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Energy Innovation & the Transformation of Electricity

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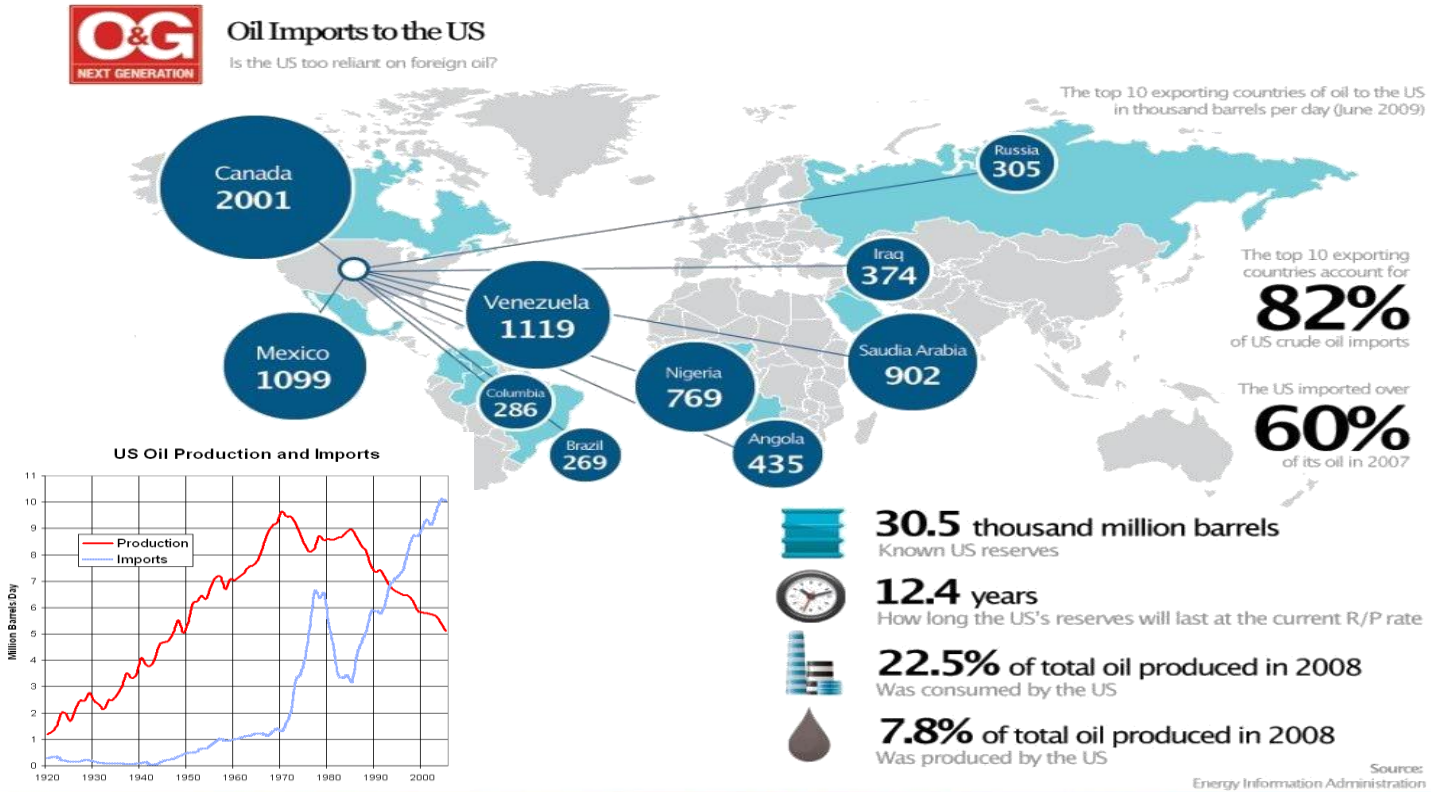
Program Director
ARPA-E

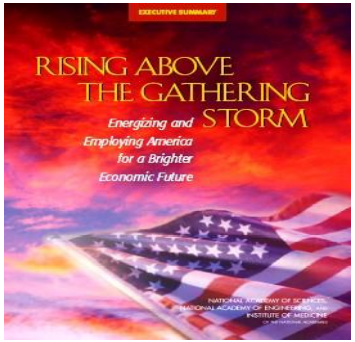
FUTURE WORLD 2011 2031

The U.S. dependence on imported oil is an economic weakness as well as a political and environmental challenge



In 2007, with oil at $70 per barrel, the U.S. trade deficit in petroleum products was 36% of the total of $819 billion deficit.

CREATION OF ARPA-E



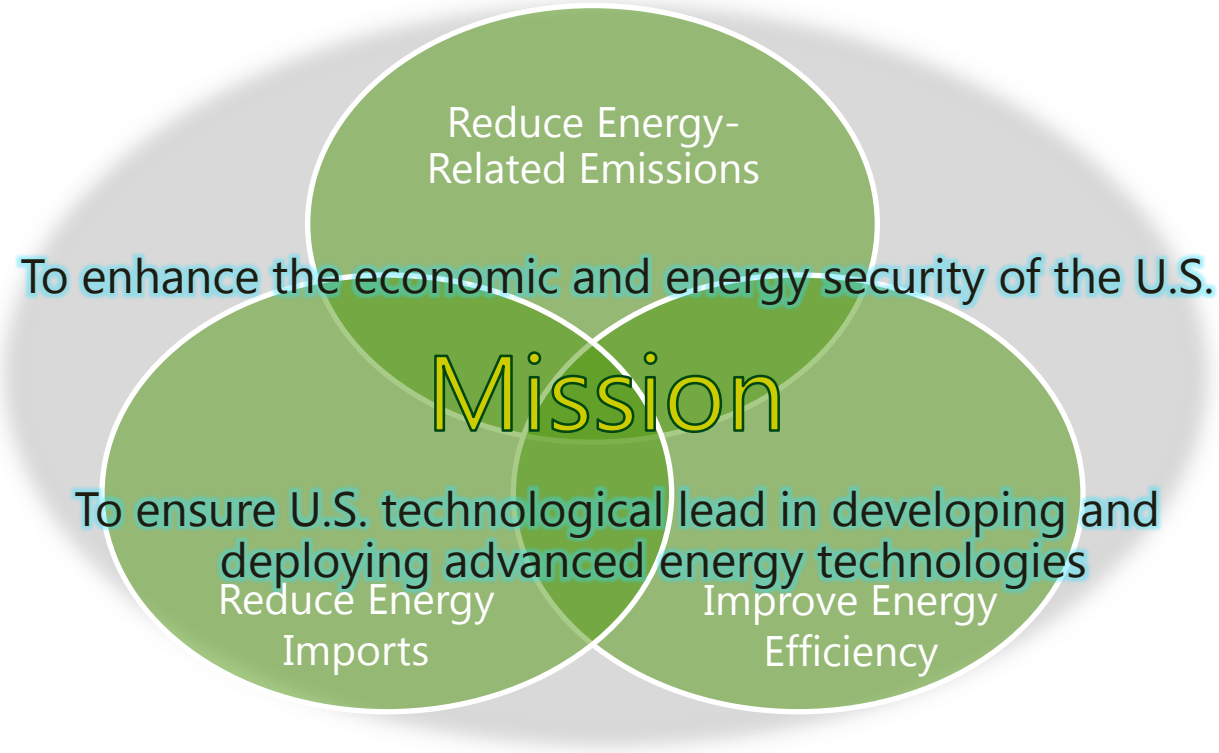
2006
Rising Above the Gathering Storm
(National Academies)

