Aalto University
School of Engineering

Distributed Generation Technologies

ELEC-E8424 - 5 ECTS

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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).

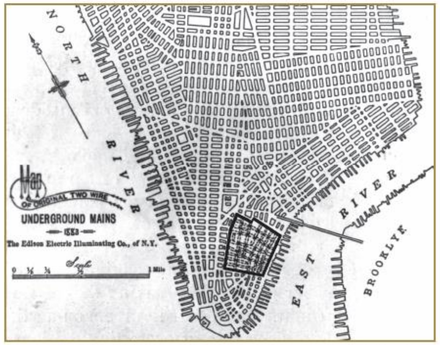


figure 1. Map of lower Manhattan showing the original area served by the Pearl Street station and its distribution system (courtesy of the Consolidated Edison Company of New York).

Pearl Street Station:
"Jumbo" 100 kW, 110 V
generators

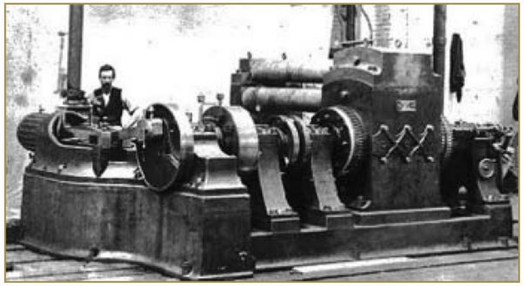
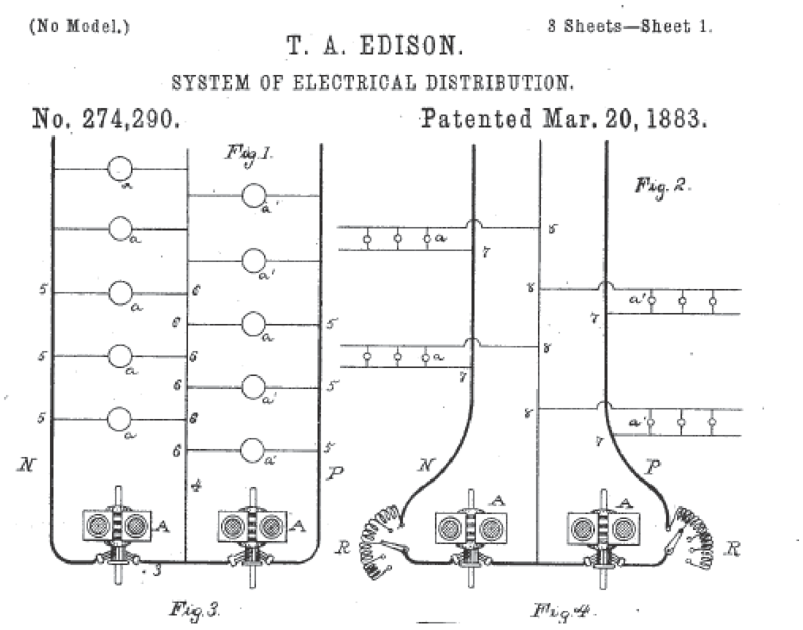


figure 3. Edison's 100-kW engine-driven "Jumbo" dynamo of the type installed at the Pearl Street station (photo courtesy of the Edison National Historical Site, U.S. Department of the Interior, National Park Service).



(No Model.) 3 Sheets—Sheet 1.

T. A. EDISON.

SYSTEM OF ELECTRICAL DISTRIBUTION.

No. 274,290. Patented Mar. 20, 1883.

"Eyewitness to dc history" Lobenstein, R.W. Sulzberger, C.

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.

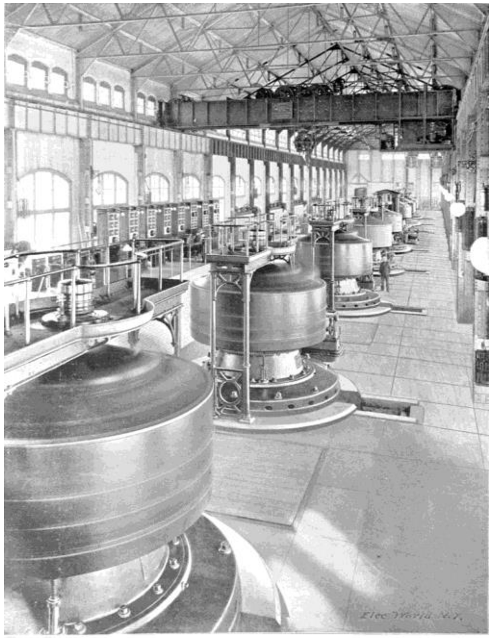
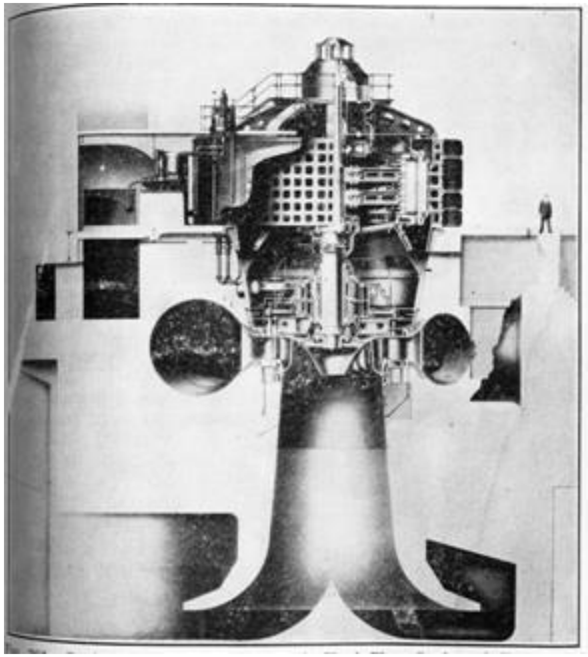


Fig. 11.—A View of the Dynamo Room, Looking South from the Visitors' Gallery.



