Unit Commitment for Sustainable Integration of Large-Scale Wind Power and Responsive Demand

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ECE and EPP, Carnegie Mellon

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Docket AD10-12
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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

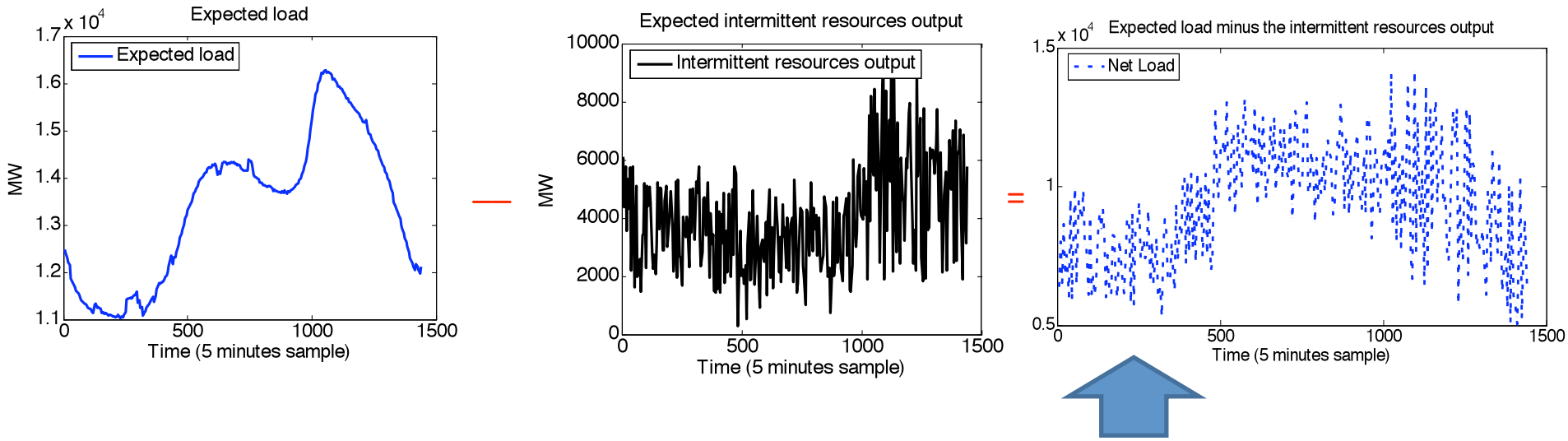
- Interests range across technical, policy, sensing, communications, computing and much more; emphasis on systems aspects of the changing industry, model-based simulations and decision making/control for predictable performance.

Outline

- Wind power and demand side management—new sources of complexity
- Problem formulation for integrating wind and elastic demand—centralized UC/MPC; an example
- Scalability problem in centralized UC and UC market implementation—common challenge/approach
- Temporal vs spatial LR issue --basic efficiency/ emissions concern with today's UC
- Managing complexity—Distributed Interactive Unit Commitment (DIUC)
- Numerical example/comparison with benchmark solution- Integration of >50% wind

New source of complexity

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



Today: Choose output levels from conventional power plants to meet the expected "net load" at minimum cost.

Unit commitment for sustainable integration of wind and demand side

- Net system demand function of system imbalance; greatly complicates the unit commitment problem

  -number of states potentially huge in inelastic demand case;

  - number of decision variables potentially huge in the demand elastic case.

- Two qualitatively different methods"

  -Centralized UC---Demand, wind and generation cost functions short-run marginal cost; UC constraints explicit at the ISO level.

  - Distributed Interactive UC (DIUC) -When demand and cost functions account for UC constraints (DIUC) [1—6]; computationally manageable and provable lower bound performance under certain conditions

Motivation

Better Prediction of Intermittent Resources?

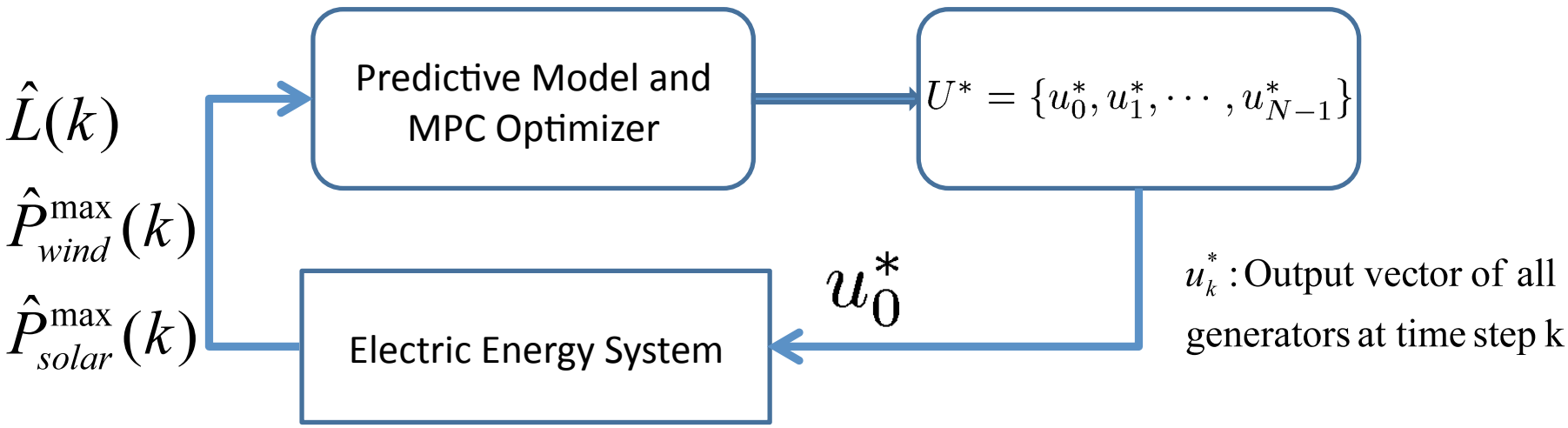
More efficient utilization of intermittent resources

More reliable operation of intermittent resources

Managing wind power—our approach [5]

- Actively control the output of available intermittent resources to follow the trend of time-varying loads.
- By doing so, the need for expensive fast-start fossil fuel units is reduced. Part of the load following is done via intermittent renewable generation.
- The technique used for implementing this approach is called model predictive control (MPC) [5].
- Implicit value of storage

Centralized MPC --Benchmark



- Predictive model of load and intermittent resources are necessary.
- Optimization objective: minimize the total generation cost.
- Horizon: 24 hours, with each step of 5 minutes.