2007
America COMPETES Act

American Recovery and Reinvestment Act of 2009 (Recovery Act)

$400M appropriated for ARPA-E
President Obama launches ARPA-E in a speech at NAS on April 27, 2009

ARPA-E'S Work



- Find and fund high-risk, high-impact projects
- Invest in the best ideas and teams
- Will tolerate and manage high technical risk
- Accelerate translation from science to markets
- Proof of concept and prototyping

DOE ORGANIZATIONAL CHART









Loan Programs Office

American Recovery & Reinvestment Act Office

Office of the Secretary
Dr. Steven Chu, Secretary

Daniel B. Poneman,
Deputy Secretary*

Chief of Staff

Federal Energy Regulatory Commission

Inspector General

Office of the Under Secretary For Nuclear Security/ Administrator for National Nuclear Security Administration
Thomas P. D'Agostino

- Deputy Administrator for Defense Nuclear Nonproliferation
- Deputy Administrator for Naval Reactors
- Associate Administrator for Defense Nuclear Security
- Associate Administrator for Infrastructure & Environment
- Deputy Administrator for Defense Programs
- Deputy Under Secretary for Counter-terrorism
- Associate Administrator for Emergency Operations
- Associate Administrator for Management & Administration

Office of the Under Secretary for Science

Dr. Steven E. Koonin
Under Secretary for Science

Office of Science

- Advanced Scientific Computing Research
- Basic Energy Sciences
- Biological & Environmental Research
- Fusion Energy Science
- High Energy Physics
- Nuclear Physics
- Workforce Development for Teachers & Scientists

Office of the Under Secretary

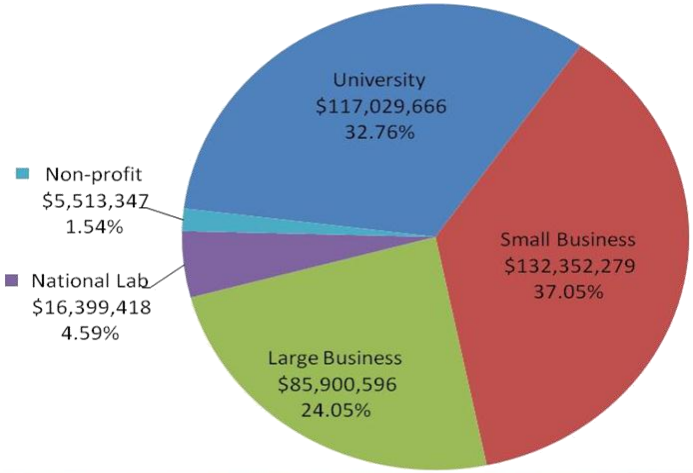
- Assistant Secretary For Energy Efficiency And Renewable Energy
- Assistant Secretary for Electricity Delivery and Energy Reliability
- Assistant Secretary for Nuclear Energy
- Assistant Secretary For Environmental Management
- Assistant Secretary for Fossil Energy
- Legacy Management
- Civilian Radioactive Waste Management

- Energy Information Administration
- Bonneville Power Administration
- Southwestern Power Administration
- Southeastern Power Administration
- Western Area Power Administration
- Management
- Health Safety & Security
- Hearings & Appeals

- Assistant Secretary for Policy & International Affairs
- Assistant Secretary for Congressional & Intergovernmental Affairs
- General Counsel
- Chief Financial Officer
- Chief Human Capital Officer
- Chief Information Officer
- Intelligence & Counterintelligence
- Public Affairs
- Economic Impact & Diversity

ARPA-E Currently has six focused programs plus a broad portfolio of projects from its first solicitation