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

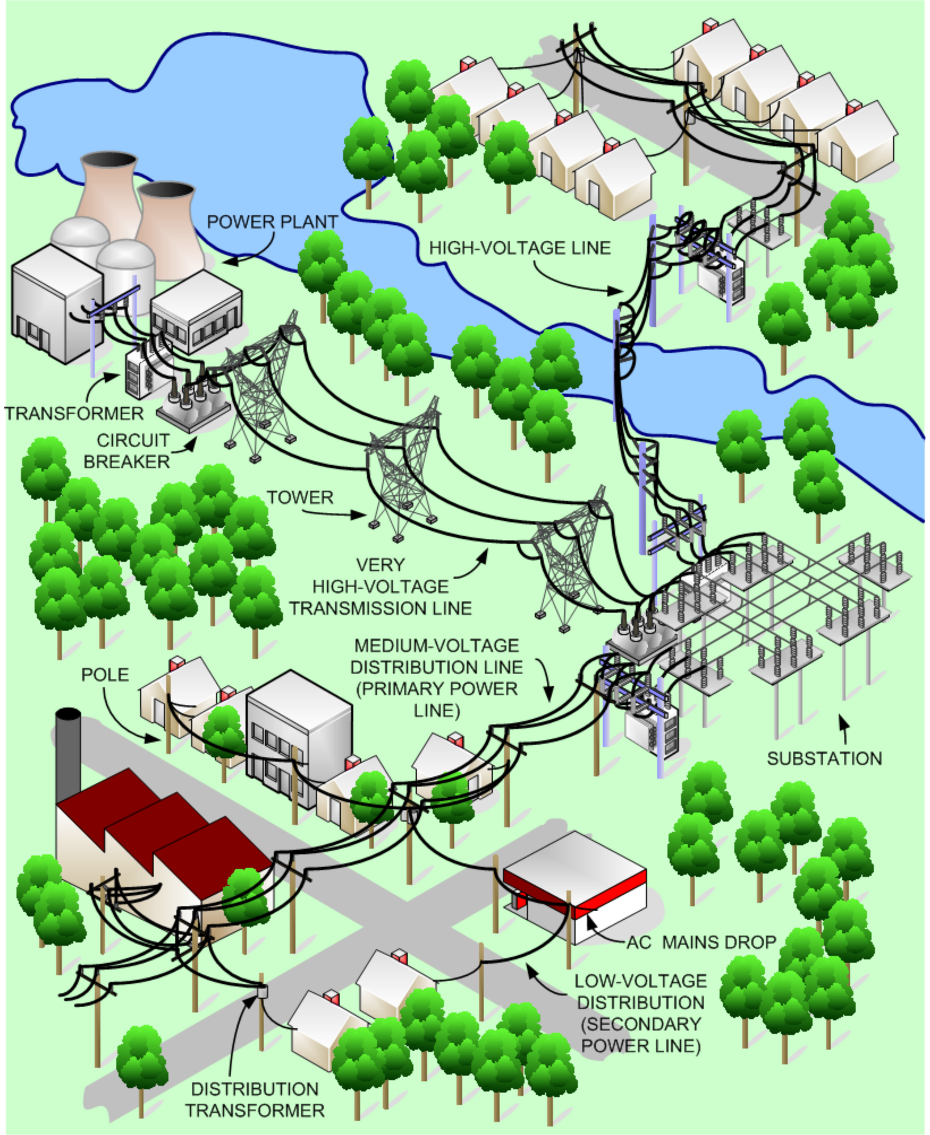
http://spiff.rit.edu/classes/phys213/lectures/niagara/niagara.html

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 dc motors.
- 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 motor.

History



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.
- Unsecure.
- Need to balance generation and demand.
- Lack of flexibility.

History

Conventional grids operation:

- In order to keep frequency within a tight stable operating range, generated power needs to be balanced at all time with consumed power.

- A century working around adding electric energy storage by making the grid stiff by:
  - Interconnecting many large power generation units (high inertia = mechanical energy storage).
  - Individual loads power ratings are much smaller than system's capacity.

- Conventional grid "stiffness" make them lack flexibility.

- Lack of flexibility is observed by difficulties in dealing with high penetration of renewable energy sources (with a variable power output).

- Electric energy storage can be added to conventional grids but in order to make their effect noticeable at a system level, the necessary energy storage level needs to be too high to make it economically feasible.

History

Edison’s distribution system characteristics: 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 presents issues with 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.

