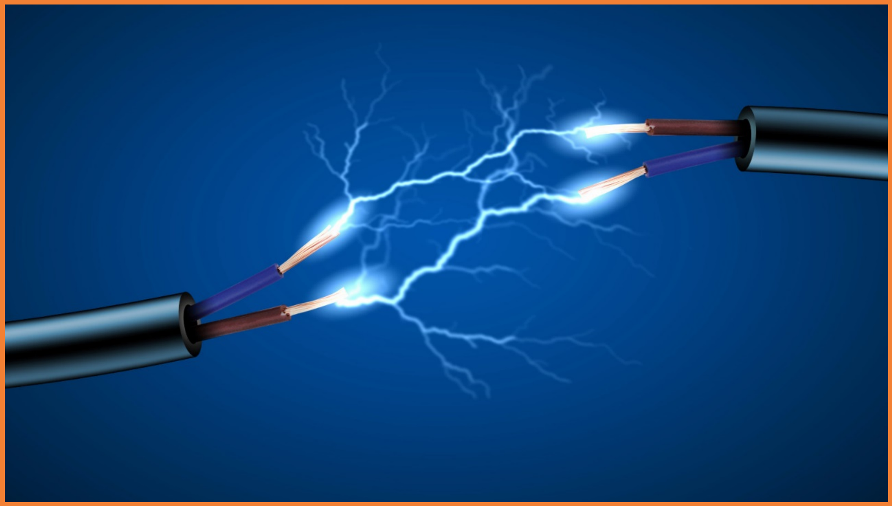
# Smart Grid:
# The Internet of Energy

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With thanks to Minjie Chen (Princeton) and Saleh Soltan (Amazon)



School of Engineering and Applied Science
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# Outline

- Background
- Smart Grid – Motivation
- Smart Grid – Some Solutions & Challenges
- Summary and R&D Needs

# Background

# Electric Power Grids

## Greatest Engineering Achievements OF THE 20TH CENTURY

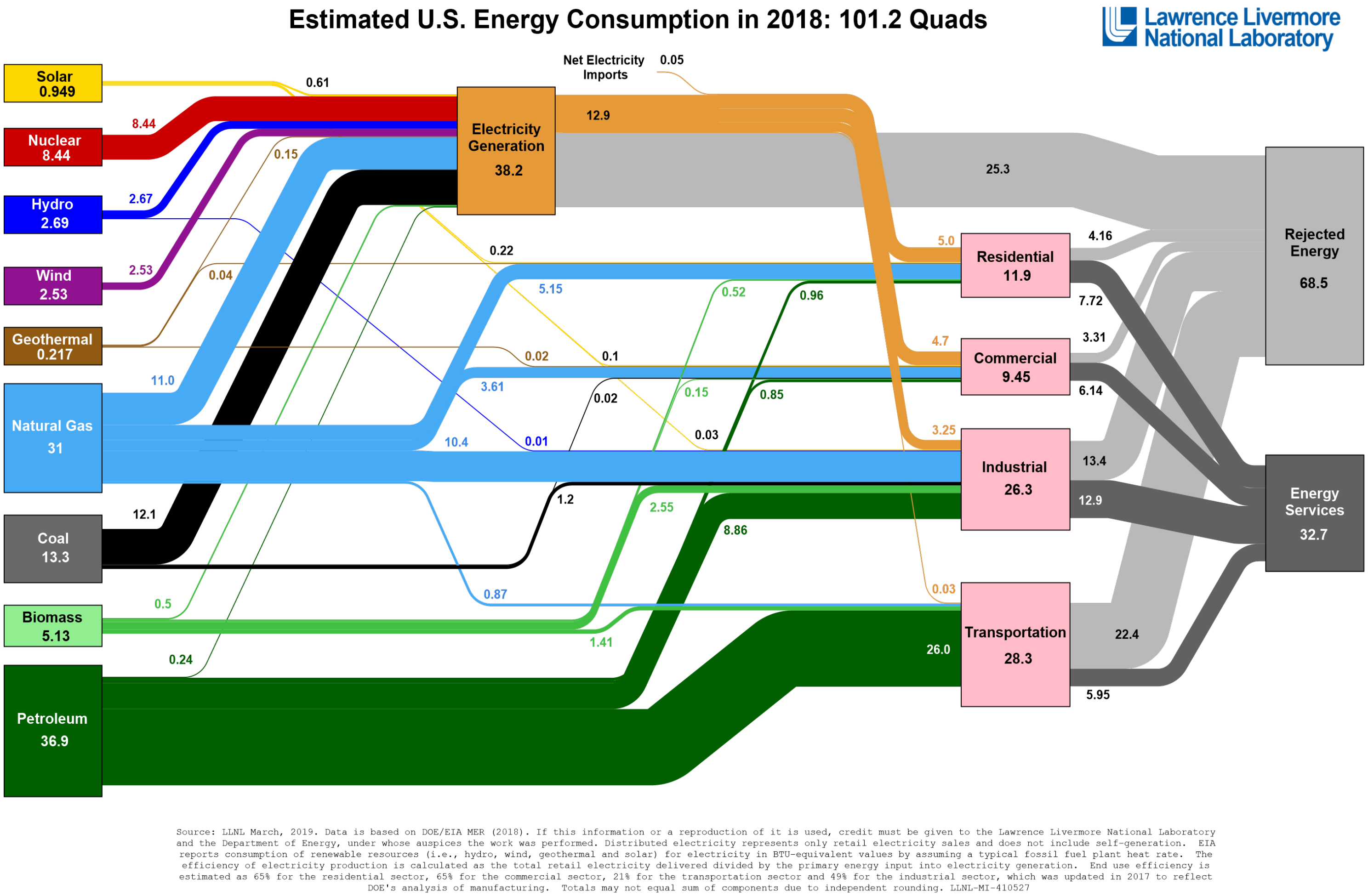
**Welcome!**
How many of the 20th century's greatest engineering achievements will you use today? A car? Computer? Telephone? Explore our list of the top 20 achievements and learn how engineering shaped a century and changed the world.

1. Electrification
2. Automobile
3. Airplane
4. Water Supply and Distribution
5. Electronics
6. Radio and Television
7. Agricultural Mechanization
8. Computers
9. Telephone
10. Air Conditioning and Refrigeration
11. Highways
12. Spacecraft
13. Internet
14. Imaging
15. Household Appliances
16. Health Technologies
17. Petroleum and Petrochemical Technologies
18. Laser and Fiber Optics
19. Nuclear Technologies
20. High-performance Materials

Greatest Achievements

A transformative technology – but almost invisible (until it's not there!).

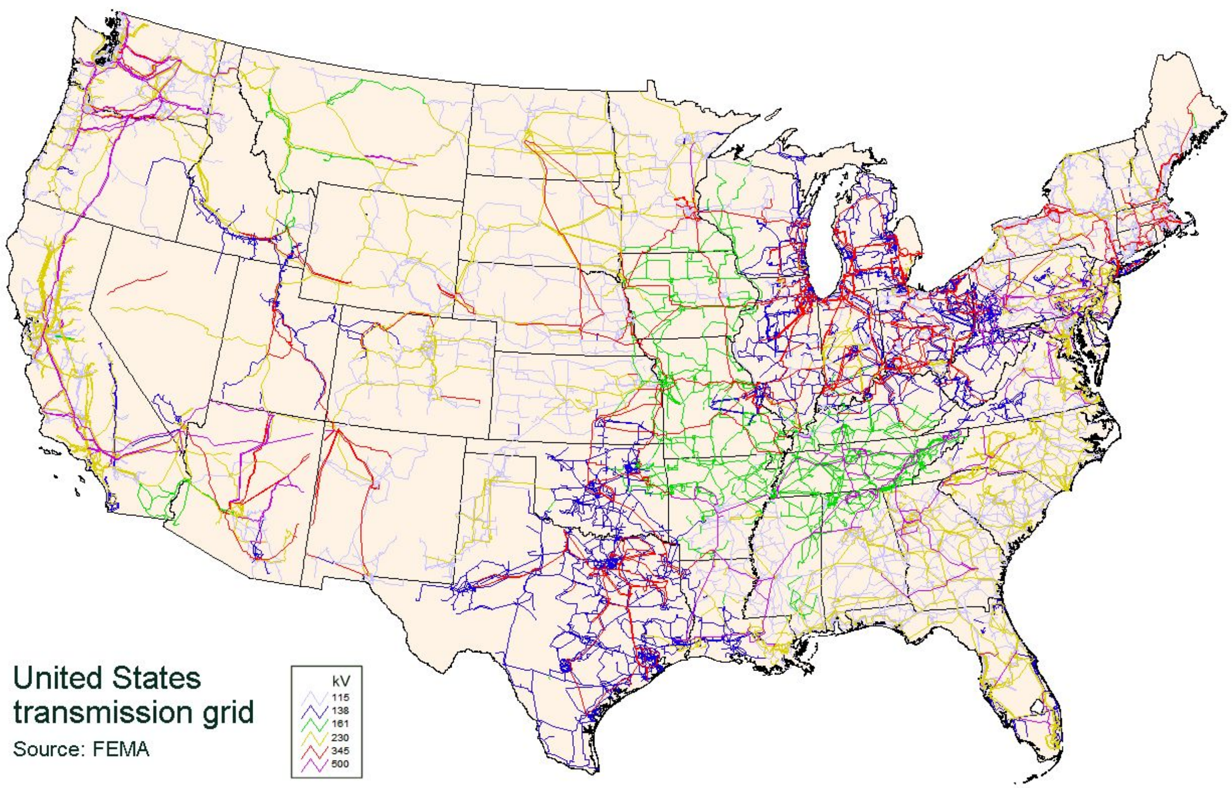
# Energy Use in the US - 2018




Electricity generation represents just under 40% of US energy use – a lot of that is wasted as heat.