Broad Solicitation



Transportation

Electrofuels

BEEST

Stationary Power

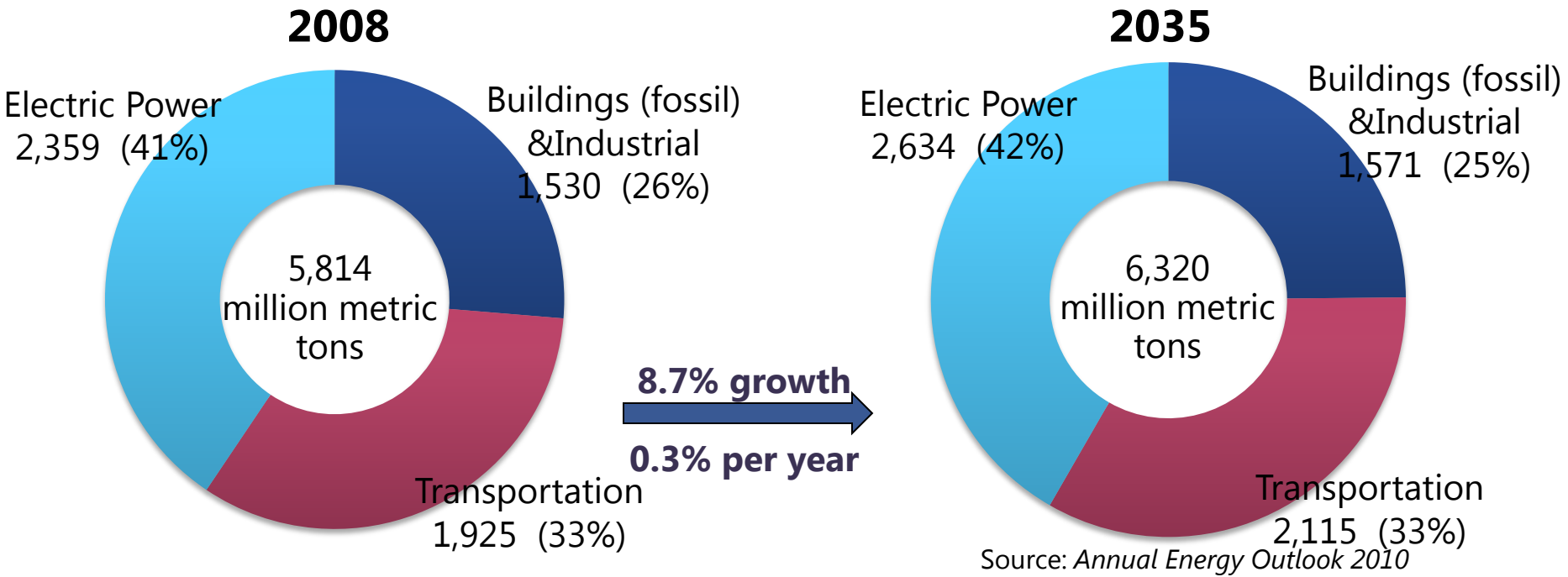
IMPACCT

GRIDS

End-Use Efficiency

BEETIT

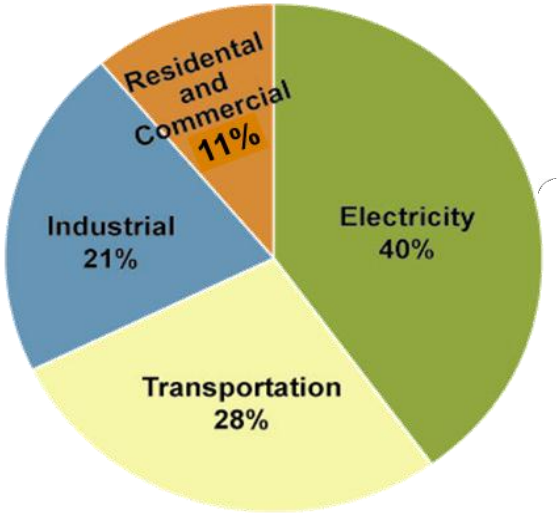
ADEPT



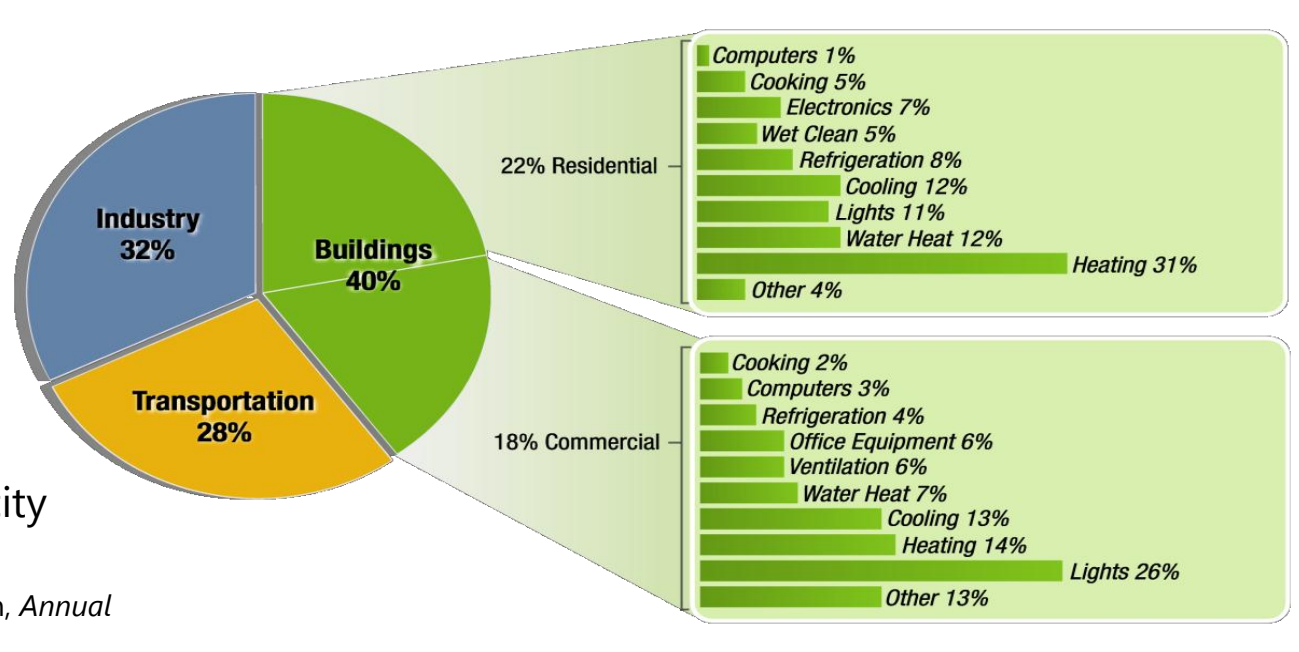
Source: *Annual Energy Outlook 2010*

Historically, electrical power has been the largest source of CO_2 emissions, the main contributor to climate change. But in the upcoming decades electricity can become a key lever in evolving towards a low carbon economy.