Problem 3A: Centralized MPC-based Dispatch with Inelastic Demand

$$\text{Solve}: \min_{P_G} \sum_{k=1}^{K} \sum_{i \in G} (C_i(P_{G_i}(k))), i \in G \tag{39}$$

$$s.t. \sum_{i} P_{G_i}(k) = \sum_{z} \hat{L}_z(k), i \in G, z \in Z; \tag{40}$$

$$\hat{L}_z(k) = f_z(L_z(k-1)), z \in Z; \tag{41}$$

$$\hat{P}^{max}_{G_j}(k) = g_j(\hat{P}^{max}_{G_j}(k-1)); \tag{42}$$

$$\hat{P}^{min}_{G_j}(k) = h_j(\hat{P}^{min}_{G_j}(k-1)); \tag{43}$$

$$\hat{P}^{\min}_{G_j} \leq P_{G_j}(k) \leq \hat{P}^{\max}_{G_j}, j \in G_r; \tag{44}$$

$$P^{\min}_{G_i} \leq P_{G_i}(k) \leq P^{\max}_{G_i}, i \in G \setminus G_r; \tag{45}$$

$$|P_{G_i}(k+1) - P_{G_i}(k)| \leq R_i, i \in G; and, \tag{46}$$

$$|F(k)| \leq F^{max}. \tag{47}$$

Problem 3B: Centralized MPC-Based Dispatch with Elastic Load

$$\text{Solve}: \min_{P_G, L} \sum_{k=1}^{K} \Big(\sum_{i \in G} (C_i(P_{G_i}(k))) - \sum_{z \in Z} (B_z(L_z(k))) \Big), \tag{48}$$

$$s.t. \sum_{i \in G} P_{G_i}(k) = \sum_{z \in Z} L_z(k); \tag{49}$$

$$\hat{P}^{max}_{G_r}(k) = g_j(\hat{P}^{max}_{G_r}(k-1)), r \in G_r; \tag{50}$$

$$\hat{P}^{min}_{G_r}(k) = g_j(\hat{P}^{min}_{G_r}(k-1)), r \in G_r; \tag{51}$$

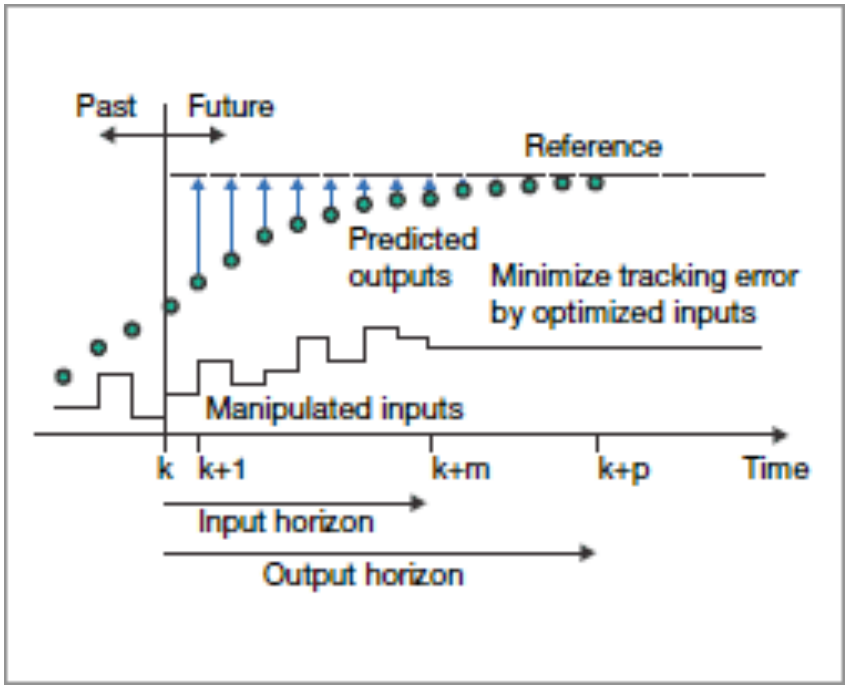
$$\hat{P}^{\min}_{G_j} \leq P_{G_j}(k) \leq \hat{P}^{\max}_{G_j}, j \in G_r; \tag{52}$$

$$P^{\min}_{G_i} \leq P_{G_i}(k) \leq P^{\max}_{G_i}, i \in G \setminus G_r; \tag{53}$$

$$|P_{G_i}(k+1) - P_{G_i}(k)| \leq R_i, i \in G; and, \tag{54}$$

$$|F(k)| \leq F^{max}. \tag{55}$$

Model Predictive Control—Based



www.jfe-rd.co.jp/en/seigyo/img/figure04.gif

- MPC is receding-horizon optimization based control.
- At each step, a finite-horizon optimal control problem is solved but only one step is implemented.
- MPC has many successful real-world applications.

Numerical Example

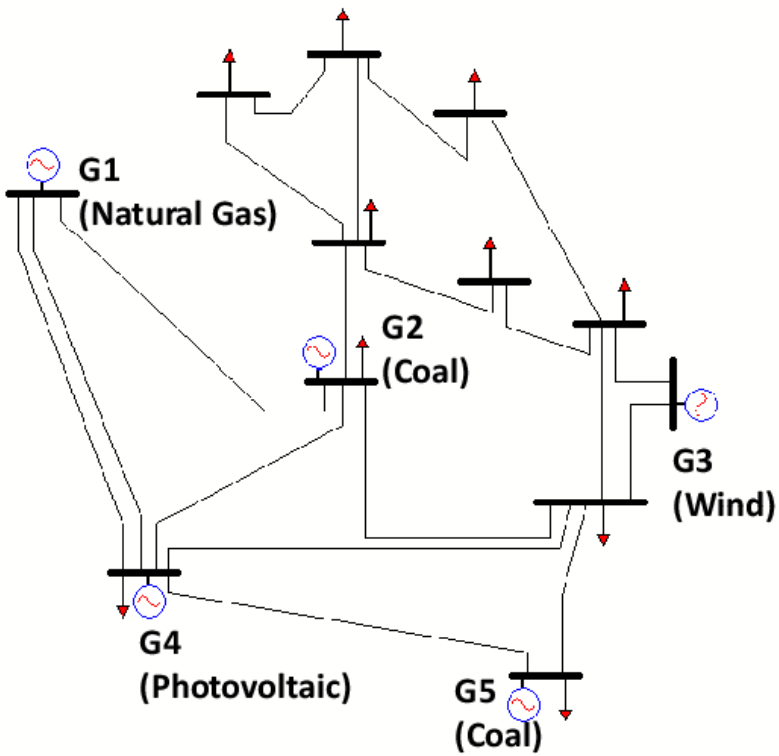
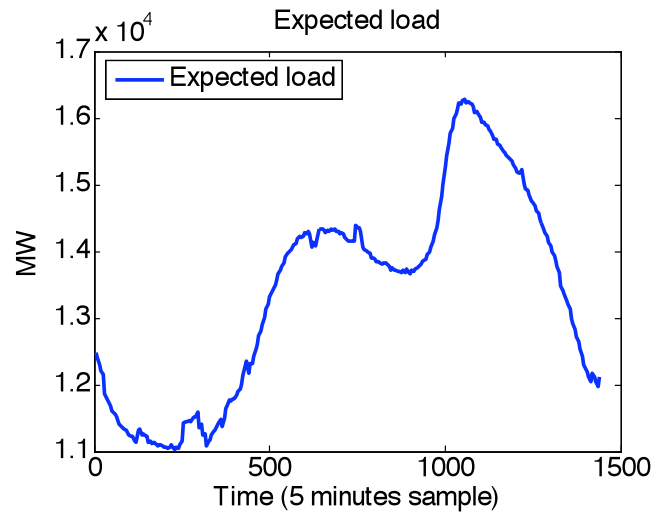