(1 quad = $10^{15}$ BTUs)

# U.S. Generation and Transmission



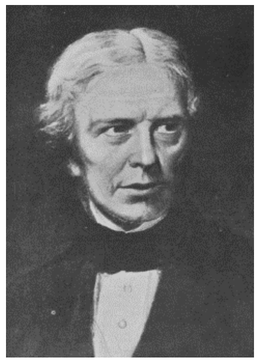

Largest running machine in the world

- 9,200 Generating Units
- 1,000,000 MW of Generating Capacity
- 300,000 Miles of Transmission Lines
- 150,000 Miles of Transmission Lines > 230kV
- 99.97% Reliable

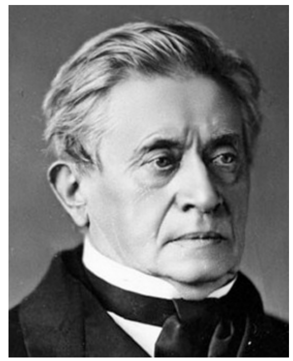
# Before Electrification, the World Was Lit by Fire

# Physical Rules for the Electric Grid (1820s-60s)

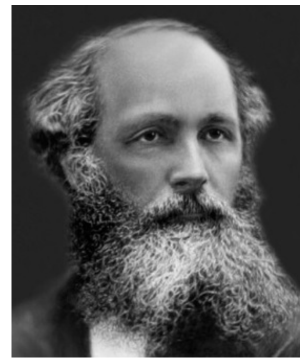
Georg Ohm



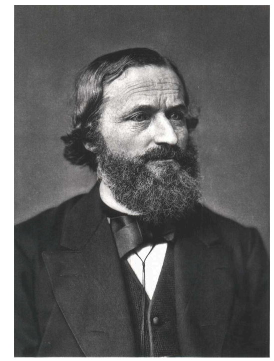
Michael  Faraday



Joseph Henry

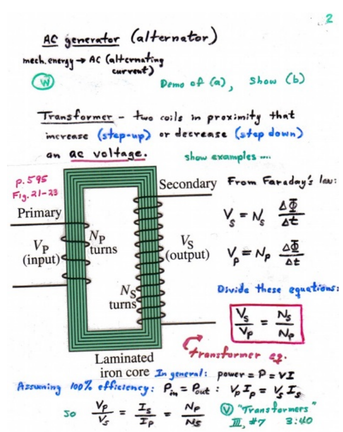


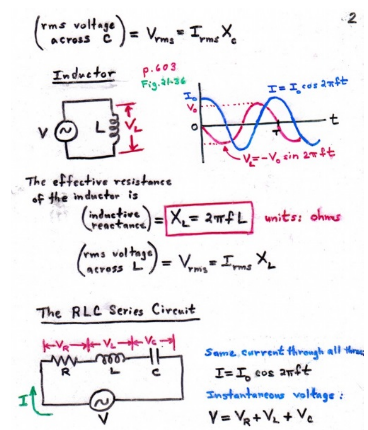
James Maxwell



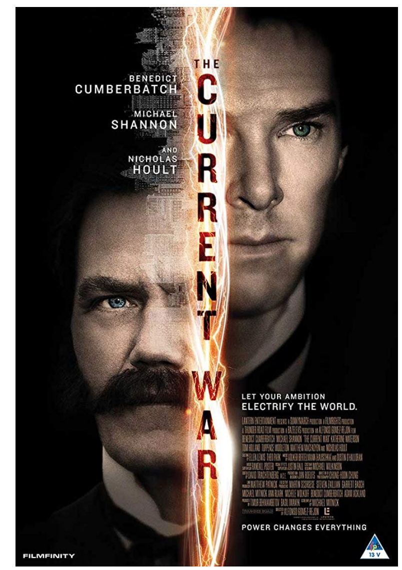
Gustav Kirchhoff

Ohm’s Law
Faraday/Henry’s Law
Maxwell’s Equations
Kirchhoff’s Law



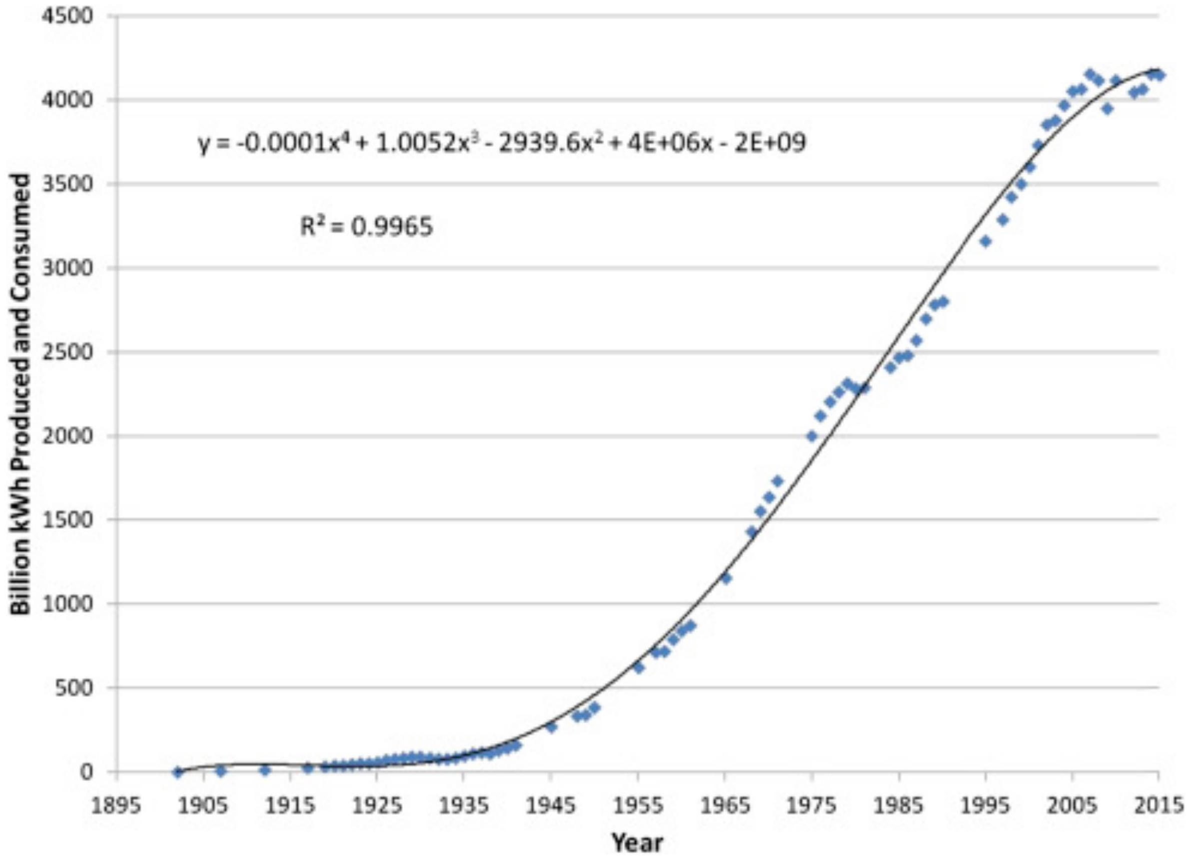
# Edison,Tesla & Westinghouse
## (“War of the Currents” – 1880s-90s)



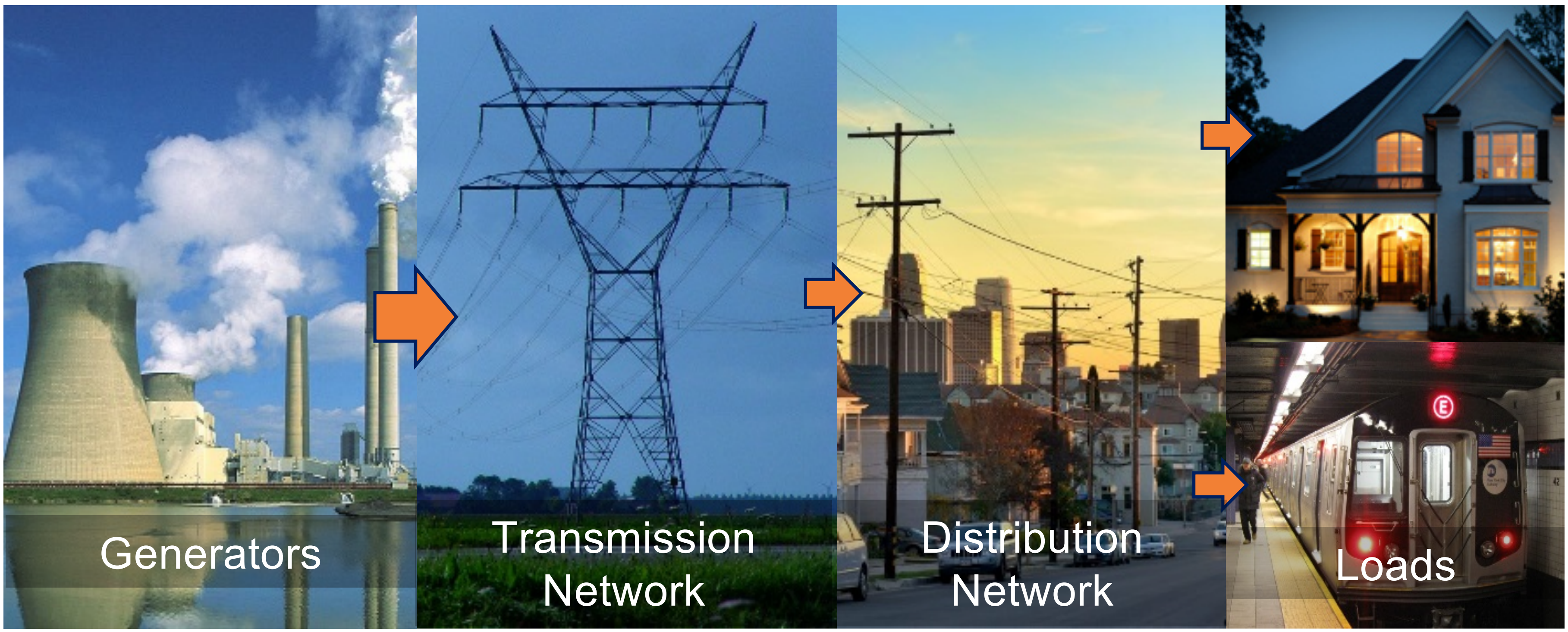

Direct Current (DC)