- International Electricity Partnership, Dec. 2009



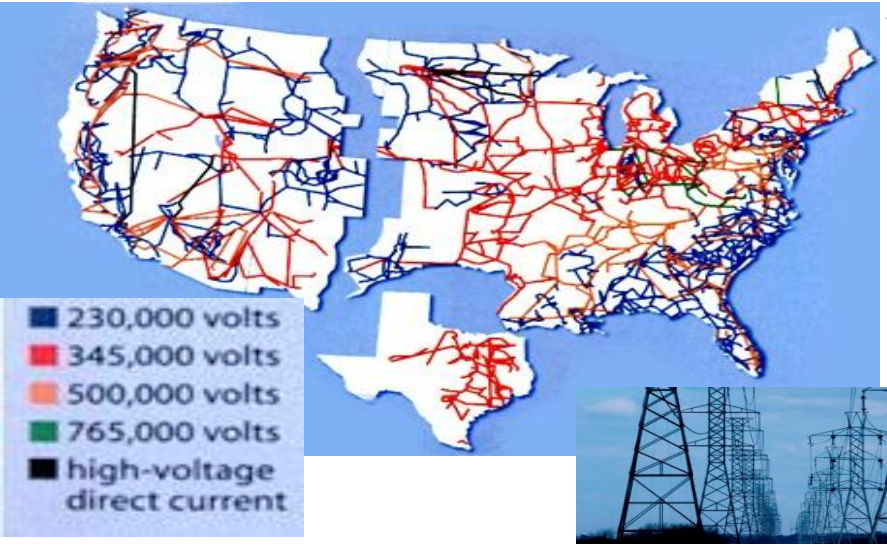
Primary Energy Use by Sector



Electricity

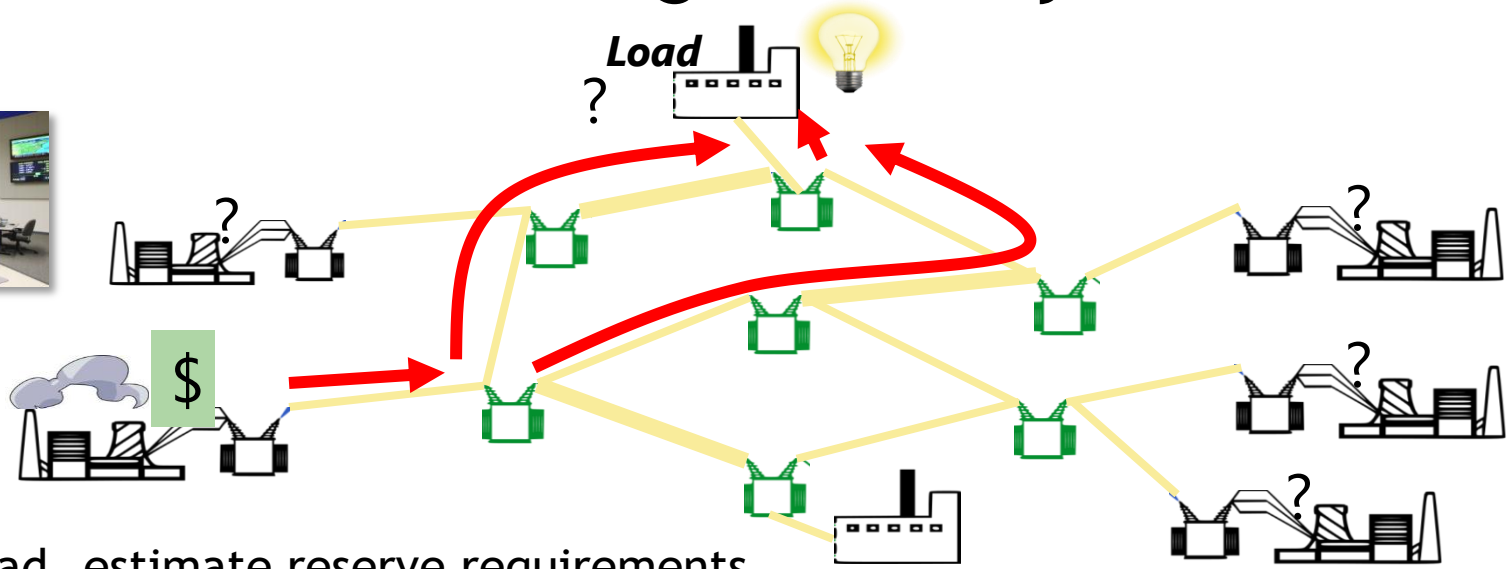
Source: Energy Information Administration, *Annual Energy Review 2008*

Electricity Transmission



- $354 B electricity sales
- 166,000 miles operated by 500 companies
  98% AC, voltages > 100kV
- 3 major interconnections
- 3,170 utility companies
- Over 140 control areas
- 14,000 transmission substations
- ~44 million liquid-immersed distribution transformers in service in 1995
- ~12 million dry transformers

Delivering Electricity



Determine load…estimate reserve requirements

…open auction market (renewables have pre-arranged costs)

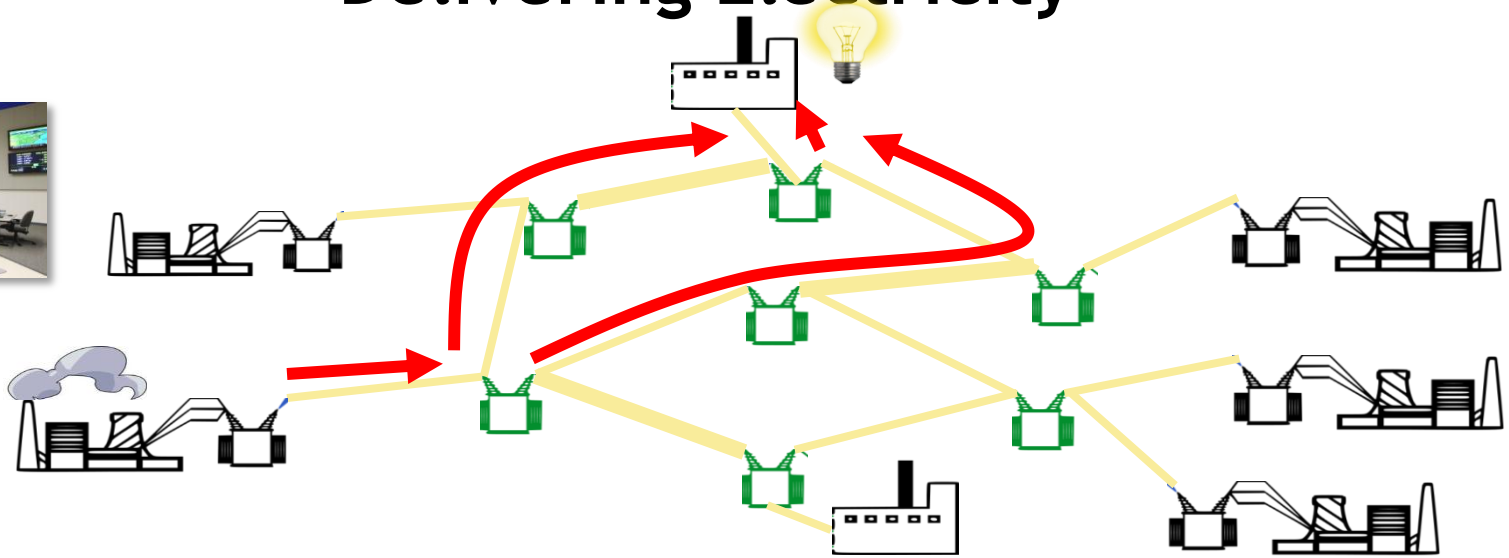
…contingency (N-1) analysis and unit commitment (set price)