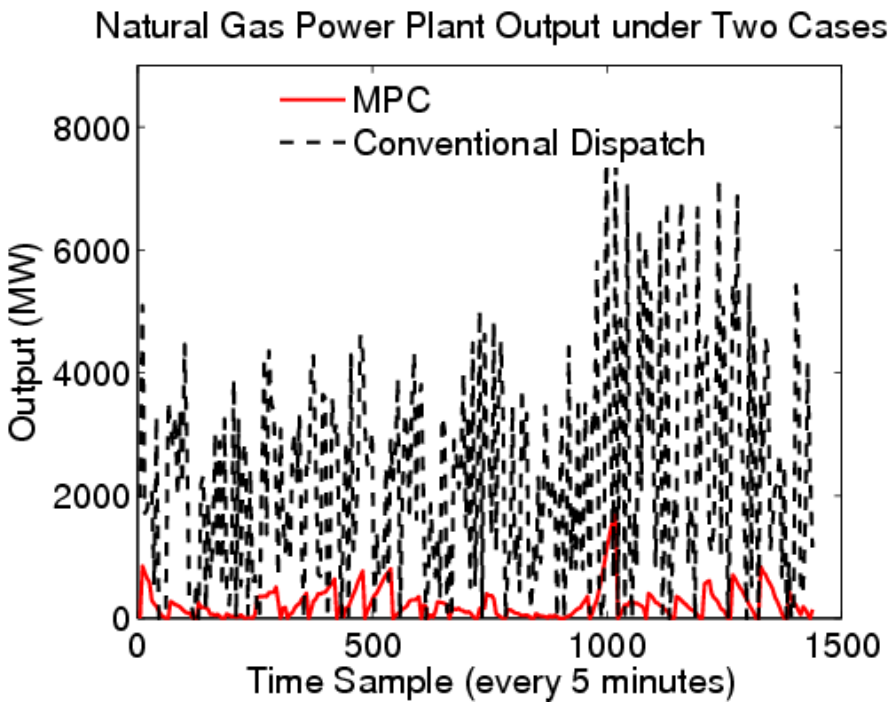
TABLE I
GENERATOR PARAMETERS OF THE 12-BUS SYSTEM

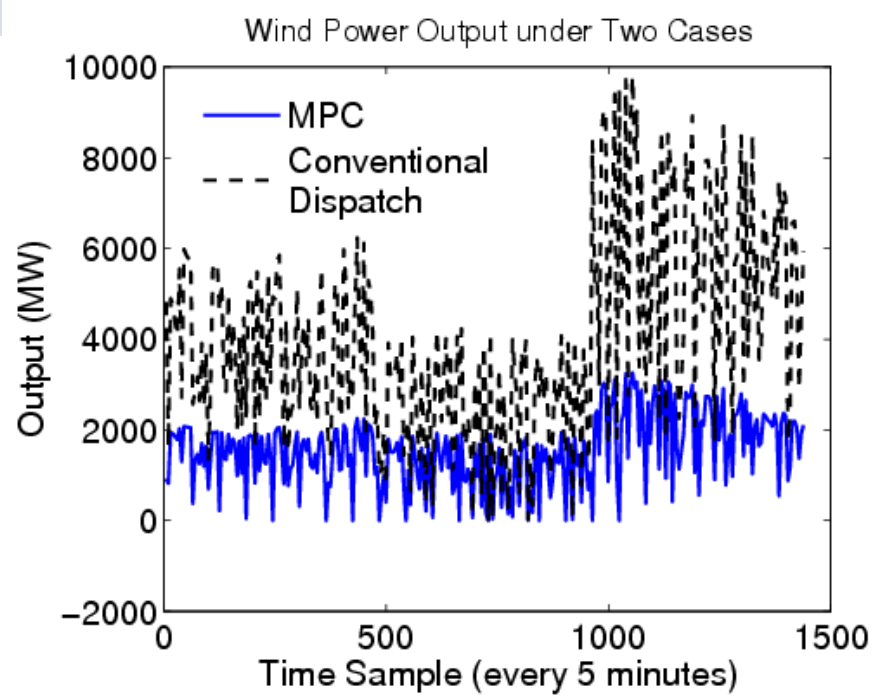
Gen ID	Type	Capacity	Marginal Cost	Ramp Rate
1	Natural Gas	5000MW	1000$/MWh	100MW/5 min
2	Coal	9000MW	500$/MWh	1000MW/hour
3	Wind	3500MW	0$/MWh	150MW/5 min
4	Photovoltaic	1500MW	0$/MWh	100MW/5 min
5	Coal	8000MW	300$/MWh	800MW/hour



Compare the outcome of ED from both the conventional and proposed approaches.

Conventional cost over 1 year *	Proposed cost over the year	Difference	Relative Saving
$ 129.74 Million	$ 119.62 Million	$ 10.12 Million	7.8%





*: load data from New York Independent System Operator, available online at http://www.nyiso.com/public/market_data/load_data.jsp

Rethinking the problem—
limits to complexity

- Clear that today' MPC algorithms not scalable as of now;
- Typical approximation—LR w.r.t. time; assumes hierarchical time scale separation of SCED and UC
- LR w.rt. to time questionable with persistent changes in system inputs; complexity will grow with new technologies (physics vs. binary decisions);

The basic efficiency/emissions concern

- Natural "optimal" schedules of different technologies very different; horizontal vs. vertical unit commitment
- Brute-forcing all technologies to re-commit using common clock is generally very inefficient
- Two possible solutions:

  - centralized multi-stage UC over several time horizons; still very complex

  -interactive UC between the resources and system operators; no LR wrt time; LR wrt units

•Decomposition over (portfolia) of resources critical; otherwise, the problem is not solvable; this is particularly true when combining with line switching

•Proposed new approach-Distributed Interactive UC (DIUC) [2-7]

-LR w.r.t. (portfolia of) units NOT w.r.t. time

-for the changing industry (distributed, interactive)

-for the regulated industry (centralized algorithm)