Alternating Current (AC)

# US Electricity Consumption: 1900–2015



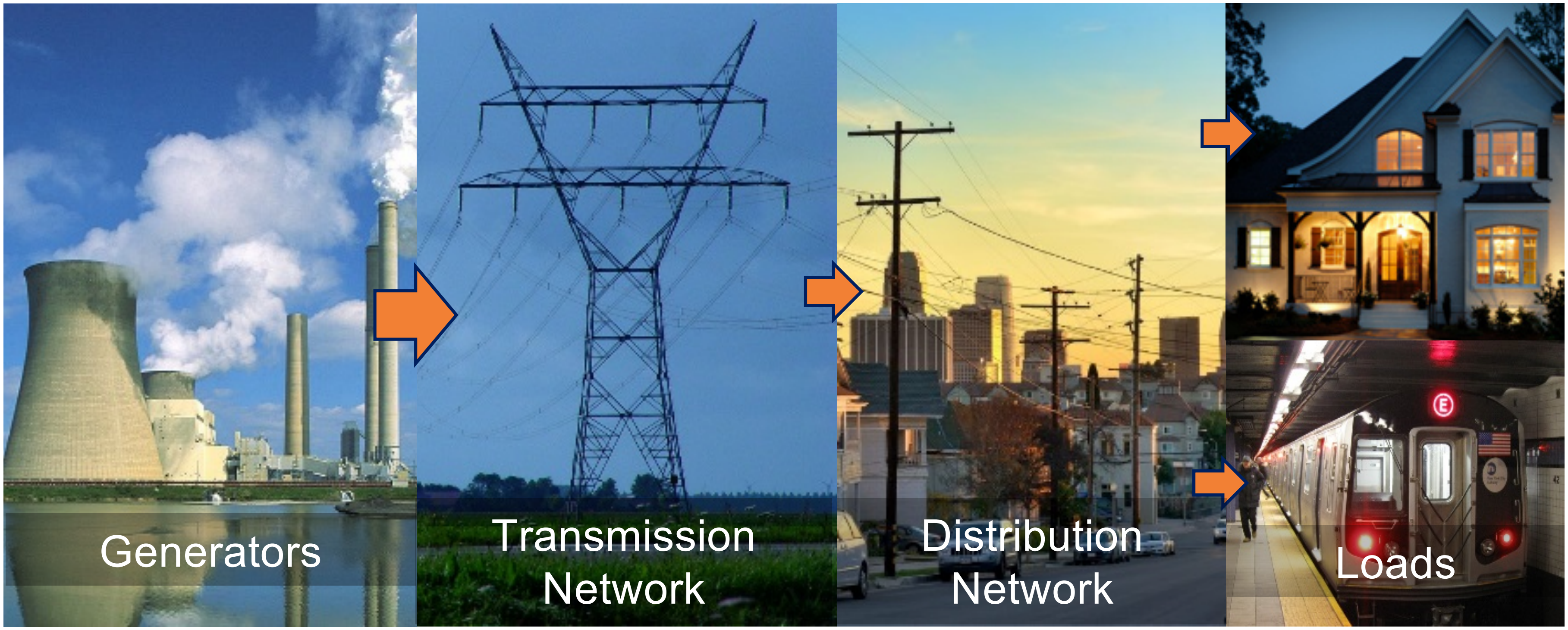
# Major Components of Traditional Grid




765 kV-110 kV

34.5 kV-110 V

# Major Components of Traditional Grid (this model is being disrupted)




765 kV-110 kV

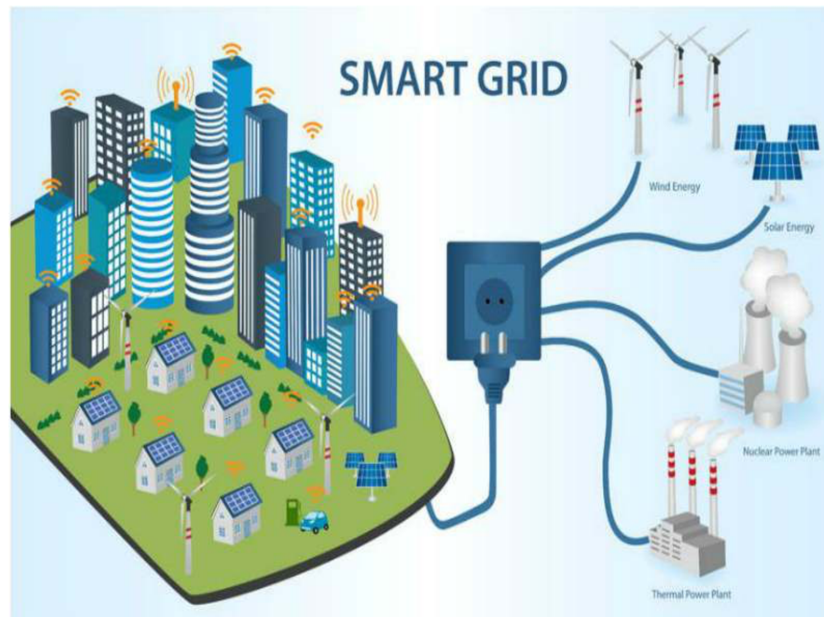
34.5 kV-110 V

# … Ripe for Innovation

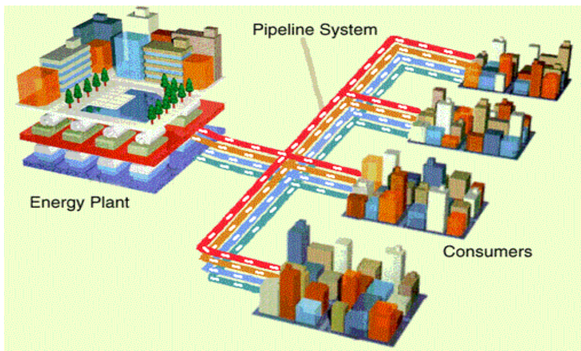
- If Alexander Graham Bell were somehow transported to the 21st century, he would not begin to recognize the components of modern telephony – mobile networks, smart phones, etc.

- While Thomas Edison would be quite familiar with much of the grid.

# Smart Grid - Motivation

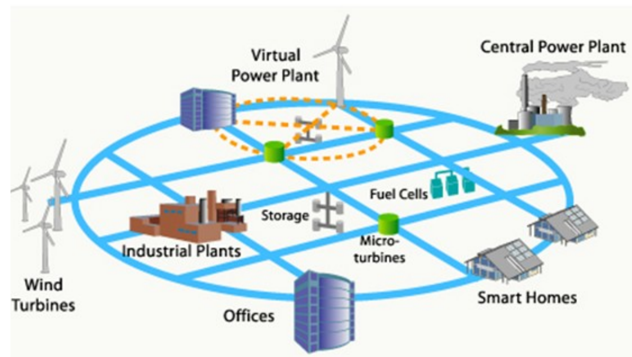


# Smart Grid – “The Internet of Energy”




**Traditional Grid**

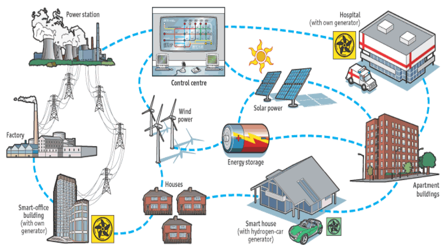
- Electromechanical system
- Centralized generation
- Few sensors
- Manual monitoring & restoration
- Failures and blackouts
- Few customer choices




**Smart Grid**

- Cyber-physical system
- Distributed generation (renewables)
- Advanced sensing and power electronics
- Self-monitoring & self-healing
- Adaptive and reliable
- Many customer choices

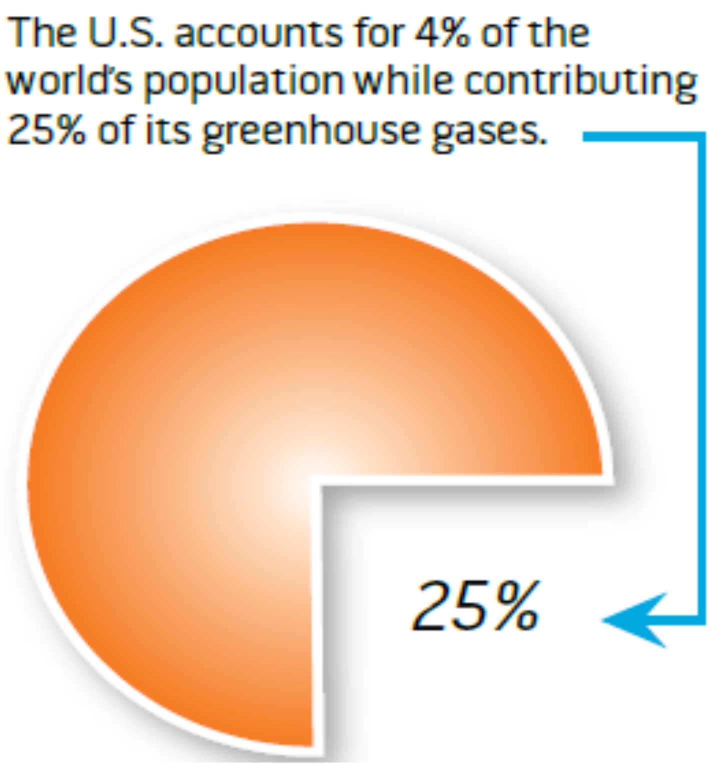
# Why Have a Smart Grid?




