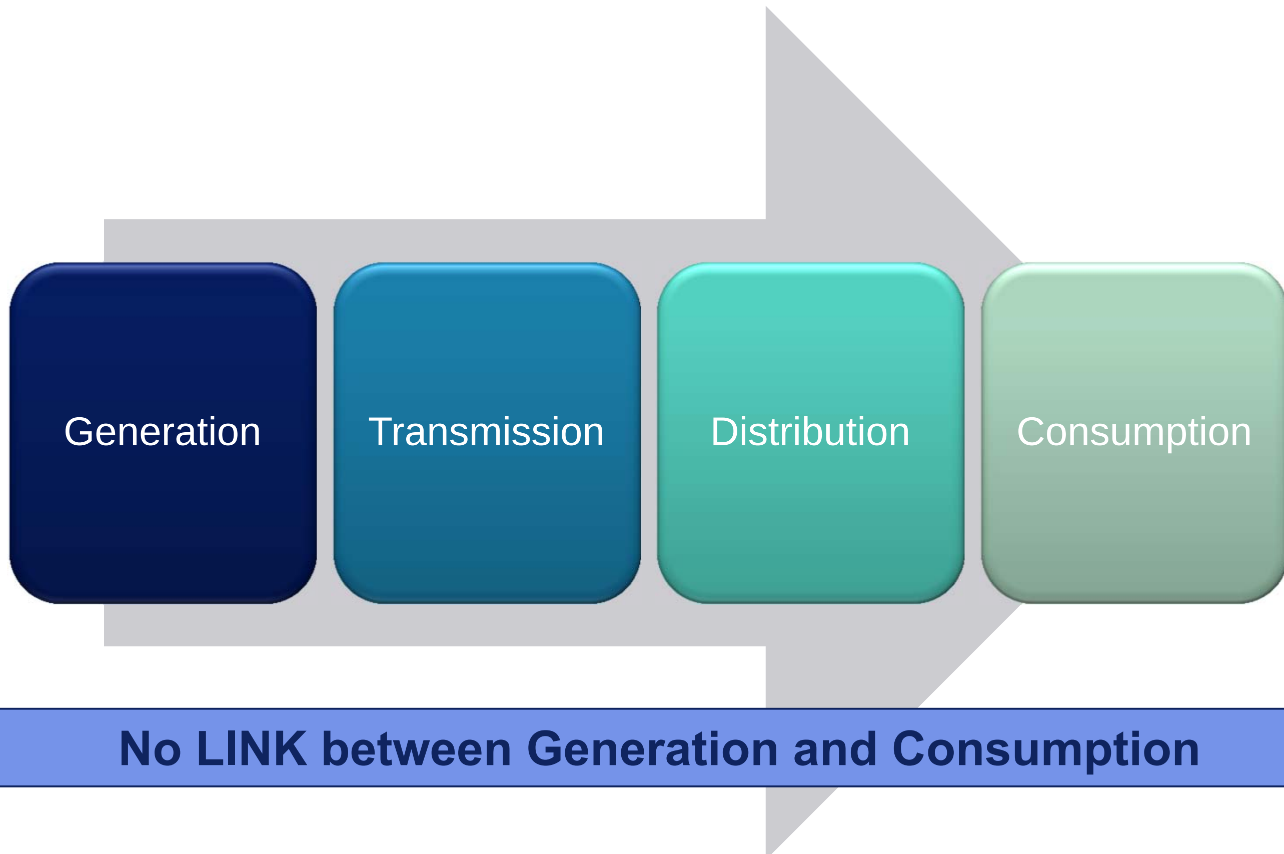
Recognition

Thanks to:

- **Prof. Alexis Kwasinski – University of Texas at Austin**
- **Dennis Symanski – EPRI**

For material used in this presentation.

Before Smart Grid
The Generation-Consumption Gap



No LINK between Generation and Consumption

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With Smart Grid Intelligent Integration

Distributed Generation is LINKED to Efficient Consumption as a new interconnected Energy Value Chain is created

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History

Competing technologies for electrification in 1880s:

- Edison:
  - dc.
  - Relatively small power plants (e.g. Pearl Street Station).
  - No voltage transformation.
  - Short distribution loops – No transmission
  - Loads were incandescent lamps and possibly dc motors (traction).

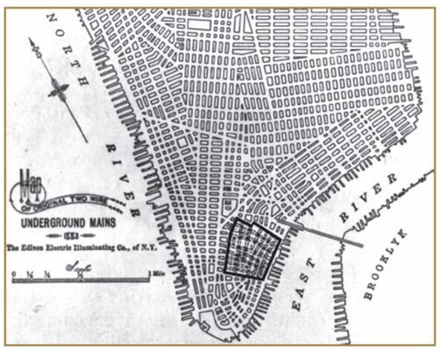


figure 1. Map of lower Manhattan showing the original area served by the Pearl Street station and its distribution system (courtesy of the Consolidated Edison Company of New York).

Pearl Street Station:
6 “Jumbo” 100 kW, 110 V generators

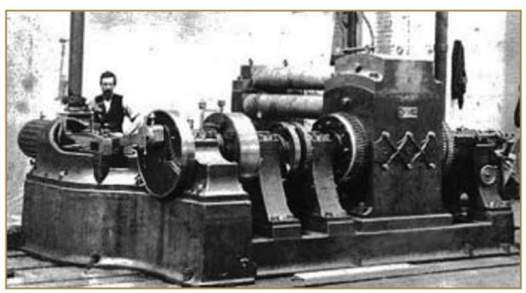
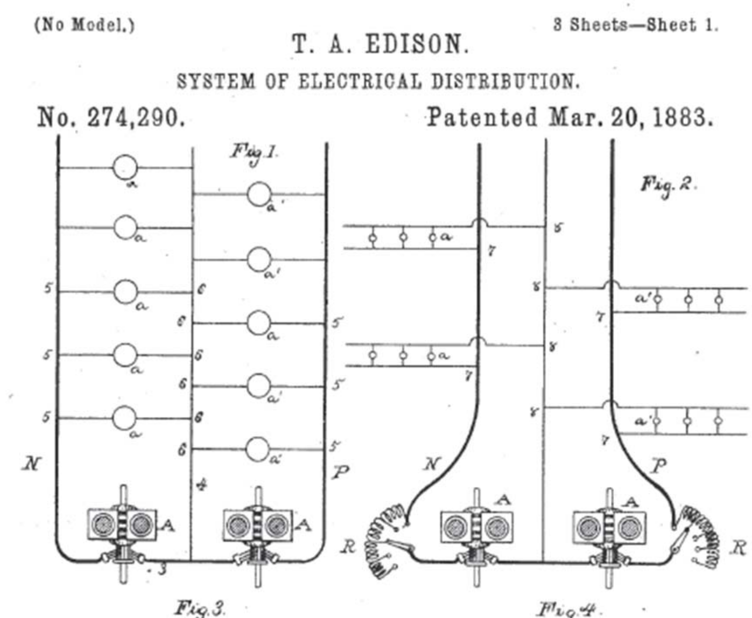


figure 3. Edison’s 100-kW engine-driven “Jumbo” dynamo of the type installed at the Pearl Street station (photo courtesy of the Edison National Historical Site, U.S. Department of the Interior, National Park Service).



“Eyewitness to dc history” Lobenstein, R.W. Sulzberger, C.

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History

Competing technologies for electrification in 1880s:

- Tesla:
  - ac
  - Large power plants (e.g. Niagara Falls)
  - Voltage transformation.
  - Transmission of electricity over long distances
  - Loads were incandescent lamps and induction motors.

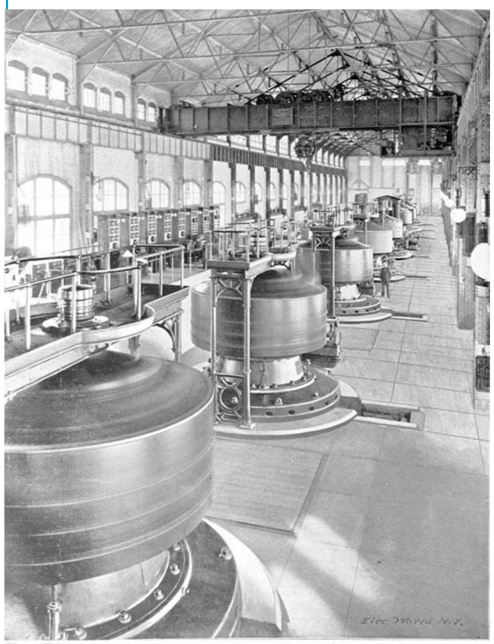
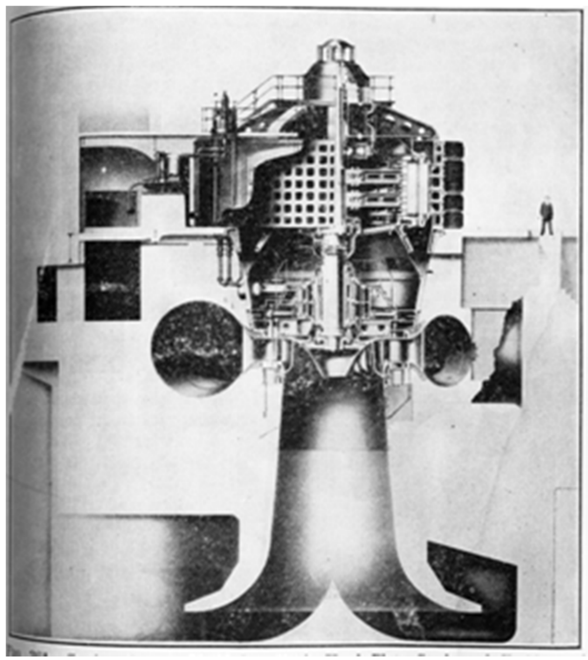


Fig. 11.—A View of the Dynamo Room, Looking South from the Visitors' Gallery.



Niagara Falls historic power plant:
38 x 65,000 kVA, 23 kV, 3-phase generatods

http://spiff.rit.edu/classes/phys213/lectures/niagara/niagara.html

History

Edison's distribution system characteristics: 1880 – 2000 perspective

- Power can only be supplied to nearby loads (< 1mile).
- Many small power stations needed (distributed concept).
- Suitable for incandescent lamps and traction motors only.
- Cannot be transformed into other voltages (lack of flexibility).
- Higher cost than centralized ac system.
- Used inefficient and complicated coal – steam actuated generators (as oppose to hydroelectric power used by ac centralized systems).
- Not suitable for induction motors.

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History towards the future

Edison's distribution as the basis for 2000 – future perspective

- Power supplied to nearby loads is more efficient, reliable and secure than long power paths involving transmission lines and substations.
- Many small power stations needed (distributed concept).
- Existing grid not suitable for dc loads (e.g., computers) or to operate induction motors at different speeds. Edison's system suitable for these loads.
- Power electronics allows for voltages to be transformed (flexibility).
- Cost competitive with centralized ac system.
- Can use renewable and alternative power sources.
- Can integrate energy storage.
- Can combine heat and power generation.

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Power Electronics

- Measure
- Control
- Manipulate
- Anticipate

- OPEX
- Reliability
- Efficiency
- Recovery

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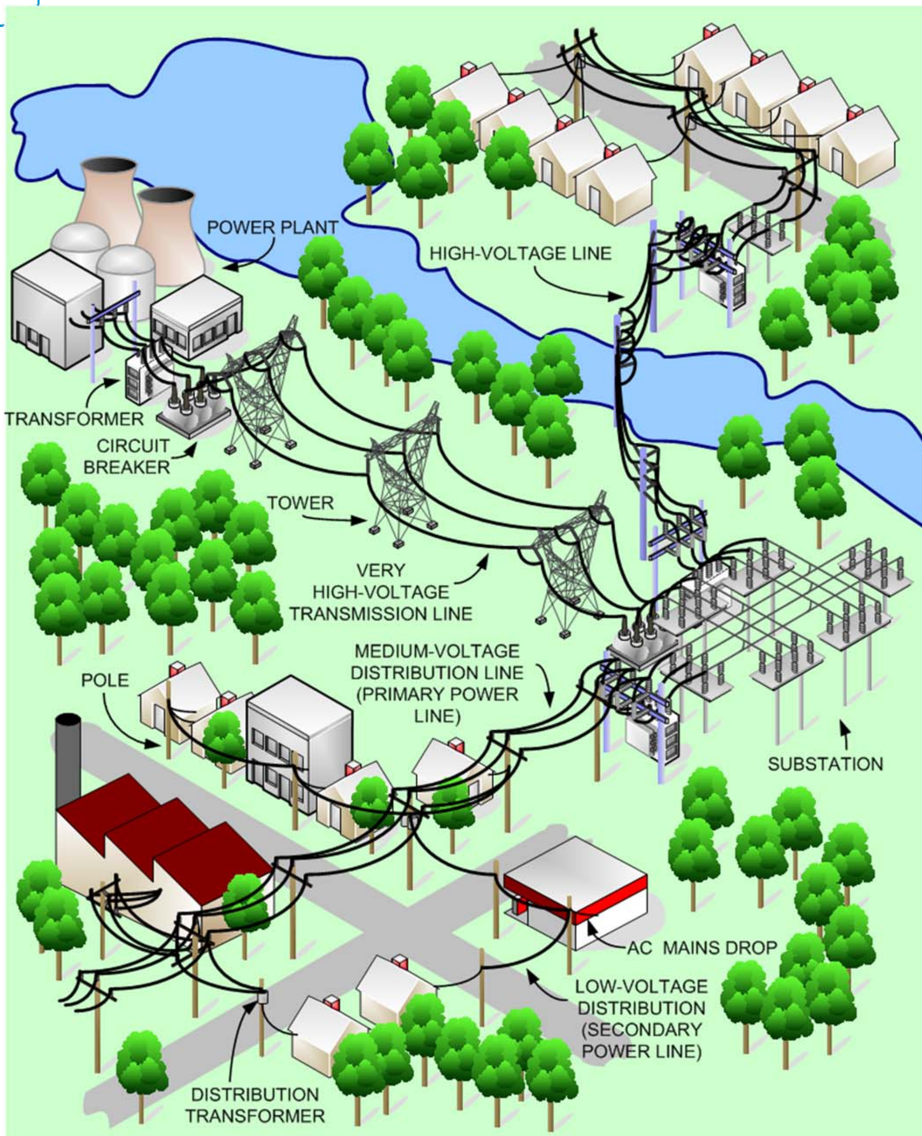
The traditional dull electric grid



Traditional technology - the electric grid:

- Generation, transmission, and distribution.
- Centralized and ***passive*** architecture.
- Extensive and very complex system.
- Complicated control.
- Not reliable enough for some applications.
- Relatively inefficient.
- Stability issues.
- Vulnerable.
- Lack of flexibility.

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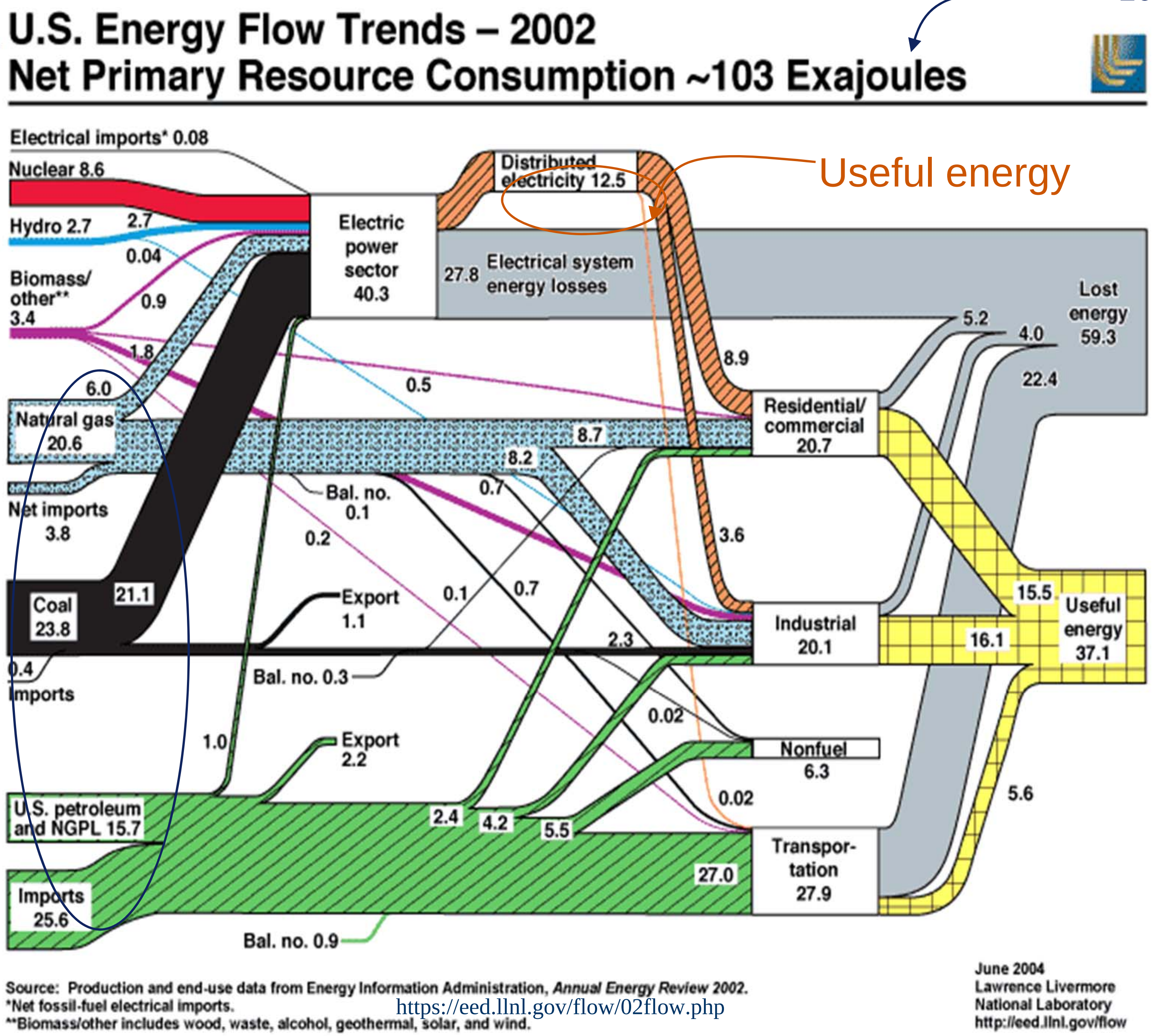
Traditional Electricity Delivery Methods