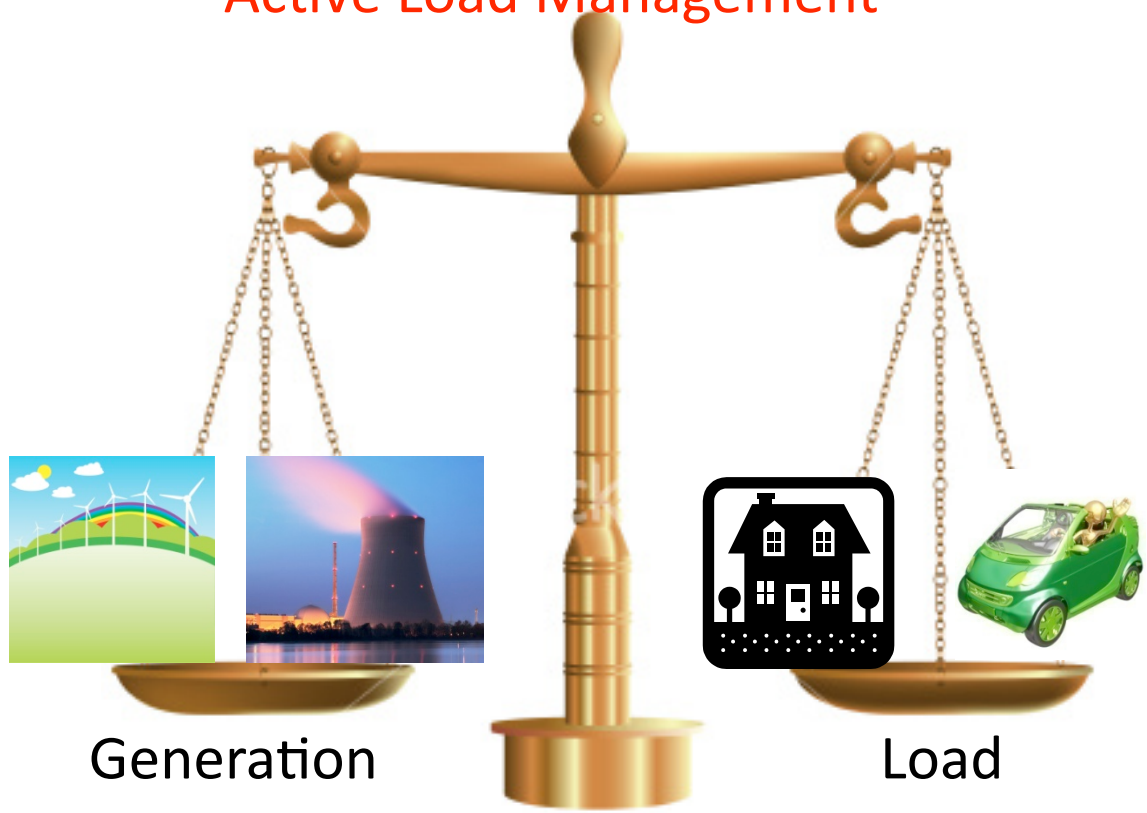
Basic idea of minimally coordinated self-dispatch —Distributed Interactive UC (DIUC)

- Different technologies perform look-ahead decision making given their unique temporal and spatial characteristics and system signal (price or system net demand); 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.

Our Proposed Framework: DIUC

Look-ahead Dispatch with Active Load Management

Model Predictive Control (MPC)



At Generator Level—Primal Problem

$$\text{Solve}: \max_{P_{G_i}} \sum_{k=1}^{K} (\lambda_i(k) * P_{G_i(k)} - C_i(P_{G_i(k)})), k = 1, \cdots, K$$

Max(Total Profit)

$$s.t. \lambda_i(k) = \lambda_i^{DA}(H), \text{ if interval k in the hour H;}$$

Predicted price

$$\hat{P}_{G_j}^{max}(k) = g_j(\hat{P}_{G_j}^{max}(k-1), \cdots, \hat{P}_{G_j}^{max}(k-n_j));$$

$$\hat{P}_{G_j}^{min}(k) = h_j(\hat{P}_{G_j}^{min}(k-1), \cdots, \hat{P}_{G_j}^{min}(k-n_j));$$

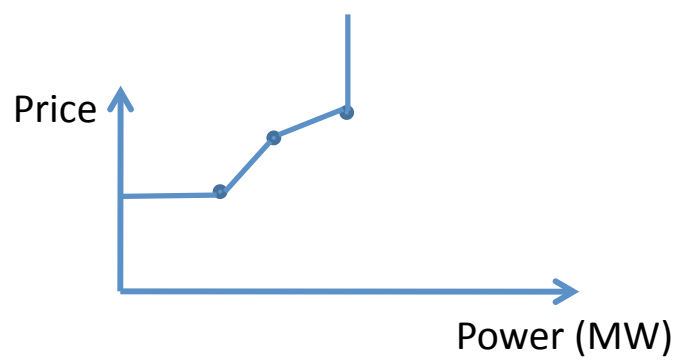
Available Generation Prediction

$$\hat{P}_{G_j}^{\min} \leq P_{G_j}(k) \leq \hat{P}_{G_j}^{\max}, i \in G;$$

Gen Capacity Constraint

$$|P_{G_i}(k+1) - P_{G_i}(k)| \leq R_i, i \in G.$$

Ramp Rate Constraints



Note: In regulated industry – predicted net system demand

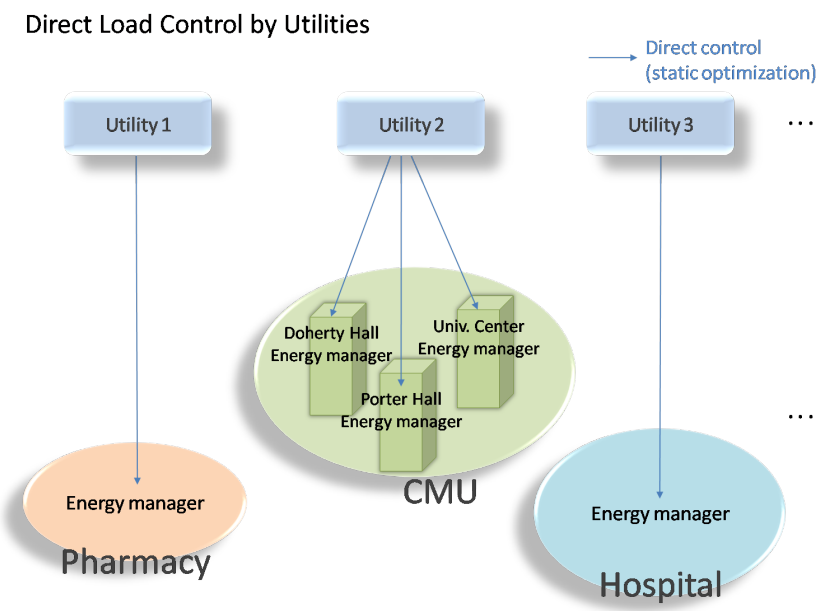
Main ideas of Adaptive Load Management (ALM)

- Reflecting various end-users' needs and preferences into demand response
  - End-users' info on preference sent to system
  - Mapping physical preference into economic preference → demand function

- (current systems) top-down control of loads → (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.

