Designing Sustainable Electricity Services—The Relevance of Systems Thinking and Automation

©Marija Ilic
ECE and EPP, Professor CMU milic@ece.cmu.edu
February 3, 2010
Energy Seminar, Stanford University
Acknowledgment

Electric Energy Systems Group (EESG)

http://www.eesg.ece.cmu.edu

• A multi-disciplinary group of researchers from across Carnegie Mellon with common interest in electric energy.

• Truly integrated education and research

• Interests range across technical, policy, sensing, communications, computing and much more; emphasis on systems aspects of the changing industry, model-based simulations and decision making/control for predictable performance.
Outline

• Multiple attributes of sustainability; Need for JIT, JIP and JIC IT-enabled automation
• Drivers of change
• Our proposed approach (DYMONDS)
• Examples of sustainable minimally coordinated integration of wind power, responsive demand and PHEVs using the proposed approach
• Systems engineering challenge
Multiple attributes of sustainability (context)

- ability for supply and demand to match during normal conditions (viability);
- ability for supply and demand to match during abnormal conditions (reliability);
- short- and long-term efficient energy utilization (efficiency);
- low pollution (environmental sustainability); and,
- impacts on technology providers and consumers (business sustainability and well being).
Need for new functionalities

- **Just-in-Time (JIT)** --predictions; dynamic look-ahead decision making

- **Just-in-Place (JIP)** --distributed, interactive, multi-layered

- **Just-in-Context (JIC)** ---- performance objectives function of organizational rules, rights, and responsibilities (3Rs) and system conditions.

- Sample examples of improved performance—ongoing work in EESG http://www.eesg.ece.cmu.edu
## Single optimization subject to constraints (old) vs. Reconciling multi-dimensional tradeoffs (new)

<table>
<thead>
<tr>
<th>Single optimization subject to constraints</th>
<th>Reconciling tradeoffs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schedule supply to meet given demand</td>
<td>Schedule supply to meet demand (both supply and demand have costs assigned)</td>
</tr>
<tr>
<td>Provide electricity at a predefined tariff</td>
<td>Provide electricity at QoS determined by the customers willingness to pay</td>
</tr>
<tr>
<td>Produce energy subject to a predefined CO₂ constraint</td>
<td>Produce amount of energy determined by the willingness to pay for CO₂ effects</td>
</tr>
<tr>
<td>Schedule supply and demand subject to transmission congestion</td>
<td>Schedule supply, demand and transmission capacity (supply, demand and transmission costs assigned)</td>
</tr>
<tr>
<td>Build storage to balance supply and demand</td>
<td>Build storage according to customers willingness to pay for being connected to a stable grid</td>
</tr>
<tr>
<td>Build specific type of primary energy source to meet long-term customer needs</td>
<td>Build specific type of energy source for well-defined long-term customer needs, including their willingness to pay for long-term service, and its attributes</td>
</tr>
<tr>
<td>Build new transmission lines for forecast demand</td>
<td>Build new transmission lines to serve customers according to their ex ante (longer-term) contracts for service</td>
</tr>
</tbody>
</table>
Today’s power grid

- **Central Mesh Network**
- **Generators**
- **Control center**
- **Transmission lines**

**Substations**:
- Industrial Load
- Residential Load

**Loads**:
- A) Grandma’s House
- B) House in warm place
- C) House in warm place under extreme grid conditions
- D) House in a cold place
- E) Factory
Diverse users

A) Grandma's House:  
Smart Metering, Automation for Appliances

B) Sunny Place 1:  
Solar Panel

C) Sunny Place 2:  
Solar Panel, Backup Power, Storage

D) Cold Place:  
Backup Power, Micro CHP

E) Green Factory: Automation, Proximity to Wind Farm
Power System Scheduling

- **Unit Commitment (UC):** for the forecasted demand, how to schedule the ON and OFF of the units over daily intervals.

- **Economic Dispatch (ED):** given a mixture of energy resources, how to determine the output of individual energy resources so that
  - power supply always balances demand
  - social welfare is maximized

Conventional Approach to ED

- Supply the expected inelastic load with whatever produced by intermittent resources combined with other traditional power plants.