…generator dispatch and power flows into the grid

…electrons flow along path of least resistance

…the load draws power from the grid

Delivering Electricity

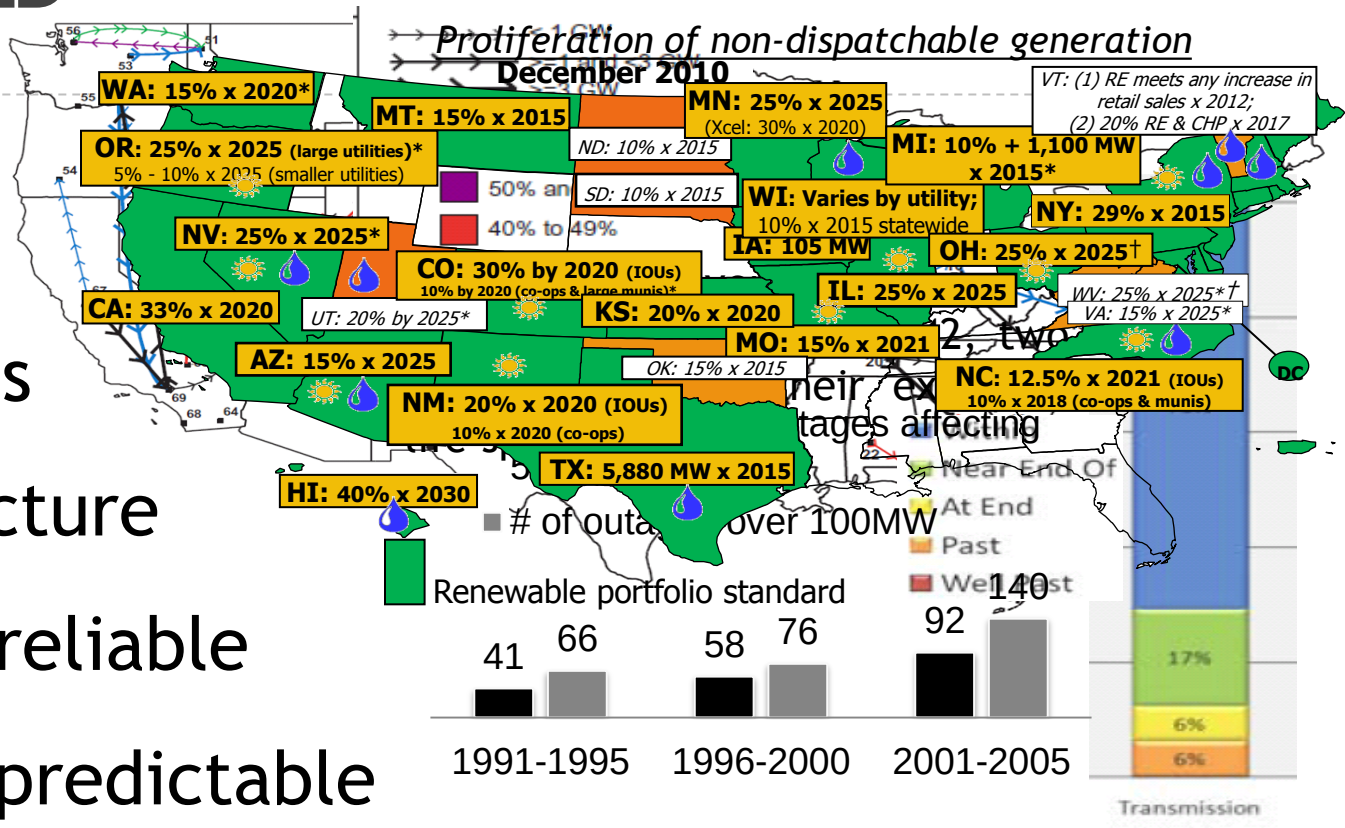


- Negligible storage – just in time delivery of power
- Centrally controlled
- Negligible control of path – Joules are indistinguishable

Not the internet

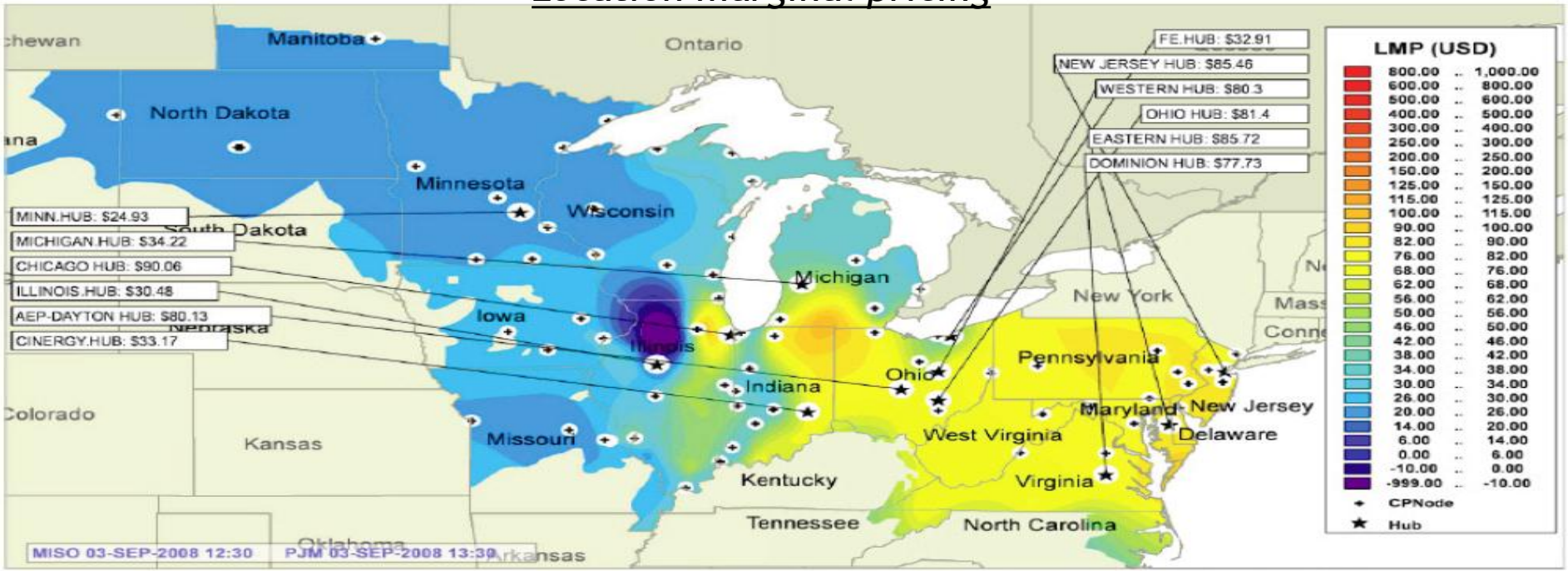
STATE OF THE GRID

- Congested Lines
- Aging Infrastructure
- Increasingly unreliable
- Increasingly unpredictable