- Enhance efficiency of existing generation
- Facilitate deployment of renewable energy sources
- Enable resilience to and self-healing from disruption
- Automate maintenance and operation
- Improve grid security
- Smooth transition to electric vehicles and storage
- Demand side management (consumer choices)
- Enable new products, services and markets
- I.e., greater efficiency, reliability and security

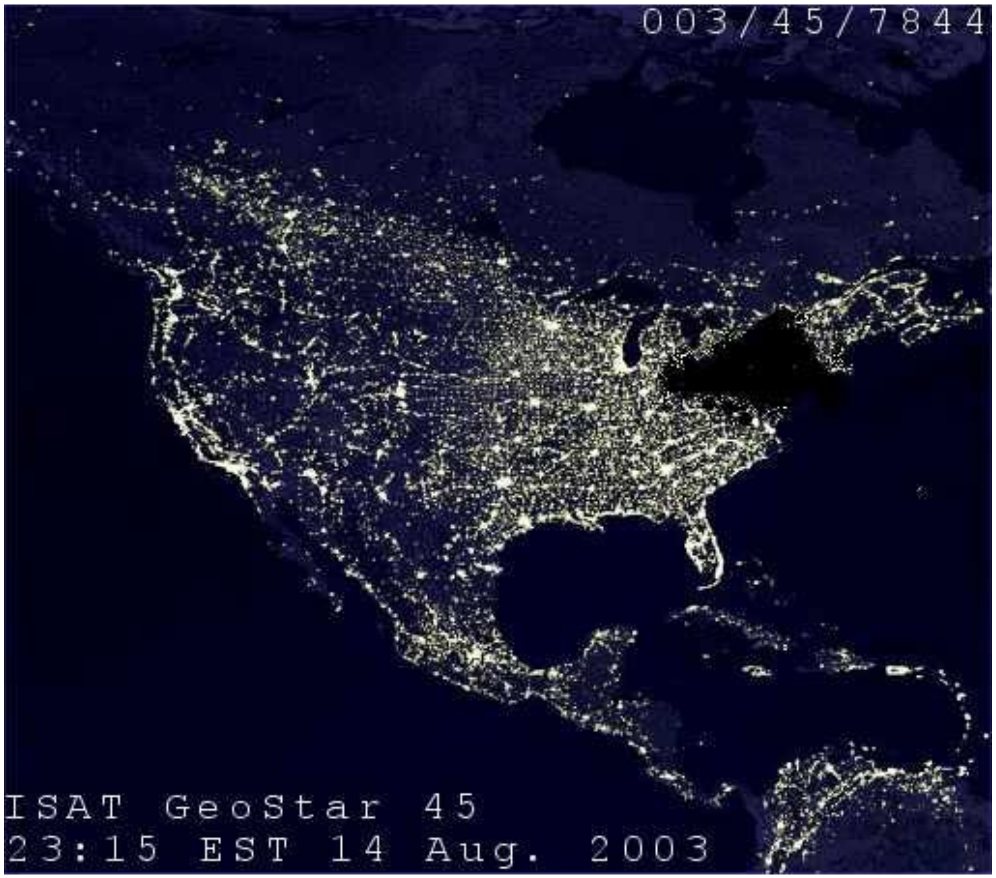
Source: National Institute of Standards and Technology. NIST framework and roadmap for smart grid interoperability standards, release 1.0, http://www.nist.gov/public affairs/releases/upload/smartgridinteroperability final.pdf. January 2010.

# Important Issues - Efficiency




If the U.S. grid were just 5% more efficient, the energy savings would equate to permanently eliminating the fuel and greenhouse gas emissions from 53 million cars.

# Important Issues - Reliability




Blackouts and brownouts occur due in part to the slow response times of mechanical switches, and insufficient "situational awareness" on the part of grid operators.

# Important Issues - Security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POLITICS

## Russian Hackers Reach U.S. Utility Control Rooms, Homeland Security Officials Say

Blackouts could have been caused after the networks of trusted vendors were easily penetrated



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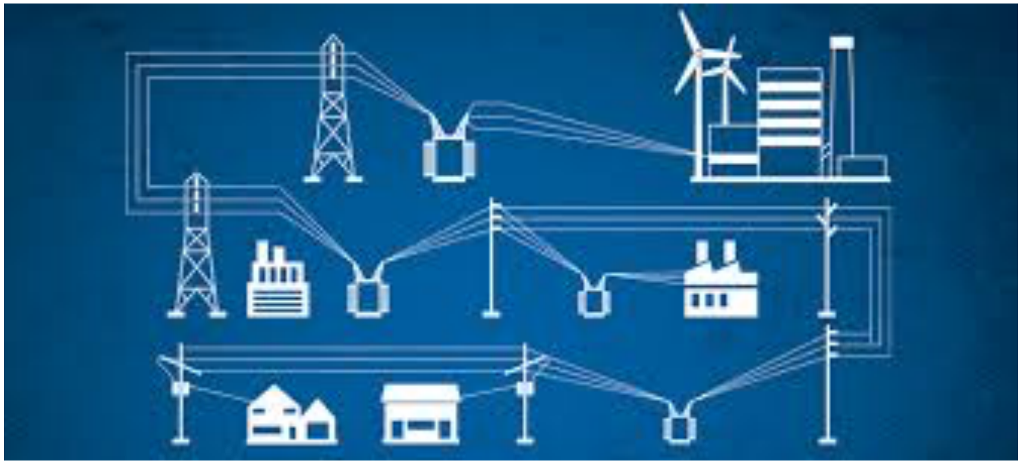
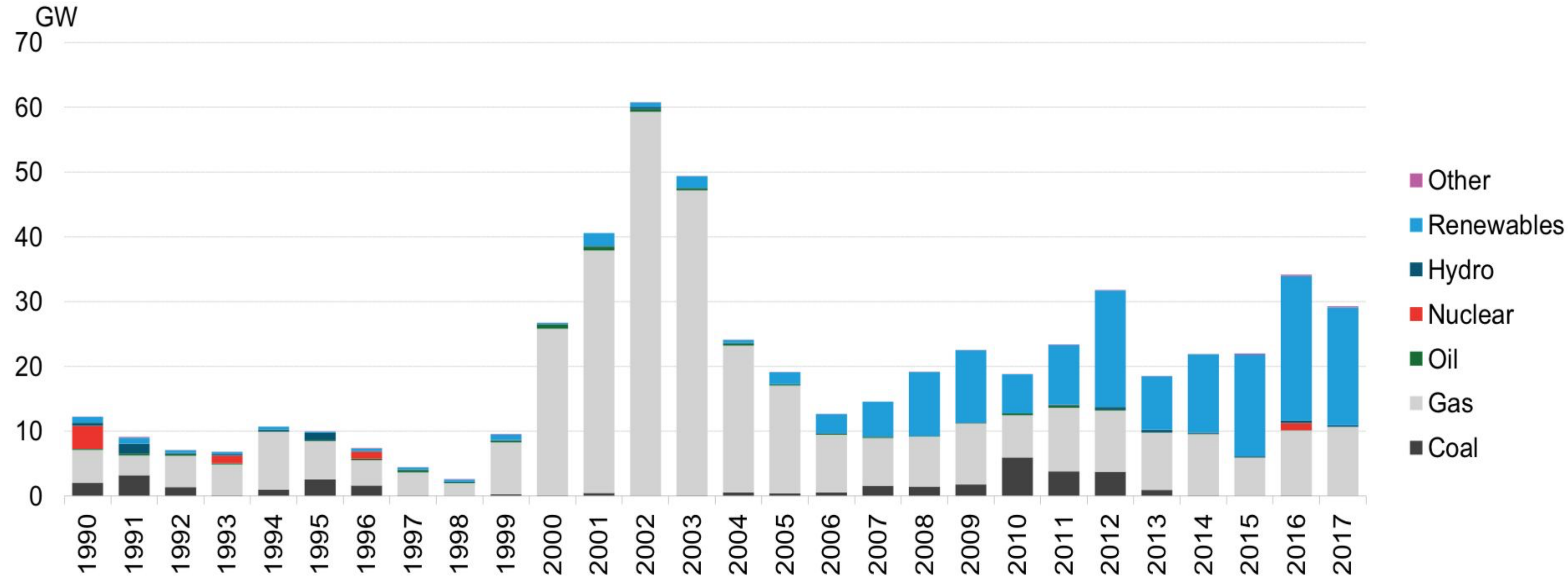
The interdependencies of grid components can enable a domino effect – a cascading series of failures that could bring banking, traffic, security, communications, systems, etc., to a complete standstill.