Economic Dispatch (ED): Choose output levels from conventional power plants to meet the “net load” at minimum cost.
What is Changing?

• Much more action at the D level due to:
  (1) responsive demand; (2) variable distributed resources (DRs); (3) new security and environmental constraints.

• Much harder to predict supply-demand (SD) imbalance accurately by the control centers without self-commitment by the DRs and LSEs (both short-term and long-term).

• Correlating diverse loads and DRs much harder than in the past (T level cannot assume D-loads known.)
Future Smart Grid (Physical system)
Critical: Transform SCADA

• From single top-down coordinating management to the multi-directional multi-layered interactive IT exchange.

• At CMU we call such transformed SCADA Dynamic Monitoring and Decision Systems (DYMONDS) and have formed a Center to work with industry and government on: (1) new models to define what is the type and rate of key IT exchange; (2) new decision tools for self-commitment and clearing such commitments. \http:www.eesg.ece.cmu.edu.
New SCADA

Hydro Gen. and Pumped Storage

Substation

Transmission lines

Central Mesh Network

Generators

Large Scale Wind Farm

Transmission lines

Substation

Industrial Load

Medium Size D.G.

Battery Storage

Industrial Load

Residential Load

Residential Load

Residential Load

PHEV Fleet

A) Grandma's House of the future

B) House in warm location

C) House in warm location with extreme grid conditions

D) House in cold location

E) Green factory with wind farm
Smart users

A) Grandma’s House:
Smart Metering, Automation for Appliances

B) Sunny Place 1:
Solar Panel

C) Sunny Place 2:
Solar Panel, Backup Power, Storage

D) Cold Place:
Backup Power, Micro CHP

E) Green Factory: Automation, Proximity to Wind Farm
DYMONDS-enabled Physical Grid
Our Proposed Approach: DYMONDS

Look-ahead Dispatch with Active Load Management

Generation

Load

Model Predictive Control (MPC)
Basic idea of minimally coordinated self-dispatch

• Different technologies perform look-ahead decision making given their unique temporal and spatial characteristics; they create bids and are cleared by the layers of coordinators

• Putting Auctions to Work in Future Energy Systems

• We illustrate next a supply-demand balancing process in an energy system with wind, solar, conventional generation, elastic demand, and PHEVs.
Model Predictive Control: Concept

- MPC is a receding-horizon optimization based technique
- At each step, a finite-horizon optimal control problem is solved but only one step is implemented
- MPC has many successful real-world applications (e.g. process control)
DYMONDS Implementation

The System Operator: Maximize Social Welfare While Observing Transmission Constraints

Supply function
\[ S_i(P_i(k+1), \lambda_i(k+1)) \]

Clearing Price
\[ \lambda_i(k) \]

Demand function
\[ B_j(P_Lj(k+1), \lambda_j(k+1)) \]

Clearing Price
\[ \lambda_j(k) \]

Predictive Model and MPC Optimizer

Aggregated Predictive model and MPC Optimizer

Generator i

Load j

\[ \hat{P}_i^{\text{max}}(k+1) \]
\[ \hat{P}_i^{\text{min}}(k+1) \]
\[ \hat{\lambda}_i(k+1) \]

\[ x_j^{\text{max}}(k+1) \]
\[ x_j^{\text{min}}(k+1) \]
\[ \hat{\lambda}_j(k+1) \]
Bid curves for different technologies—result of distributed MPC.
Main ideas of Adaptive Load Management (ALM)

• Reflecting various end-users’ needs and preferences into demand response
  – End-users’ info on preference sent to system
  – Mapping physical preference into economic preference \(\rightarrow\) demand function

• (current systems) top-down control of loads \(\rightarrow\) (future systems) two-way communicative and adaptive control

• Load aggregators’ role
  – Mediator between system/market and end-users
  – **Value of aggregating different resources and risk management**
    • Different load profiles, inelastic and elastic demands, distributed energy resources (DER), etc.
Previous demand response scheme: Direct load control

- One-way flow of information
  - Load management conducted by utilities
  - Top-down control

- Exclusive contracts between supply and demand

- Direct load control
  - Regardless of end-users’ preferences
  - No access to market information for end-users
  - End-users’ information invisible to system
Adaptive Load Management (ALM) – Look-ahead distributed self-dispatch