INEFFICIENT MARKETS

Location marginal pricing



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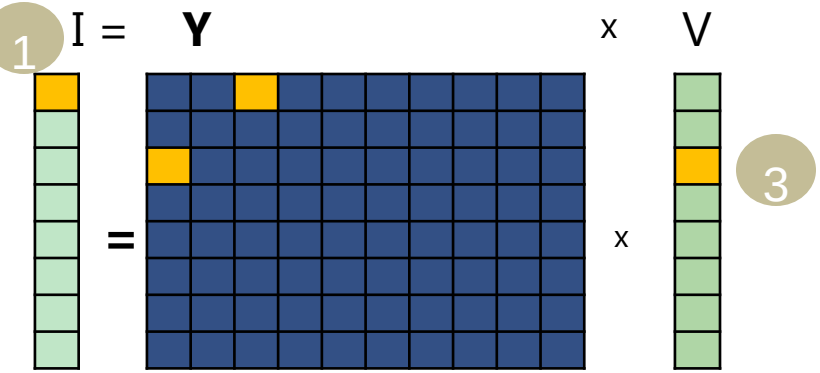
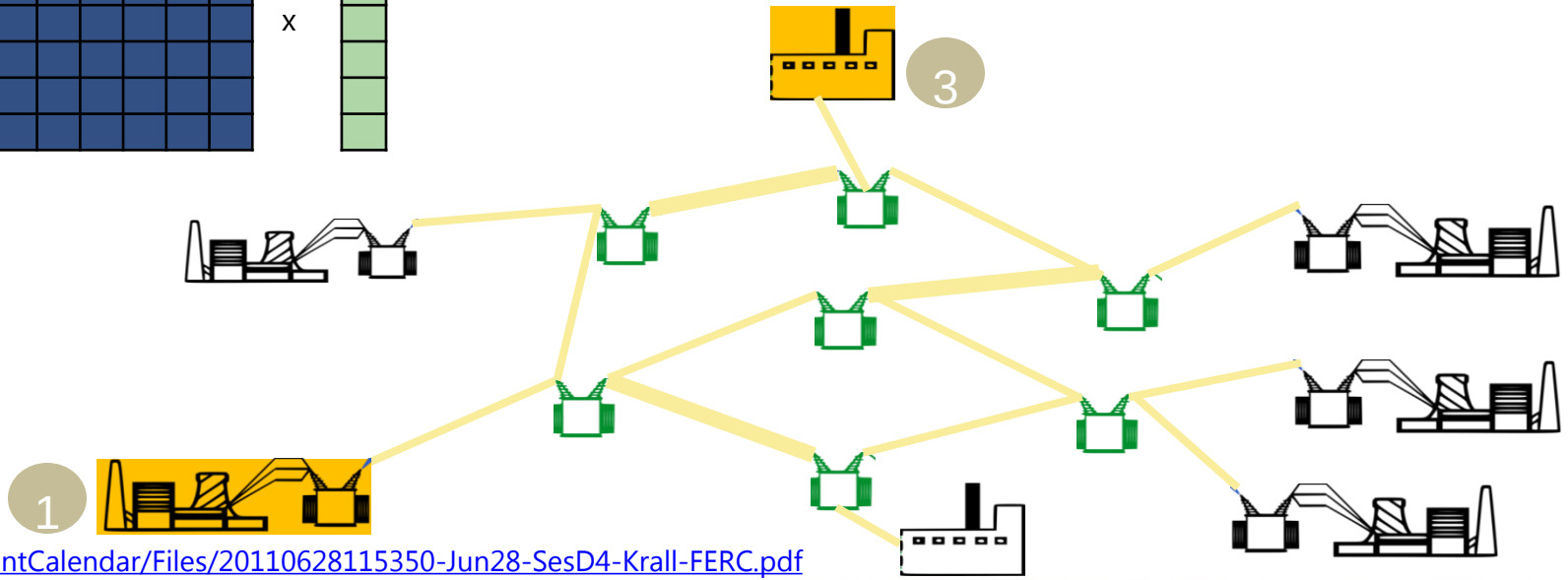
Designing Power Flow



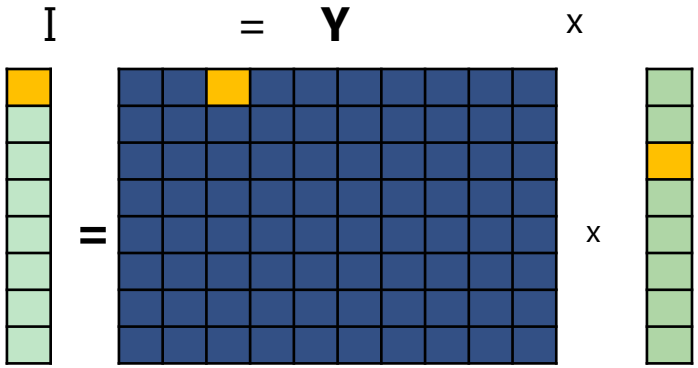
Minimizing the cost of fuel to deliver power is Hard (NP)

- constrained by system balance, nodal balance, transmission constraints, generator constraints

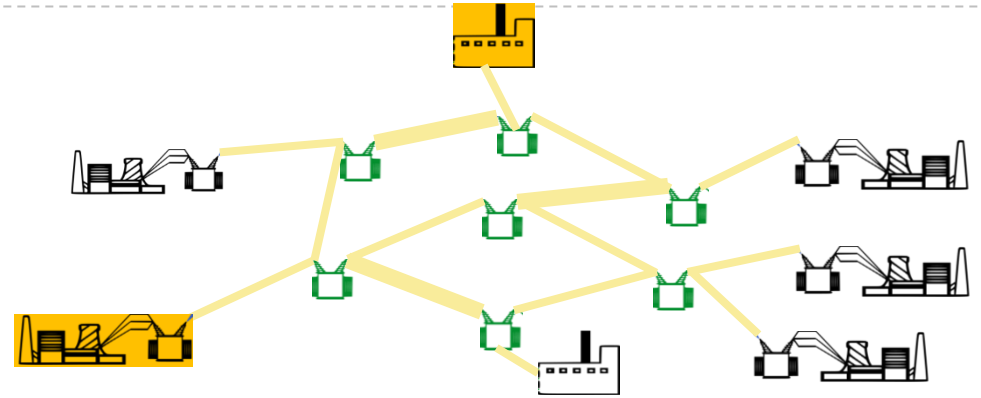


http://www.ferc.gov/EventCalendar/Files/20110628115350-Jun28-SesD4-Krall-FERC.pdf

