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Presentation Outline

- What is the smart grid? (Short Answer)
- Why is it being created?
- Who stands to benefit?
- What is the smart grid? (Long Answer)
- Some Examples
- How does one participate?
What is the Smart Grid?

**NIST Smart Grid Collaboration Wiki:**

By integrating an end-to-end, advanced communications infrastructure into the electric power system, a Smart Grid can provide consumers near real-time information on their energy use, support pricing that reflects changes in supply and demand, and enable smart appliances and devices to help consumers avoid higher energy bills.
What is the Smart Grid?

DOE Smart Grid Primer:

The electric industry is poised to make the transformation from a centralized, producer-controlled network to one that is less centralized and more consumer interactive.

The move to a smarter grid promises to change the industry’s entire business model and its relationship with all stakeholders, involving and affecting utilities, regulators, energy service providers, technology and automation vendors and all consumers of electric power.
What is the Smart Grid?

Wikipedia:

A smart grid is an electrical grid that uses information and communications technology to gather and act on information, such as information about the behaviors of suppliers and consumers, in an automated fashion to improve the efficiency, reliability, economics, and sustainability of the production and distribution of electricity.
What is the Smart Grid?
What is the Smart Grid?
What is the Smart Grid?

![Diagram of the Smart Grid]

- Physical Layer
- Market Layer
- Cyber Layer
- Transmission Network
- Generators
- Consumers
The Transmission Network

**GENERATION**
Electricity is generated at various kinds of power plants by utilities and independent power producers.

**TRANSMISSION**
Electric transmission is the vital link between power production and power usage. Transmission lines carry electricity at high voltages over long distances from power plants to communities.

**DISTRIBUTION**
Electricity from transmission lines is reduced to lower voltages at substations, and distribution companies then bring the power to your home and workplace.
Some Transmission Network Examples

6 – Bus Network

15 – Bus Network
Some Larger Examples

54 – Bus Network

118 – Bus Network
What is the Smart Grid?

![Diagram of the Smart Grid]

- **Physical Layer**
  - Generators
  - Transmission Network
  - Consumers

- **Cyber Layer**
  - Market Layer

- **Market Layer**
  - Financial transactions and information exchange
What’s wrong with the Dumb Grid?

- Gas Turbines
- Coal Fired
- Nuclear

A balance between power generation and power consumption must be maintained at all times.

Consumer Demand

[Graph showing consumer demand over days]
What’s wrong with the Dumb Grid?

- Gas Turbines
- Coal Fired
- Nuclear

If demand is low then few generators needed

Consumers

User Demand

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What’s wrong with the Dumb Grid?

If demand is high then many generators needed

Gas Turbines
Coal Fired
Nuclear

Consumers

Consumer Demand

If demand is high then many generators needed
What’s wrong with the Dumb Grid?

Gas Turbines

Coal Fired

Nuclear

Renewable Sources

Consumers

Consumer Demand
What’s wrong with the Dumb Grid?

If demand is low and wind is high then almost no generators needed

Gas Turbines

Coal Fired

Nuclear

Renewable Sources

Consumers

Consumer Demand

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What’s wrong with the Dumb Grid?

Gas Turbines
Coal Fired
Nuclear
Renewable Sources

If demand is high and wind is low then all generators needed

Consumers

Renewable Sources

Consumer Demand
Some Solutions to the Dispatch Problem

Gas Turbines

Coal Fired

Nuclear

Renewable Sources

The Smart Grid

Consumers

Massive Energy Storage

Consumer Flexibility

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Presentation Outline

• What is the smart grid? (Short Answer)
• Why is it being created?
• Who stands to benefit?
• What is the smart grid? (Long Answer)
• Some Examples
• How does one participate?
What is the Smart Grid?
Motivating Consumer Flexibility
Centralized Power Systems

Gas Turbines
Coal Fired
Nuclear
Renewables

Electric Utility

Consumers

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Deregulated Power Systems

Gas Turbines
Coal Fired
Nuclear
Renewables

Independent System Operator

Consumers
Consumers
Consumers
Deregulated Power Systems

• Managed by an Independent System Operator (ISO)
• Auction based rather than centralized decisions
• Pay as highest accepted bid (usually)
Cost of Power Generation

- **Coal Plant**
- **Gas Turbine**

![Graph showing the cost of power generation for coal plants and gas turbines. The graph plots operating costs against power output.]
Price of Electricity

If demand is 600MW then, electricity price is $18/MW-hr
Price of Electricity

If demand is 1200 MW then, electricity price is $33/MW-hr
Time Dependent Pricing for Electricity

PJM Western Hub, Day-Ahead prices: June 1, 2001 through June 20, 2001,
Real-time Pricing for Electricity

Texas Hub: July 2012
Consumers

Load-Serving Entity

Gas Turbines
Coal Fired
Nuclear
Renewables

ISO

LSE
LSE
LSE

Electricity price to consumers is the annual average

Consumers
Consumers
Consumers
Why consider time dependent prices?