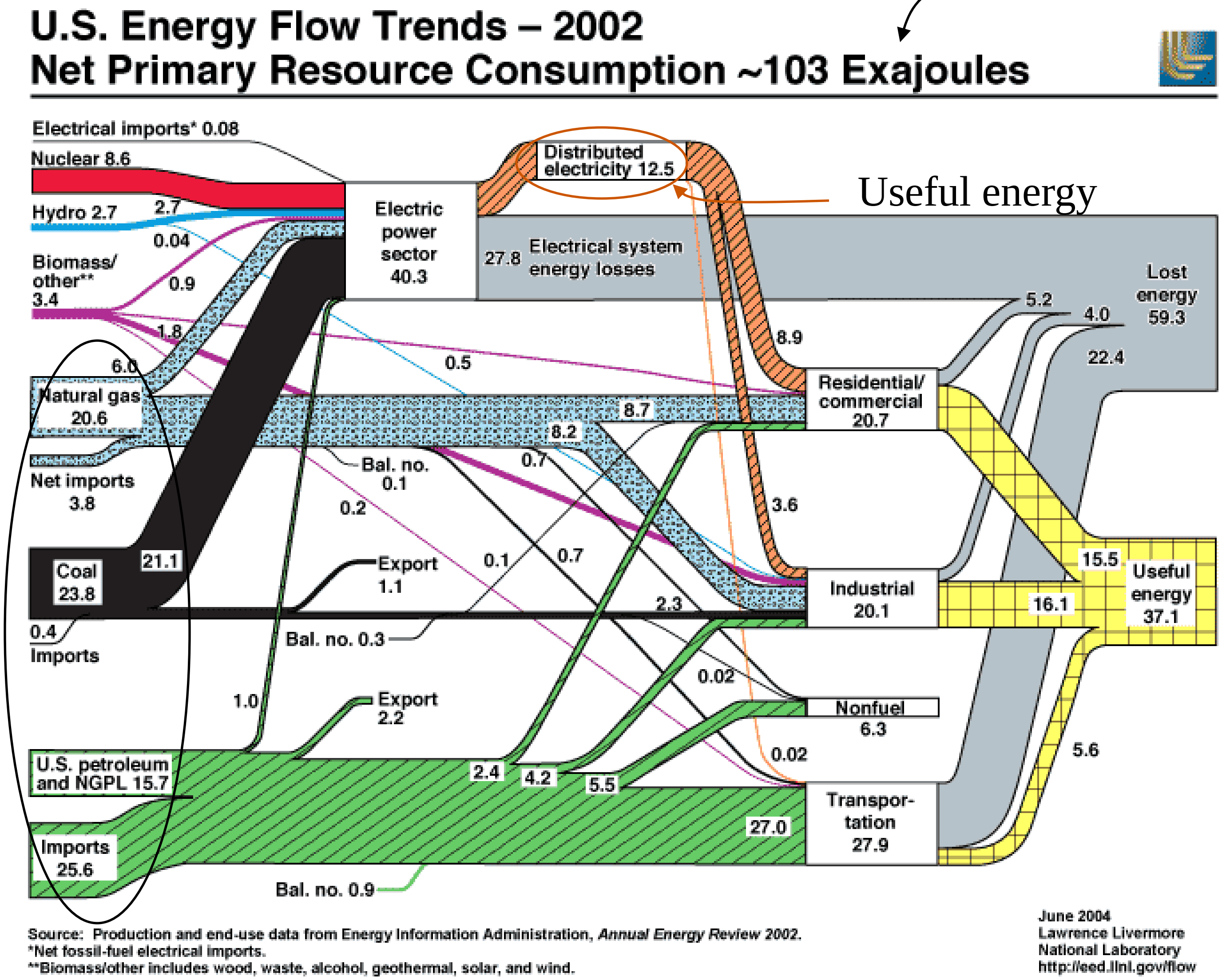
- Can use renewable and alternative power sources.

- Can integrate energy storage.

- Can combine heat and power generation.

Sustainability

$103 \ 10^{18}$ Joules



U.S. Energy Flow Trends – 2002
Net Primary Resource Consumption ~103 Exajoules

Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2002*.
*Net fossil-fuel electrical imports.
**Biomass/other includes wood, waste, alcohol, geothermal, solar, and wind.

