Smart Grid Technologies and Applications for the Industrial Sector

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Outline

• Smart grid background
• Electricity and the industrial sector
• Power markets
• Smart grid “technologies” and case studies
• Engaging the process operations research community in smart grids
• Conclusions
Global and Regional Priorities

- Motivations for smart grids are similar worldwide
  - reduce fossil fuel, especially coal, use; increase renewables penetration
  - reduce dependence on imported oil and gas
  - reduce energy costs for utilities and customers
- Countries and regions have different priorities
  - US: efficiency
  - Europe: renewables integration
  - Japan: microgrids

Electrical Power Systems (Traditional View)

- Fraction of U.S. energy needs met by electricity has grown substantially (Galvin et al., 2009)
  - 2% (1900) → 11% (1940) → 20% (1960) → 40% (today)
One smart grid motivation—renewables

Operating with 33% Renewables presents significant challenges

Large proportion of renewable sources (especially wind and solar) limits control of generation

Uncertainty not just in loads, but now in generation as well

A more active role for consumers—demand-side management
Smart Grids—Systems of Systems

*NIST Framework and Roadmap for Smart Grid Interoperability Standards.* Special Publication 1108, National Institute of Standards and Technology, US Dept. of Commerce

SmartGrids European Technology Program
### Industrial sector—power use diversity

<table>
<thead>
<tr>
<th>Industry sector</th>
<th>Total electricity used (10^6 kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemicals</td>
<td>207,107</td>
</tr>
<tr>
<td>Primary Metals</td>
<td>139,985</td>
</tr>
<tr>
<td>Paper</td>
<td>122,168</td>
</tr>
<tr>
<td>Food</td>
<td>78,003</td>
</tr>
<tr>
<td>Petroleum and Coal Products</td>
<td>60,149</td>
</tr>
<tr>
<td>Transportation Equipment</td>
<td>57,704</td>
</tr>
<tr>
<td>Plastics and Rubber Products</td>
<td>53,423</td>
</tr>
<tr>
<td>Nonmetallic Mineral Products</td>
<td>44,783</td>
</tr>
<tr>
<td>Fabricated Metal Products</td>
<td>42,238</td>
</tr>
<tr>
<td>Machinery</td>
<td>32,733</td>
</tr>
<tr>
<td>Wood Products</td>
<td>28,911</td>
</tr>
<tr>
<td>Computer and Electronic Products</td>
<td>27,542</td>
</tr>
<tr>
<td>Textile Mills</td>
<td>19,753</td>
</tr>
<tr>
<td>Beverage and Tobacco Products</td>
<td>17,562</td>
</tr>
<tr>
<td>Printing and Related Support</td>
<td>13,089</td>
</tr>
<tr>
<td>Electrical Equip., Appliances, and Components</td>
<td>12,870</td>
</tr>
</tbody>
</table>

(plus smaller contributors)

- **Electricity use in industry**
  - electrically driven equipment
  - process heating
  - non-process purposes

- **High per-plant consumption**
  - annual U.S. refinery average > 300 million kWh
  - peak load in large metals plants > 500 MW

- **Industrial plants often connect directly to transmission grids**
Industrial energy management—complexities

- **Industrial plants can be high consumers of electricity**
  - up to 100s of MW at peak load and 100Ms of kWh annual consumption

- **Connections to the grid can be at high voltage levels**
  - direct to transmission (138 kV and 230 kV) and distribution (4 kV – 69 kV) grids

- **Large manufacturing facilities can have substantial on-site generation**
  - nationwide industrial generation: 142 B kWh, about 15% of net electricity demand
  - sales and transfers offsite: 19 B kWh

- **Large plants can play important roles for grid reliability and frequency regulation**
  - automatic generation control (AGC) and ancillary services

- **Some processes require high-speed meter data**
  - real-time, not “near-real-time”—milliseconds in some cases

- **Industrial users have high interest in ownership and protection of usage data**
  - load information is often highly confidential and competition-sensitive

- **Manufacturing processes can be inflexible with respect to time**
  - interdependencies in process must be respected, for performance and safety