$103\ 10^{18}$ Joules

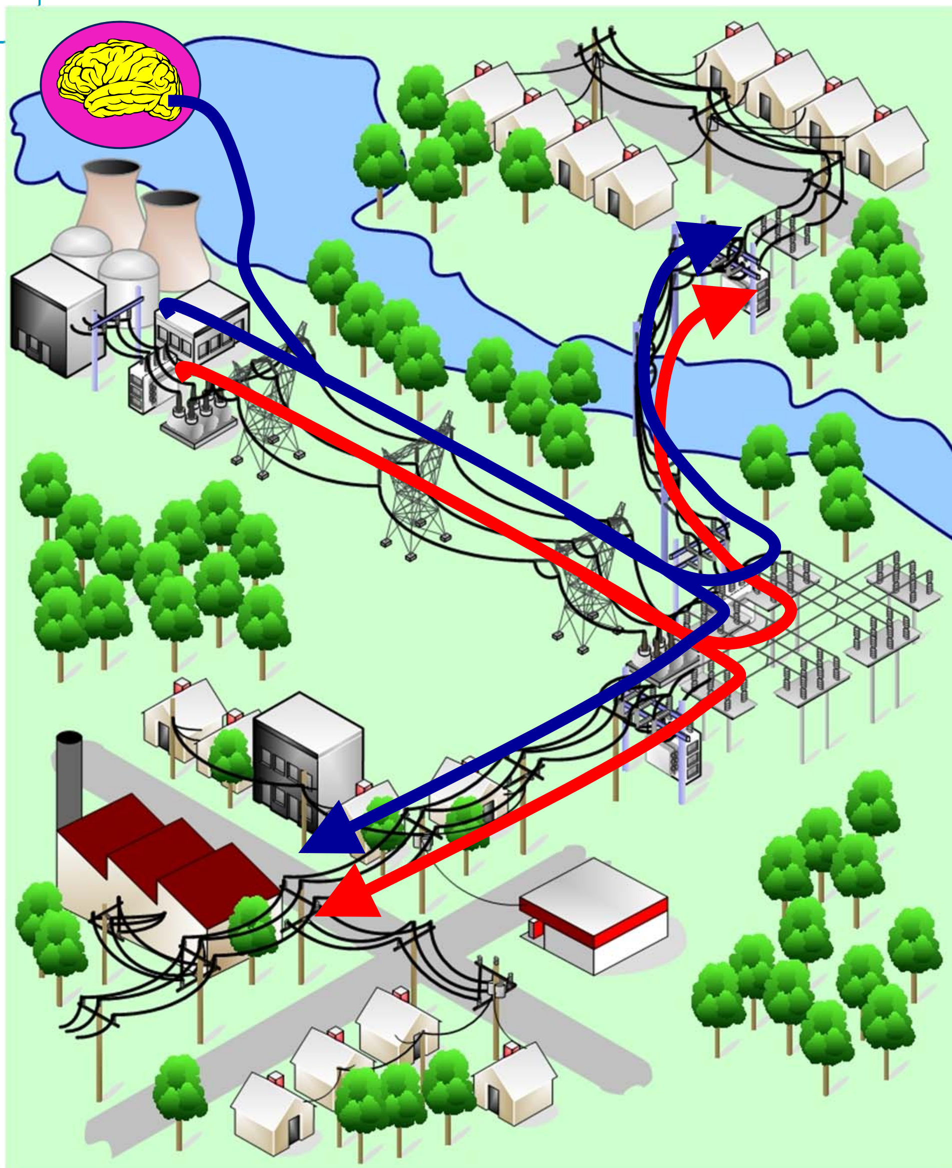


Useful energy

High polluting emissions

https://eed.llnl.gov/flow/02flow.php

Traditional Electricity Delivery Methods: Reliability



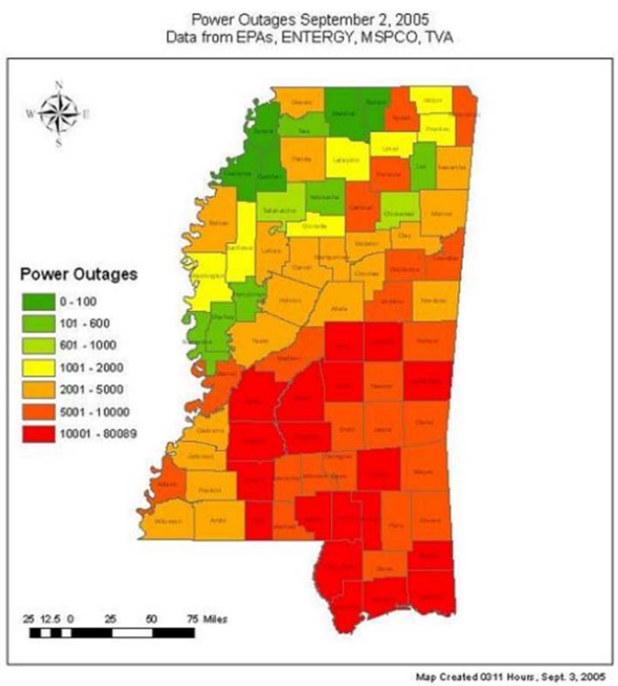
Traditional grid availability:
Approximately 99.9 %

Availability required in critical applications:
Approximately 99.999% - 99.9999%

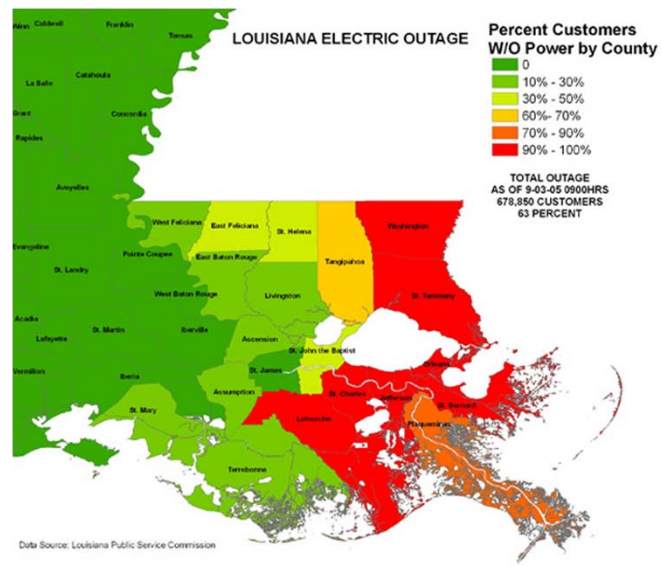
Traditional Electricity Delivery Methods: Reliability

Large storms or significant events reveal the grid's reliability weaknesses:

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



http://www.nnvl.noaa.gov/cgi-bin/index.cgi?page=items&ser=109668



http://www.gismonitor.com/news/newsletter/archive/092205.php

http://www.oe.netl.doe.gov/docs/katrina/la_outage_9_3_0900.jpg

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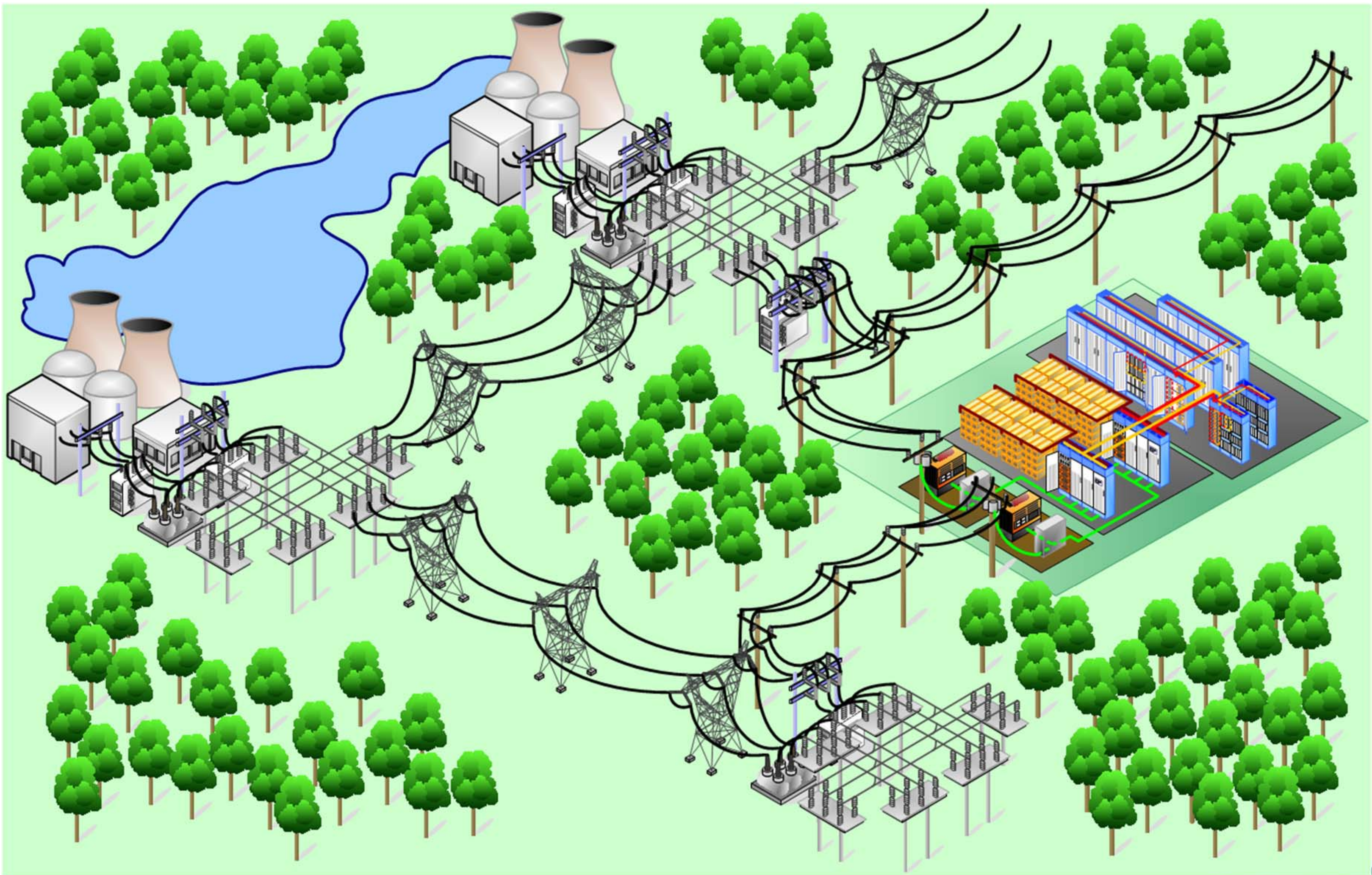
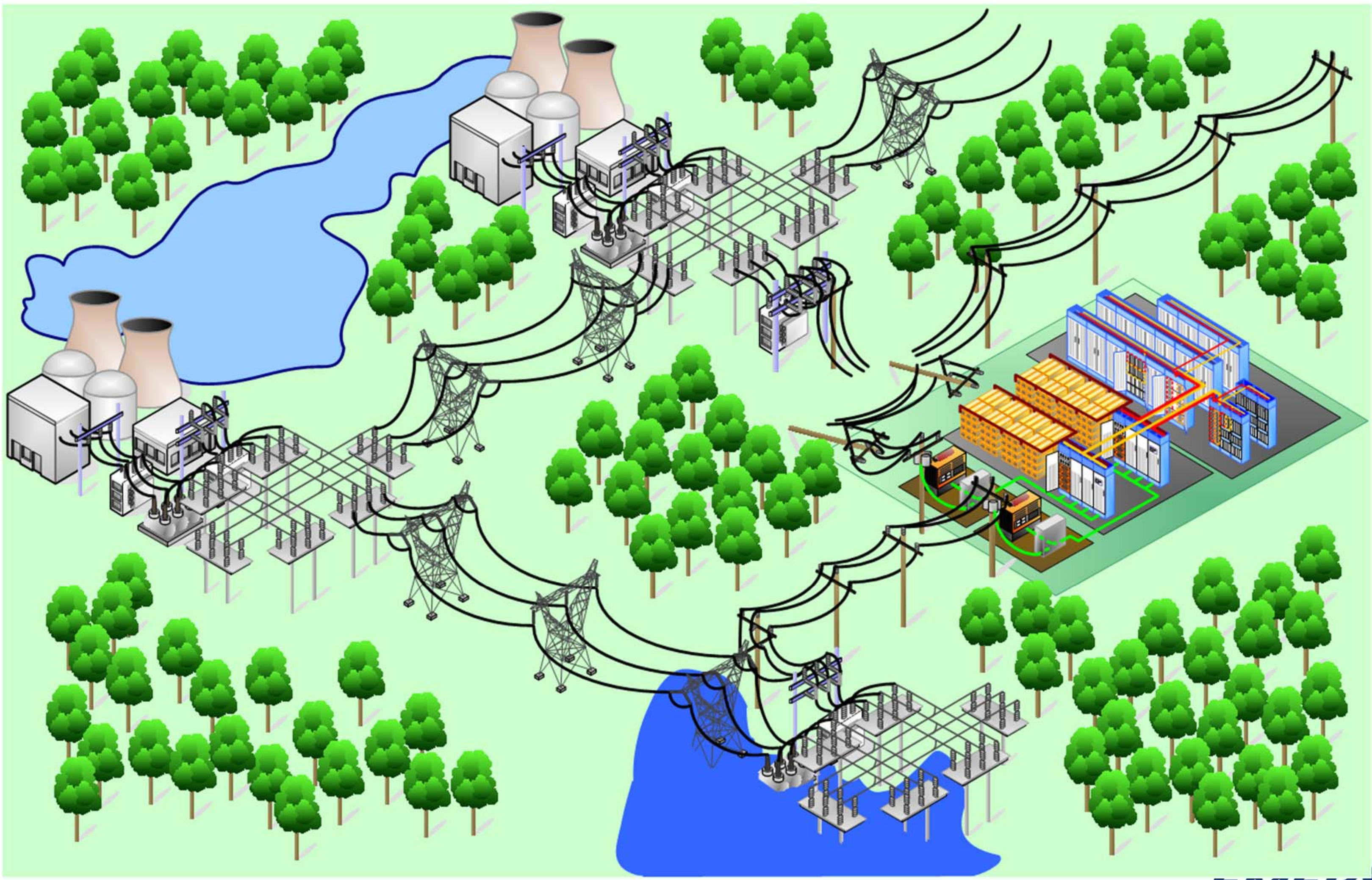
Traditional Electricity Delivery Methods: Reliability

Example of lack of diversity

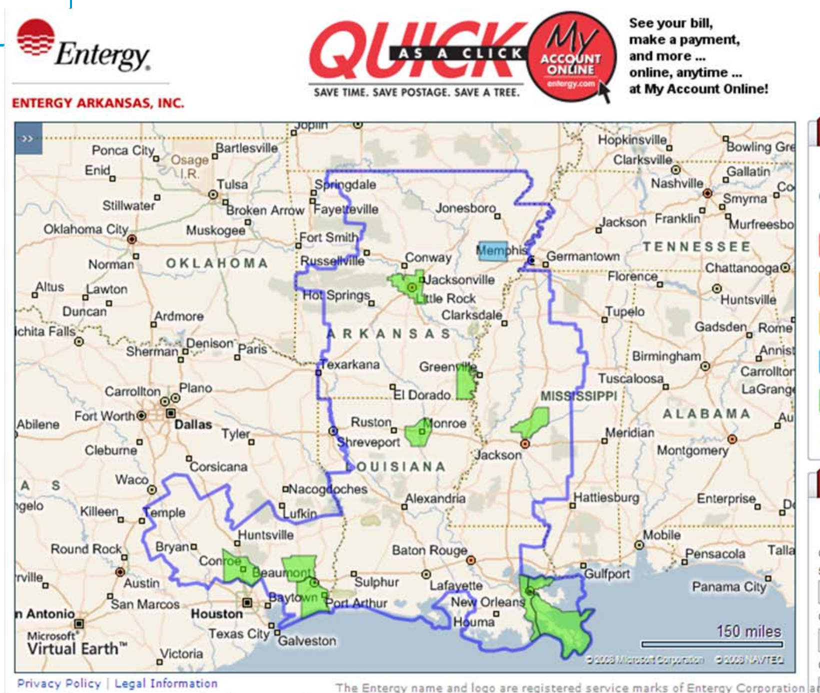


Traditional Electricity Delivery Methods: Reliability

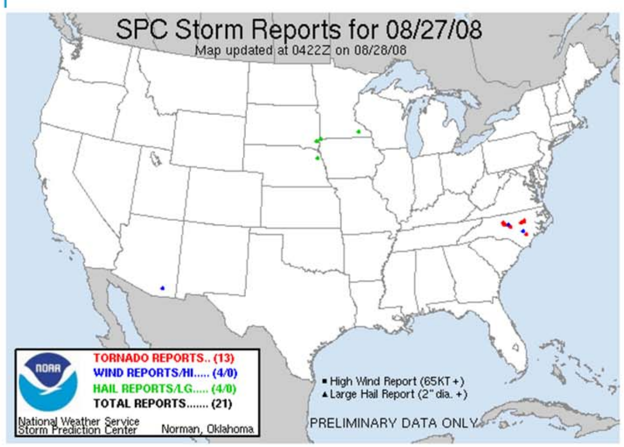
Example of lack of diversity

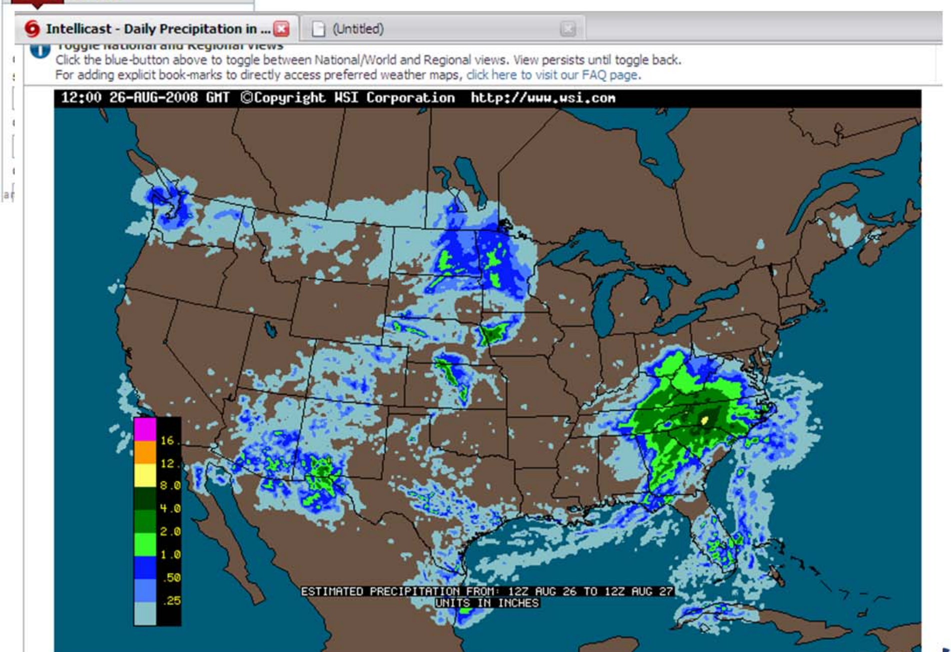


Traditional Electricity Delivery Methods: Reliability



Although they are hidden, the same reliability weaknesses are prevalent throughout the grid. Hence, power outages are not too uncommon.