June 2004
Lawrence Livermore
National Laboratory
http://eed.llnl.gov/flow

Useful energy

High
polluting
emissions

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

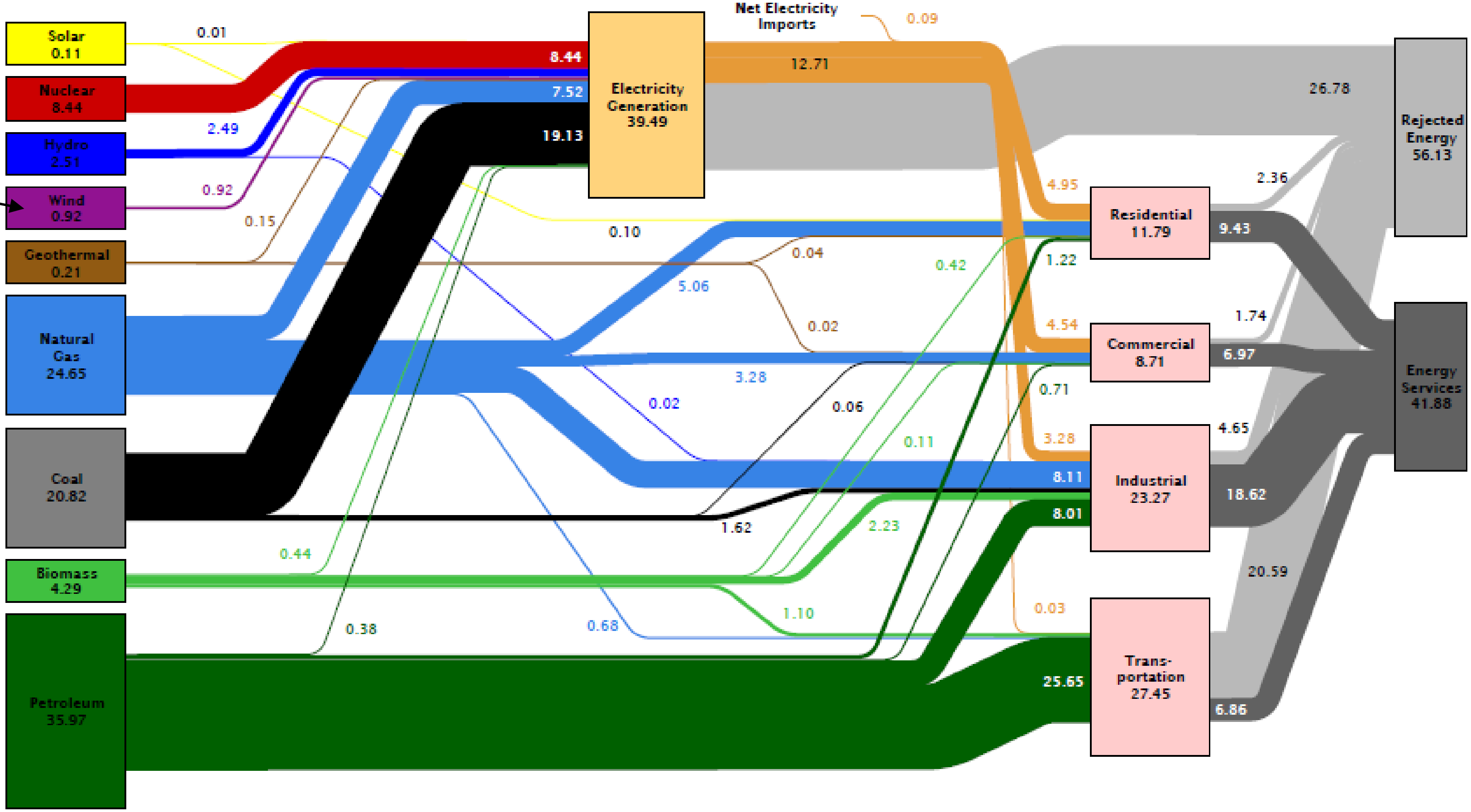
Sustainability

103.4 Exajoules

Estimated U.S. Energy Use in 2010: ~98.0 Quads

Lawrence Livermore National Laboratory

“New” renewable sources



Source: LLNL 2011. Data is based on DOE/EIA-0384(2010), October 2011. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports flows for hydro, wind, solar and geothermal in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." (see EIA report for explanation of change to geothermal in 2010). The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 80% for the residential, commercial and industrial sectors, and as 25% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