# Smart Grid – Some Solutions & Challenges

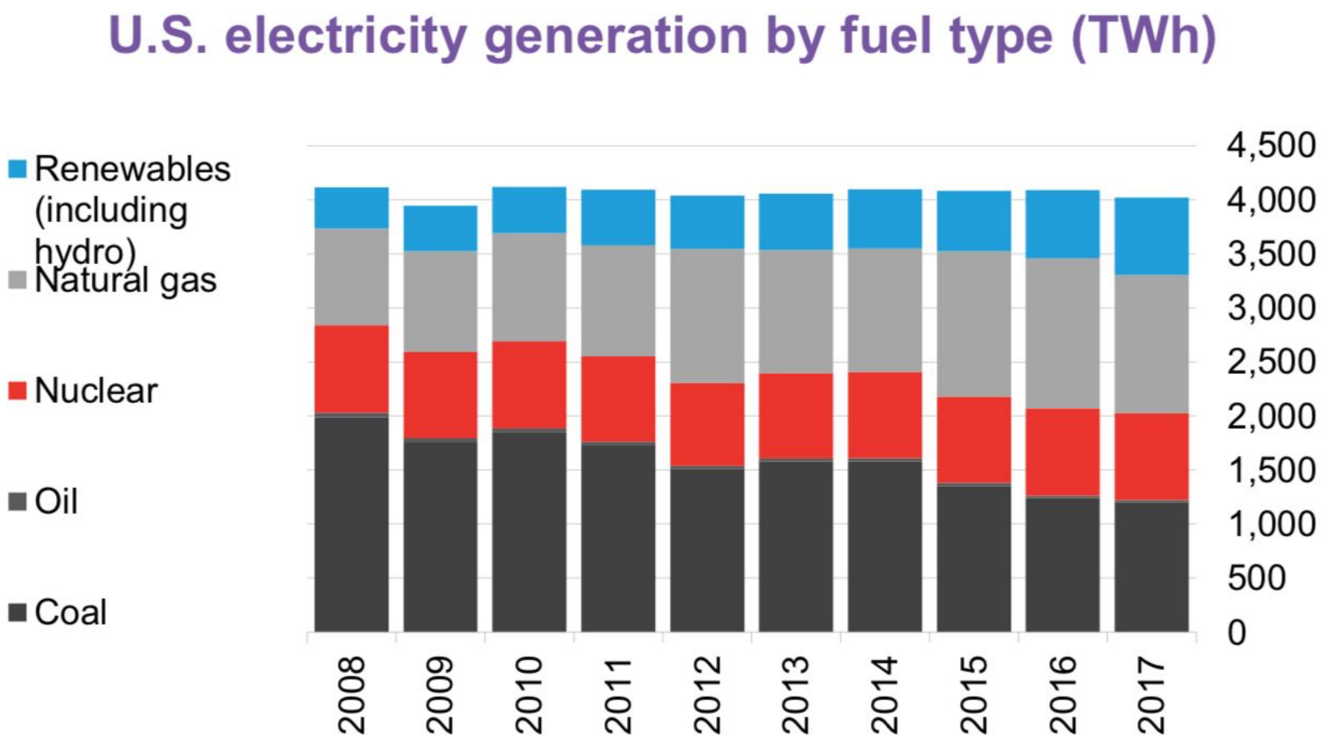


# Solution: Integration of Renewables

## U.S. energy overview: Electric generating capacity build by fuel type



# Solution: Integration of Renewables




https://www.greentechmedia.com/articles/read/renewable-energy-generation-nuclear-bnef#gs.96pmsg

# Renewables: Blowing in the Wind

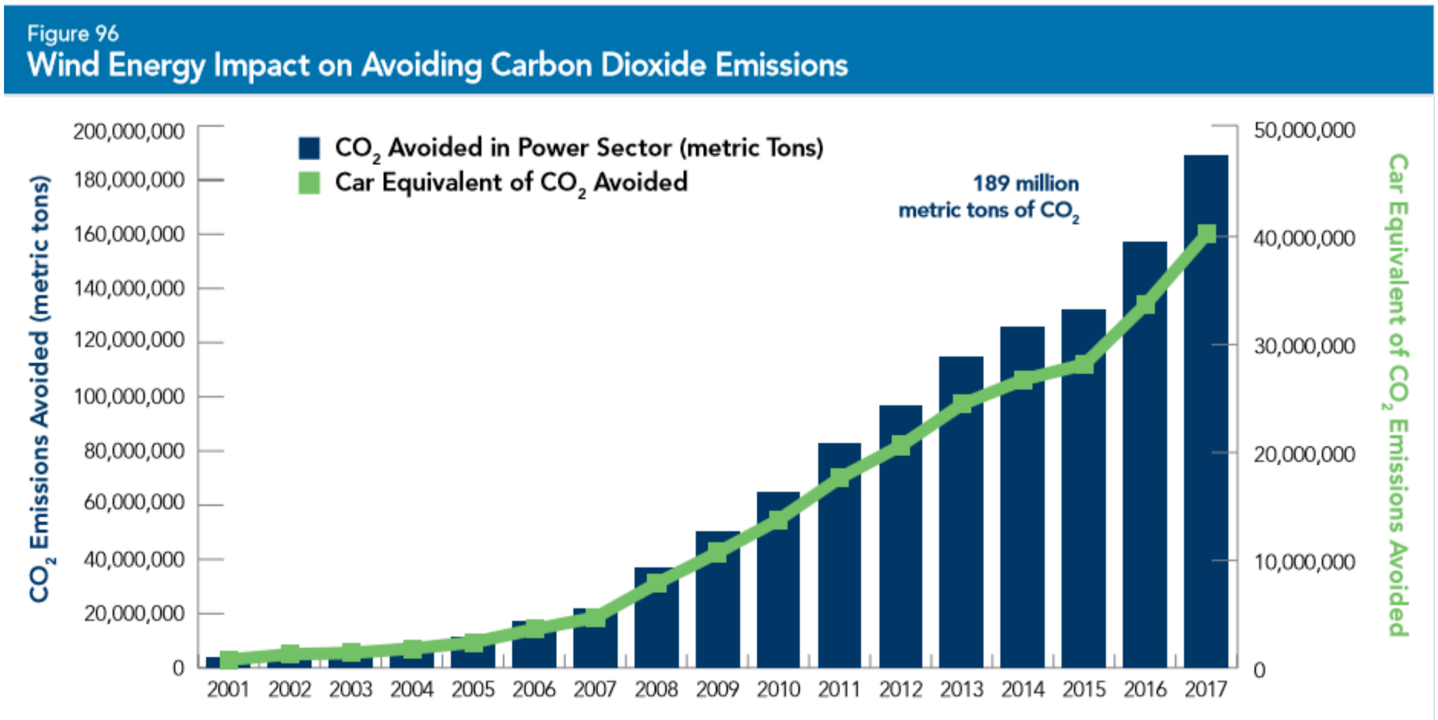
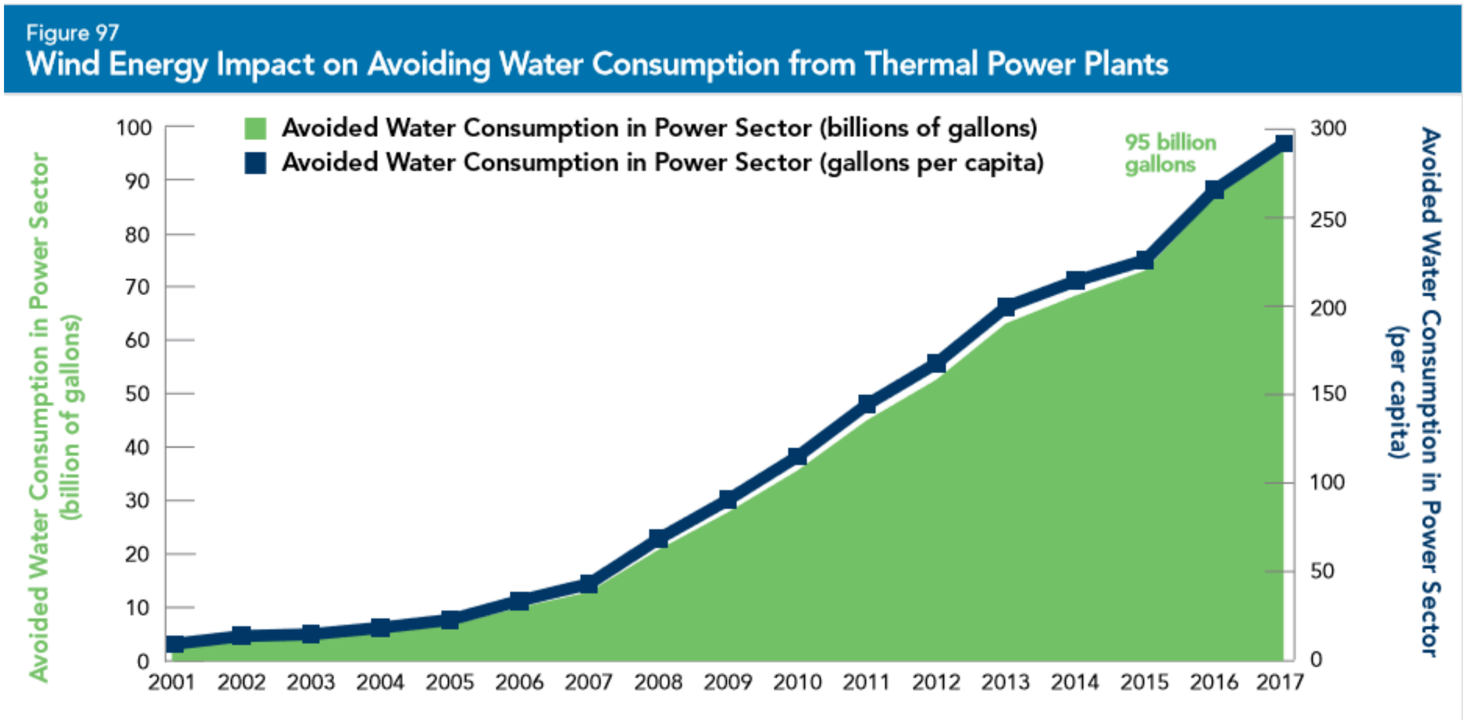