- **Many customers require dynamic pricing models for process optimization**
  - forecasted pricing and special tariffs from utilities in many cases

*Domain knowledge essential for load management*
Electricity Markets

- **Wholesale**: large variations, usually hidden from consumers
  - increasing volatility; as high as $1000s / MWh; as low as < $0 / MWh
  - congestion and reliability overheads (locational marginal pricing [LMP])
  - ancillary services for grid balancing—large loads can participate
- **Retail**: rates fixed or overseen by public utility commissions
  - average U.S. residential rate ~11.5 ¢ / kWh
  - dynamic pricing tariffs for large industrial and commercial customers
  - deregulated markets allow large customers to directly negotiate rates with utility
- **Market designs and rate structures vary significantly**
  - in U.S. by state, utility, ISO / RTO / balancing authority, . . .
Texas Heat Wave, August 2011: Nature and Effects of an Electricity Supply Shortage

ERCCOT August day-ahead on-peak price, North Zone, August 2011

A prolonged August heat wave in Texas produced two periods of very high wholesale prices in the Electric Reliability Council of Texas (ERCOT), the wholesale market operator for most of the State. Day-ahead, on-peak wholesale power prices for August 2011 rose far above the range of prices seen during the previous five Augusts (see chart above).

The increase in wholesale prices may appear in retail bills more quickly in Texas than they would in other states, as Texas mandates that most retail customers choose a competitive electricity supplier—thus removing the traditional cost-of-service retail rate regulation process which often delays the blow of high wholesale prices.

http://www.eia.gov/todayinenergy/detail.cfm?id=3010
Retail markets: Alternatives to flat rates

Figure 3. Time Varying Electricity Pricing with Example Rates

- Dynamic prices available for large commercial and industrial consumers
- ToU and other dynamic rates for residential in some regions—increasing with smart meter deployment

A. Faruqui et al., The Brattle Group

Source: Fox Penner (2009), page 41.
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Customer-centric Smart Grid “Technologies”

• Automated demand response
• Storage
• Microgrids
• Energy efficiency
• Direct load control
• Distributed generation
What Is Automated Demand Response (Auto-DR)?

• Imbalances in the grid may cause reliability issues or energy price fluctuations, both of which may result in the need to actively balance grid supply/demand

• Options for dealing with imbalances include:
  • purchasing power from another state/country (expensive)
  • starting up old generation plants (AQMD issues)
  • building new power plants (very costly)
  • black outs, brown outs (high customer impact)
  • voluntary customer power reductions (demand response)

• Auto-DR is a well defined, automated, voluntary reaction to a DR event called by utilities and ISOs requiring energy consumption/reduction during an anticipated period of imbalance in the grid
Automated demand response—customer is in control; demand management based on utility signals (e.g., prices)