• Problem setup
  – 10 end-users with different temperature preferences
  – Optimizing energy usage over 24 hours
    • Hourly-varying electricity price given (real-time pricing)
    • Outdoor weather temperature given

<table>
<thead>
<tr>
<th>End-user index</th>
<th>Temperature setpoints (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td>75</td>
</tr>
<tr>
<td>2</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>77</td>
</tr>
<tr>
<td>3</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>75</td>
</tr>
<tr>
<td>4</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>79</td>
</tr>
<tr>
<td>5</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>80</td>
</tr>
<tr>
<td>6</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>75</td>
</tr>
<tr>
<td>7</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>77</td>
</tr>
<tr>
<td>8</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>79</td>
</tr>
<tr>
<td>9</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>77</td>
</tr>
<tr>
<td>10</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>81</td>
</tr>
</tbody>
</table>
Multi-layered adaptive load management – end-users to LAs

• Obtaining individual demand function subject to temperature comfort level

\[
\min_{\{x_i\}} \sum_{k=k_0}^{k_0+N} \left[ \lambda^{LA}[k] \cdot x_i[k] + \left( T_i[k] - T_i^{\text{max}} \right)^2 + \left( T_i[k] - T_i^{\text{min}} \right)^2 \right]
\]

where \( T_i[k+1] = A_i T_i[k] + B_i x_i[k] \)

subject to \( T_i^{\text{min}} \leq T_i[k] \leq T_i^{\text{max}} \)

• Obtain different \( x_i[k] \)s for different \( \lambda[k] \)s to infer demand functions

\( \rightarrow \) Analogous to sensitivity analysis
Demand function

• Objective
  – To model price-responsive loads to integrate into the system optimization
  – To include information of end-users’ utility (benefit) in system optimization
  – To see if price-responsive loads compensate with volatile intermittent resources

• What it is
  – Function of end-users’ willingness-to-pay with respect to electricity demand quantity

\[ d(P_D) = aP_D + b \]
Demand function (cont’d)

• How to obtain
  – Calculate optimal energy usage by hours with a given electricity price
  – Perturb the given price by a certain percentage (e.g. ±20%) and re-calculate optimal energy usage with new prices
  – Curve-fit price-demand quantity pairs to identify the parameters of a demand function
Resulting bid curves by demand

- Demand functions of end-user #1

![Graphs showing WTP vs. energy usage for hours 13 to 20](#)
Information flow of ALM—Auctions Put to Work

Tertiary level

Market

Bid function \( b(\lambda) \)

Secondary level

Demand function \( b(\lambda^I) \)

Primary level

End-user

End-user price \( \lambda^I \)

Load aggregator I

Load aggregator II

Load aggregator III

Market price \( \lambda \)
Information flow of ALM (cont’d)

• Primary layer (from end-users to load aggregators)
  – Physical preference $\rightarrow$ economic preference
  – Individual demand function

• Secondary layer (from load aggregators to market)
  – Aggregating end-users’ energy usage + risk management
  – Optimal energy purchase/market transaction given system price

• Back to primary layer (from load aggregators to end-users)
  – Energy price adjusted according to system/locational price: $\lambda^{LA}$ as a function of $\lambda^{system}$
Multi-layered adaptive load management – end-users to LAs

Tertiary level

Bid function $y(\lambda)$

Secondary level

Market price $\lambda$

Primary level

Demand function $x(\lambda^1)$

End-user

Load aggregator I

Load aggregator II

Load aggregator III
Multi-layered adaptive load management– LAs to market

• Optimizing aggregated energy usage based on end-user’s WTP

\[
\min_{y_j[k]} \sum_{k=k_0}^{k_0+N} \left( \lambda[k] y_j[k] - \sum_{i \in J} \lambda^{LA}[k] x_i[k] \right)
\]
subject to \( \sum_{i \in J} x_i[k] = y_j[k] \)

• \( \lambda^{LA} \)
  – Rate applied to end-users within a load aggregator’s area
  – Function of \( \lambda \) (system-wide price)
    : end-user’s rate affected by system-wide price
  – Lagrangian multiplier with respect to equality constraint
Wind prediction, look-ahead management using storage