Figure 96
Wind Energy Impact on Avoiding Carbon Dioxide Emissions

<u>Sulfur Dioxide and Nitrogen Oxides</u>

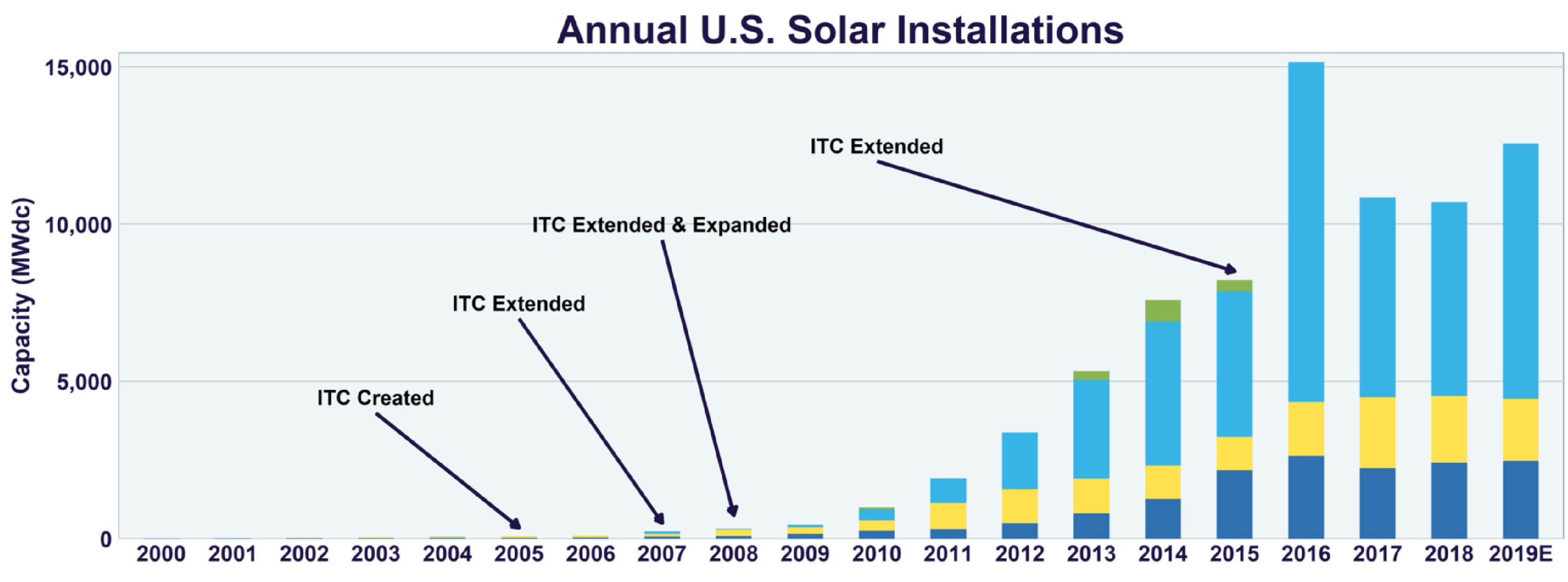
Wind also helps cut significant amounts of air pollutants known for creating smog and triggering asthma attacks. Reducing these pollutants helps to reduce rates of asthma and other respiratory issues. These created $9.4 billion in public health savings in 2018 alone.

# Renewables: Blowing in the Wind




In 2017, wind energy generation reduced water consumption at existing power plants by approximately 95 billion gallons—the equivalent of 723 billion bottles of water.

# Renewables: Solar on Fire

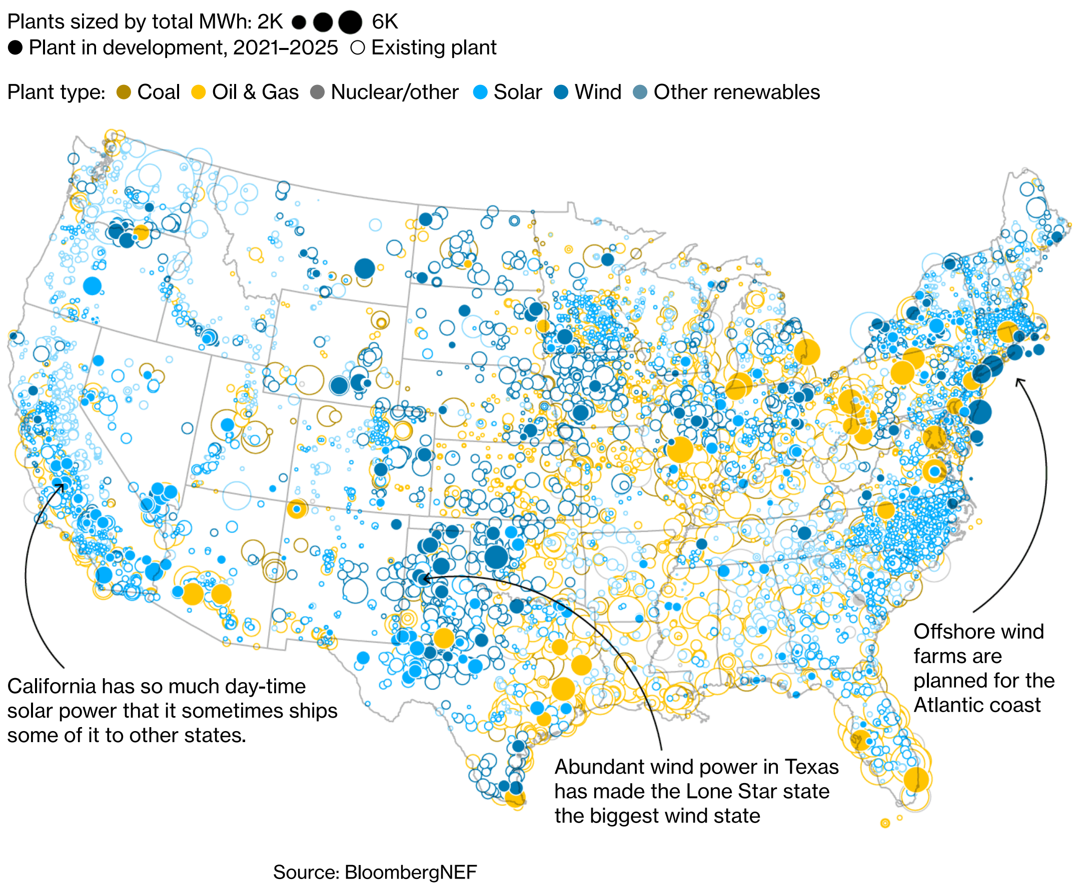



Source: SEIA/Wood Mackenzie Power & Renewables U.S. Solar Market Insight

Wood Mackenzie POWER & RENEWABLES

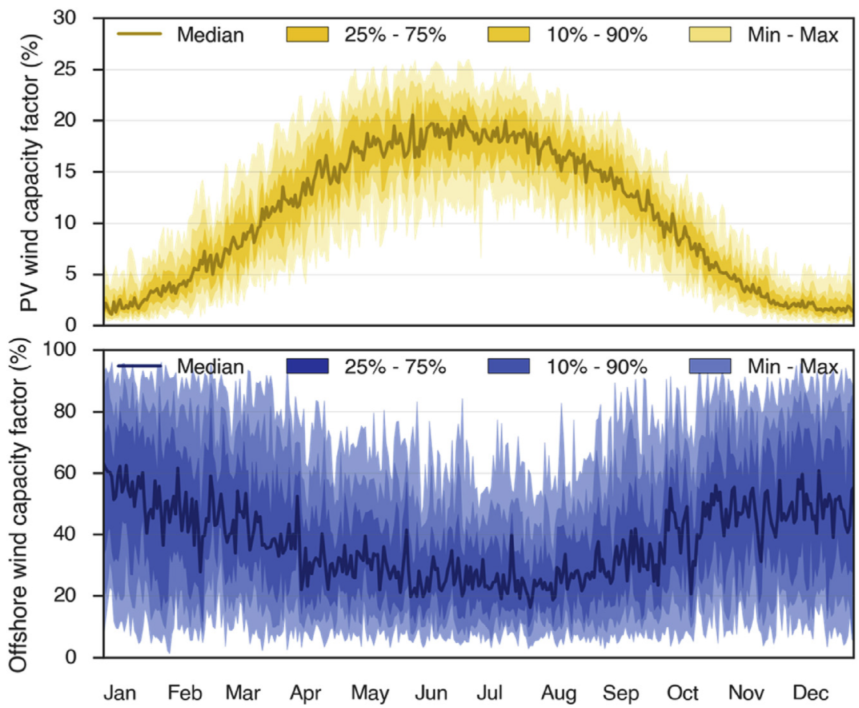
SEIA Solar Energy Industries Association®

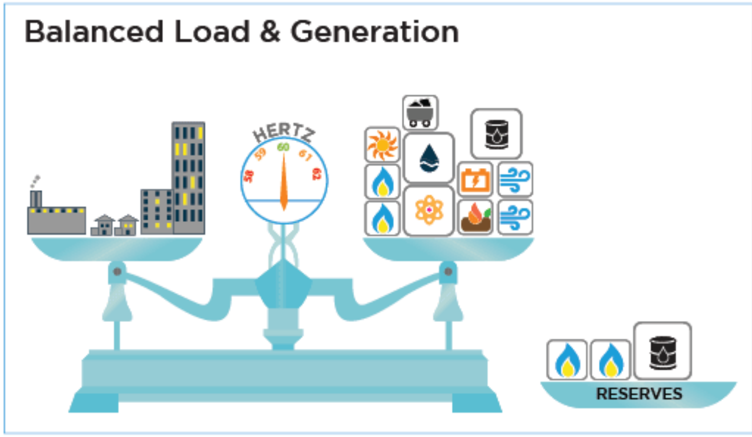
# Future Development of Renewables




Widespread development of renewable generation.

# Challenge: Volatility of Generation




**Source**: : Staffell and Pfenninger, "The increasing impact of weather on electricity supply and demand," Energy Journal, 2017

# Challenge: Lack of Inertia

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## AEMO releases final report into SA blackout, blames wind farm settings for state-wide power failure

By political reporter Nick Harmsen

Updated 28 Mar 2017, 1:01am

**Overly sensitive protection mechanisms in some South Australian wind farms are to blame for the catastrophic statewide blackout in September last year, the Australian Energy Market Operator (AEMO) says.**

In its fourth and final report into the September 29 blackout, AEMO said it was the action of a control setting responding to multiple disturbances that led to the 'black system'.

The report said the unexpected operation of the control settings resulted in the sudden loss of generation from the wind farms.

**PHOTO:** AEMO is working with industry to build power system resilience. (AAP: Angela Harper)

Unlike traditional means of electricity generation, solar and wind generators lack inertia.

# Challenge: Bidirectional Flow

The presence of distributed generation units in the network at low voltage levels can cause reverse power flows that may lead to complications in grid stability and control.

# Solution: Storage

Need for Energy Storage Resources (ESRs) to compensate for volatility of renewable resources and their low inertia

**What's an ESR?**
Energy Storage Resources are devices used to capture energy produced at one time for use at a later time.