- Average price includes price spikes
- Flexible consumers can beat the average by avoiding spikes
- Flexible consumers can beat the average by exploiting low price periods
- Time dependent prices might be imposed on consumers, so now is the time to prepare
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- How does one participate?
Back to the Dumb Grid w/o Deregulation

Gas Turbines

Coal Fired

Nuclear

Consumers

Consumer Demand

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Time-Scale Decomposition

Operational Time-Scale

Hours

Minutes

Seconds

Minutes

Seconds

Real-time Optimization

Multivariate Constrained Control

Regulatory (PID) Control

Chemical Plant

Safety Systems and Emergency Shutdown
Load Flow Analysis

Provides the underlying model for a transmission network

Bus 1

Bus 2

Bus 3

Bus 4

Bus 5

$E_1$, $I_1$

$E_2$, $I_2$

$E_3$, $I_3$

$E_4$, $I_4$

$E_5$, $I_5$
Load Flow Analysis (current and voltage)

Voltage at each bus: \( E = [E_1 \ E_2 \ E_3 \ E_4 \ E_5]^T \)

Current injected at each bus: \( I = [I_1 \ I_2 \ I_3 \ I_4 \ I_5]^T \)

Admittance matrix:

\[
Y = \begin{bmatrix}
Y_1 \\
Y_2 \\
Y_3 \\
Y_4 \\
Y_5 \\
\end{bmatrix}
\]

Voltage-current relation: \( I = YE \)
Load Flow Analysis (injected power)

Power injected at bus $k$:
\[
\Rightarrow \quad S_k = E_k I_k^* \\
\Rightarrow \quad S_k = E_k Y_k^* E^*
\]

* is complex conjugate

Voltage in phasor form:
\[
E_k = U_k e^{j\theta_k}
\]

Complex power at bus $k$:
\[
S_k = P_k + jQ_k
\]

Active Power: $P_k$

Reactive Power $Q_k$
Load Flow Analysis (bus types)
Time-Scale Decomposition

Operational Time-Scale

Unit Commitments

Optimal Power Flow

Frequency and Voltage Control

Electric Power Network

Security Constraints and Contingency Response

Real-time Optimization

Multivariate Constrained Control

Regulatory (PID) Control

Chemical Plant

Safety Systems and Emergency Shutdown

Hours

Minutes

Seconds

Seconds
Frequency Control
Frequency Control

• Servo-loop at each generator

• **Control Variable:** System frequency

• **Manipulated Variable:** Mechanical power

• **Disturbance:** Load power
Voltage Control

Voltage Control-Loop?
Load Flow Analysis (imaginary part)

Reactive Power and Voltage Magnitude coupled

Transmission lines consume Reactive Power

Generators need to produce Reactive Power to provided Voltage support
Voltage Control

• Servo-loop at each reactive generator

• **Control Variable**: Voltage magnitude

• **Manipulated Variable**: Reactive power injection

• **Disturbances**: Reactive load and losses
Time-Scale Decomposition

Unit Commitments

Optimal Power Flow

Frequency and Voltage Control

Electric Power Network

Security Constraints and Contingency Response

Operational Time-Scale

Hours

Minutes

Seconds

Real-time Optimization

Multivariate Constrained Control

Regulatory (PID) Control

Chemical Plant

Safety Systems and Emergency Shutdown
Optimal Power Flow?

System operator selects generator states such that

- all load demands are met: \( P_k \) and \( Q_k \) at loads fixed

- all buses satisfy voltage constraints: \( 0.9 \leq U_k \leq 1.1 \) p.u.