Direct load control—utility controls devices in facilities

Many commercial applications; few in industrial
## DR Shed Strategies

<table>
<thead>
<tr>
<th>Building use</th>
<th>HVAC</th>
<th>Lighting</th>
<th>Other</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Global temp. adjustment</td>
<td>Duct static pres. Increase</td>
<td>FAN VFD limit</td>
</tr>
<tr>
<td></td>
<td>SAT Increase</td>
<td>Fan qty. reduction</td>
<td>Pre-cooling</td>
</tr>
<tr>
<td></td>
<td>CHW temp. Increase</td>
<td>Cooling valve limit</td>
<td>Boiler lockout</td>
</tr>
<tr>
<td></td>
<td>Slow recovery</td>
<td>Extended shed period</td>
<td>Common area light dim</td>
</tr>
<tr>
<td></td>
<td>CHW temp. Increase</td>
<td>Off area light dim</td>
<td>Turn off light</td>
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<tr>
<td></td>
<td>Extended shed period</td>
<td>Dimmable ballast</td>
<td>Bi-level switching</td>
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<tr>
<td></td>
<td>Non-critical process shed</td>
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<tr>
<td>ACWD</td>
<td>Office, lab</td>
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<td>X</td>
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<tr>
<td>B of A</td>
<td>Office, data center</td>
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<td>X</td>
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<tr>
<td>Chabot</td>
<td>Museum</td>
<td>X</td>
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<tr>
<td>2530 Arnold</td>
<td>Office</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>50 Douglas</td>
<td>Office</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>MDF</td>
<td>Detention facility</td>
<td>X</td>
<td></td>
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<tr>
<td>Echelon</td>
<td>Hi-tech office</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Centerville</td>
<td>Junior Highschool</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Irvington</td>
<td>Highschool</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Gilead 300</td>
<td>Office</td>
<td></td>
<td></td>
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<tr>
<td>Gilead 342</td>
<td>Office, Lab</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Gilead 357</td>
<td>Office, Lab</td>
<td>X</td>
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<tr>
<td>IKEA EPaloAlto</td>
<td>Furniture retail</td>
<td></td>
<td></td>
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<tr>
<td>IKEA Emeryville</td>
<td>Furniture retail</td>
<td></td>
<td></td>
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<tr>
<td>IKEA WSacto</td>
<td>Furniture retail</td>
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<tr>
<td>Oracle Rocklin</td>
<td>Office</td>
<td>X</td>
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<tr>
<td>Safeway Stockton</td>
<td>Supermarket</td>
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<td>Solectron</td>
<td>Office, Manufacture</td>
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<td>Svenhard’s</td>
<td>Bakery</td>
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<td></td>
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<tr>
<td>Sybase</td>
<td>Hi-tech office</td>
<td>X</td>
<td></td>
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<tr>
<td>Target Antioch</td>
<td>Retail</td>
<td></td>
<td>X</td>
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<td>Target Bakersfield</td>
<td>Retail</td>
<td>X</td>
<td>X</td>
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<tr>
<td>Target Hayward</td>
<td>Retail</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Walmart Fresno</td>
<td>Retail</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Shed strategies defined manually today—a need for model-based optimization informed by load characteristics (including dynamics)
Example of a Typical Event

GRID STRESS → Notification → Client Actions

- Turn off 1 of 4 elevators
- Pre-cool building in early morning hours
- Turn on emergency generator (can use as monthly generator test)
- Turn off non-essential lighting

Grid Relief

Event called
Client reduces burden on electric grid
Event over
Summer Time Shed In California

AutoDR saves both capacity and energy—reduces kW and kWh
Automated demand response for ancillary services

- Ancillary services that “support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system.” (FERC)
- Demand-side resources can now participate in ancillary services
  - some industrial plants capable of providing regulation services, the most challenging

<table>
<thead>
<tr>
<th>Ancillary Services</th>
<th>Response Time</th>
<th>Duration</th>
<th>Telemetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulation Up</td>
<td>Start in &lt;1 min.; reach limit in &lt;10 min.</td>
<td>15 – 60 min.</td>
<td>4 sec.</td>
</tr>
<tr>
<td>Regulation Down</td>
<td>Start in &lt;1 min.; reach limit in &lt;10 min.</td>
<td>15 – 60 min.</td>
<td>4 sec.</td>
</tr>
<tr>
<td>Non-Spinning Reserves</td>
<td>Output in &lt; 10 min.</td>
<td>30 min.</td>
<td>4 sec.; every minute</td>
</tr>
<tr>
<td>Spinning Reserves</td>
<td>Instant start; full output in &lt;10 min.</td>
<td>30 min.</td>
<td>4 sec.; every minute</td>
</tr>
</tbody>
</table>

(Products and requirements of ancillary services markets in California)
Application 1: Aluminum Processing

- Alcoa (Warrick, Ind.) participation in Midwest ISO ancillary services market—regulation through control of smelters
- Reimbursed for load modulation as if the energy was generated
- Up to 70 MW of regulation services provided
- Control strategies include cycling and voltage control of smelting potlines
- About $700K investment, ROI in 4 months

MISO – Midwest ISO
AGC – Automatic Generation Control
EMS – Energy Management System
LCPD – Smelter Potline Load Control System
ICCP – Inter-Control Center Communications Protocol

