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Presentation Outline

- What is the smart grid?
- Why would the chemical industry be interested?
- How does one participate in the smart grid?
- Who should participate in the smart grid?
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?

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?

**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?
What’s wrong with the Dumb Grid?

Gas Turbines

Coal Fired

Nuclear

Consumers

Consumer Demand
What’s wrong with the Dumb Grid?

Gas Turbines

Coal Fired

Nuclear

If demand is low then few generators needed

Consumers

Consumer Demand
What’s wrong with the Dumb Grid?

If demand is high then many generators needed

Gas Turbines
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If demand is high then many generators needed

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What’s wrong with the Dumb Grid?

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Renewable Sources

Consumers

Consumer Demand

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What’s wrong with the Dumb Grid?

Gas Turbines

Coal Fired

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

Consumers

Renewable Sources

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

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

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

Consumer Demand
Some Solutions to the Dispatch Problem

Gas Turbines

Coal Fired

Nuclear

Renewable Sources

The Smart Grid

Massive Energy Storage

Consumers

Consumer Flexibility

Advanced Communication Network

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Motivating Consumer Flexibility
Centralized Power Systems

- Gas Turbines
- Coal Fired
- Nuclear
- Renewables

Electric Utility

Consumers

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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

![Graph showing the cost of power generation for Coal Plant and Gas Turbine.](image)
If demand is 600MW then, electricity price is $18/MW-hr
Price of Electricity

If demand is 1200MW then, electricity price is $33/MW-hr.
Real-time 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

Electricity Price ($/MWhr)

Time (days)
Electricity price to consumers is the annual average.
Why of Interest to the Chemical Industry?

• 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
• Real-time prices might be imposed on consumers, so now is the time to prepare
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Presentation Outline

- What is the smart grid?
- Why would the chemical industry be interested?
- How does one participate in the smart grid?
  - Power Generation Example
  - HVAC Example
  - Chemical Plant Example
- Who should participate in the smart grid?
Integrated Gasification Combined Cycle

[Diagram of the Integrated Gasification Combined Cycle process, showing the flow of coal, water, syngas, and the production of electricity and sludge.]
Integrated Gasification Combined Cycle with Dispatch Capability

\[ \dot{\mathcal{M}}_{\text{H}_2} - \frac{P_G}{\beta} \]
\[ 0 \leq M_{\text{H}_2} \leq M_{\text{H}_2}^{\text{max}} \]
\[ 0 \leq P_G \leq P_G^{\text{max}} \]

\[ P_G = \beta \nu_{\text{H}_2,G} \]
Economic Model Predictive Control

\[
\min_{x,u} \int_{t}^{t+T} g(x,u,w) \, d\tau
\]

s.t. \[z = h(x,u,w)\]

\[z_{\min} \leq z(\tau) \leq z_{\max}\]

Economic Objective

\[g(x,u,w) = - \text{(Instantaneous Profit)}\]
Literature on Economic MPC

• Conceptual Development and Stability Issues: Rawlings and Amrit (2009); Diehl, et al. (2011); Huang and Biegler (2011); Heidarinejad, et al. (2012)

• Process Scheduling: Karwana and Keblisb (2007); Baumrucker and Biegler (2010); Lima et al. (2011); Kostina et al. (2011)

• Building HVAC Systems: Braun (1992); Morris et al. (1994); Kintner-Meyer and Emery (1995); Henze et al. (2003); Braun (2007); Oldewurtel et al. (2010), Ma et al. (2012); Mendoza and Chmielewski (2012)

• Power Scheduling: Zavala et al. (2009); Xie and Ilić (2009), Hovgaard, et al. (2011), Omell and Chmielewski (2013)
EMPC Applied to IGCC with Dispatch

\[
\min_{P_G} \int_{t}^{t+T} -C_e P_G d\tau
\]

s.t. \( \dot{\Lambda}_{H_2} - \frac{P_G}{\beta} \)

\[
0 \leq M_{H_2} \leq M_{H_2}^{\text{max}}
\]

\[
0 \leq P_G \leq P_G^{\text{max}}
\]