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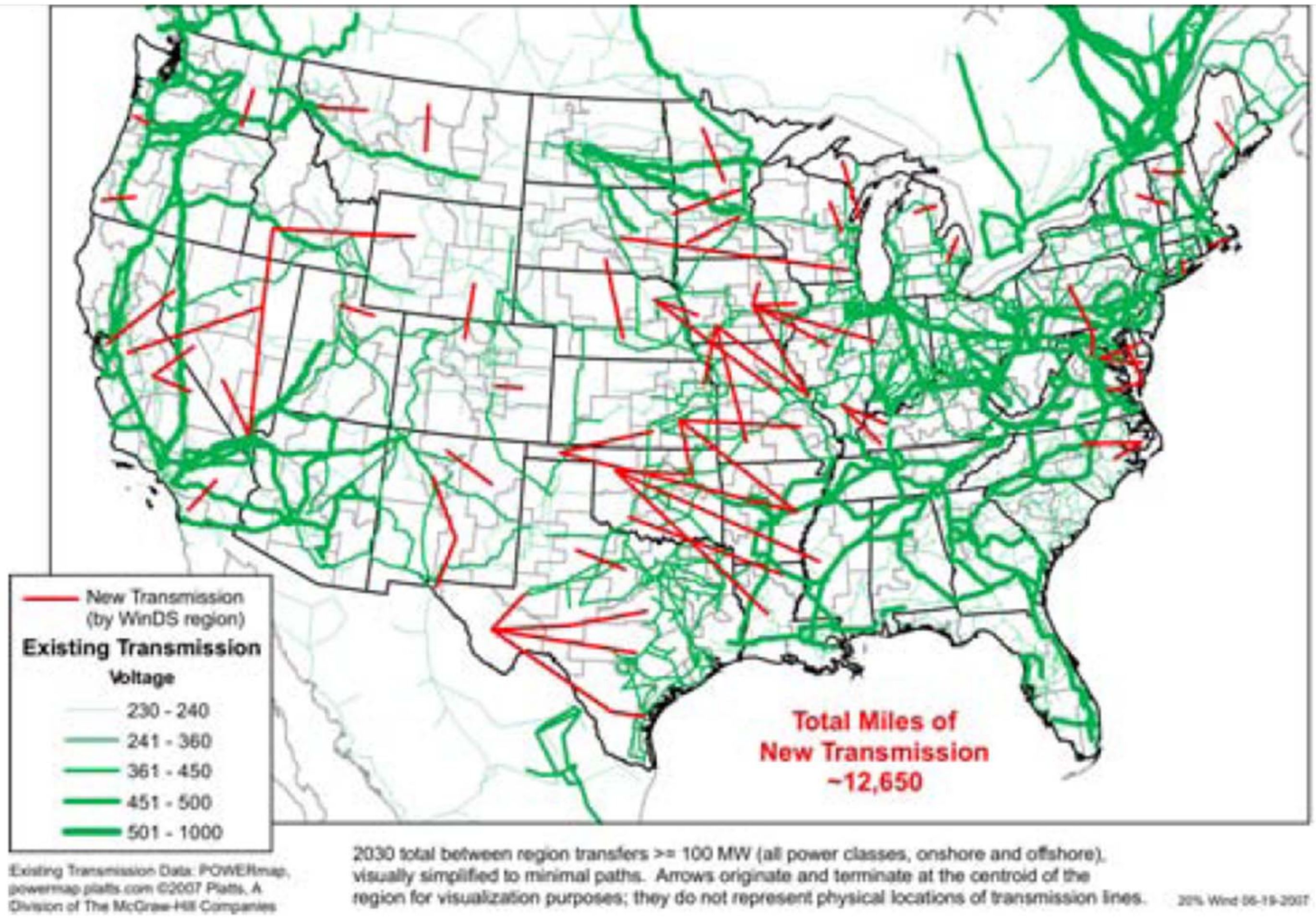
Traditional Electricity Delivery Methods: Security

Long transmission lines are extremely easy targets for external attacks.



U.S. DOE OEERE “20% of Wind Energy by 2030.”

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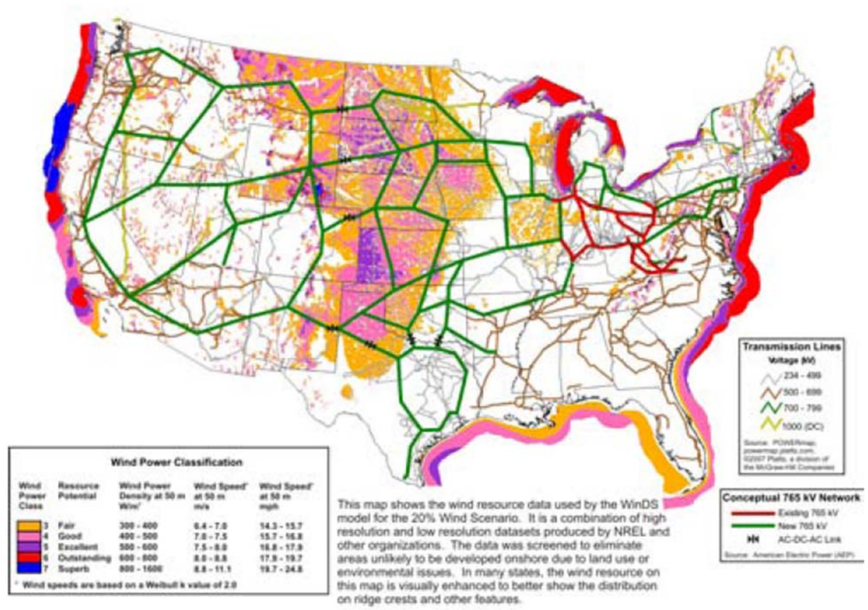
Traditional Electricity Delivery Methods: Cost

• Traditional coal power plants is not seen as a suitable solution as it used to be.

• Future generation expansion capacity will very likely be done through nuclear power plants, and renewable sources (e.g. wind farms and hydroelectric plants).

• None of these options are intended to be installed close to demand centers. Hence, more large and expensive transmission lines need to be built.

Figure 1-9. Conceptual transmission plan to accommodate 400 GW of wind energy (AEP 2007)



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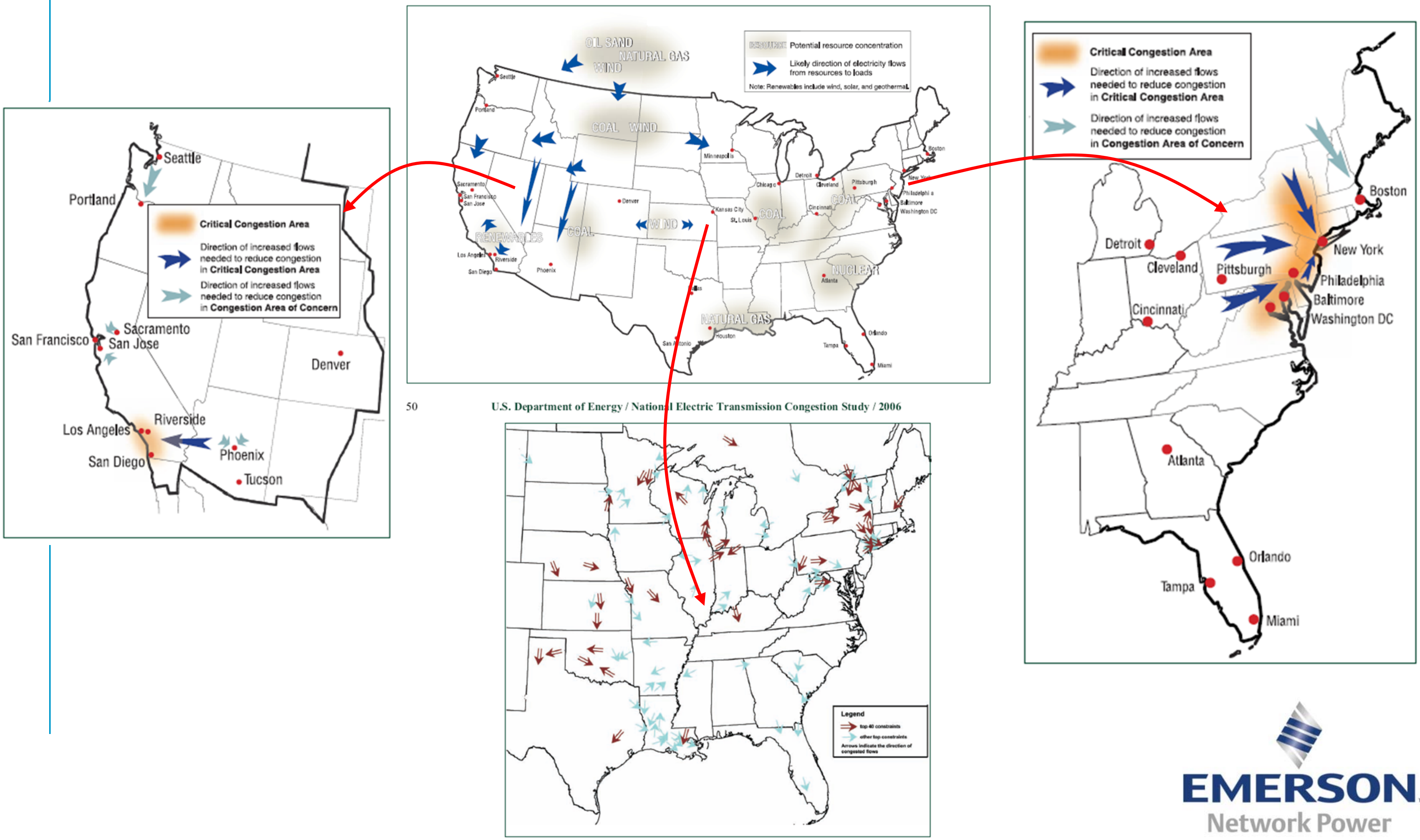
Limited transmission capacity

- Congestion areas lead to higher costs and lower availability



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Traditional grid: Operation and other issues

- Centralized integration of renewable energy issue: generation profile unbalances.

- Complicated stability control.

- The grid lacks operational flexibility because it is a passive network.

- The grid user is a passive participant whether he/she likes it or not.

- The grid is old: it has the same 1880s structure. Power plants average age is > 30 years.

Traditional grid: Operation and other issues

•Variable (movable) loads and energy storage (e.g. PHEV) cannot be properly integrated in the grid.

• High cost of power from new nuclear/coal plants

• Pending cap and trade legislation

• Reduce greenhouse gas emissions, use more wind/solar/natural gas

• Increasing workforce average age - Trained work force needed

Smart grid concept

- Technologies and concepts:
  - Distributed energy resources (generation and storage) are fundamental parts. They provide the necessary active characteristics to an otherwise passive grid.
  - Advanced and distributed communications. All the grid components are able to communicate. The grid operates like a power-Internet (distributed, multiple-redundant, interactive and autonomous).
  - Intelligent metering.
  - Policies and regulatory actions. Necessary to achieve integration of all the parts.
  - Grid modernization.

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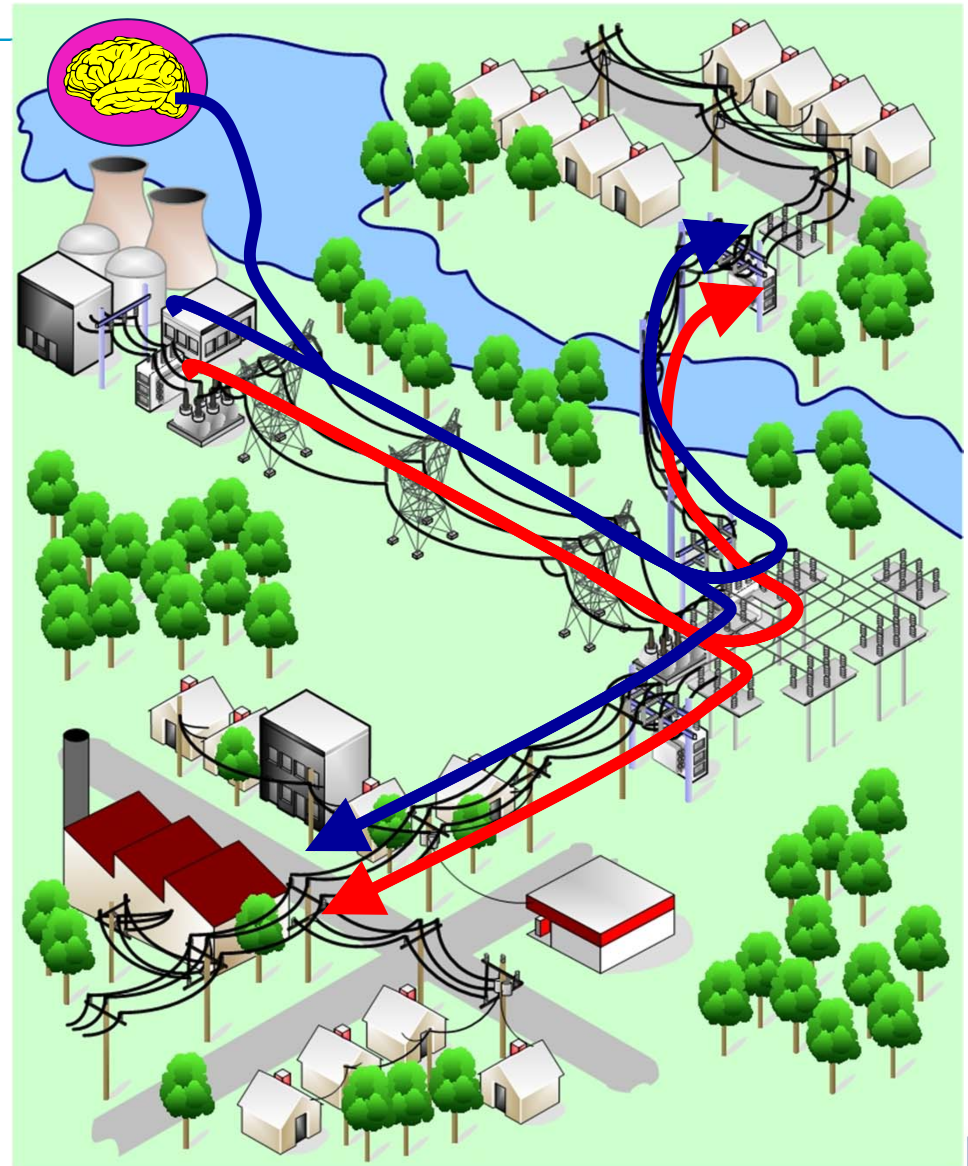
Smart grid evolution: dull past/present

- Centralized operation and control
- Passive transmission and distribution.
- Lack of flexibility
- Vulnerable



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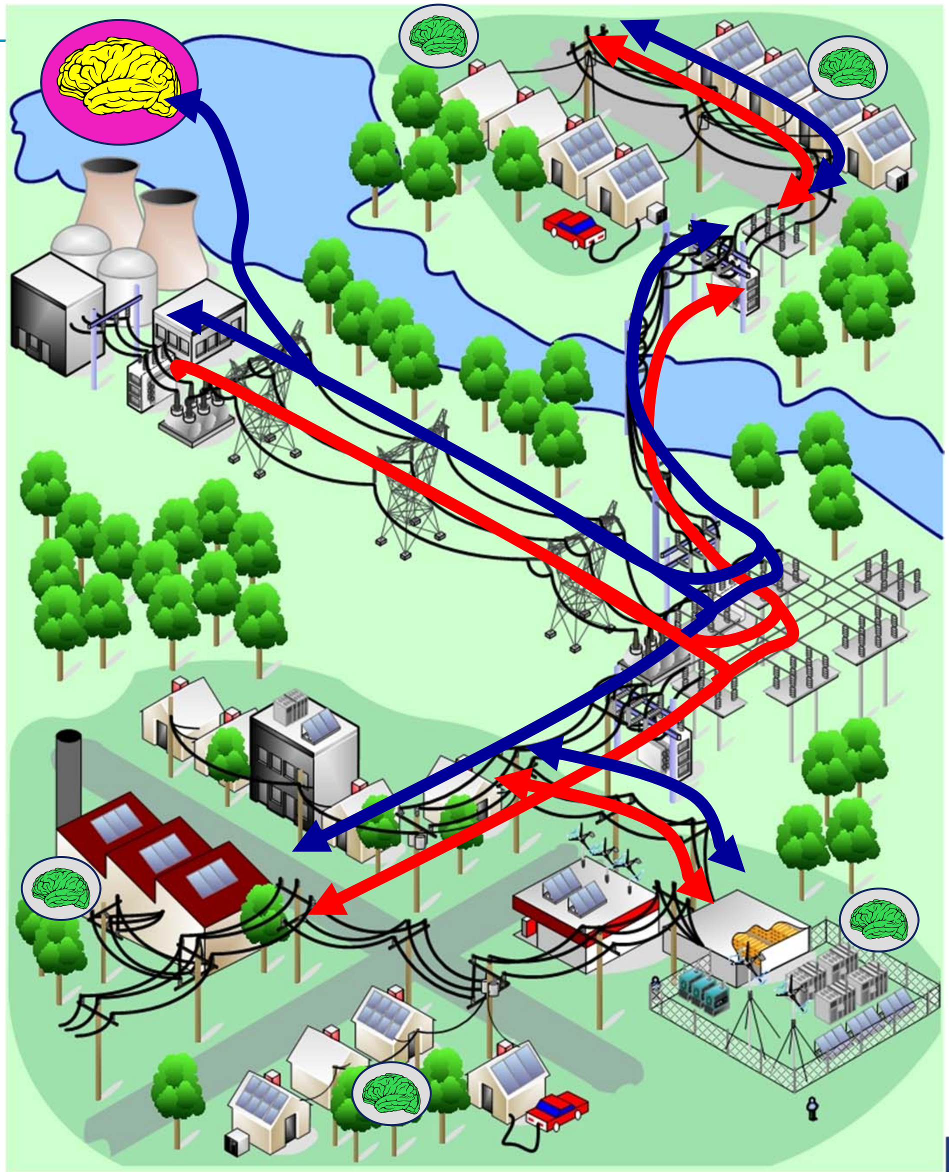
Smart grid evolution: present/immediate future