(Todd et al., 2009)
Demand response—markets and power

- What are appropriate demand response signals?
  - price signals? load reduction commands?
- When and how should DR signals be issued?
  - frequency, timing, variation
- How can we model load flexibility and consumer response?
  - delays, learning, fatigue, ...
- What are the performance and stability implications of coupling markets and power systems?
  - real-time automated DR
- What is the minimum necessary direct load control component?
  - utility control should be limited, but it removes uncertainty
- How can automated DR be extended to storage and co-gen?
Storage as a smart grid technology

- Storage can help decouple power consumption from operation
- Multiple types of storage
  - electrical storage (batteries, flywheels, pumped hydro)
  - thermal storage (precooling, preheating)
  - inventory storage (especially useful for industrial applications)
- Dual-purpose electric vehicles—mobility and plant power source
  - high charge rates of EVs must be managed
  - other constraints on battery charge/discharge

*When is investment in new storage technologies justified?*
*How can storage be optimally operated?*
Application 2: Process with Cooling Demand

- Industrial plant in NYC with significant process cooling demand
- High peak prices in NYC as a result of limited power import capacity
- Plant creates ice slurry at night with chillers and stores the slurry in insulated tanks
  - slurry used during the day to cool refrigerant without running electric chillers
  - 5,000 ton-hours of cooling capacity available
- Peak demand reduction of > 600 kW realized
- Similar ice storage technologies also being used in commercial facilities—e.g., see www.ice-energy.com

(Epstein et al., 2005)
Application 3: Cement Manufacture

- Lafarge Building Materials (NY) participation in NYSERDA and NYISO load reduction and demand response programs for industrial facilities
- On request from NYISO, Lafarge can shut down its rock crushers, shedding up to 22 MW of load
- Production unaffected; stockpiled crushed rock available
- As part of DR program, Lafarge can schedule equipment maintenance when grid prices are high—$2M revenues for DR
- Installation of fiber-optic Ethernet, Internet connectivity, EMS functionality required

(Epstein et al., 2005)
Microgrid: Comprehensive campus energy management

- Energy Storage: Electrical / Thermal / Mechanical / Chemical
  White Oak, U of MN

- Diesel Genset

- Absorption Chiller

- Steam/hot water

- Gas Turbine CHP

- Central Utility Plants
  Electric / Thermal loads
  White Oak, Bragg, St. E

- Island from Utility Grid
  White Oak, Wheeler

- Intelligent Distribution Mgmt

- AutoDR for Renewable Integration and Ancillary Services to ISO:
  CAISO and HECO Pilots

- Demand Side Management (EE & DR)
  ESPC, BoS
  AutoDR (ARRA in CA)

- Demand management: Behavior change in response to real-time or TOU price information.

- Eco-cities: commercial, industrial and residential loads

- Energy security
  - Renewable generation sources
  - Storage & demand management to integrate renewables

- Increased reliability
  - Islanding to avoid blackouts

- Improved efficiency
  - Waste heat recycled for heating/cooling of buildings
  - Reduced T&D losses

Optimal utilization of on-site generation and storage in response to utility prices.
AutoDR and islanding capability increases energy security and reliability for critical loads.
Microgrid Assets

• Supply side
  – cogeneration units (combined heat and power [CHP])
  – distributed renewable generation (wind, solar)
  – stand-alone diesel gensets
  – the electricity distribution network (power grid)

• Demand side
  – critical loads: must be met at all times
  – curtailable loads: can be temporarily lowered
  – reschedulable loads: can be flexibly shifted in time

• Energy storage
  – electricity storage
  – thermal storage
  – electric and plug-in-hybrid vehicles
Application 4: Utility Plant

Utility plant – Atrium hospital, Heerlen

PRICES

Stluka, Godbole, Samad (IEEE CDC, 2011)

LOADS
A supply-side microgrid formulation

Minimize

\[
\sum_{t=1}^{T} \sum_{i=1}^{N} \left[ X_{t,i} \cdot \left( f_i(P_{t,i}) + C_i^{\text{fixed}} \right) + C_{t,i}^{\text{start}} \max(X_{t,i} - X_{t-1,i}, 0) \right] + P_{t,u} R_{t}^{\text{sell}}
\]

s.t.