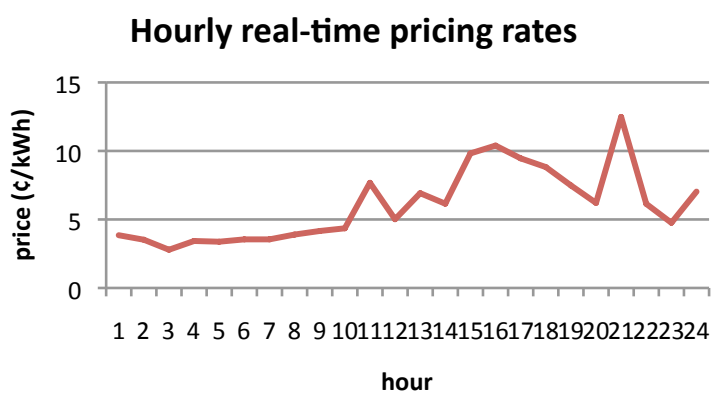
Today's demand response scheme: Direct load control



- 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



End-user index	Temperature setpoints (^{0}F)	
1	68	75
2	70	77
3	72	75
4	74	79
5	75	80
6	64	75
7	63	77
8	72	79
9	72	77
10	73	81

Primal problem at the demand level

- Obtaining individual demand function subject to temperature comfort level

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

where $T_i[k+1] = A_i T_i[k] + B_i x_i[k]$

subject to $T_i^{\min} \le T_i[k] \le T_i^{\max}$ for all k

- Obtain different $x_i[k]$s for different $\lambda[k]$s to infer demand functions

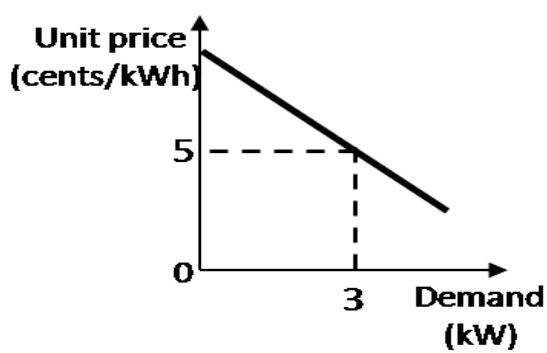
→ PHYSICS AT PLAY

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

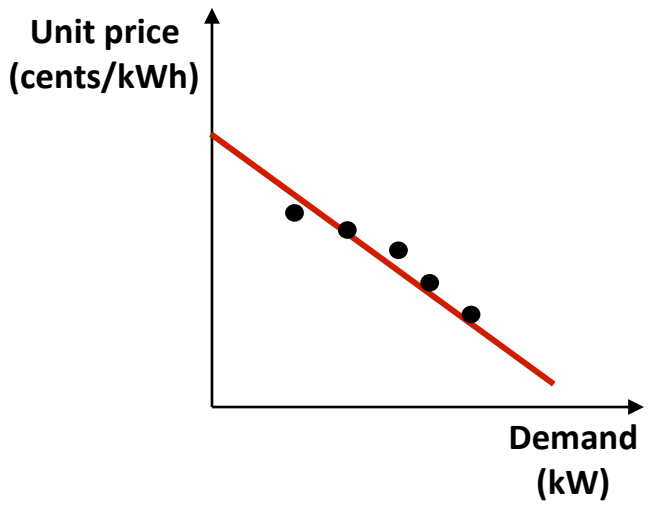
- What it is
  - Function of end-users' willingness-to-pay with respect to electricity demand quantity

$$d(P_D) = aP_D + b$$



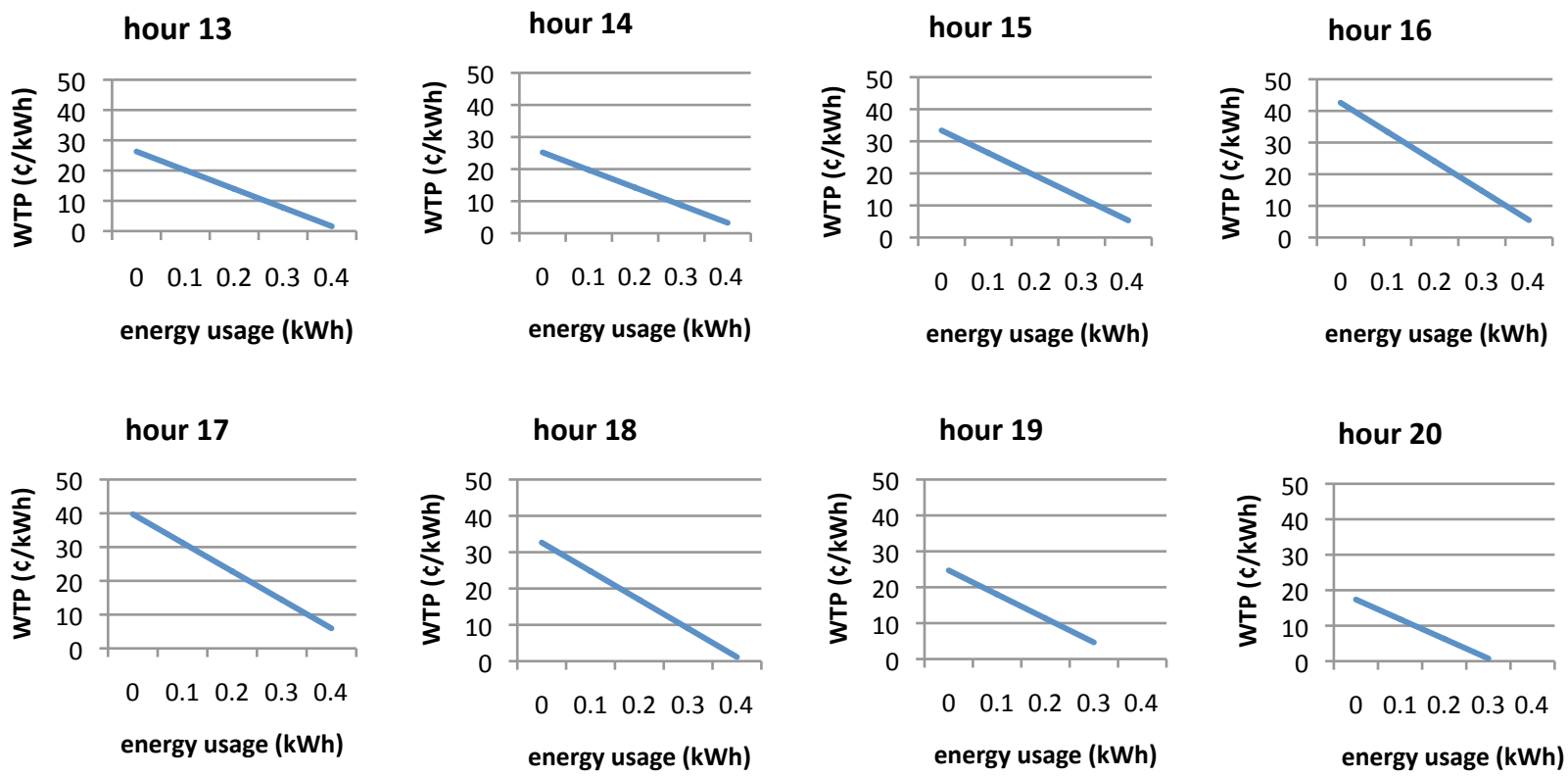
Demand function (cont'd)