https://flowcharts.llnl.gov/

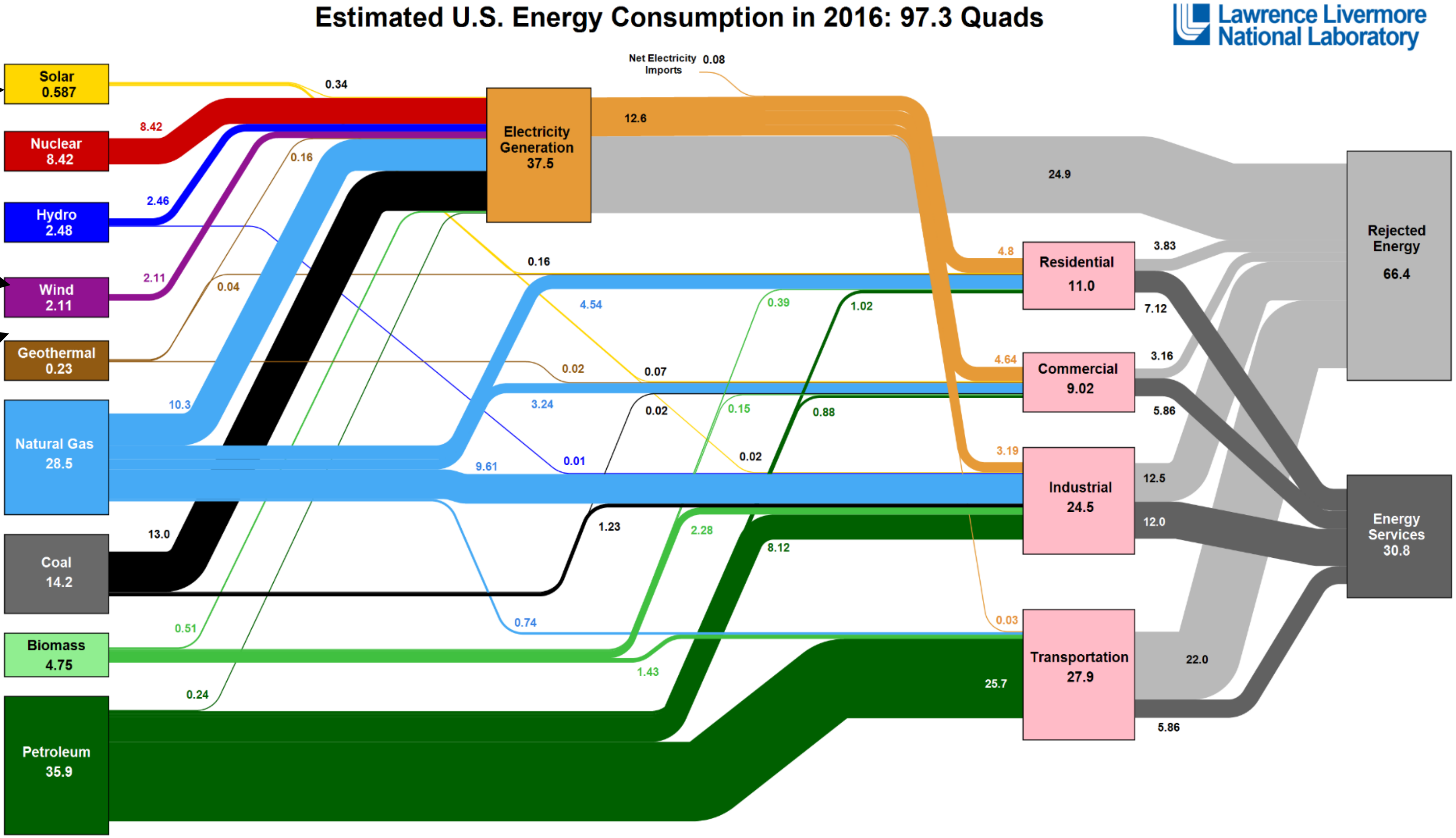
Sustainability

"Americans used less energy in 2016"
"Americans used more clean energy in 2016"

102.65 Exajoules

“New” renewable sources

Estimated U.S. Energy Consumption in 2016: 97.3 Quads



Source: LLNL March, 2017. Data is based on DOE/EIA MER (2016). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes made in mid-2016 to the Energy Information Administration's analysis methodology and reporting. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector, and 49% for the industrial sector which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

https://flowcharts.llnl.gov/

Sustainability

- **Issues with integration of “new” renewable sources into large conventional power grids**

- Variable output (part stochastic) may lead to potential stability and power quality issues.

- No (or very little) “inertia”.

- **Other issues with renewable sources in general (inc. hydroelectric plants)**

- Not usually sufficiently available near load centers (so cost evaluation need to add construction of transmission lines).

- Ecological issues:
  1. Land Use
  2. Wildlife and Habitat
  3. Public Health and Community
  4. Water Use
  5. Life-Cycle Global Warming Emissions

Availability/Resilience

- Resiliency:

  "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 analogy between the concept of resiliency and that of availability.

- Although reliability tends to be the best known term for indicating how much time a system is working well, the term "availability" its more technically correct and fits better for assessing power systems performance both in normal conditions and during extreme events.

Availability/Resilience

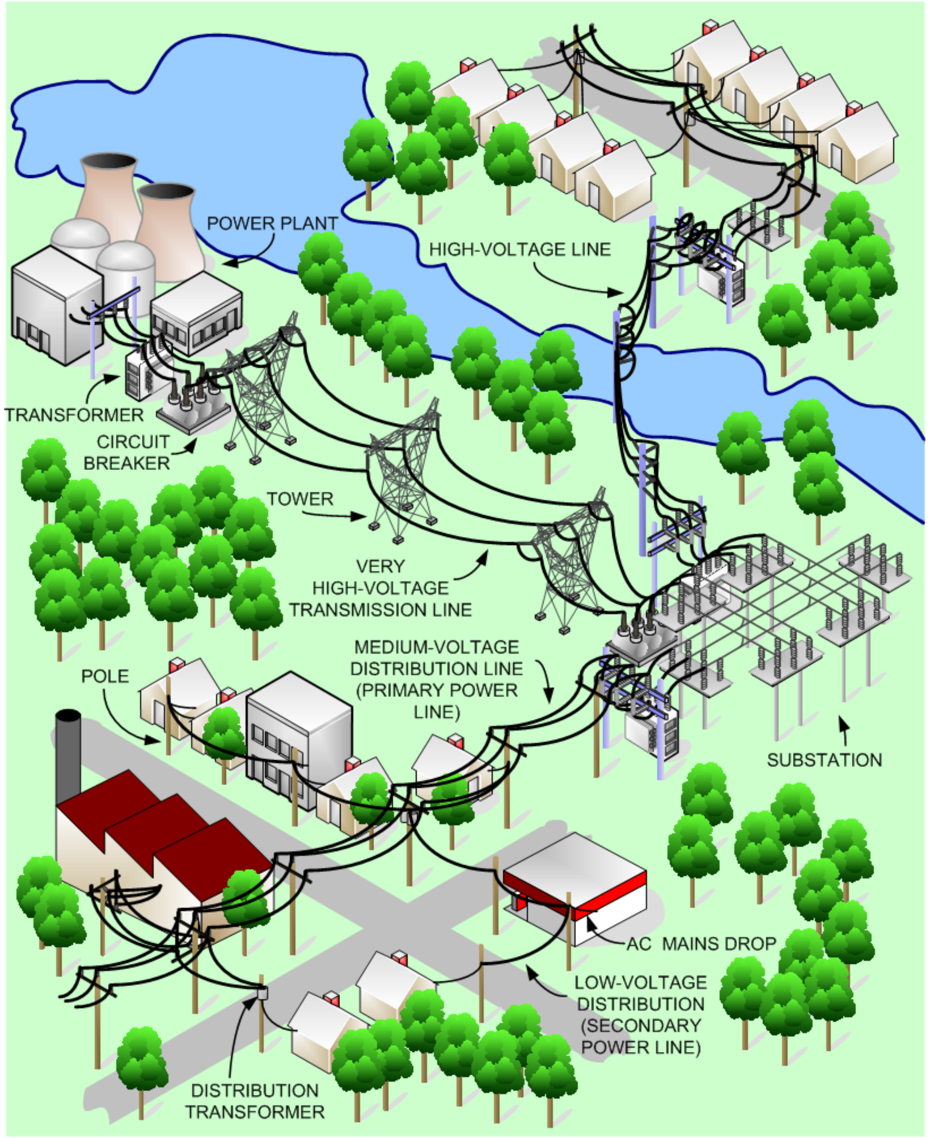
- Availability calculation:

$$A = \frac{MUT}{MTBF} = \frac{MUT}{MUT + MDT} = \frac{\mu}{\mu + \lambda}$$

MTBF: Mean time between failures

- The expected time a system is working meeting its operational goals is the “mean up time” (MUT). It equals the inverse of the failure rate λ. It is mostly related with hardware issues.
- The expected “off-line time” can also be called “mean down time” (MDT). It equals the inverse of the repair rate μ. It is influenced by human processes and aspects, such as logistical management, as well as hardware-related issues.
- Unavailability (*U*) equals *1-A*
- Through the failure rate, availability is a system-based concept that expands the concept of reliability.

Availability/Resilience

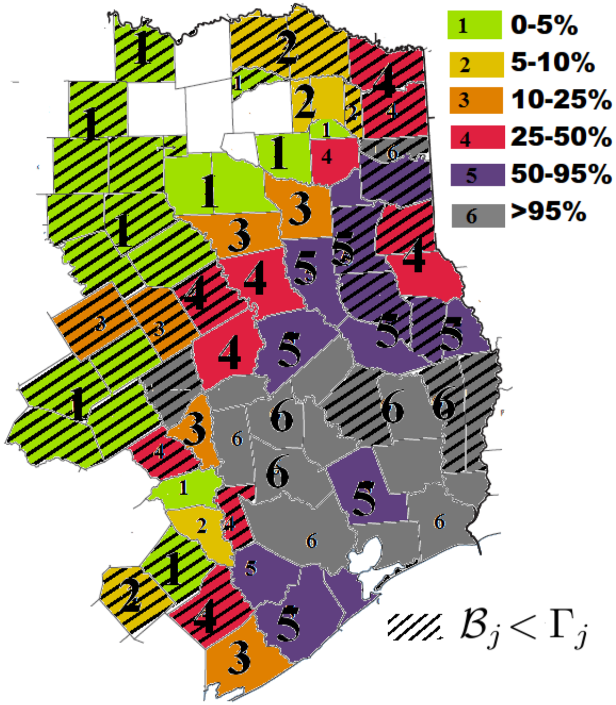


Conventional U.S. grid availability in normal conditions:
Approximately 99.9 %

Availability required in critical applications:
Approximately 99.999%

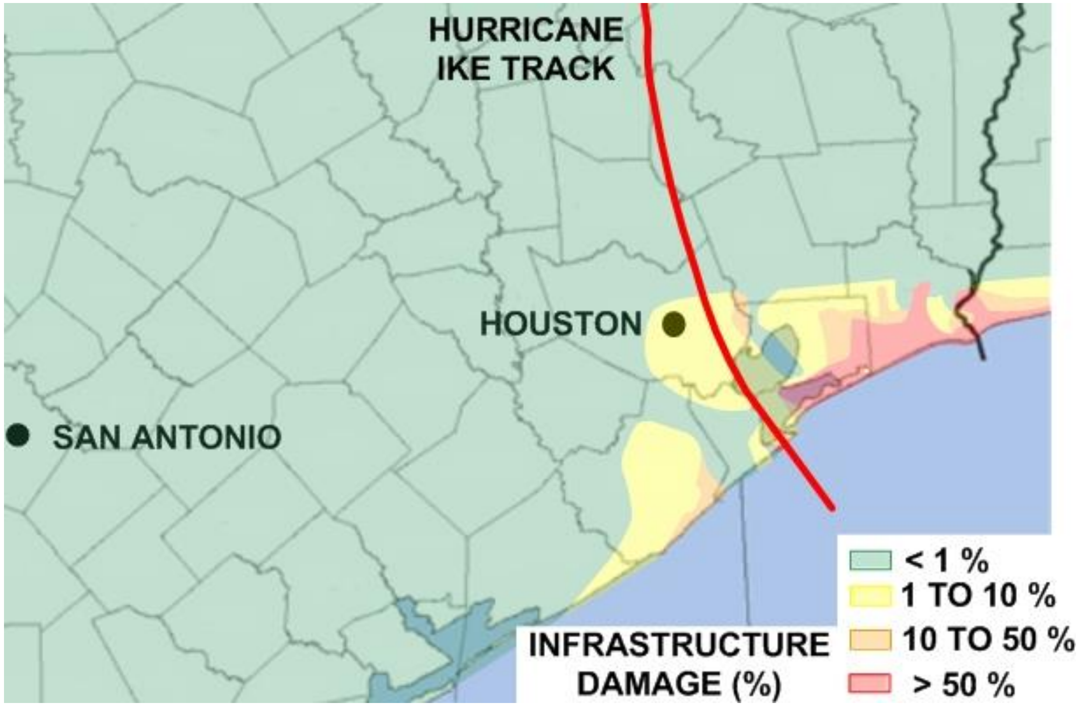
Availability/Resilience

- 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.