- Still primarily centralized control.
- Active distribution network (distributed local generation and storage).
- Addition of communication systems
- Advanced more efficient loads
- Flexibility issues
- Somewhat more robust



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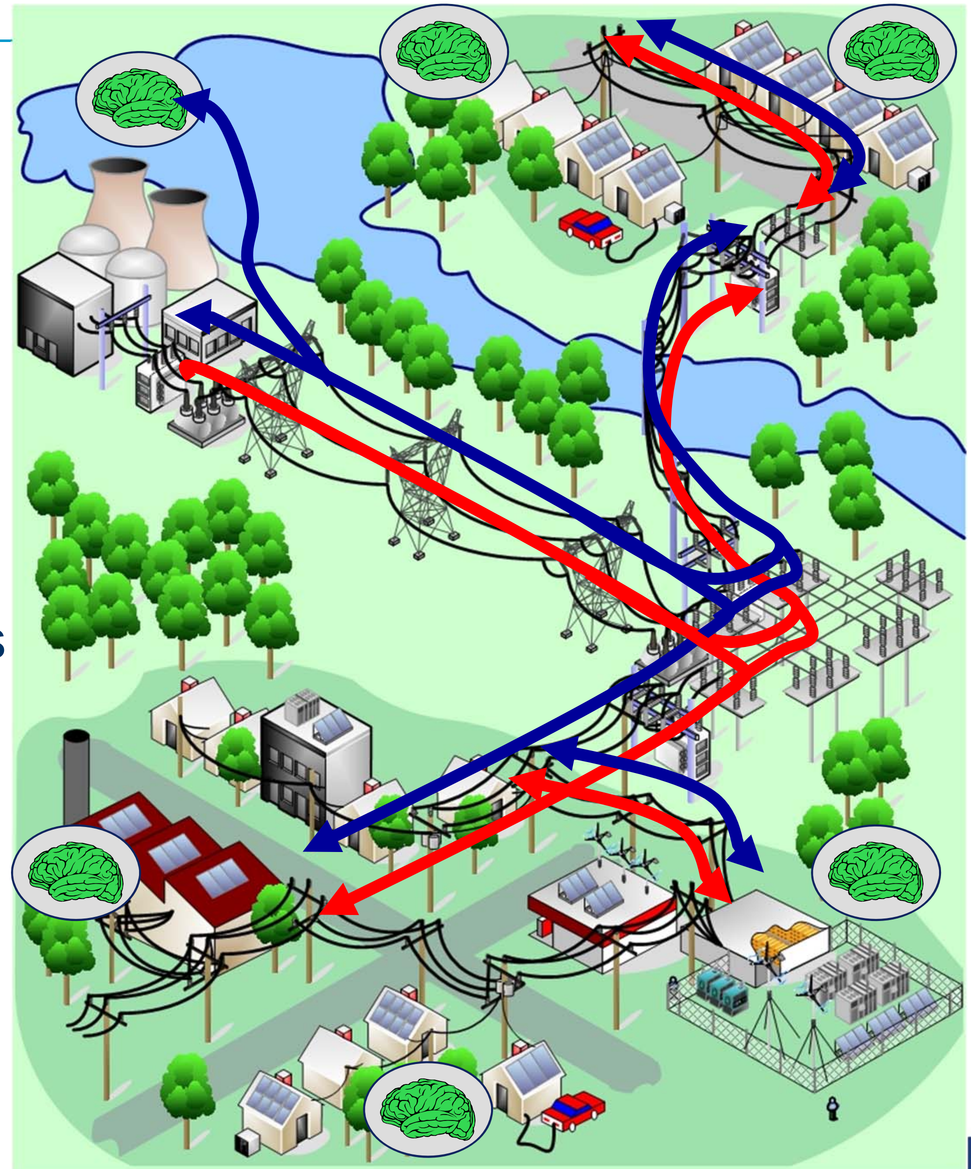
Smart grid evolution: Future

- Distributed operation and control
- Active distribution network (distributed local generation and storage).
- Integrated communications
- Advanced more efficient loads
- Flexible
- More robust



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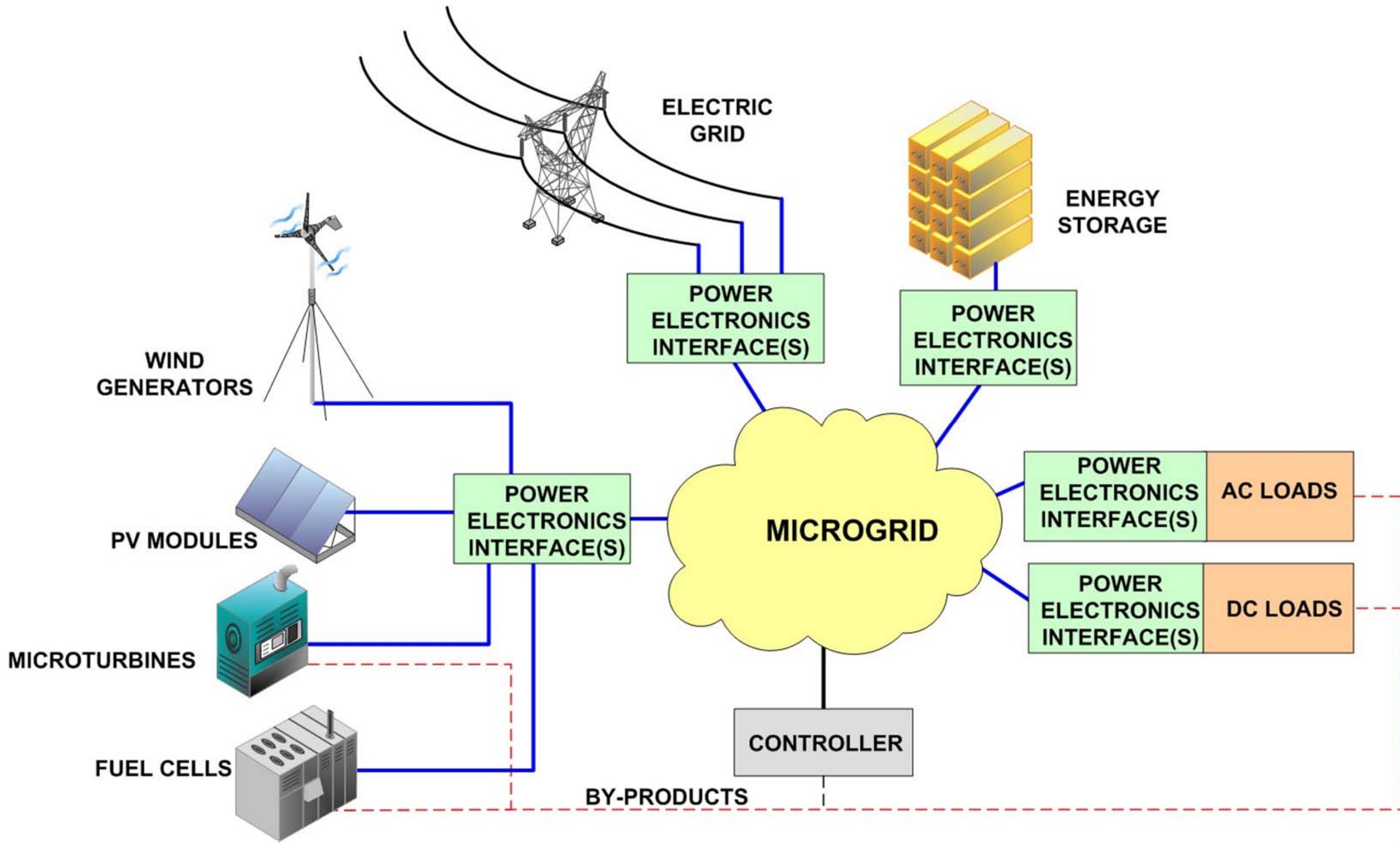
Distributed Generation: Concept

Microgrids are independently controlled (small) electric networks, powered by local units (distributed generation).



Distributed Generation: Concept

- **Key concept: independent control.**

  - **The key concept implies that the microgrid has its own power generation sources (active control vs. passive grid).**

  - A microgrid may or may not be connected to the main grid.

  - DG can be defined as "a subset of distributed resources (DR)" [T. Ackermann, G. Andersson, and L. Söder, "Distributed generation: A definition." Electric Power Systems Research, vol. 57, issue 3, pp. 195-204, April 2001].

  - DR are "sources of electric power that are not directly connected to a bulk power transmission system. DR includes both generators and energy storage technologies" [T. Ackermann, G. Andersson, and L. Söder, "Distributed generation: A definition." Electric Power Systems Research, vol. 57, issue 3, pp. 195-204, April 2001]

  - DG "involves the technology of using small-scale power generation technologies located in close proximity to the load being served" [J. Hall, "The new distributed generation," Telephony Online, Oct. 1, 2001 http://telephonyonline.com/mag/telecom_new_distributed_generation/.]

- Thus, microgrids are electric networks utilizing DR to achieve independent control from a large widespread power grid.

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Distributed Generation: System Components

Generation units = microsources (aprox. less than 100 kW)
- PV Modules.
- Small wind generators
- Fuel Cells
- Microturbines

Energy Storage (power profile)
- Batteries
- Ultracapacitors
- Flywheels

Loads
- Electronic loads.
- Plug-in hybrid cars.
- The main grid.

Power electronics interfaces
- dc-dc converters
- inverters
- Rectifiers

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Distributed Generation: Advantages

- **With respect to the traditional grid, well designed microgrids are:**
  - More reliable (with diverse power inputs).
  - More efficient
  - More environmentally friendly
  - More flexible
  - Less vulnerable
  - More modular
  - Easier to control
  - Immune to issues occurring elsewhere

  - Capital investment can be scaled over time

  - Microgrids can be integrated into existing systems without loosing the load.

  - Microgrids allow for combined heat and power (CHP) generation.

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Distributed Generation: Issues

- Load following
- Power vs Energy profile in energy storage
- Stability
- Cost
- Architecture / design
- Optimization
- Autonomous control
- Fault detection and mitigation
- Cost
- Grid interconnection

Smart Grid Challenges/Unknowns

•Design of the grid

•Power vs. Energy storage – How distributed should it be?

•Redundancy and reliability for peak/base loads – Large penetration of renewable sources with variable generation profile

•Power flow management

•Power stability

•Cybersecurity

•Automation/decentralized control – communications (bandwidth vs. resources: last mile problem

•Power electronics

•ac vs. dc

Energy Storage

- Two main uses of energy storage devices in DG:
  - Power buffer for slow, bad load followers, DG technologies. Power to compensate short term power generation shortages usually occurring in intermittent/stochastic sources (e.g. solar panels or wind generators)
  - Energy supply for long-term stochastic generation profiles (e.g. solar power during night).

- Power delivery profile: short, shallow and often energy exchanges.
  - Flywheels
  - Ultracapacitors

- Energy delivery profile: long, deep and infrequent energy exchanges.
  - Batteries
  - Batteries can be used in power delivery profile applications but they need to be significantly oversized in order to avoid shorter life due to continuous deep cycling.

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Microgrids and the Grid

- Microgrids could have a grid interconnection to
  - Improve system economics
  - Improve operation
  - Improve availability
- With a suitable planning, grid planning can benefit from having microgrids by
  - Reducing conductor's size
  - Improving availability
  - Improving stability
- Tools, strategies and techniques for an effective integration of a microgrid into the main grid:
  - Net metering – bi-directional power flow.
  - Peak shaving
  - Advanced communications and controls
  - Demand response (?)

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Microgrids and the Grid

- Potential issues with microgrids integration into the main grid:
  - Infrastructure long term planning / economics:
    - There is no coordination in planning the grid and microgrids.
    - The grid is planned on a long term basis considering traditional loads.
    - Microgrids may “pop-up” afterwards “without notice.”
    - Grid’s planning links economic (cost of grid’s electricity, future demand…..) and technical aspects (line congestion….)

  - Stability: microgrids are variable loads with positive and negative impedance (they can act as generators)

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Microgrids and the Grid

- More potential issues with microgrids integration into the main grid:
  - Safety: When there is a fault in the grid, power from the microgrid into the grid should be interrupted (islanding)

  - Availability: Microgrids can trigger protections (directional relays) upstream in the grid and interrupt service to other loads

- Key issue: microgrids are supposed to be <u>independently</u> controlled cells within the main grid.
  - How much independence microgrids should have?
    - Does independence apply also to planning?
    - How much interaction / communications should be between the grid and the microgrid?

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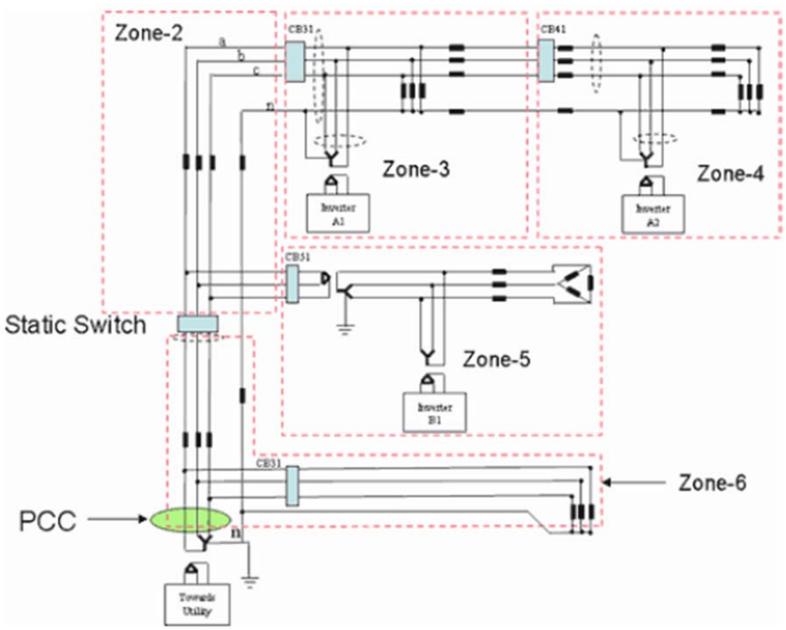
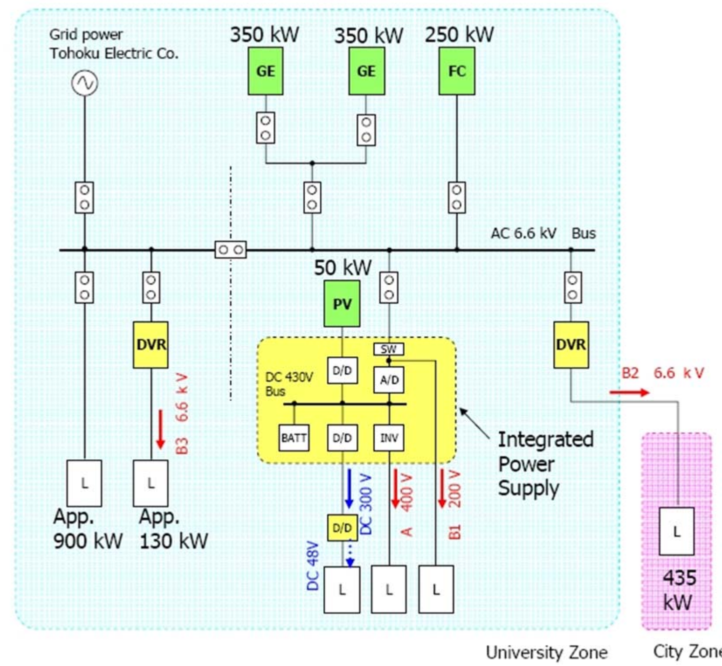
Microgrids and the Grid

- Grid interconnection might be different for dc or ac microgrids
- For ac microgrids, grid interconnection can be done directly, with a disconnect switch, and a transformer only.
- For dc microgrids an inverter is necessary
- Examples:



AEP/CERTS Microgrid Schematic

CERTS microgrid (ac)



NTT Facilities Sendai project (ac and dc)

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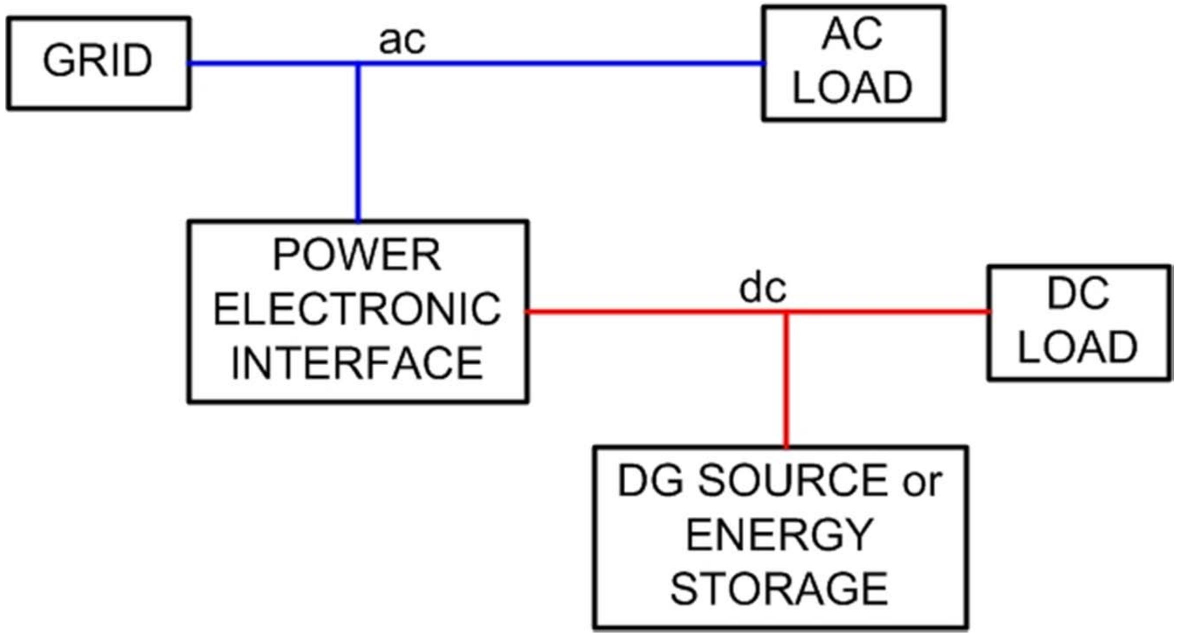
Microgrids and the Grid

• dc microgrids integration with the grid



• The interface may or may not allow for bidirectional power flow. Bidirectional power flow can be needed for:

- Energy storage
- dc loads

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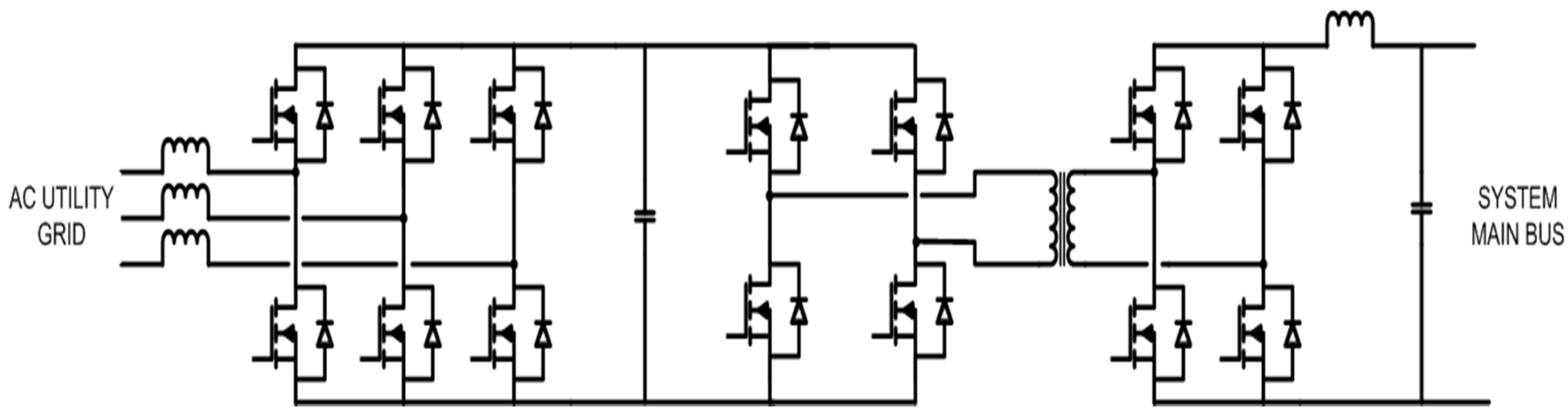
Microgrids and the Grid



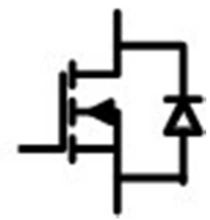
- Power electronic interfaces (bidirectional rectifier/inverter)

Power electronics basics

- Types of interfaces:
  - dc-dc: dc-dc converter
  - ac-dc: rectifier
  - dc-ac: inverter
  - ac-ac: cycloconverter (used less often)

- Power electronic converters components:
  - Semiconductor switches:
    - Diodes
    - MOSFETs
    - IGBTs
    - SCRs
  - Energy storage elements
    - Inductors
    - Capacitors
  - Other components:
    - Transformer
    - Control circuit

Diode



MOSFET

IGBT

SCR

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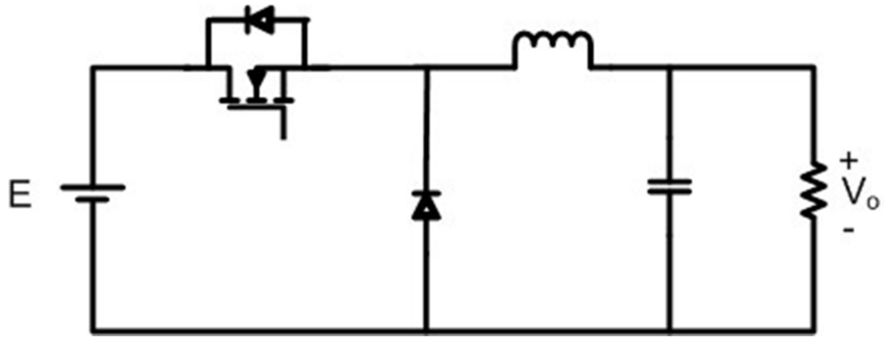
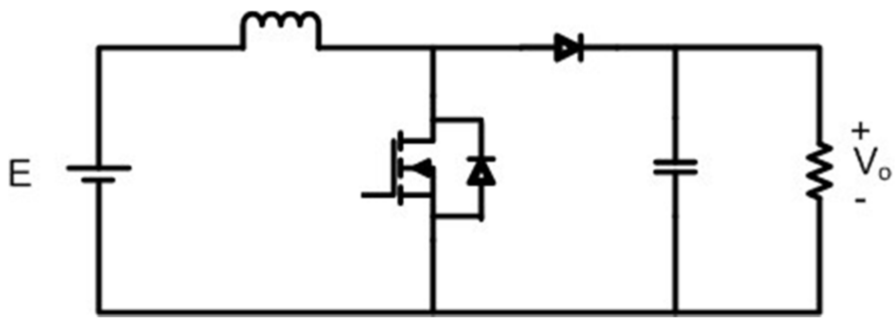
Power electronics basics

- dc-dc converters



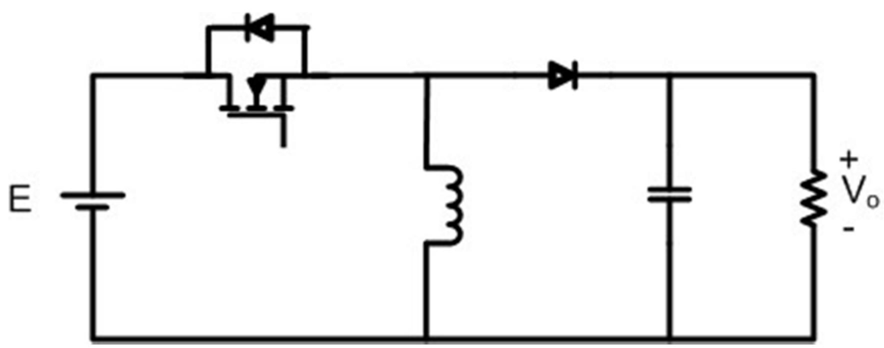
- *Buck converter*

$$V_o = DE$$



- *Boost converter*

$$V_o = \frac{E}{1-D}$$



- *Buck-boost converter*

$$V_o = -\frac{DE}{1-D}$$

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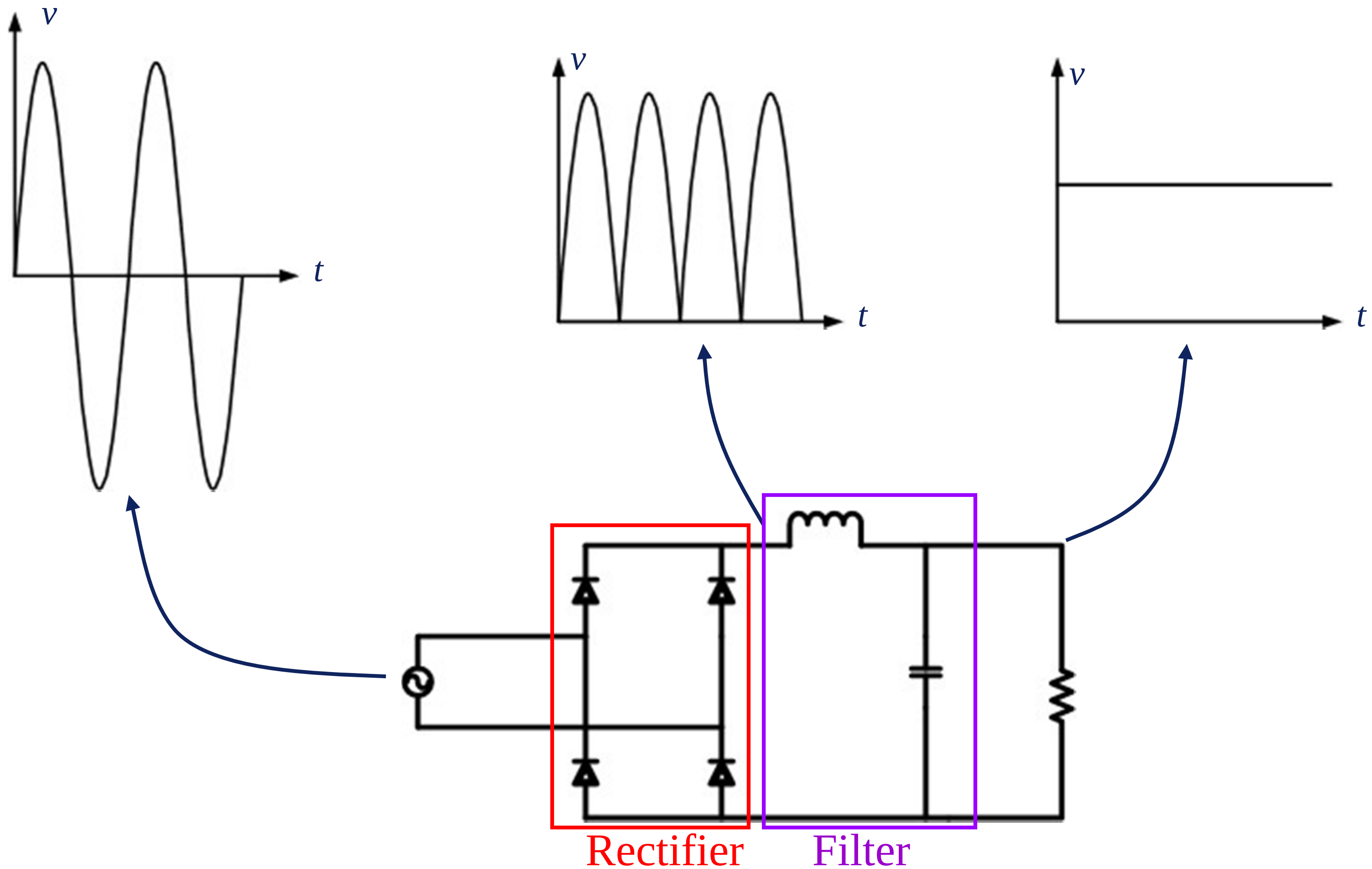
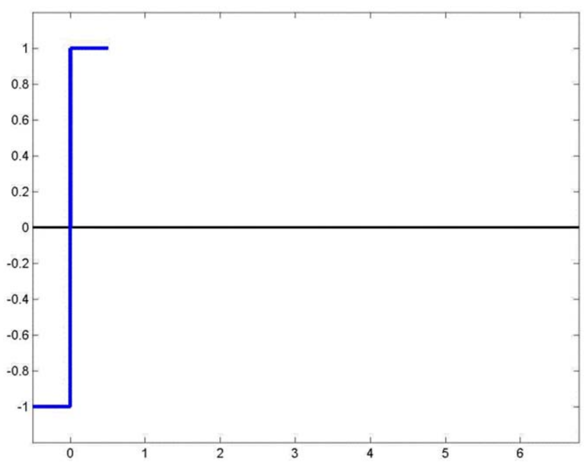
Power electronics basics

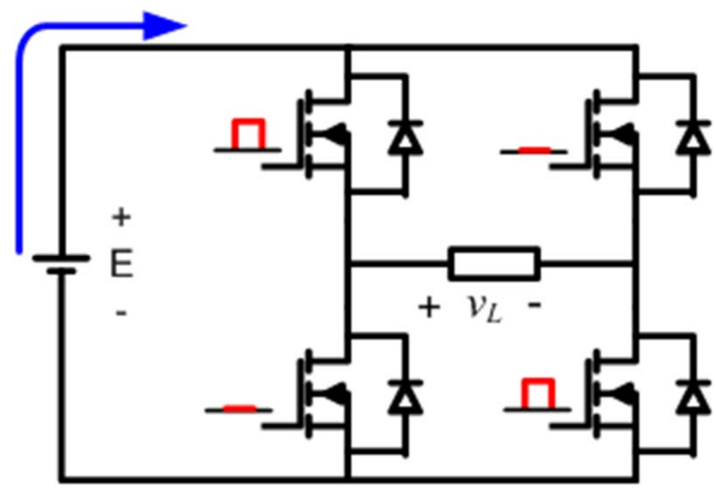
- Rectifiers



Power electronics basics

- Inverters
- dc to ac conversion
- Several control techniques. The simplest technique is square wave modulation (seen below).
- The most widespread control technique is Pulse-Width-Modulation (PWM).





Energy Efficiency
Net Zero Energy Buildings

What's likely to change in the approach to design/build?

1. **Integrated design** and operations planning
2. **Site renewable energy** strategies get maxed out
3. **Energy Storage technology** will allow Grid independence breakthroughs
4. **System Intelligence** - More control, monitoring, verification of everything

NZE Buildings

2030: All new commercial buildings

2040: 50% of commercial building stock

2050: All commercial buildings

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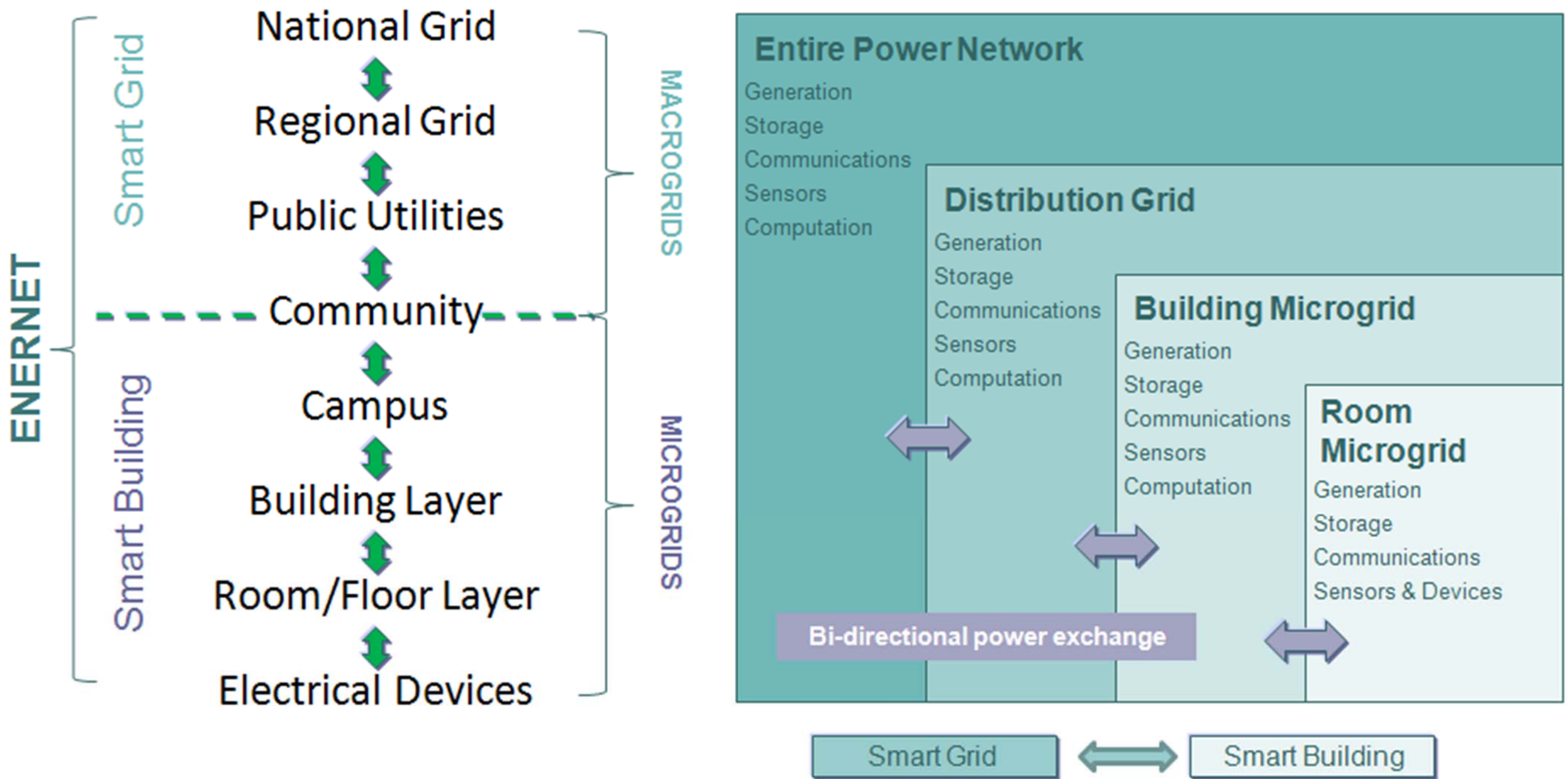
Smart Grid to Smart Buildings: Buildings as Microgrids in Energy Networks



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Hybrid Power Platform for Buildings

- **Open Standards for DC Microgrids**
  - Hybrid platform of AC and DC power distribution
  - Reduce or eliminate wasteful AC-DC conversions
- **Creating More Flexible & Sustainable Buildings**
  - Plug and play reconfigurability
  - Simplified electronics – improved reliability
- **Energy Savings Potential from**:
  - More efficient use of DC-based loads

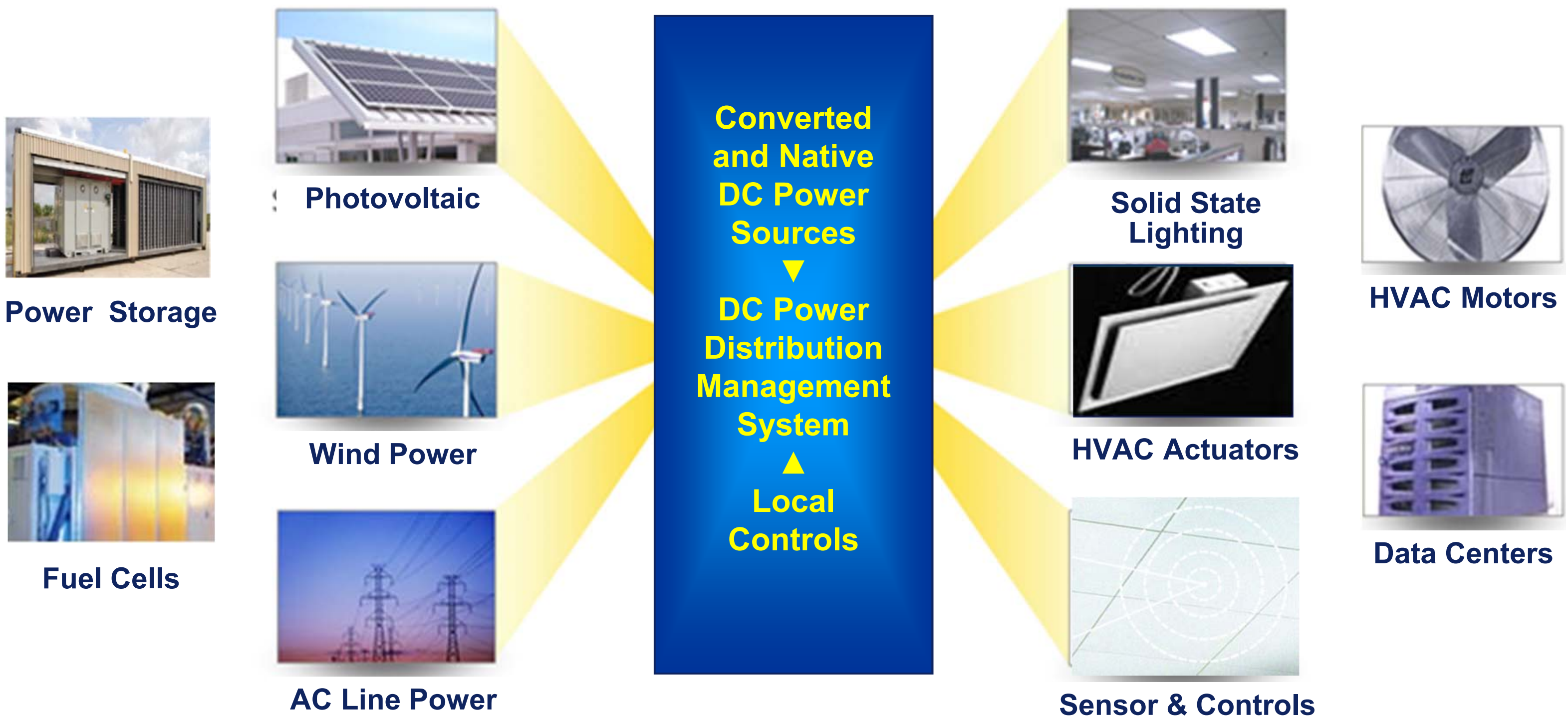
    (i.e. LED lighting, controls, data and telecom centers, EV chargers, variable speed drives, etc.)
  - Direct integration of DC energy sources