- 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

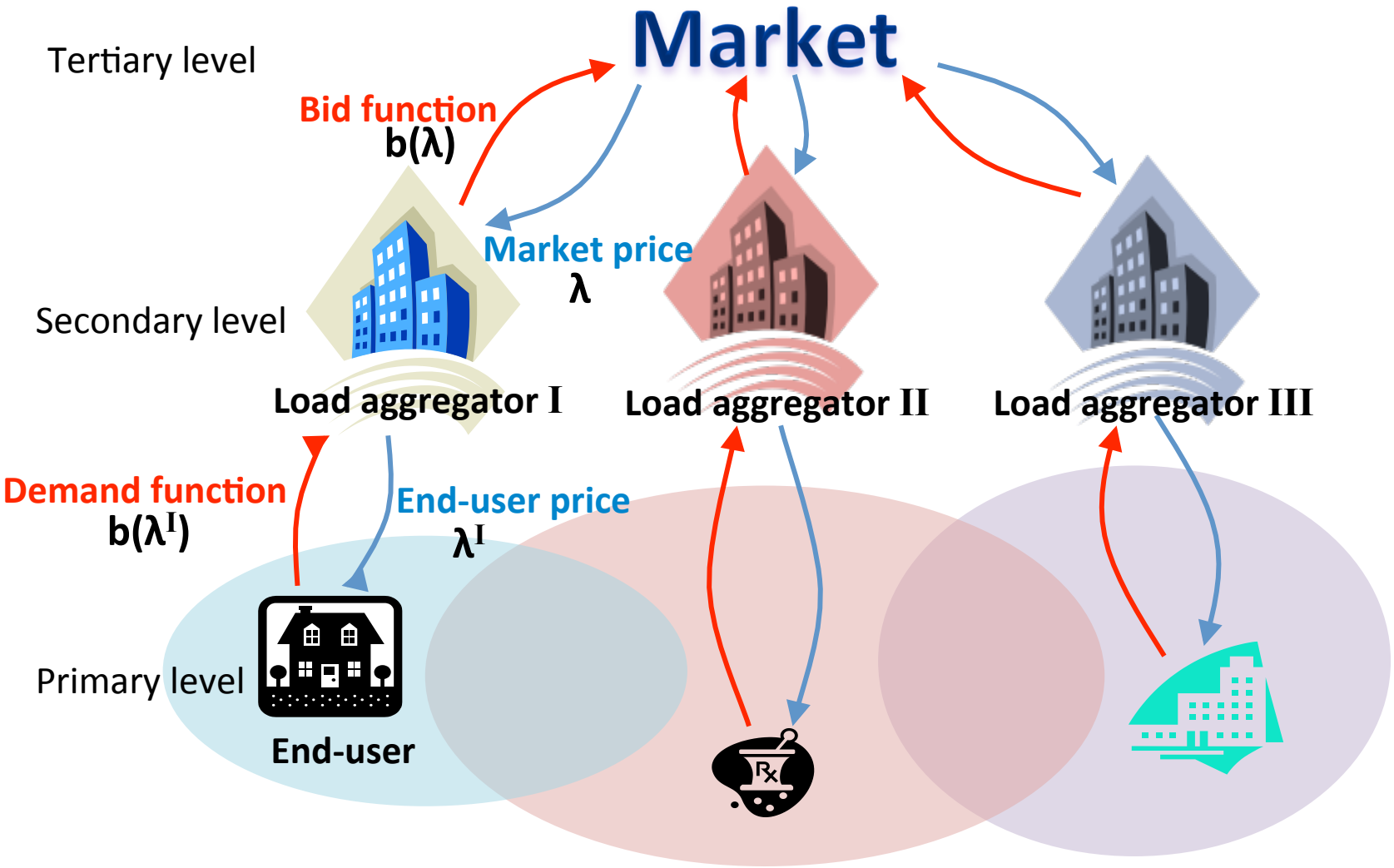


Resulting bid curves by demand—Result of solving primal problem

- Demand functions of end-user #1



Information flow of ALM—Auctions Put to Work (Primal-Dual Solution Interactions)