\( C_e(t) \) is the cost (or value) of electricity
EMPC Applied to IGCC with Dispatch

- Energy Value ($/MWhr)
- Generated Power (MW)
- H$_2$ in Storage (tonnes)

Time (days)
Presentation Outline

- What is the smart grid?
- Why would the chemical industry be interested?
- How does one participate in the smart grid?
  - Power Generation Example
  - HVAC Example
  - Chemical Plant Example
- Who should participate in the smart grid?
HVAC Power Consumption

Cooling is mainly required during the hottest times of a day...

Traditional HVAC System

- Heat is removed from the building by a chiller
- Chiller consumes electric power
- Heat removal correlated with real-time electricity prices
Correlation Between Cooling Load and Energy Prices

August 3 - 6, 2001.
Pittsburgh, PA.
Thermal Energy Storage (TES)

TES helps time shift electricity consumption to periods of low electricity prices.
Impact of Thermal Energy Storage

Heat from Environment \(\rightarrow\) Building \(\rightarrow\) Heat from Building \(\rightarrow\) Heat to Chiller \(\rightarrow\) Chiller \(\rightarrow\) Heat to TES \(\rightarrow\) Thermal Energy Storage

- Heat Flow (KW\(_e\))
- Time (days)

- Heat to Chiller
- Heat from Room

Heat Flow (KW\(_e\))

Time (days)
EMPC Simulation with TES

Note: EMPC Prediction Horizon is 12 hours
Presentation Outline

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Who should participate in the Smart Grid?

Those with revenue gains larger than investment costs!
Impact of Thermal Energy Storage

Heat from Environment → Building → Heat from Building → Heat to Chiller → Chiller

Power Consumption

Heat from Environment → Building → Heat to Chiller

Chiller

Thermal Energy Storage

Thermal Energy Storage

Chiller

Heat to Chiller

Heat from Room

Chiller Cooling Load (Qc)

Time (days)

Heat Flow (KWe)

23 24 25 26

200
300
400
500
600

200 300 400 500 600

Heat to Chiller

Heat from Room
Capital Cost of Thermal Energy Storage

?? $$$$
Design Questions

- What are the energy expenditures?
- What is the appropriate size of the TES?
- Is there a benefit to changing chiller size?
Chiller and TES Sizing

Equipment costs:

Chiller: \( C_c = 500 \ $/kW_e \)
TES: \( C_s = 28.4 \ $/kW_{Thr} \)

Present value parameters:

\( r_i = 7\% \)
\( n = 30\text{yrs} \)
\[ PV_f = 365 \times 24 \frac{1}{r_i} \left[ 1 - \frac{1}{(1 + r_i)^n} \right] \]
### Chiller and TES Sizing

<table>
<thead>
<tr>
<th>$\Sigma_{ce} \ ($/\text{MWhr})^2$</th>
<th>$E_s^{\text{max}} \ (\text{MW}_\text{Thr})$</th>
<th>$P_c^{\text{max}} \ (\text{kW}_\text{e})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20$^2$</td>
<td>0.05</td>
<td>113.8</td>
</tr>
<tr>
<td>45$^2$</td>
<td>1.15</td>
<td>106.5</td>
</tr>
</tbody>
</table>

⇒ 28.4 $\$/\text{kW}_\text{Thr}$ for the TES is too expensive
Utility Plant Configuration

[Diagram showing a process flow with labeled components: P1, P2, P3, P4, Hot Oil Utility, Electric Grid, Hot Oil Based Utility Plant, and corresponding flow arrows.]
Hot Oil Utility Plant

**Fuel**

**Furnace**

*Hot Utility Oil (to the process)*

*Cold Utility Oil (from the process)*
Utility Plant with Electric Power Option

- **Hot Utility Oil** (to the process)
- **Cold Utility Oil** (from the process)
- **Electric Power** (from the grid)

**Furnace**

**Electric Heater**
Energy Costs in 2005

![Energy Costs 2005 Graph](image_url)