Maximum power outage incidence ($O\%_{max}$) after Ike

$$O\%_{max} = 100\frac{\#\ of\ outages\ (O)}{\#\ of\ custormers\ (B)}$$



Percentage of power grid damage after Ike

- Information obtained from field damage assessments

Availability/Resilience

- **Other weaknesses of power grids observed during natural disasters**

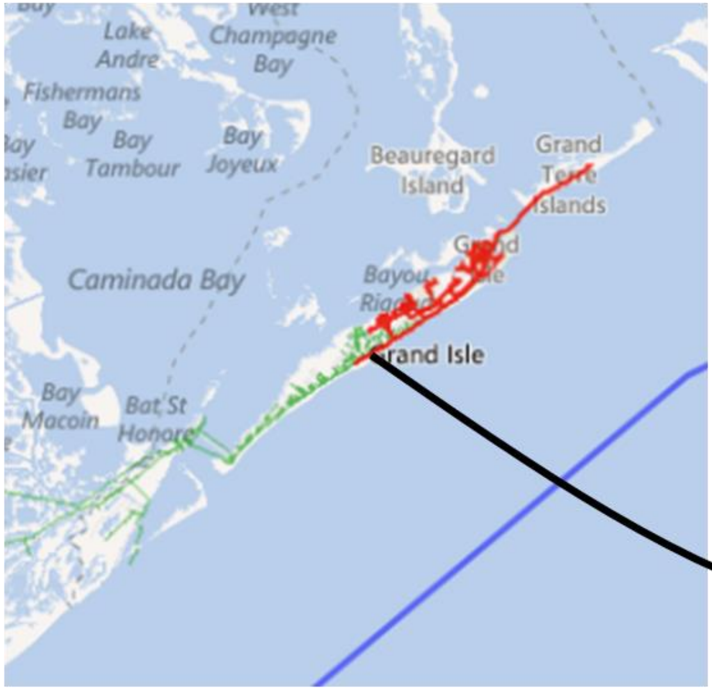
- Very extensive network (long paths and many components).
- Typically, sub-transmission and distribution portions of the grid lack redundancy. As a result, long restoration times usually originate at the distribution level of power grids.
- Need for continuous balance of generation and demand.
- Difficulties in integrating meaningful levels of electric energy storage.
- Aging infrastructure.
- Aging workforce (people is an essential part of infrastructure systems).

Availability/Resilience

○ Example of lack of redundancy at sub-transmission/distribution

- 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

Availability/Resilience

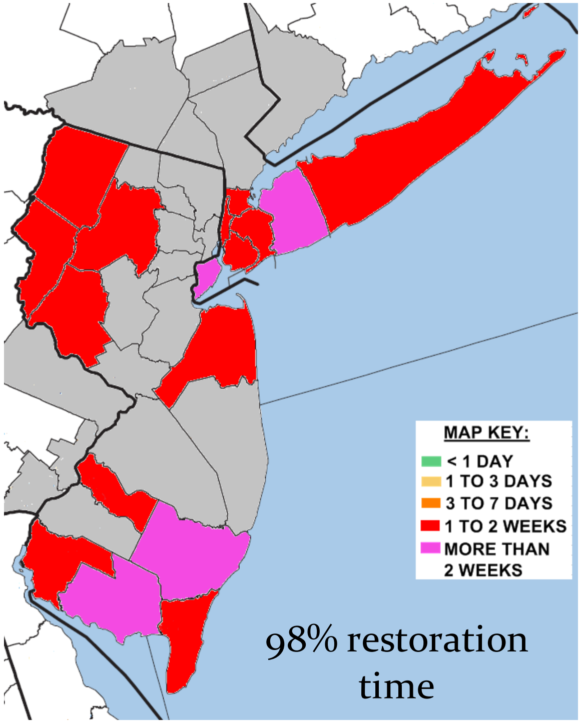
○ Power grids performance during natural disasters