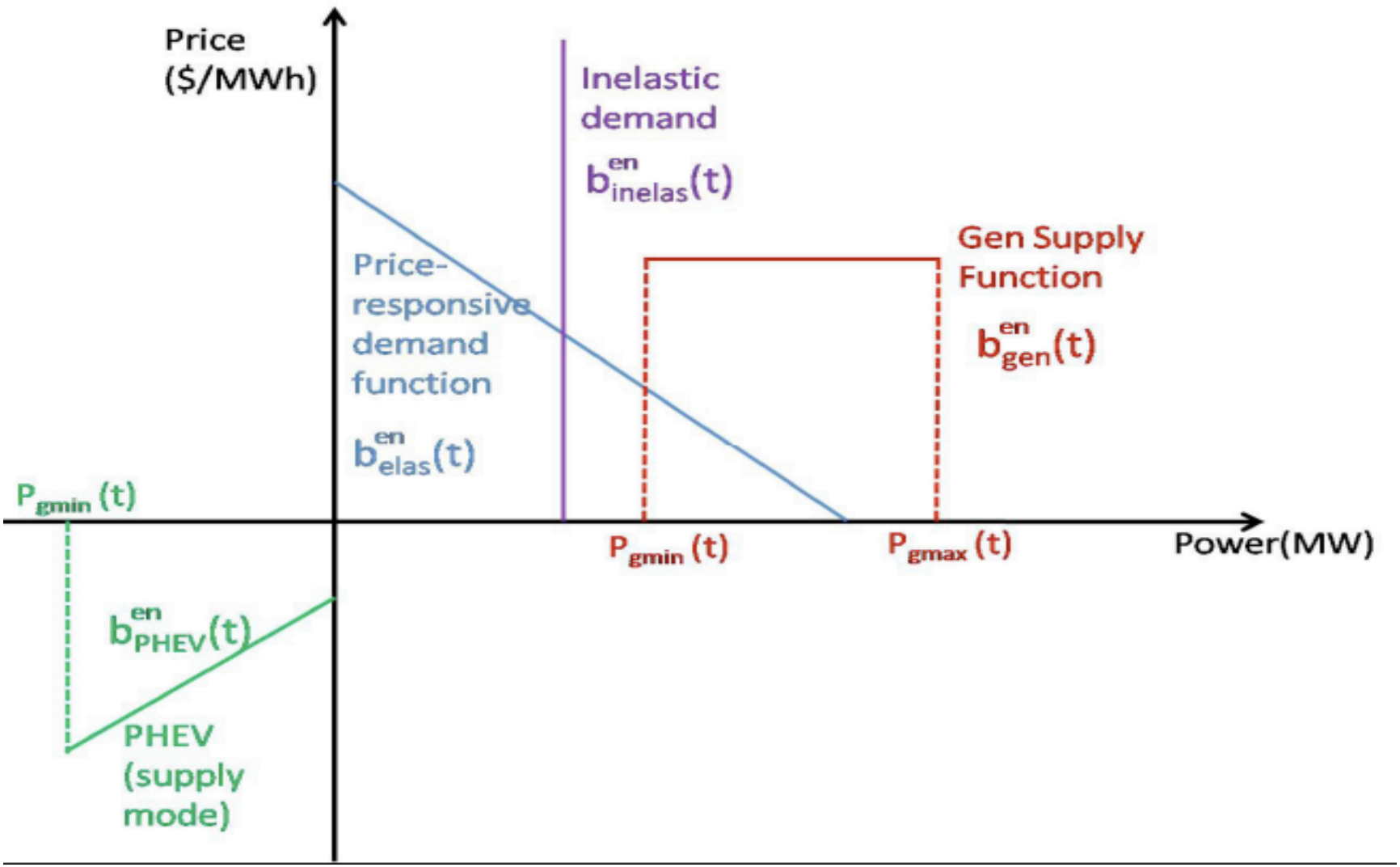
Information flow of ALM

- Primary layer (from end-users to load aggregators)
  - Physical preference → economic preference
  - Individual demand function

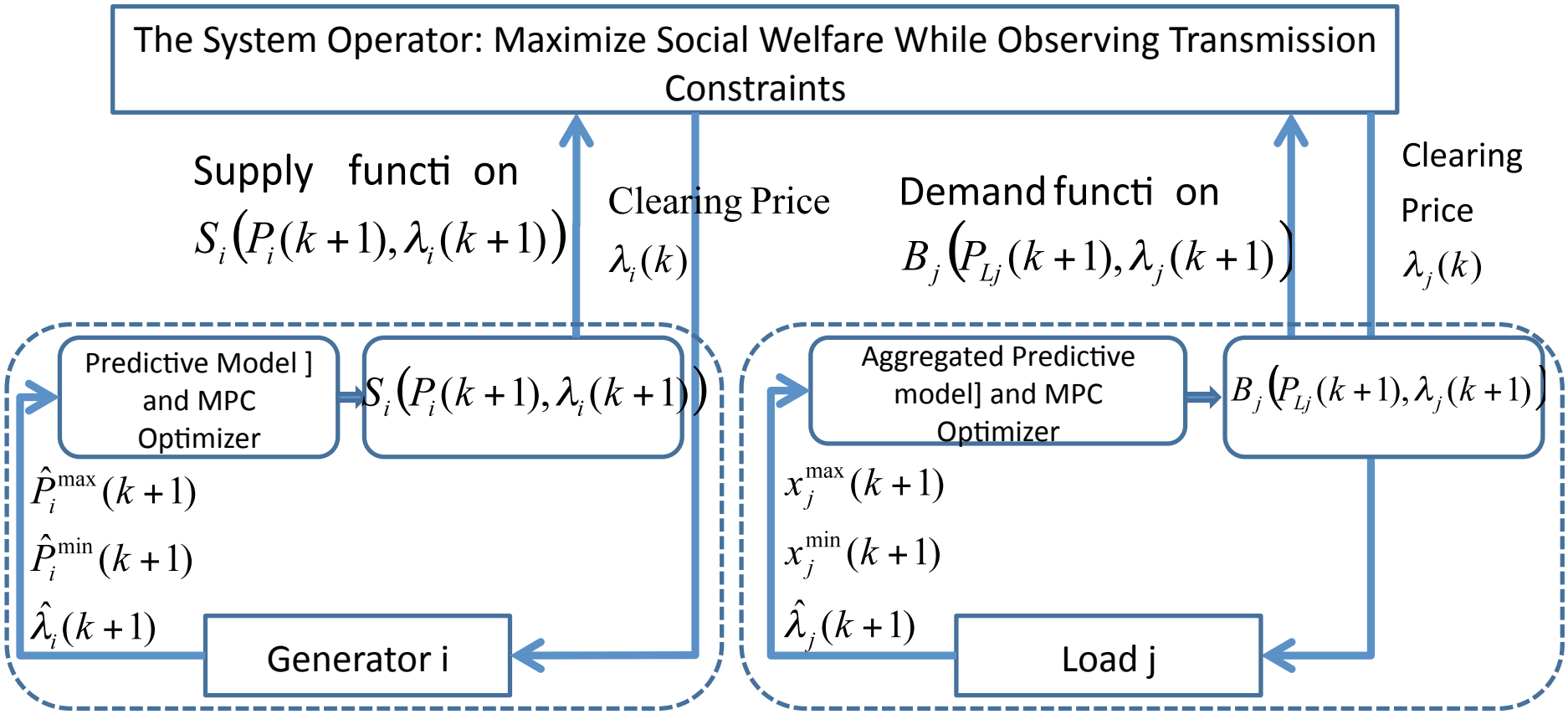
- Secondary layer (from load aggregators to market)
  - Aggregating end-users' energy usage + risk management
  - Optimal energy purchase/market transaction given system price

- Back to primary layer (from load aggregators to end-users)
  - Energy price adjusted according to system/locational price : λ^{LA} as a function of λ^{system}

Bid curves for different technologies—result of distributed MPC



Implementation in Markets—DIUC---Primal-Dual Solution Interactions (spatial/not temporal)



[2] N. Abdel-Karim and M. Ilic,"Short Term Wind Speed Prediction by Finite and Infinite Impulse Response Filters: A State Space Model Representation Using Discrete Markov Process", IEEE PowerTech Conference, Romania June 2009
[3] J. Joo and M.D. Ilic, "A Multi-Layered Adaptive Load Management (ALM) system: information exchange between market participants for efficient and reliable energy use," submitted to 2010 IEEE PES Transmission and Distribution Conference.