    (i.e. on-site solar, wind, fuel cells, dc storage)

DC MICROGRID MODEL

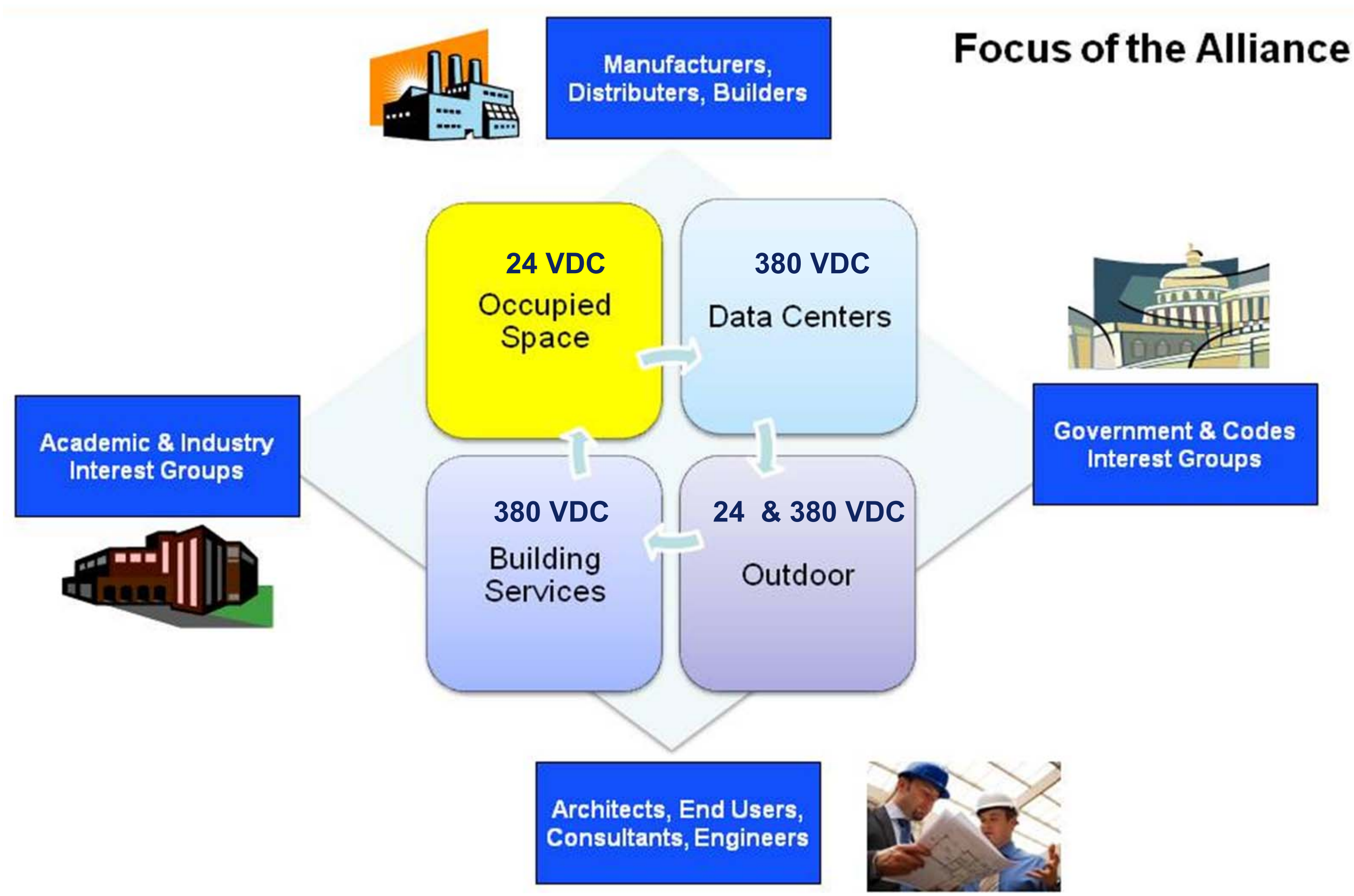
ELECTRICAL ENERGY SOURCES

ELECTRICAL ENERGY CONSUMPTION



OPTIMUM POWER SOURCING, USE & MANAGEMENT

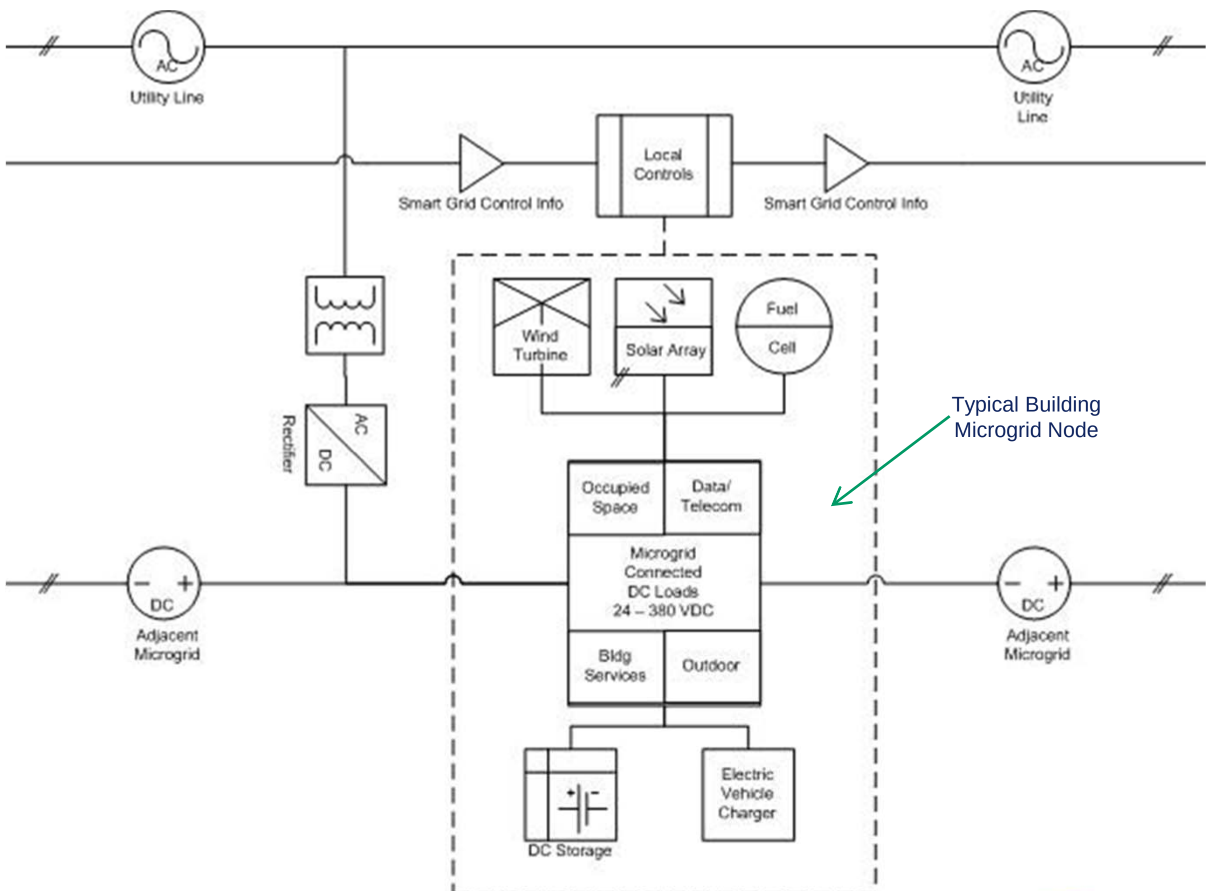
Vision - DC Microgrids throughout Buildings



Emergence of the Enernet

DC Microgrids – A Mesh Network

Characteristic
24V Class 2 – Room Level
380 V Class 1 Distrib. Voltage
Site Generated Voltage
Vehicle Charging/Sourcing
PoE & Task Connectivity
Intelligent Sub-metering
Microgrid Requirements
Utility Feed Voltages
Life-Safety Power
Bi-Directional & Intell. Routing



Energy Savings Potential from Going DC

DC Microgrids throughout Buildings – Owner View

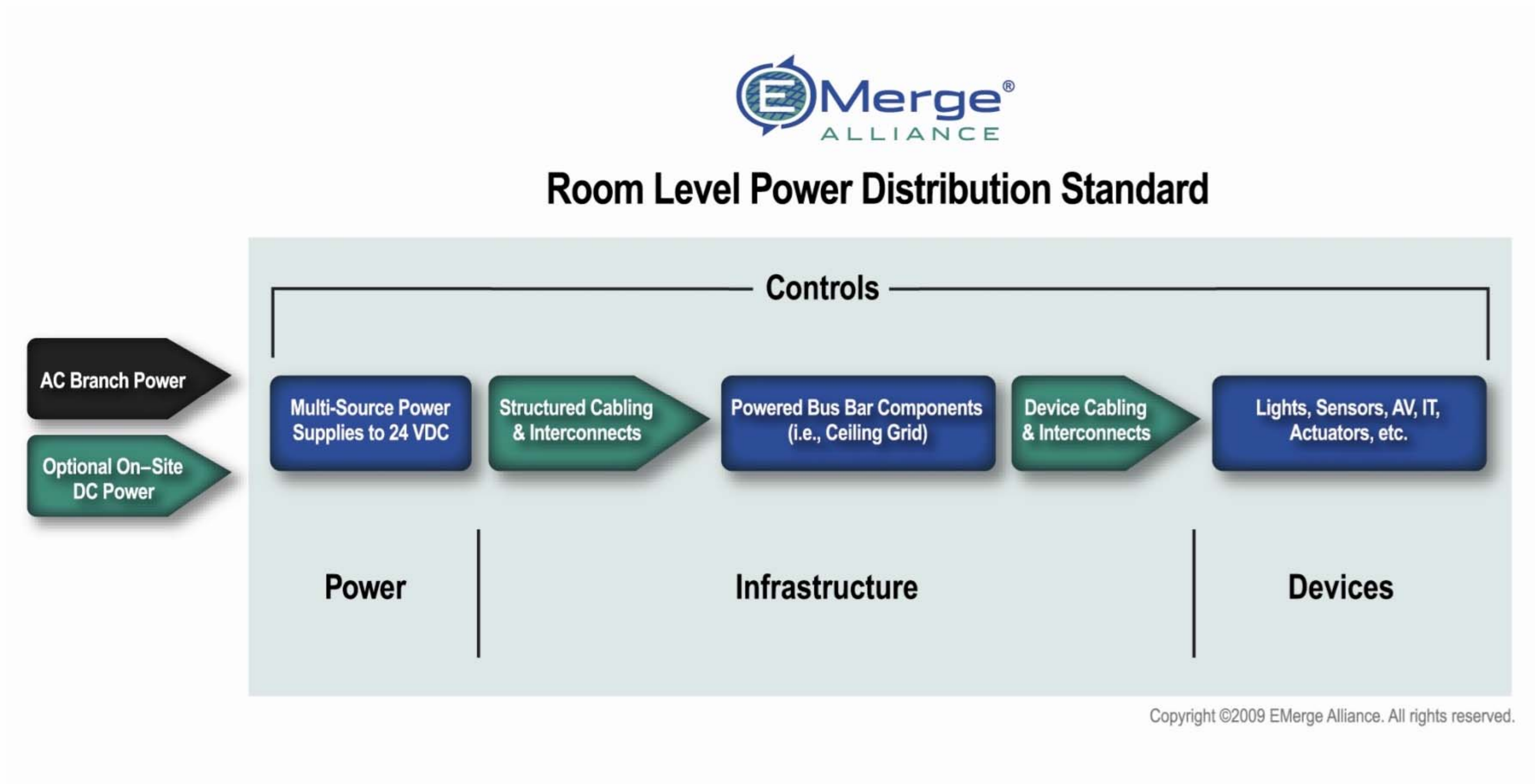
Combining sub-systems for larger overall Building savings

Building Applications *(in priority timing of EMerge Alliance)*	**Ave % of Building Energy Used**	**Potential Energy Savings**	**Keys to Maximizing Efficiency in Going DC**
Interiors (Lighting)*	28%*	Up to 15%	LED, Renewables
Data/Telecom	17%	Up to 30%	Higher voltage conversions, Renewables
Service/Utility (HVAC)	36%	Up to 10%	Renewables
Outdoor	6%	Up to 10%	LED, Renewables
Other (misc equip loads)	13%	Up to 5%	Different voltage conversions

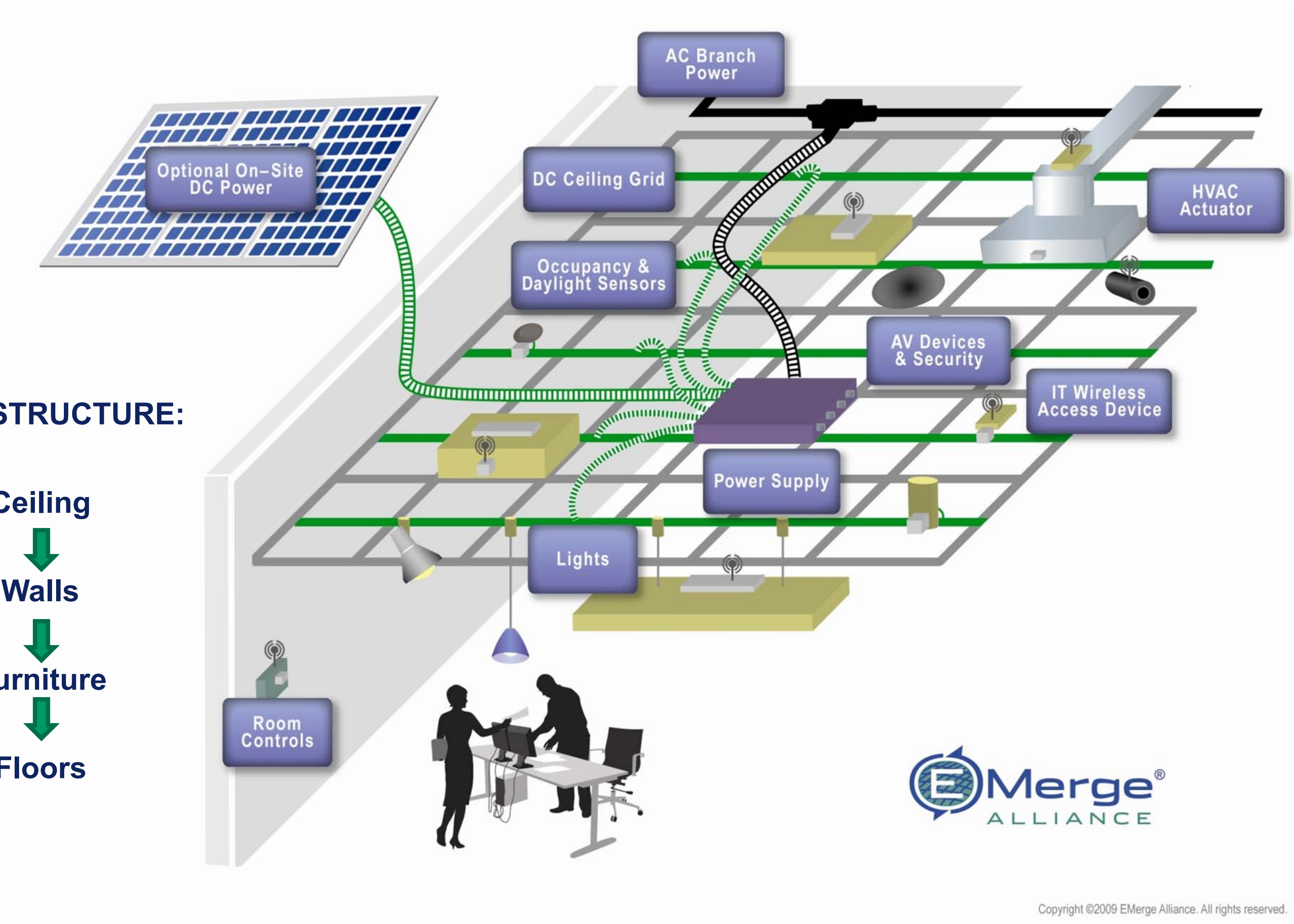
*Higher energy use in office buildings, up to 40%

CommonStandards can impact all areas to improve energy efficiency – LED's & RENEWABLES AS KEY DRIVERS TO MAXIMIZE SAVINGS

1st Standard – For Occupied Interior Spaces



1st Standard – Ceiling View



INFRASTRUCTURE:

Ceiling

Walls

Furniture

Floors

Product Example: Fluorescent DC Ballasts

- Typical 32 W fluorescent lamp operates at 28W on an electronic ballast
- Direct DC input eliminates AC-DC conversion
- Can improve ballast efficiency by 15 or more
- Results in higher lighting system efficacy (light output per watt)
- Can improve ballast reliability significantly by eliminating HV inductors

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Benefits of the DC Grid

Flexibility

- Plug & play use of devices, upgradeable
- Faster, easier, cheaper for moves, adds & changes