Controlling Power Flow



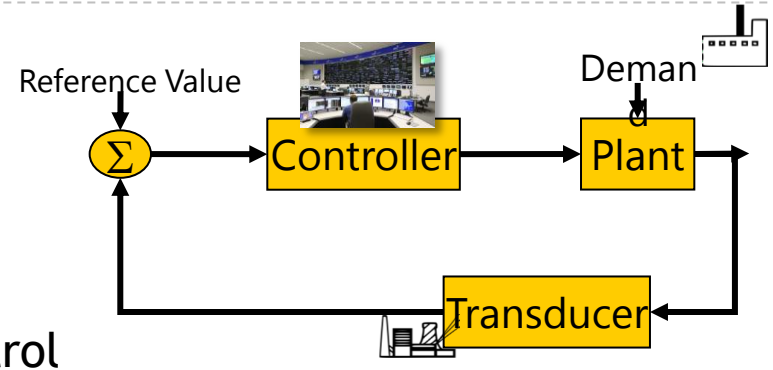
V



What kind of control?

- Linear vs. Non-linear
- Deterministic vs. Stochastic
- Time-invariant vs. Time-varying
- Continuous-time vs. Discrete-time

Controlling Power Flow



Power Flow Control

- Feed-forward control
- Assume:
  - Linear
  - Deterministic
  - Time Invariant

- Central control

Error (Frequency, Voltage)

- Feedback control
- Account for
  - Non-linearity
  - Dynamics

- Distributed or local control

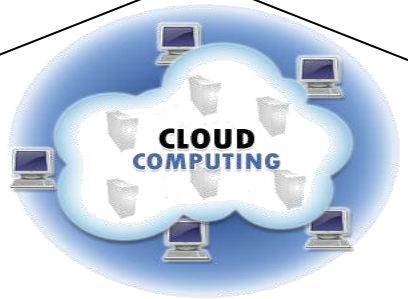
Control Infrastructure

Improved Sensing

A PMU measures
- Current (Hall sensor)
- Frequency (LC Circuit)
- Time (GPS)
- Voltage
- Relative Phase
- **Sample 30 msec**
- Petabyte-scale data

Improved Communications

Grid Connected Router
- Low-latency
- MPLS
- Cyber security
- 100-600 μs for crypto



Distributed computing
- Fast
- Secure
- Resilient

Need total control latency of 10-100ms

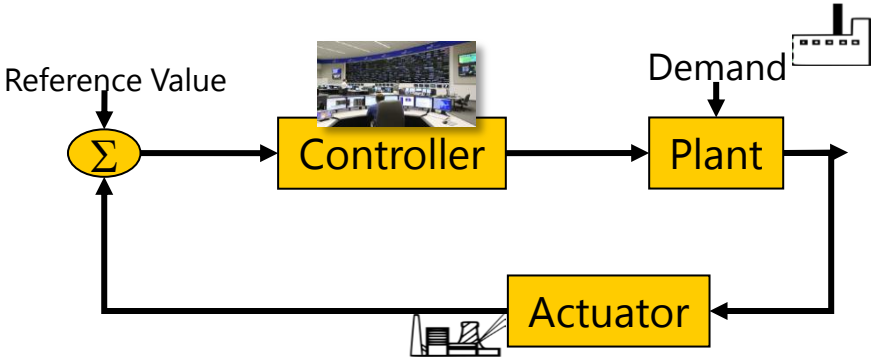
Improved Computation

Control Challenges

- Traditional control theory assumes centralized feedback control.

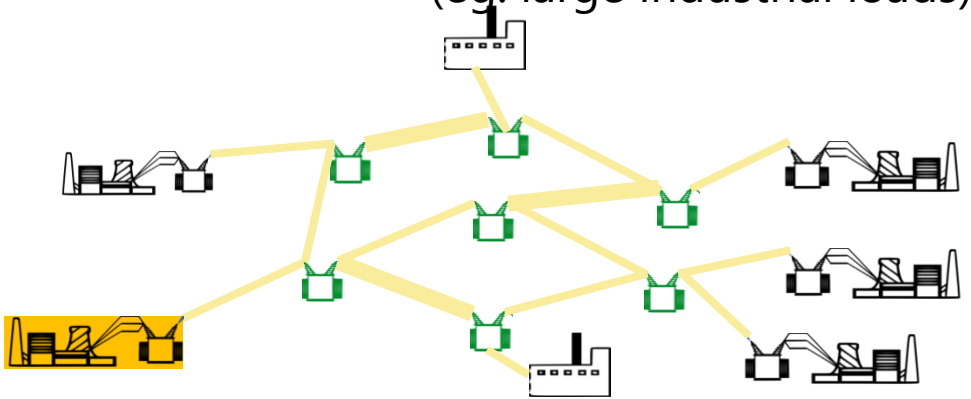
- Not always feasible for large-scale distributed systems:
  - Inability to communicate with all subsystems
  - Incomplete/imperfect information
  - Complexity of centralized decision-making
  - Asynchrony
  - Heterogonous decision-makers with different objective and uncertain responses

Actuators



Demand Response

Schedule demand
(eg. large industrial loads)