**Capacitors**
Components that store potential energy in an electric field

**Superconductors**
Systems that store energy in a magnetic field

**Pumped Hydro**
Water stored in a reservoir to provide energy on demand

**V2G**
Vehicle-to-grid systems that use electric cars for energy storage

**Thermal**
Excess heat stored for later use

**Flow Batteries**
Batteries that contain liquid chemicals that store energy

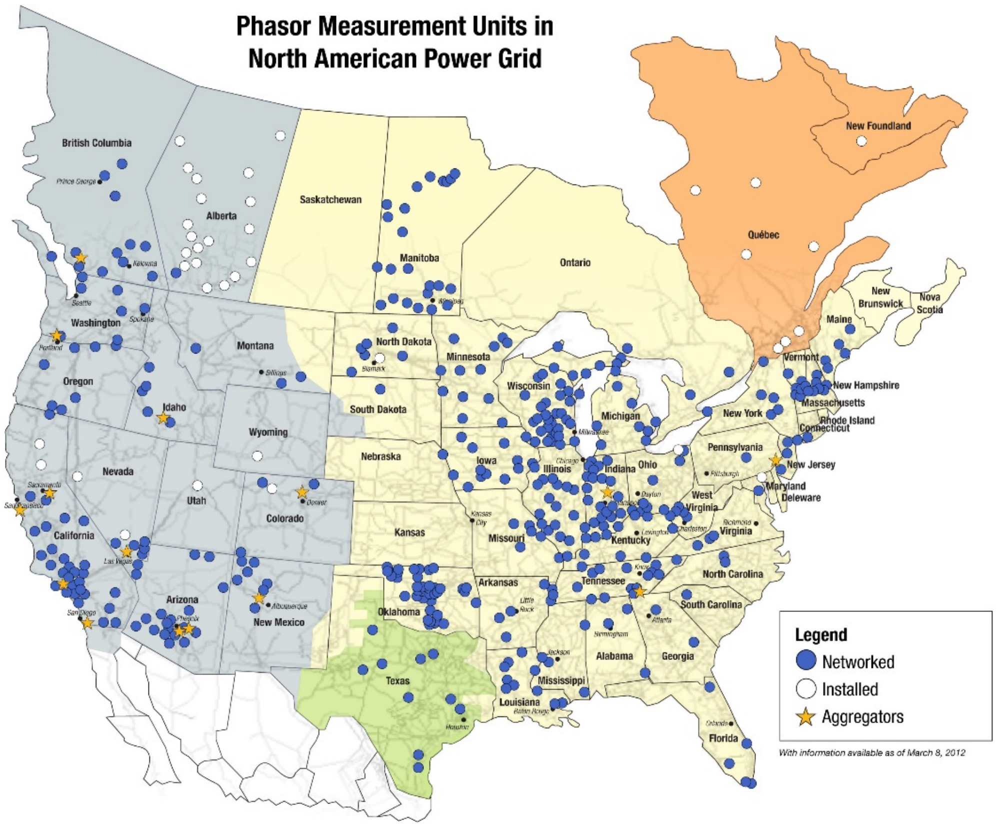
**Lithium Batteries**
Move lithium ions between positive and negative electrodes to store energy

# Solution: Advanced Measurement and Control

Next-generation energy management systems to provide greater situational awareness.

Use of high fidelity, time synchronized measurements to improve all levels of grid operation and control.

# Phasor Measurement Units (PMUs)



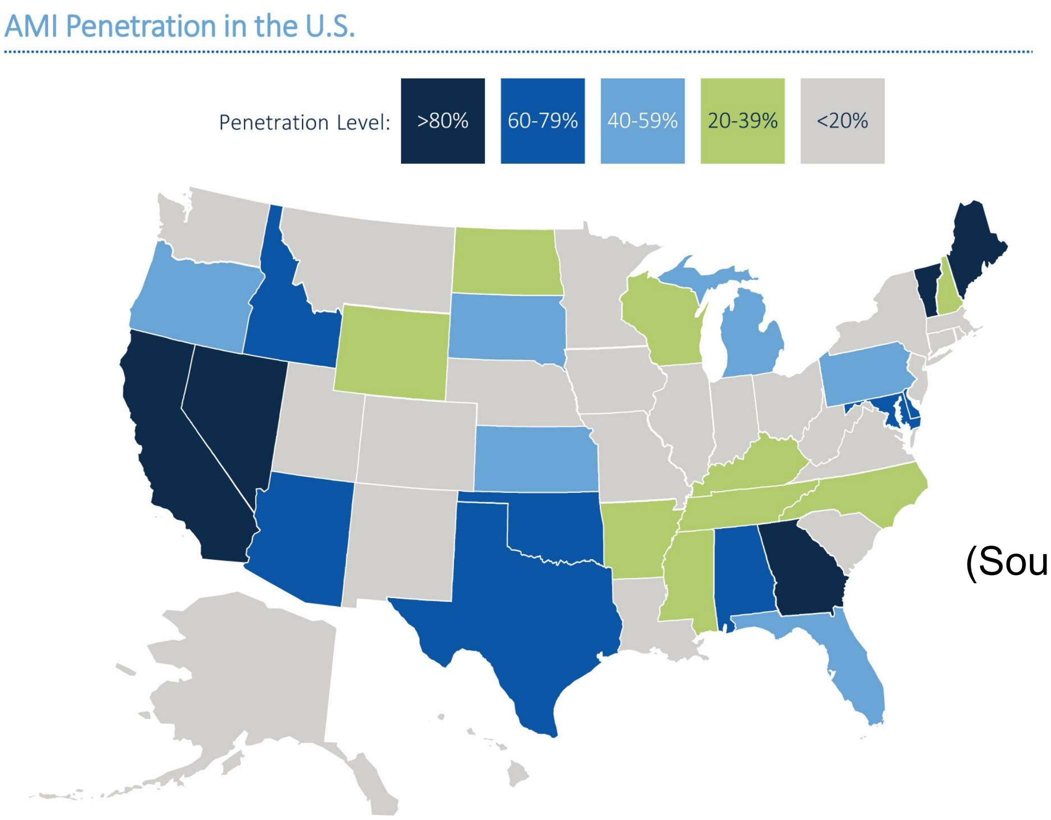

PMUs allow more frequent and accurate estimation of the grid state than traditional grid instrumentation (SCADA).

# Challenge: Security

Greater Reliance on Sophisticated Data Infrastructure Leaves the Grid Vulnerable to Cyber and Physical Attacks:

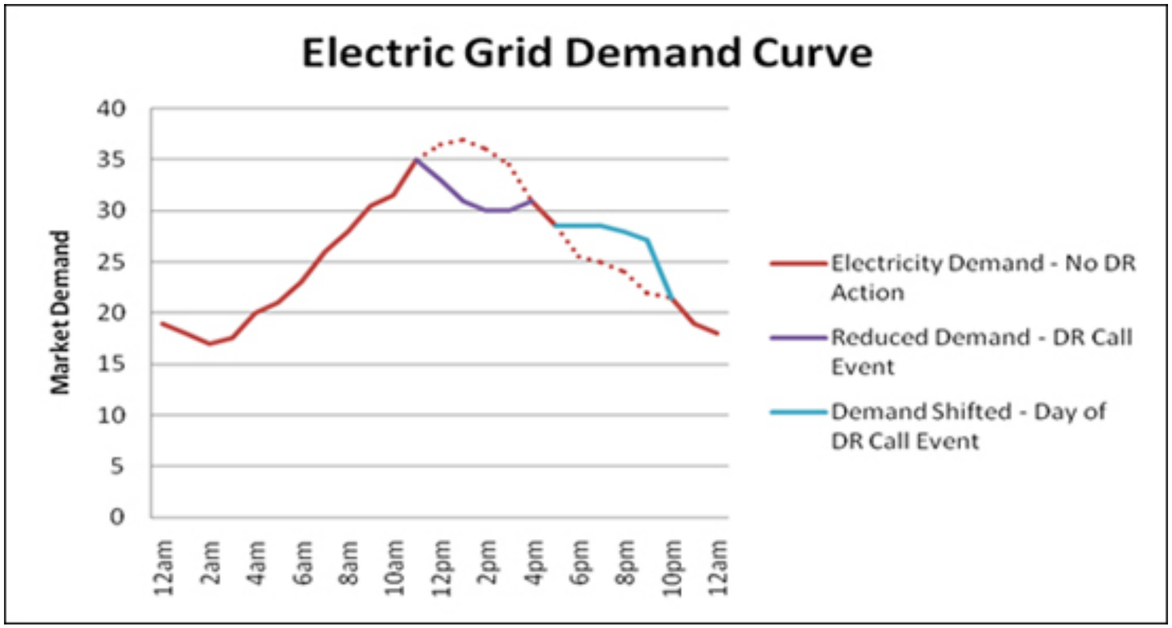
- Data injection attacks: change the grid state estimates without changing the state (compromised situational awareness)
- Physical injection attacks: change the grid state without changing the state estimates (could be implemented via a cyber attack)

# Advanced Metering Infrastructure
## (Smart Meters)




(Source EIA: 2015)

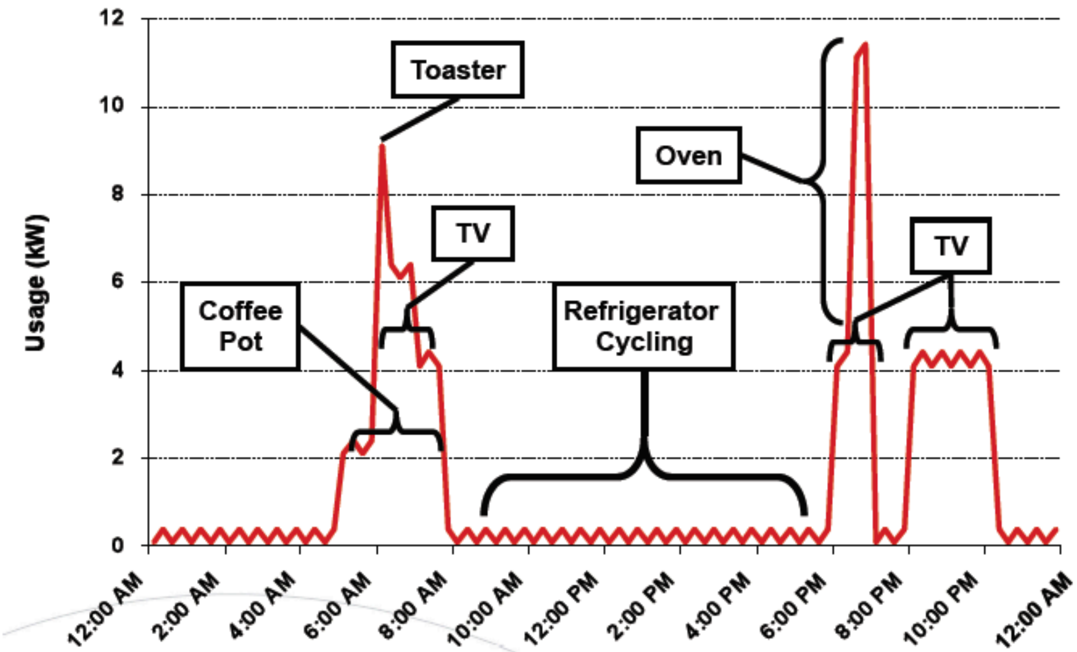
# Opportunity: Demand Response
## (Smart Homes, Smart Buildings)




Changes in the electric load - such as reductions, increases, or shifts - by end-use customers in response to specific market or system conditions.