- **Electricity**
- **Natural Gas**

Day of the Year vs. Energy Cost ($/MWhr)
Energy Costs in 2008

Energy Costs 2008

Energy Cost ($/MWhr) vs. Day of the Year

- Green dashed line: Electricity
- Red line: Natural Gas
Energy Costs in 2012

![Energy Costs 2012 Graph](image)

- **Electricity**
- **Natural Gas**
Energy Costs – Three Sample Years

Energy Costs 2005

Energy Costs 2008

Energy Costs 2012
Operating Profiles in 2005
Comparison of 2008 and 2012

- **2008**
  - Electric Power
  - Fuel Price
  - Fuel Usage

- **2012**
  - Electric Power
  - Fuel Price
  - Fuel Usage

**Graphs:**
- **Energy Rate (MW) or Cost ($/MWhr)**
- **Day of the Year**

**Legend:**
- Electricity Price
- Fuel Price
- Electric Power
- Fuel Usage
### Annual Operating Costs (in millions)

<table>
<thead>
<tr>
<th></th>
<th>2005</th>
<th>2008</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td>$37.4</td>
<td>$32.9</td>
<td>$18.8</td>
</tr>
<tr>
<td><strong>With Electric Heater</strong></td>
<td>$33.7</td>
<td>$30.3</td>
<td>$18.3</td>
</tr>
<tr>
<td><strong>Savings</strong></td>
<td>$3.7</td>
<td>$2.6</td>
<td>$0.5</td>
</tr>
<tr>
<td><strong>Percent Savings</strong></td>
<td>10%</td>
<td>8%</td>
<td>3%</td>
</tr>
</tbody>
</table>
Electric Heaters

http://www.armstrong-chemtec.com
Cost of Electric Heaters

- Cost of 5MW electric heater is $1.1 million
- Installed cost of 5MW heater is $3.3 million

- If economy-of-scale is linear, then
  - 35MW installed is $23.1 million
- If economy-of-scale is 0.6 rule, then
  - 35MW installed is $10.6 million
## Economic Analysis

<table>
<thead>
<tr>
<th></th>
<th>2005</th>
<th>2008</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Savings from electric heater</strong></td>
<td>$3.7</td>
<td>$2.6</td>
<td>$0.5</td>
</tr>
<tr>
<td><strong>Heater Cost (Linear EOS)</strong></td>
<td>$23.1</td>
<td>$23.1</td>
<td>$23.1</td>
</tr>
<tr>
<td><strong>Payback (years)</strong></td>
<td>6.2</td>
<td>8.8</td>
<td>46</td>
</tr>
<tr>
<td><strong>Heater Cost (0.6 Rule EOS)</strong></td>
<td>$10.6</td>
<td>$10.6</td>
<td>$10.6</td>
</tr>
<tr>
<td><strong>Payback (years)</strong></td>
<td>2.8</td>
<td>4.1</td>
<td>21</td>
</tr>
</tbody>
</table>
• 40% of Costs to Produce Aluminum is Electricity

• Production is Directly Proportional to Power Input

• Process Focused Demand Response – Not Aux. Load
Evolution of Alcoa Demand Response

**Base Load Consumption**
- Smelting provides steady 24/7 grid load
- Limited collaboration with energy system

**Traditional Demand Response**
- Alcoa provides emergency shutdown capability
- Smelter a last resort ancillary service

**Dynamic Demand Response**
- MISO remotely controls 75 MW of smelter load in real time
- Enables dynamic grid regulation
Utility Plant with Electric Power Option

- **Hot Utility Oil** (to the process)
- **Cold Utility Oil** (from the process)
- **Electric Power** (from the grid)

**Furnace**

**Electric Heater**

**Fuel**
Conclusions

• What is the smart grid?
  Demand Response!

• Why would the chemical industry be interested?
  Lower Energy Costs!

• How does one participate in the smart grid?
  Economic MPC!

• Who should participate in the smart grid?
  Those with positive Net Present Value!
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