- all transmission lines are below limits: \( P_{km} \leq P_{km}^{\text{max}} \)

\[
P_{km} = \frac{U_k U_m}{X_{km}} \sin(\theta_k - \theta_m)
\]

And optimizes with respect to

- operating cost
- transmission line losses
- active and reactive reserves
Generator Costs

\[ c_{Gi} = c_{0i} + c_{1i}P_{Gi} + c_{2i}(P_{Gi})^2 \]

$110$/MWhr  
$65$/MWhr
Time-Scale Decomposition

- **Unit Commitments**
  - Optimal Power Flow
    - Frequency and Voltage Control
  - Electric Power Network
    - Security Constraints and Contingency Response

- **Operational Time-Scale**
  - Hours: Real-time Optimization
  - Minutes: Multivariate Constrained Control
  - Seconds: Regulatory (PID) Control
    - Chemical Plant
      - Safety Systems and Emergency Shutdown
Unit Commitment Problem

Similar to Optimal Power Flow

- Explicit load flow analysis
- Larger horizon (day-ahead and hour-ahead)
- Optimizes with respect to
  - Costs, losses, reserves (same as OPF)
  - Integer variables for unit start-up and shut-down
Operational Time-Scale

Hours

Minutes

Seconds

Electric Power Network

Optimal Power Flow

Frequency and Voltage Control

Unit Commitments

Real-time Optimization

Multivariate Constrained Control

Regulatory (PID) Control

Chemical Plant

Safety Systems and Emergency Shutdown

Security Constraints and Contingency Response
What if a generator trips off-line?

A balance between power generation and power consumption must be maintained at all times.
Spinning Reserves and N-1 Security

\[ Q_k \]

\[ P_k \]
Time-Scale Decomposition

Operational Time-Scale

Unit Commitments
- Optimal Power Flow
  - Frequency and Voltage Control
  - Electric Power Network
  - Security Constraints and Contingency Response

Real-time Optimization
- Multivariate Constrained Control
  - Regulatory (PID) Control
  - Chemical Plant
  - Safety Systems and Emergency Shutdown
The Not So Dumb Grid!

- Centralized Operation
  - Unit Commitment Problem (UCP)
  - Optimal Power Flow (OPF)
  - Frequency Control
  - Emergency Planning (N-1 Security)
Deregulated Operation of “Dumb” Grid

Centralized Operation

- Unit Commitment Problem (UCP)
- Optimal Power Flow (OPF)
- Frequency Control
- Emergency Planning (N-1 Security)

Deregulated Operation

- Day-Ahead Market
- Real-Time Market
- Regulation Market
- Frequency Control
- Emergency Capacity Market
Where do the consumers fit in?

Gas Turbines

Coal Fired

Nuclear

Renewable Sources

The Smart Grid

Massive Energy Storage

Consumers

Consumer Flexibility
Demand Response

Centralized Operation

- Unit Commitment Problem (UCP)
- Optimal Power Flow (OPF)
- Frequency Control
- Emergency Planning (N-1 Security)

Deregulated Operation

- Day-Ahead Market
- Real-Time Market
- Regulation Market
- Frequency Control
- Emergency Capacity Market
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Thermal Energy Storage in Building HVAC

Heat from Environment → Building → Heat to Chiller → Power Consumption

Heat from Building → Heat to Chiller

Heat to TES

Thermal Energy Storage

Heat from Environment → Building → Heat to Chiller → Chiller → Heat to TES → Thermal Energy Storage

Chiller Cooling Load (Qc)

Time (days)

Heat Flow (KW)
Hot Oil Utility Plant

- **Hot Utility Oil** (to the process)
- **Cold Utility Oil** (from the process)
- **Fuel**

Diagram:

- Hot Utility Oil
- Cold Utility Oil
- Fuel

Furnace

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Utility Plant with Electric Power Option

- Hot Utility Oil (to the process)
- Cold Utility Oil (from the process)
- Electric Power (from the grid)
- Electric Heater
- Fuel
- Furnace
Energy Costs in 2005

The graph shows the energy costs for electricity and natural gas throughout the year 2005. The x-axis represents the day of the year, while the y-axis shows the energy cost per MWhr. The graph indicates fluctuating energy costs with higher peaks and troughs for both electricity and natural gas throughout the year.

Electricity costs are represented by a green dashed line, while natural gas costs are shown by a brown line. The overall trend shows an increase in energy costs over the year.
Operating Profiles in 2005

![Graph showing energy rate and cost over the year 2005. The graph compares electricity cost, fuel cost, electric power, and fuel usage.](image)
Energy Costs Change

Energy Costs 2005

Energy Costs 2012

Electricity
Natural Gas

Day of the Year

Energy Cost ($/MWhr)
Alcoa and Aluminum Smelting

- 40% of Costs to Produce Aluminum is Electricity
- Production is Directly Proportional to Power Input
Evolution of Alcoa Demand Response

- Smelting provides steady 24/7 grid load
- Limited collaboration with energy system
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- Watch the other Presentations of the Session
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Conclusions

• What is the smart grid?
  Demand Response!

• Why is it being created?
  Lower Energy Costs!

• Who will benefit?
  Those with Operational Flexability!

• How does one participate in the smart grid?
  Stick around!