Compare the outcome of ED from both the centralized and distributed MPC approaches.
BOTH EFFICIENCY AND RELIABILITY MET
Preliminary Results: 50% Wind

MPC-based DYMONDS Dispatch with 50% Wind

Time Steps (10 minutes interval)

Preliminary Results: 50% Wind

Potential Savings

Optimal Control of Plug-in-Electric Vehicles: Fast vs. Smart
Information flow—Fantastic Use of Multi-layered Dynamic Programming
Open Questions

– Future electric energy systems/markets
  • Multi-product energy markets
  • Single-product energy markets
  • Energy markets with load aggregators

• This determines the type of information which must be exchanged and impact on sustainability attributes
Plug-and-Play (No Coordination)?

Total generation and total demand imbalances in 50% wind case
Multi-product energy market

Coordinator of multiple-attribute products

Energy supply-demand arrangements
- Energy delivery arrangements
- Environmental impact arrangements

Bus 1
- \( b_{\text{coal}}(t) \)
- \( \lambda_{\text{Bus1}}(t) \)
- \( \lambda^{\text{en}}_{\text{Bus1}}(t) \)

Bus 2
- \( b_{\text{wind}}(t) \)
- \( \lambda^{\text{env}}_{\text{Bus2}}(t) \)

Bus 3
- \( b_{\text{PHEV}}(t) \)
- \( \lambda^{\text{env}}_{\text{Bus3}}(t) \)

PHEV
- \( \lambda^{\text{env}}_{\text{PHEV}}(t) \)
- \( \lambda^{\text{env}}_{\text{PV}}(t) \)

Photovoltaic
- \( \lambda^{\text{env}}_{\text{PV}}(t) \)

\( b_{12}(t) \)
\( b_{23}(t) \)
\( b_{31}(t) \)
Single-product energy market

Coordinator of Single-attribute energy product

- **Bus 1**
  - Price-responsive loads
  - \( b^\text{bundled}_{\text{Bus1}}(t) \)
  - \( \lambda^\text{sust}_{\text{Bus1}}(t) \)

- **Bus 2**
  - Natural Gas
  - \( \lambda^\text{sust}_{\text{Bus2}}(t) \)
  - \( b^\text{bundled}_{\text{Bus2}}(t) \)

- **Bus 3**
  - PHEV
  - \( \lambda^\text{sust}_{\text{Bus3}}(t) \)
  - \( b^\text{bundled}_{\text{Bus3}}(t) \)

- **Bus 1**
  - Coal
  - Wind

- **Bus 2**
  - Photovoltaic

43
Multi-product energy market with a *load aggregator*

**Energy supply-demand arrangements**
- $\lambda_{Bus1}(t)$
- $b_{en, Bus1}(t)$

**Energy delivery arrangements**
- $\lambda_{en}(t)$
- $\lambda_{del}(t)$
- $\lambda_{12}(t)$
- $b_{env}(t)$
- $b_{del}(t)$
- $b_{23}(t)$

**Environmental impact arrangements**
- $\lambda_{Bus2}(t)$
- $b_{env}(t)$
- $b_{PV}(t)$
- $\lambda_{env}(t)$

**Environment**
- Coal
- Wind
- Photovoltaic
- PHEV

Price-responsive loads

Coordinator of multiple-attribute products
Preliminary Conclusions – Need for Smart Regulation

• Need to revisit the performance metrics in the changing industry (cost vs. benefits; cost allocation vs. value-based services)
• The cost of managing uncertainties – very different depending on the context
• The value of high technologies (DYMONDS) – very different depending on the context
• Heterogeneous performance metrics (reliability, short term-, long term- efficiency; environmental impacts; cyber security)
• Who takes the risks for what and at which price?
References

- Electric Energy Systems Group (EESG) at CMU  http://eesg.ece.cmu.edu
- Ilic, Marija “Dynamic Monitoring and Decision Systems (DYMONDS) and Smart Grids: One and the Same, CMU EESG WP 019, October 2009.
- Ilic, Marija “IT-enabled Rules, Right and Responsibilities (3Rs) for Efficient Integration of Wind and Demand Side Response”, Public Utility Fortnightly Magazine, Dec 2009.