Energy Savings

- Less conversions in DC sources & loads
- LED lighting - 10-15% more efficient, driven by DC
- Solar, wind, fuel cells - 5-10% savings if used direct

Sustainability

- Re-use of buildings and equipment
- More efficient use of clean energy & DC devices
- Smarter buildings (device level controls) for Smart Grid efforts

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Installations Around the Country

PNC Financial
Headquarters Office
Pittsburgh, PA

lauckgroup
Architectural Office
Dallas, TX

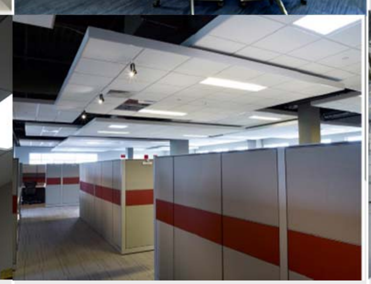
US Green Bldg Council
Conference Rooms
Washington, DC

Nextek Power
NextEnergy Center
Detroit, MI

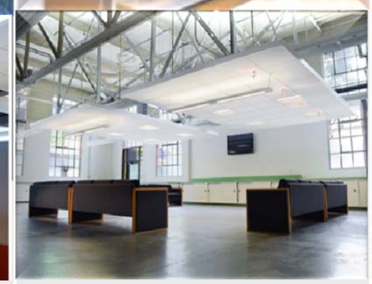
UC San Diego
Sustainability Center
San Diego, CA

Southern Cal Edison
Utility Services Office
Irwindale, CA

Johnson Controls
Headquarters Office
Milwaukee, WI



Optima Engineering
MEP Firm
Charlotte, NC



LA Community College
Trade Tech Campus
Los Angeles, CA

CLTC
UC Davis Campus
Davis, CA

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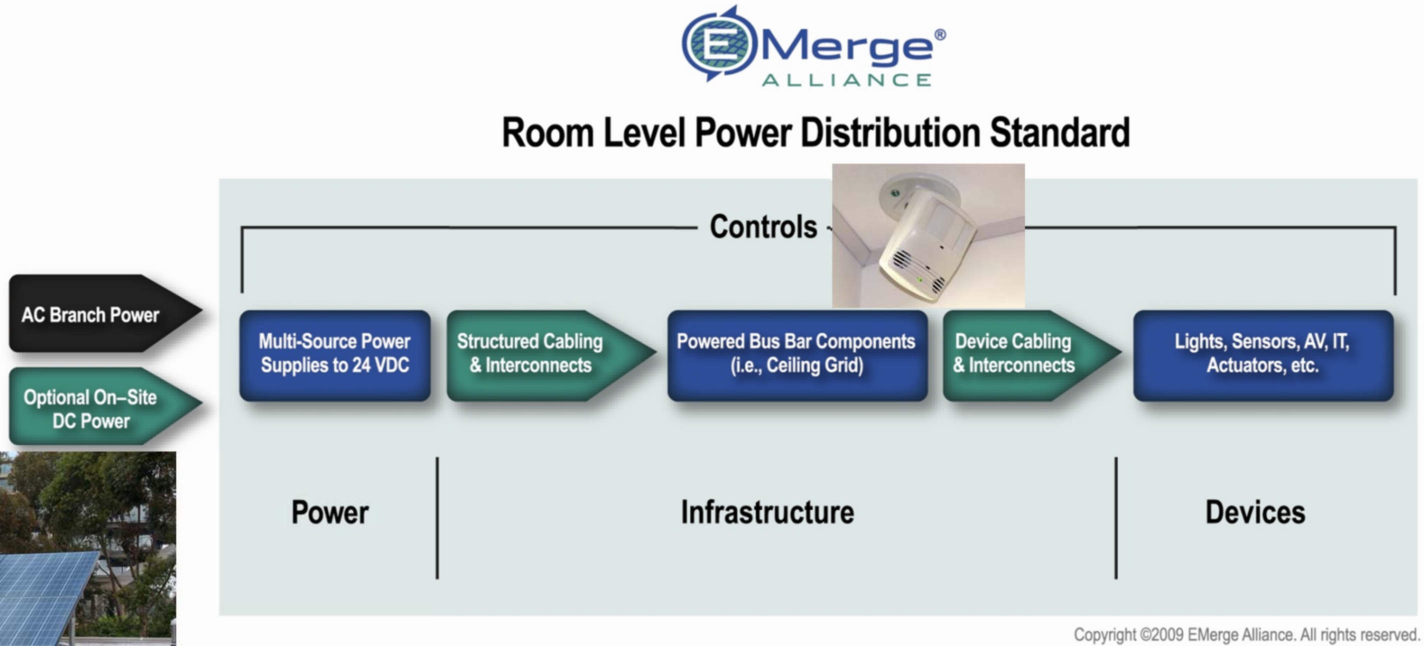
UC San Diego
Auxiliary & Plant Services

EXAMPLE: UCSD Sustainability Resource Center



UC San Diego
Local Impact, National Influence, Global Reach

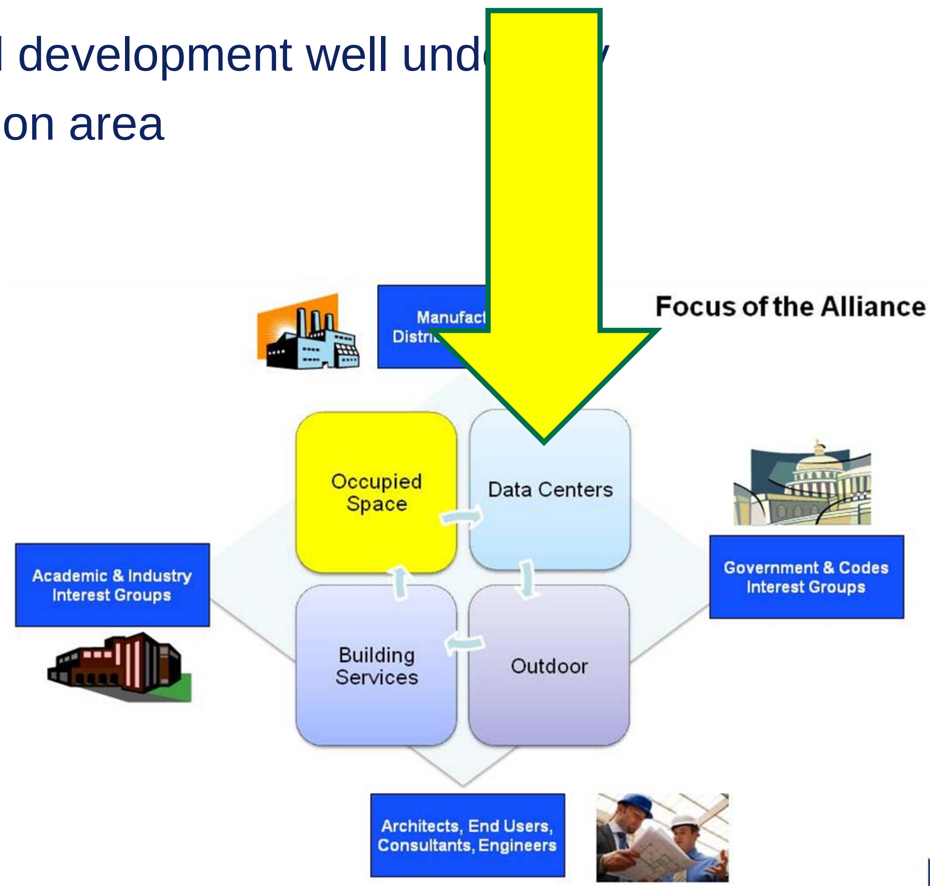
Sustainability Resource Center
Equity-Environment-Economy
UC San Diego
Local Impact, National Influence, Global Reach

EMerge™ ALLIANCE
MEMBER

New Technical Standards

New 380V DC Technical Standard

- EPRI, Intel, Emerson, Delta, Nextek, Lawrence Berkeley Labs… and others
- Committee meetings and standard development well under way
- Data centers/telecom key application area



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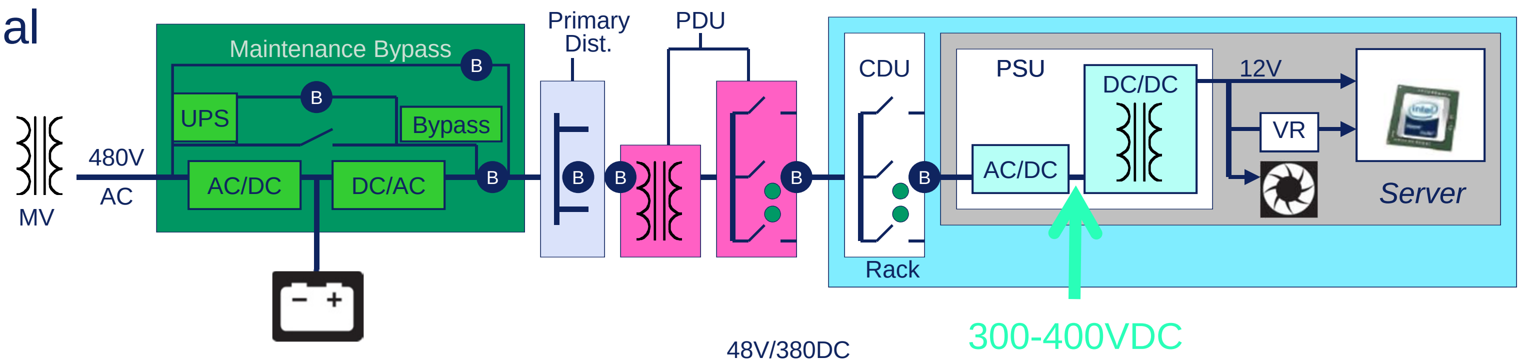
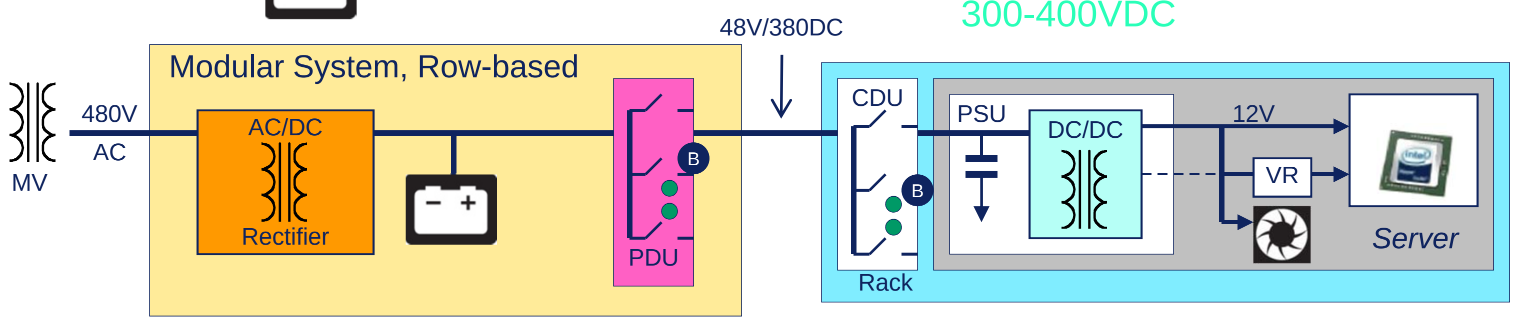
Data Center Power Protection and Distribution Basic Architectures

Traditional AC UPS



DC UPS



Attributes of a DC UPS:

- Simple input and output distribution, easy to parallel ,no load balancing (derating)
- Minimal conversion stages grid to chip – high end-to-end efficiency and reliability
- High power quality - isolated from mains, no harmonics
- Safe voltages at point of use (48VDC systems)

Advantages of integrated, modular UPS systems:

- High power density in a compact footprint
- Reduced field wiring and copper content
- Targeted for row-based deployments; no need for dedicated power room

System optimization challenge – best overall system topology for a specific application , not necessarily optimization of individual existing components.

Source: Intel

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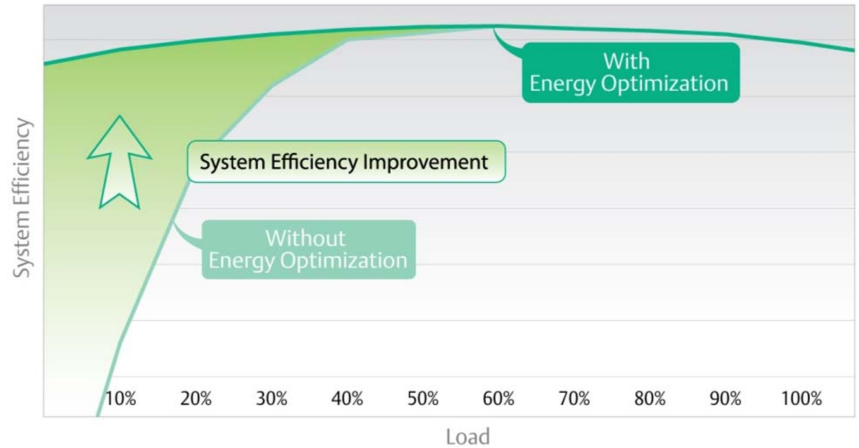
Advantage of High Modularity -Improved Efficiency with Energy Optimization Mode

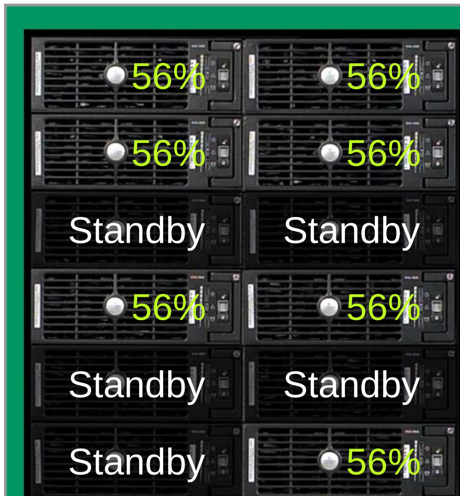
Active power management increases overall system efficiency

- Unneeded power conversion units (PCU's) set to standby in low-load conditions
- Optimizes individual PCU load for greater system efficiency
- Useful for sites with variances in load
- Periodically cycles energized PCU's for even run time



Without Energy Optimization

N+1 redundancy maintained



With Energy Optimization

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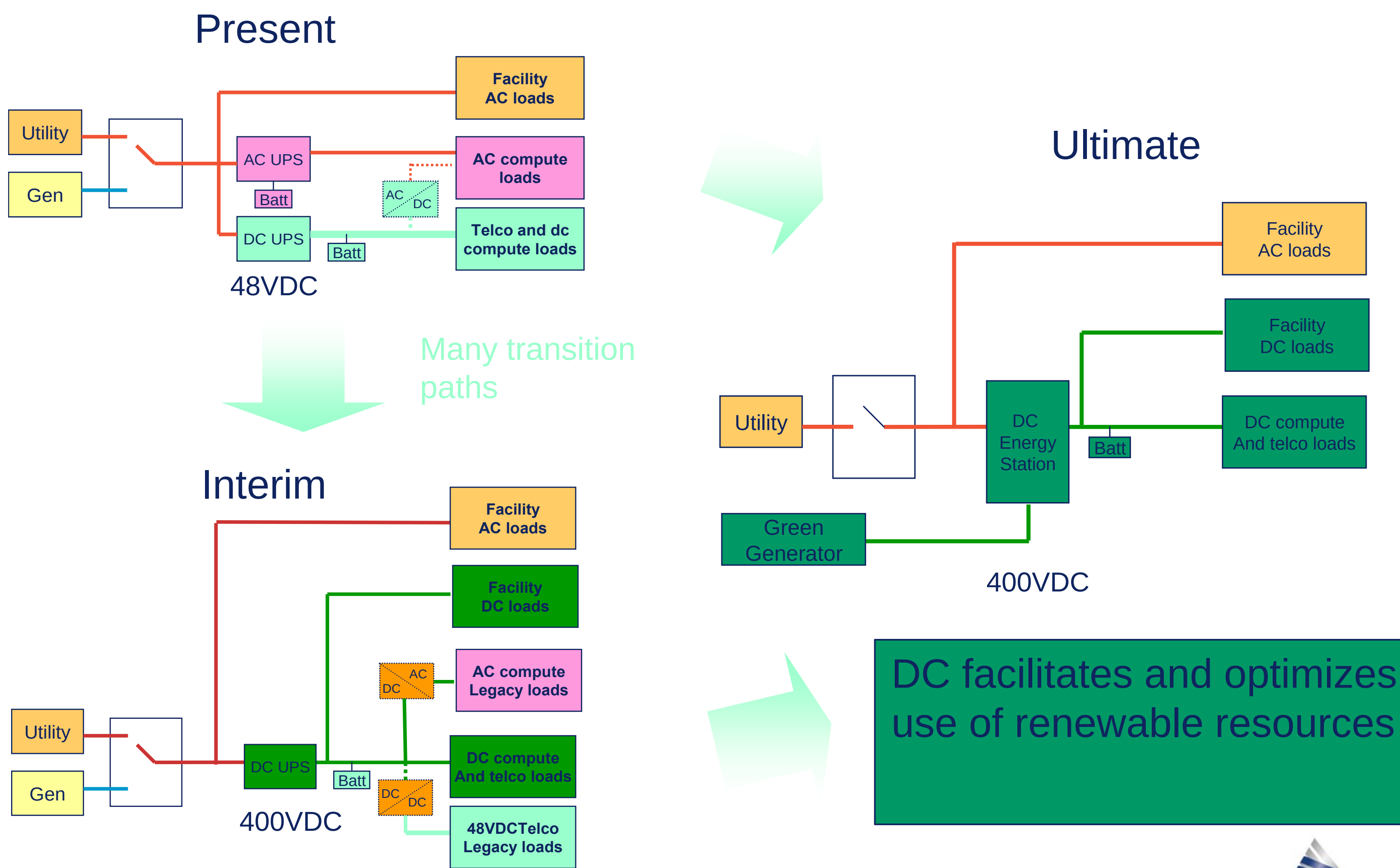
Impact of Renewable Energy Sources - Example of Telecom Facility Transformation Vision