\[
\sum_{i=1}^{N} P_{t,i} + P_{t,u} = D_t
\]

\[
P_{i,\min} X_{t,i} \leq P_{t,i} \leq P_{i,\max} X_{t,i}
\]

\[
P_{u,\min} \leq P_{t,u} \leq D_t
\]

\[
X_{t,i} \in \{0,1\}
\]

\[
X_{0,i} = \overline{X}_{0,i}
\]

MINLP problem, solved with a solution step ranging from 15 minutes to 1 hour.

Indicator for \(i\)-th generator in operation

Startup operating cost for \(i\)-th generator

Fixed operating cost for \(i\)-th generator

Variable cost for \(i\)-th generating asset at \(t\)

Cost for importing grid power at time \(t\)
Solution Workflow

Pricing data
- Cost of fuels
- Electricity tariffs (static / dynamic)

Equipment models
- Startup costs, equipment performance characteristics (efficiency curves), equipment emission levels

Weather forecast
- Temperature, wind speed, solar irradiation

Renewable generation forecasting

Energy load forecasting

System optimization
- Which boilers to use? At which load?
- Schedules for devices: starts / stops
- To charge or to discharge storage?
- How much heat and power is needed from CHP?
- Temporal load reduction: when, how much?
- etc.

Calendar
- Holidays, special days

Historical data

Consumption patterns
VERA Micro-Grid Optimization

Weather Forecast

**Input:**
- Predicted energy demand
- Predicted renewable generation
- Real-time prices

**Equipment models**

**Output:**
- Optimized schedules / set points for local co-generation, storage, load-shed & utility buy/sell

**Constraints:**
- Pollutants

**6 – 12 % energy savings annually for a decade; ROI < 1 year**
Opportunities for Research

- Data mining for energy diagnostics
- Modeling power consumption and defining pricing schemes
- Closed-loop real-time demand response
- Forecasting for renewable generation and demand
- Optimal design and operation of storage
- Integrated supply-side and demand-side microgrid optimization
- ... and many other topics for modeling, control, forecasting, optimization, and others of your favorite tools!
Optimal production planning under time-sensitive electricity prices for continuous power-intensive processes

Sumit Mitra, Ignacio E. Grossmann, Jose M. Pinto, Nikhil Arora

Center for Advanced Process Decision-making, Department of Chemical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, United States
Praxair Inc., Danbury, CT 06810, United States
Praxair Inc., Tonawanda, NY 14150, United States

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http://dx.doi.org/10.1016/j.compchemeng.2011.09.019, How to Cite or Link Using DOI

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Modeling and optimization for industrial smart grid applications, with simulation case studies for air separation units and cement plants
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Industrial Engagement in Smart Grids

- Smart grids is a “hot topic,” but not in the process industries!
  - much more interest in residential and commercial sectors
- Yet benefits of smart grid technologies already demonstrated for industrial consumers
  - a few, one-of-a-kind implementations
  - distinct opportunities for industry
- Price volatility, renewables emphasis, potential CO₂ constraints . . .
  - importance of smart grids for industrial facilities likely to increase
  - research funding available!
- Exciting areas for research in modeling, optimization, control, . . .
  - automated demand response, microgrids, storage
- Technology development and *standardization* required
  - charter of NIST Smart Grid Interoperability Panel (SGIP)
Interested in Smart Grids?

- Join SGIP and its Industry-to-Grid (I2G) working group!
  - free to join—Observer or Participating Member categories
  - biweekly I2G conference calls
  - reviews of developments
  - preparation of white papers and presentations
  - opportunities to learn and contribute
  - I2G chair: Dave Hardin (EnerNOC)
  - or Google “twiki SGIP”
- I2G: [http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/I2G](http://collaborate.nist.gov/twiki-sggrid/bin/view/SmartGrid/I2G)
  - or Google “twiki I2G”
Questions?

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