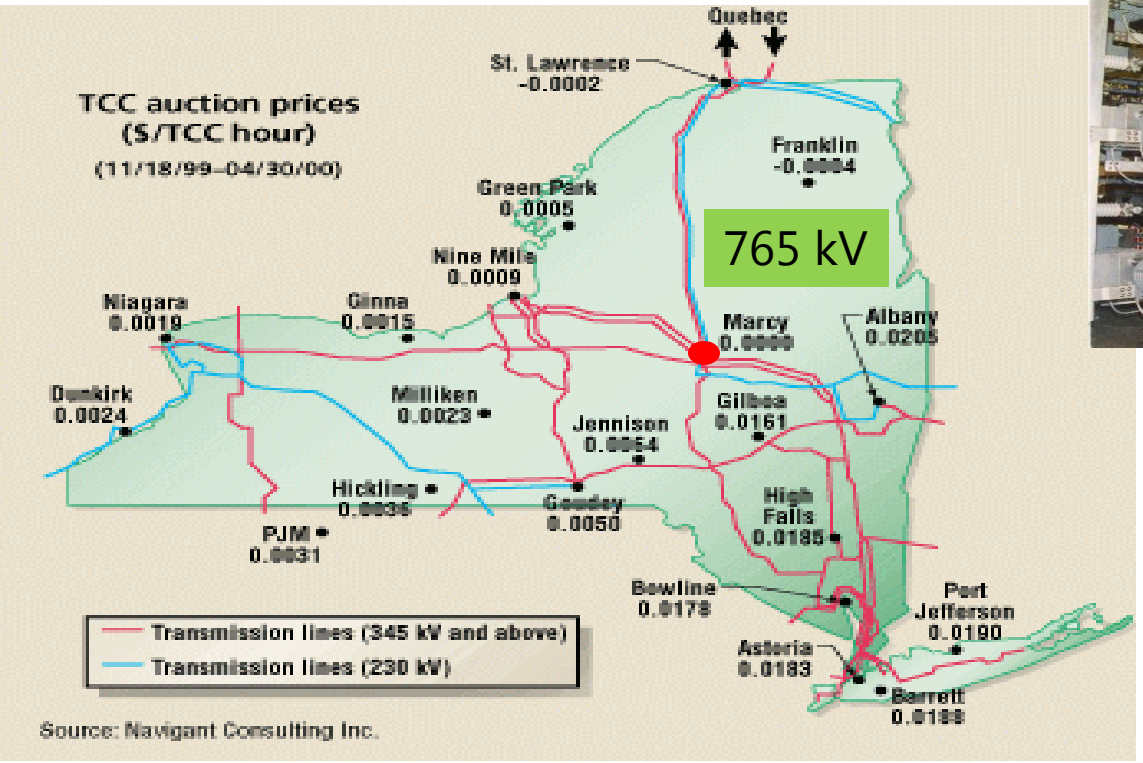
Control in the Grid

Flexible AC Transmission System:

- Static VAR
- STATCOM
- UPFC

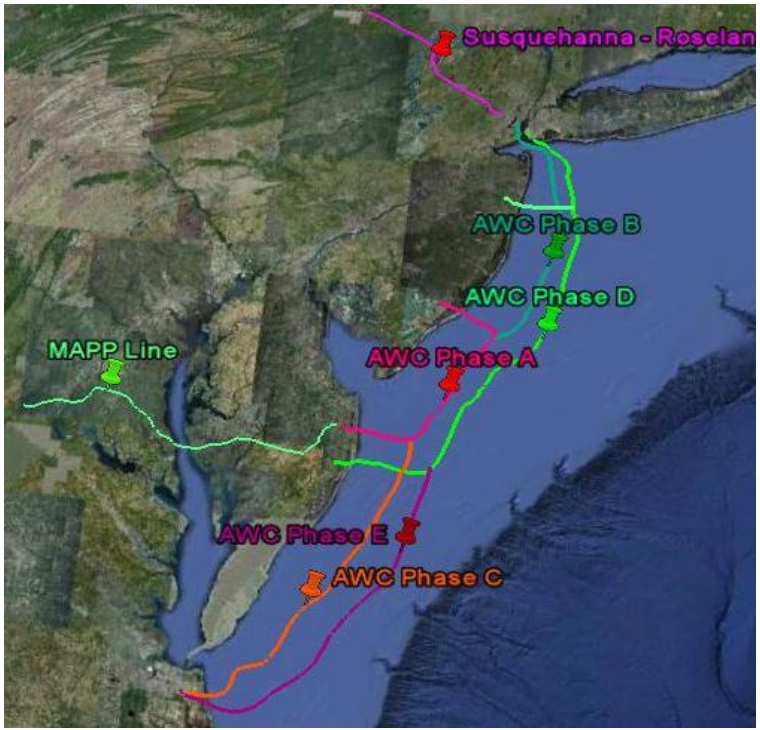
Power Flow Controller (AC)

AC Univesal Power Flow Controller



Power Flow Controller (DC)

Multiterminal HVDC

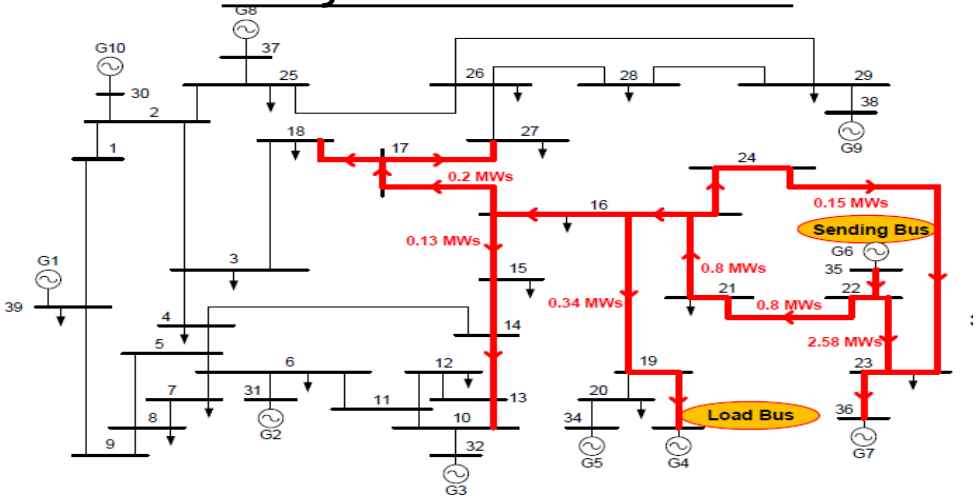


- $5.2 B (5 phases)
- Offshore multi-terminal voltage-sourced converter (VSCs) backbone
- 6000 MWs of offshore wind farms in federal waters off of NJ, DE, MD & VA
- PJM Total Peak Load = 144,644 MW
- Funded by Google, Good Energy & Marubeni Power
- Optimal power flow scheduling over 2000-MW transfer capability

Benefits of Routing Power

GA Tech study of simplified IEEE 39 Bus system with 4 control areas, operation simulated for 20 years, 20% RPS phased in over 20 years, sufficient transmission capacity added each year to eliminate curtailment of renewable generation

Today: Uncontrolled Flows



Base Case: 3.4 MW sent; 0.34 MW recd

Power Routing

- BAU case requires upgrade of 3 inter-regional paths, for a total of 186,000 MW-MILES
- Power flow control to route power along underutilized paths, 36,000 MW-miles of new lines needed, only 20% of BAU

Control Architecture

- Topic Areas:
  - Grid monitoring
  - Grid communications
  - Distributed computing
  - Distributed optimization

Benefits of Routing Power

- Improved asset utilization
- Improved alignment of customer needs and supply
- More resilient network
  - greater infrastructure security & reliability
- Load owner can transact with the generator