DC facilitates and optimizes use of renewable resources

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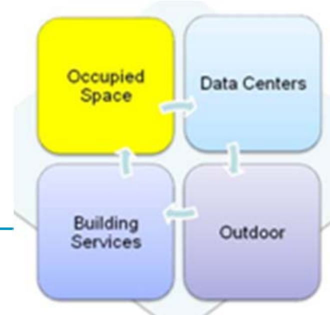
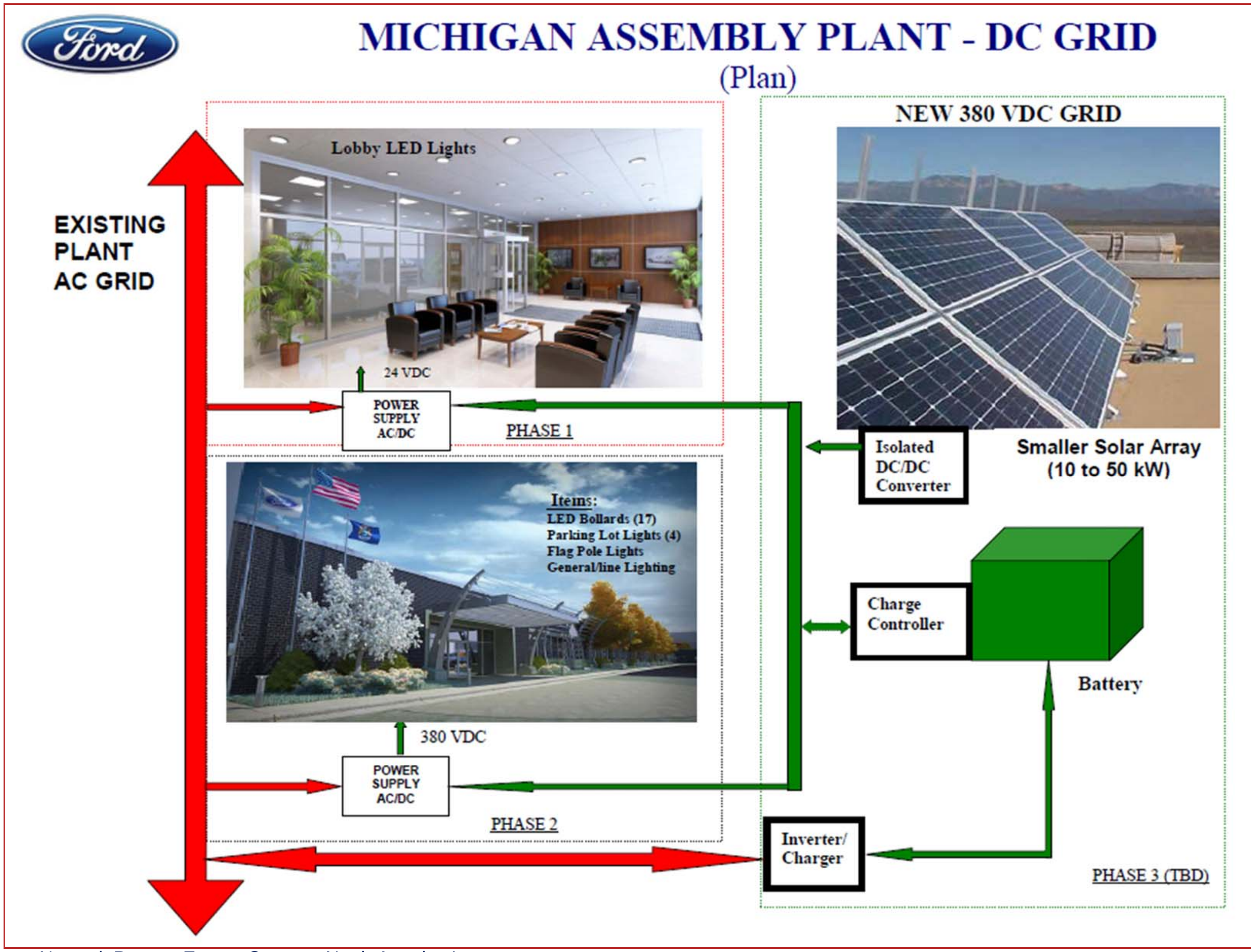
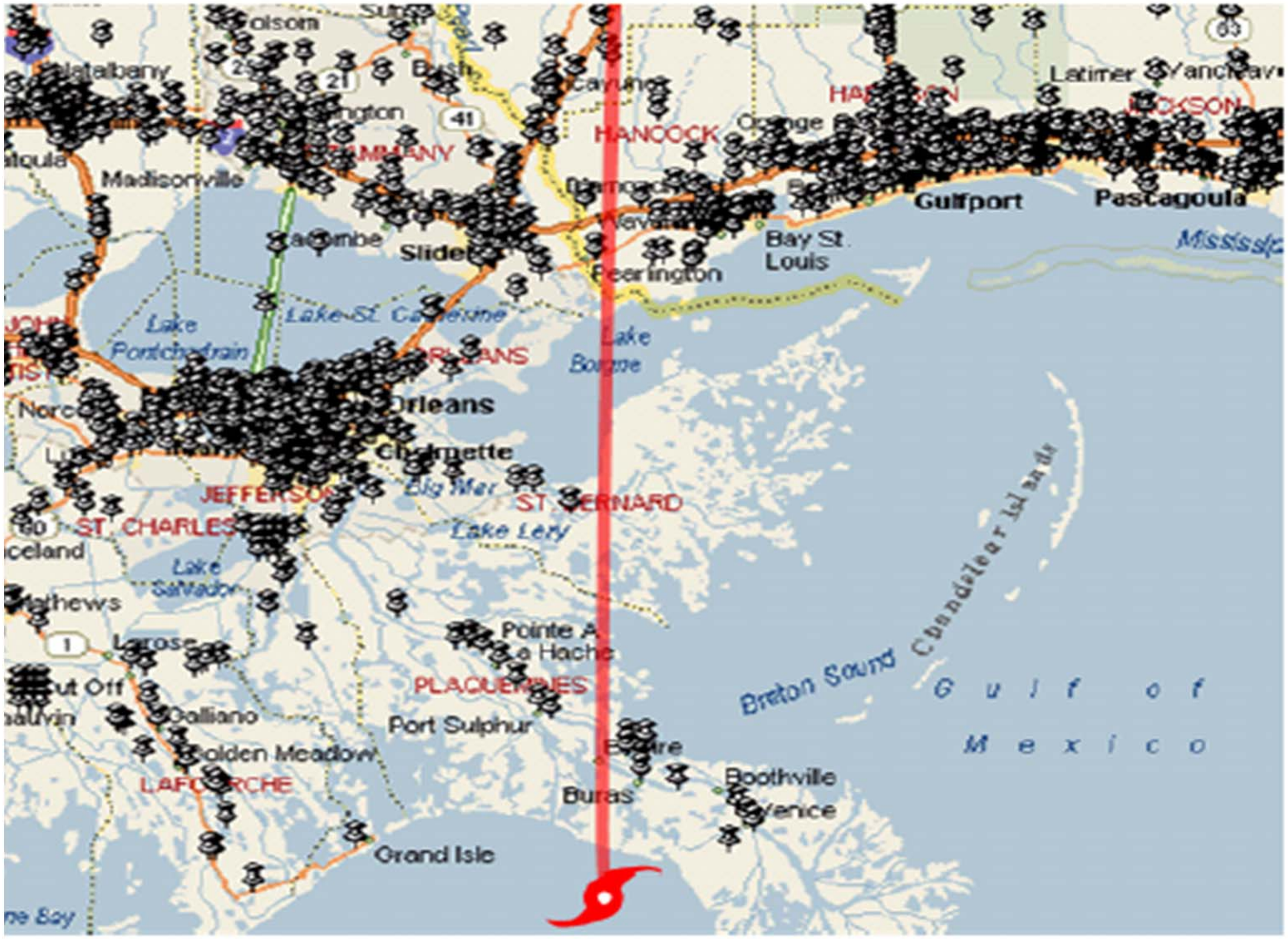
Full Building on DC Microgrid

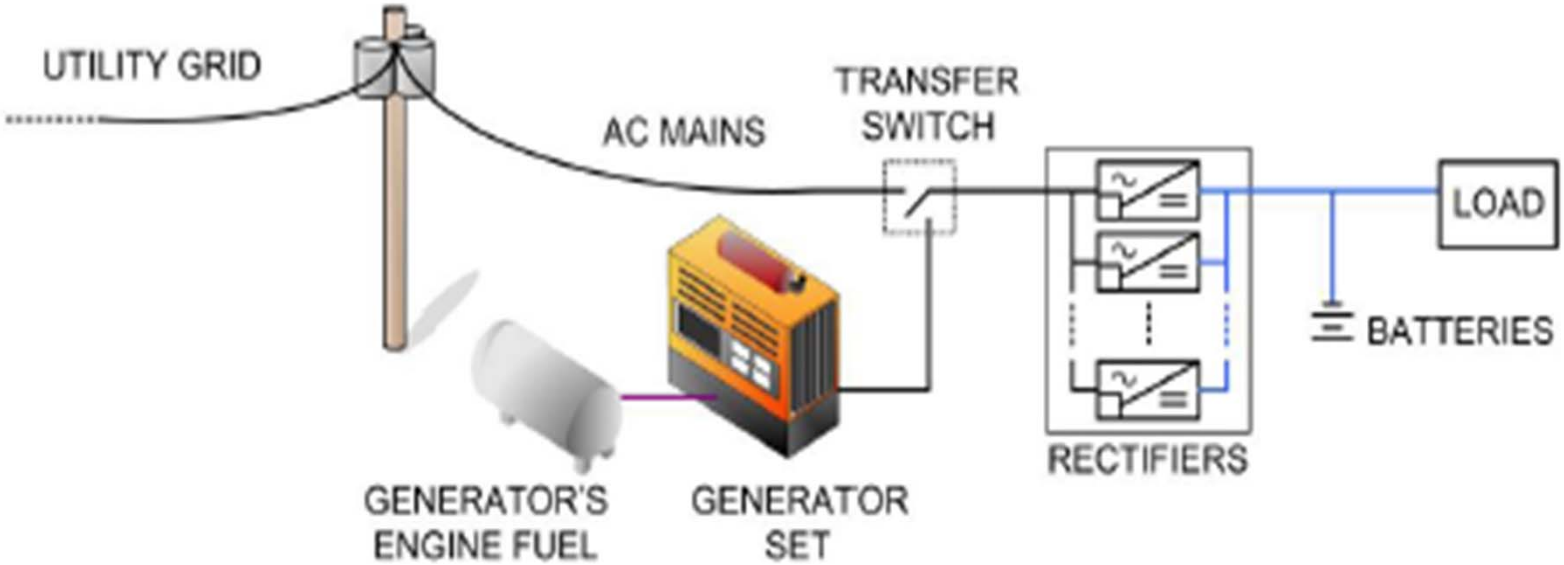




What Katrina Did



“Standard” Cell site configuration



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Value of stored energy at telecom sites

- Smart grid development creates a impact power supply in two ways: from the grid side and from the load side. Smart grid benefits for the load have already been mentioned.

- The smart grid can utilize telecom sites stored energy to improve performance, particularly to deal with semi-dispatchable renewable sources.

- There are at least about 57,200 MWh of stored energy in batteries in the US telecom sites and data centers. But, this energy is unevenly geographically distributed and using this energy will reduce telecom sites availability.

- One option is to reduce battery backup time by increasing diesel energy storage. Then

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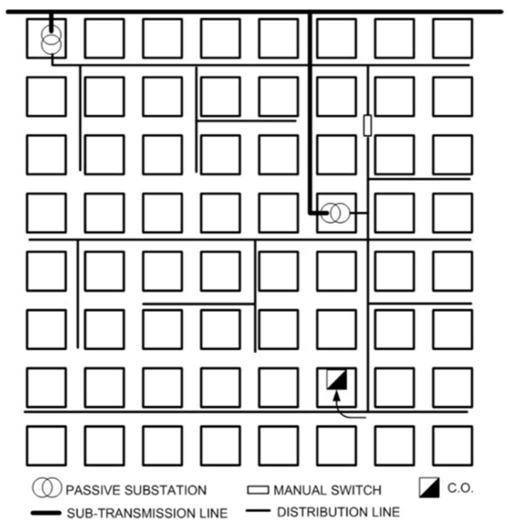
Additional smart grid effects on telecom power

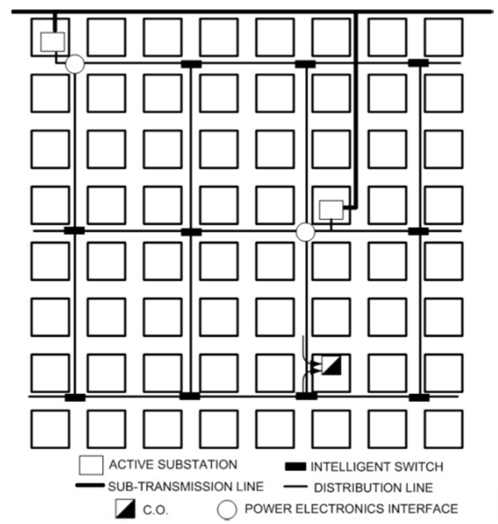
• Grid availability improvement may address power supply limitations in outside plant sites and wireless base stations. These sites are usually the weakest in terms of power supply during disasters.

• Smart grid enables new services that allow electric utilities to transition from energy sellers to service sellers (e.g. NTT-Facilities Sendai trial).

• One particular interesting service is the possibility of providing circuits with different power quality levels in hybrid ac/dc systems.

• Smart grids allow for new self-healing distribution architectures for high availability.





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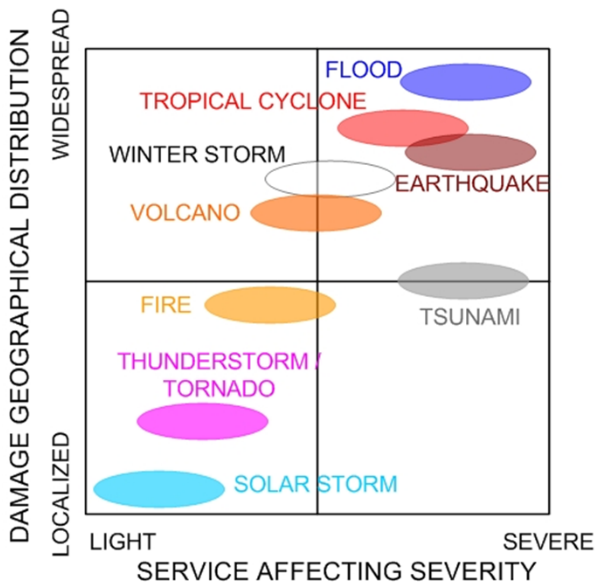
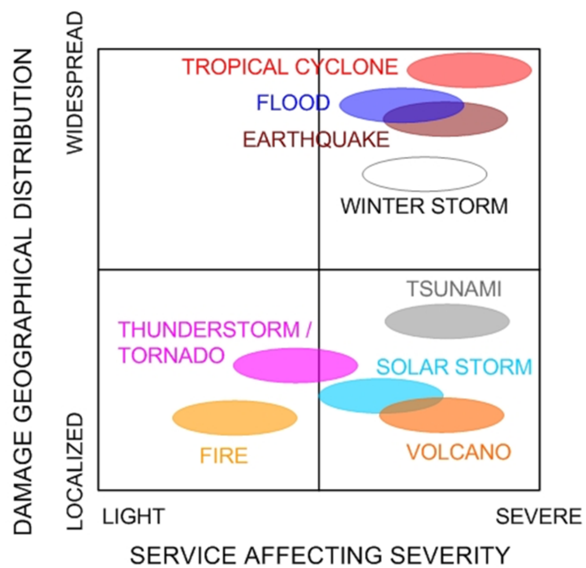
Planning for enhanced resiliency

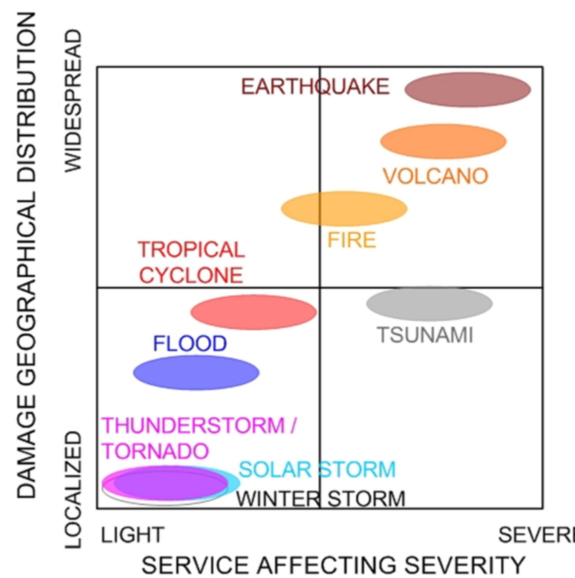
- When planning for diverse power input, it needs to be considered that hurricanes affect infrastructure differently.



Transportation and fuel delivery



Electric grid



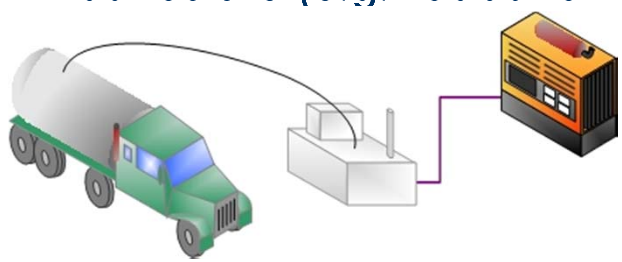
Natural gas

- Renewable sources (inherently dc) are less affected by most disasters than other infrastructures.

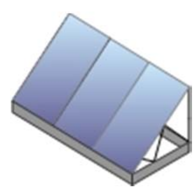
Technologies for improved power resiliency

- Local Energy Storage (batteries)
  - Suitable for a few hours of backup power
  - Long backup times expensive and impractical

- Back-up power sources (gensets, fuel cells,….)
  - Not suitable for several days of continuous operation
  - Rely on another infrastructure (e.g. roads for diesel)



- Distributed generation (PV modules, wind generators, microturbines, fuel cells,…)
  - Intended for continuous operation
  - May or may not rely on another infrastructure



Planning for enhanced resiliency

- Sustainable systems, in the sense that they endure, are resilient systems.
- Higher efficiency, and less volume and area also supports resiliency.
- Distributed generation leads to a de-centralized control architecture.
- Distributed generation adds active elements which support independent control strategies.
- Micro-grids require diverse power inputs because each distributed generation techno-logy has worst availability than the grid.

Power supply units	Fuel / source of energy	Availability *a*
Genset (operation time< 2 hours) Fail to start probability: 0.0241	Diesel / Natural gas	0.9939
Genset (operation time > 24 hours) Fail to start probability: 0.0241	Diesel / Natural gas	0.85
PV generation system*	Solar energy	0.996
PEM Fuel Cell	Hydrogen / Natural Gas	0.967742
Microturbine	Natural Gas / Propane / liquid fuels	0.993789
Wind turbine*	Wind	0.9595

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THANK YOU VERY MUCH

QUESTIONS?