# Challenge: Privacy

- Smart meter data is useful for price-aware usage, load balancing.
- But, it leaks information about in-home activity.



# Challenge: Security

Hacked Water Heaters Could Trigger Mass Blackouts Someday | WIRED 10/15/19, 8:48 PM

WIRED BUSINESS CULTURE GEAR IDEAS SCIENCE SECURITY SIGN IN

ANDY GREENBERG SECURITY 08.13.2018 07:00 AM

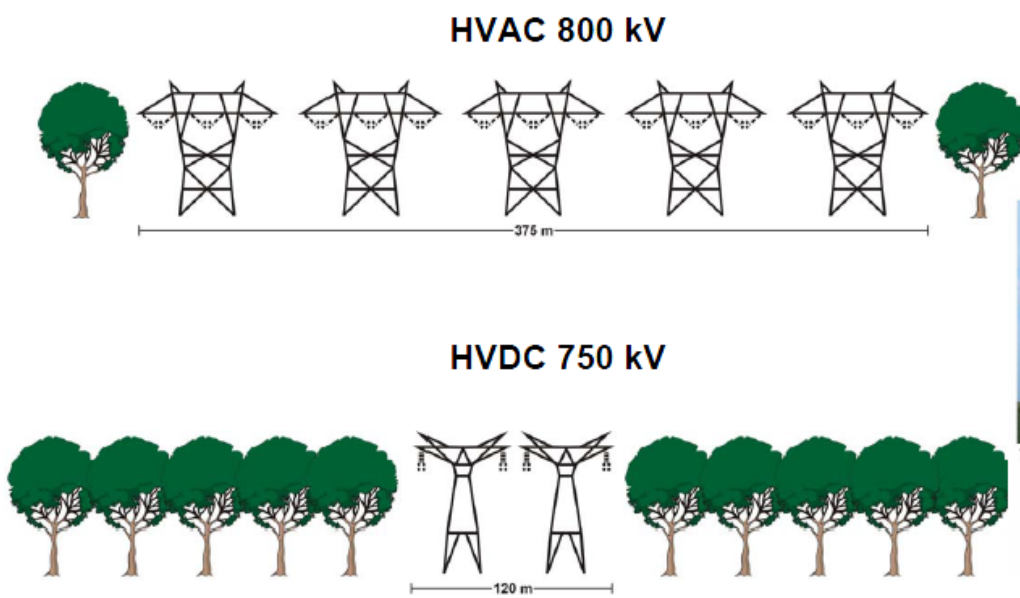
## How Hacked Water Heaters Could Trigger Mass Blackouts

A new study found that just 42,000 of those hacked home devices could be enough to leave a country of 38 million people in the dark.

GETTY IMAGES

A botnet can control IoT devices to trigger cascading grid failure.

# Solution: High-Voltage DC





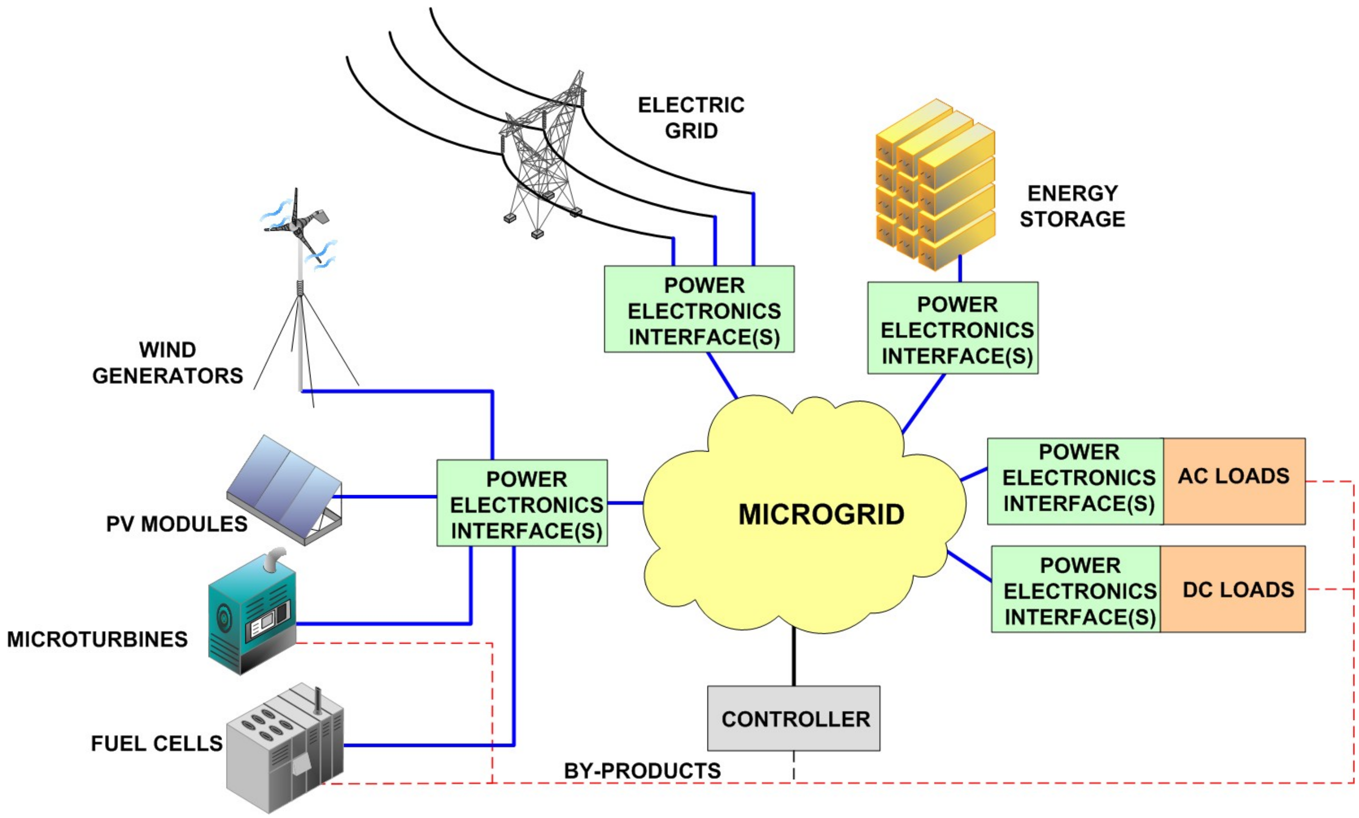
- Usually insulation materials can handle 3x more dc voltage than ac voltage, thus dc cables are lighter and can deliver more power.
- Dc transmission lines are usually two-wire systems, while ac transmission lines are usually three-wire systems, simpler tower structure.
- Dc transmission wires only have dc loss, while ac transmission wires have ac loss (due to skin and proximity effects).

# Challenge: Grid Scale Power Electronics

400 MW HVDC Station Developed by ABB

http://www.offshorewind.biz/2016/03/10/abb-to-deliver-kriegers-flak-hvdc-converter-station/

# Solution: Microgrids



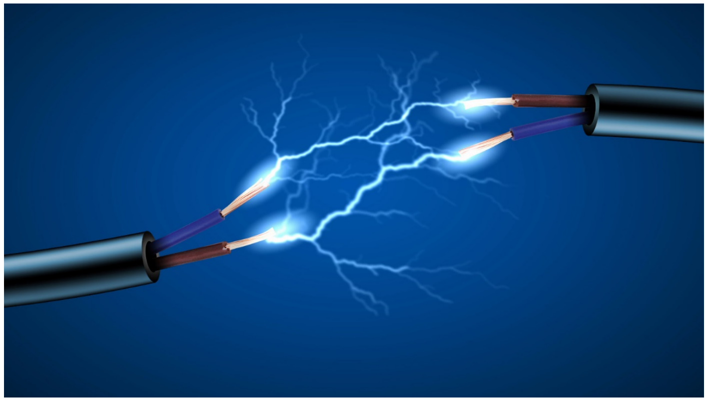

A group of interconnected loads and distributed energy resources that acts as a single controllable entity

Reliable (diverse sources), efficient (avoids transmission losses), allow co-gen of heat and electricity.

# Summary and R&D Needs

# Summary
## The Internet of Energy

- Smart grid comprises a set of potentially disruptive technologies that can produce greater efficiency, reliability and security in the grid
- Examples include
    - Integration of renewables
    - Grid-scale storage advanced power electronics
    - Advanced measurement, analytics and control
    - Microgrids
- A lot of challenges remain



# Smart Grid: R&D Needs (An Incomplete List)

- Storage technologies
- Power electronics (conversion, control, etc.)
- Advanced data analytics for greater situational awareness
- Energy trading platforms (prosumer-to-prosumer, and prosumer-to-grid)
- Security at all levels
- Privacy protections


THANK YOU!