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

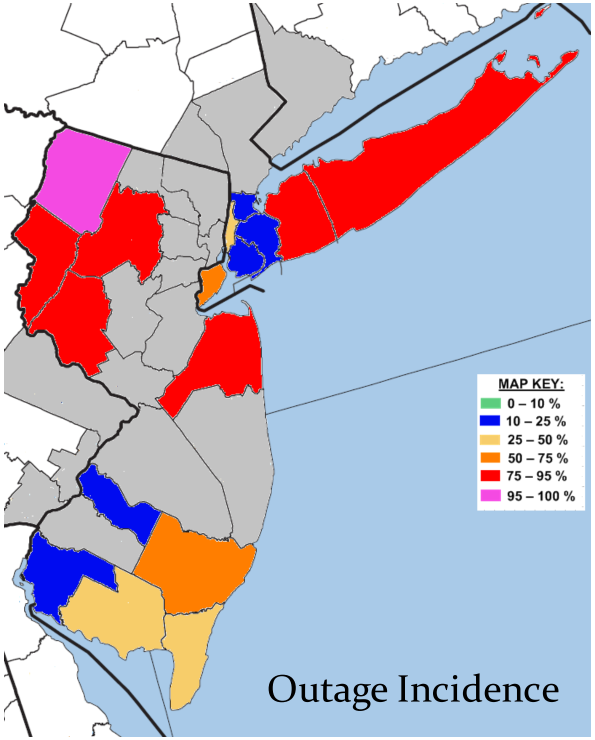
Availability/Resilience

○ Power grids performance during natural disasters

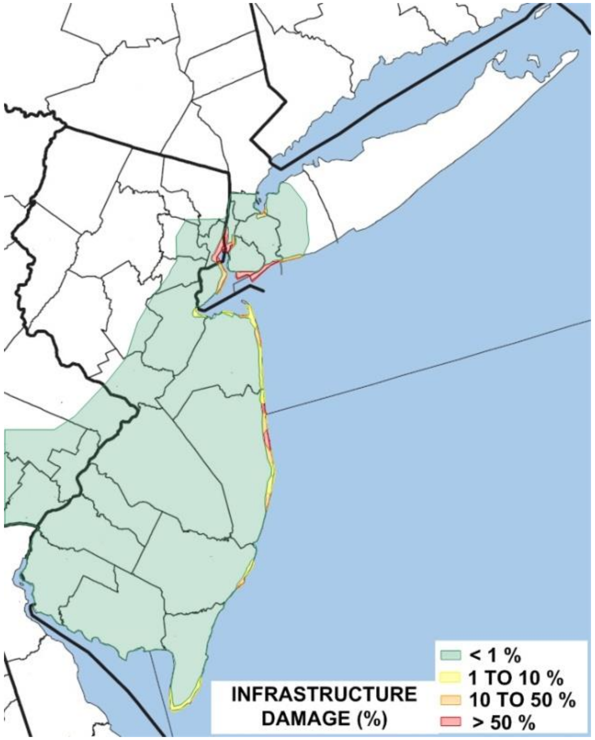
- Case study: Superstorm Sandy.
- Relatively little damage to the power grid but outages were severe.
- Longer restoration times than usual observed in areas with underground power facilities.



98% restoration time



Outage Incidence



Availability/Resilience

- **Power grids performance during natural disasters**

- Case study: Super-storm Sandy.
- Often, damage to power grids is less severe than for residences.
- Storm surge damaged some substations in coastal areas.

Security

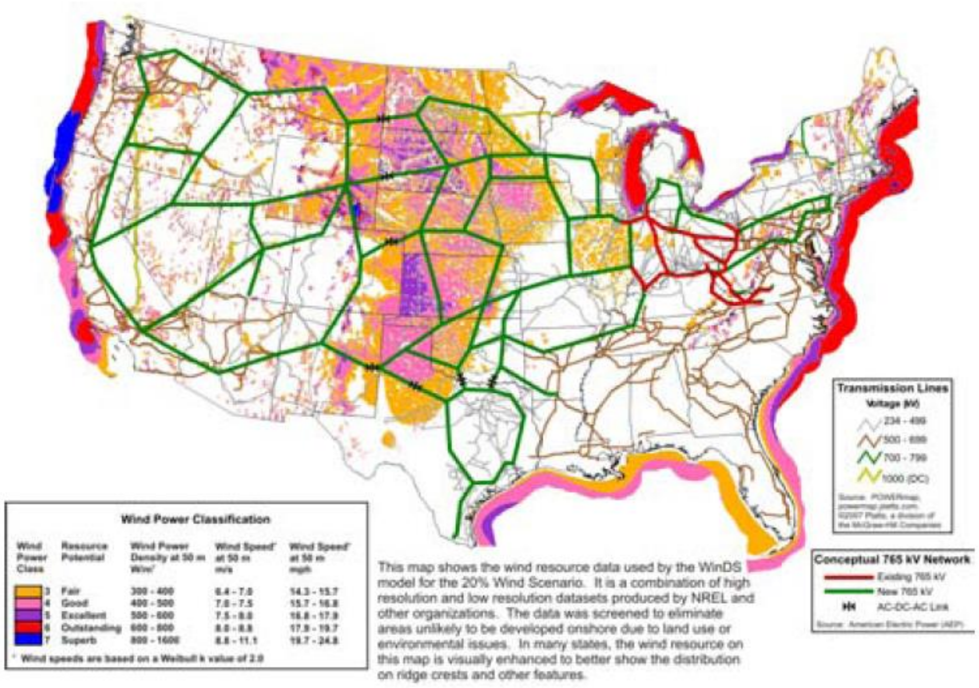
- Increased reliance on communications and cybernetics make power grids more vulnerable to external attacks.
- Long transmission lines are extremely easy targets for external attacks.


© Adam Gerrard / newsteam

Cost

- Traditional natural gas and 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)



Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed* at 50 m m/s	Wind Speed* at 50 m mph
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

* Wind speeds are based on a Weibull k value of 2.0

This map shows the wind resource data used by the WinDS model for the 20% Wind Scenario. It is a combination of high resolution and low resolution datasets produced by NREL and other organizations. The data was screened to eliminate areas unlikely to be developed onshore due to land use or environmental issues. In many states, the wind resource on this map is visually enhanced to better show the distribution on ridge crests and other features.

http://www.nrel.gov/wind/systemsintegration/images/home_usmap.jpg

Other issues in conventional grids

- 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 (e.g. users cannot set their own local power quality objectives)…. Electrification benefits are shared by all but effects or problems are felt by all.
- The grid is old: it has the same 1880s structure. Power plants average age is > 30 years.
- All these issues are added to the previously mentioned issues: sustainability, resilience, security, cost.
- Good news: Conventional power grids are well designed systems that meet their design requirements.
- Bad news: There are present operational and planning requirements for which conventional power grids were not designed for. Hence, current issues with power grids are systemic and inherent of their design and cannot be addressed with retrofits, or partial enhancements or improvements.

Solution?!
Distributed Generation (DG) Technologies!

Distributed Generation (DG)

New Approach, New Considerations

What is Distributed Generation (DG)?

DG is technique of generating electricity on a small scale from renewable and non-renewable energy sources that is on-side or close to the load center.

https://www.youtube.com/watch?v=SSpT8vAPBvk&t=3s

Questions and comments are most welcome!