Integrating fossil, wind, solar and demand side and PHEVs

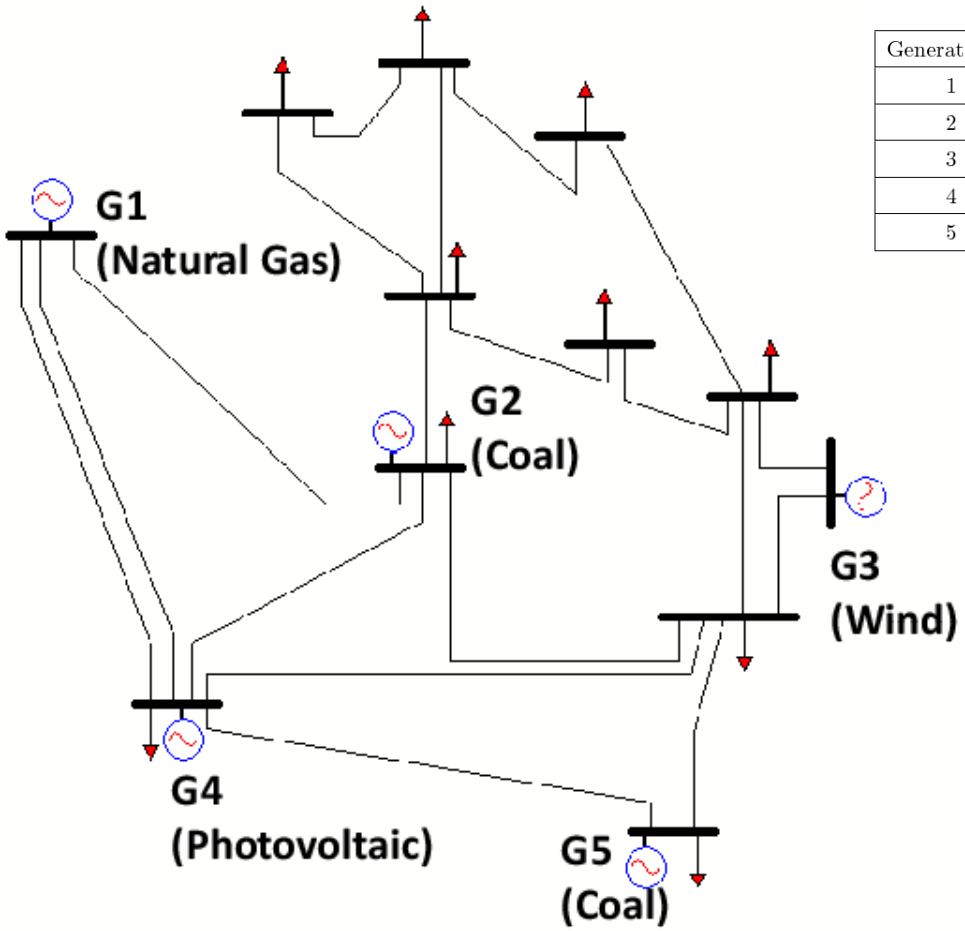
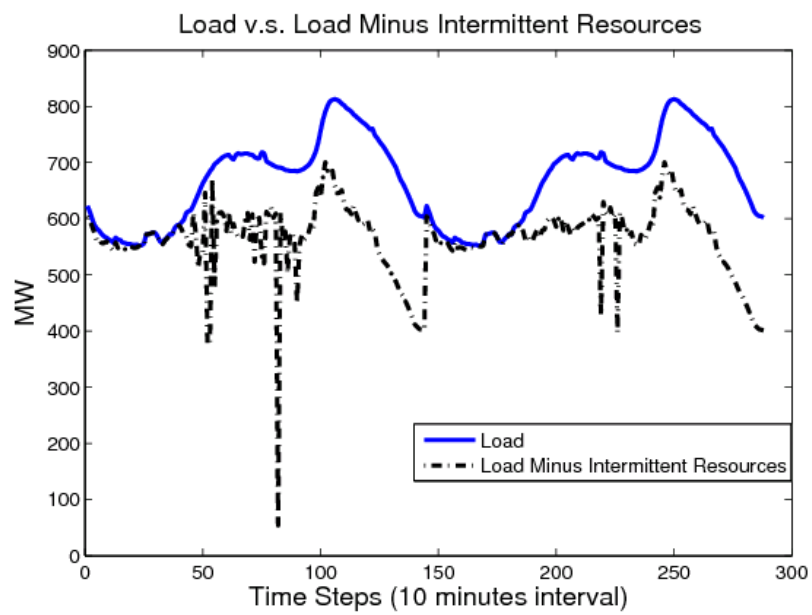
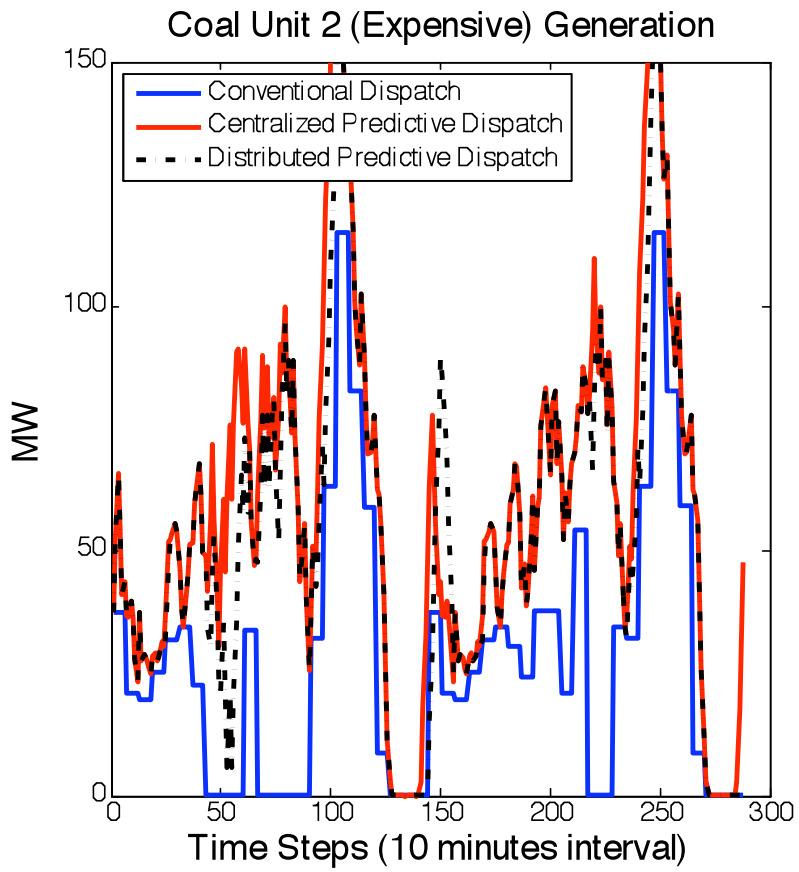


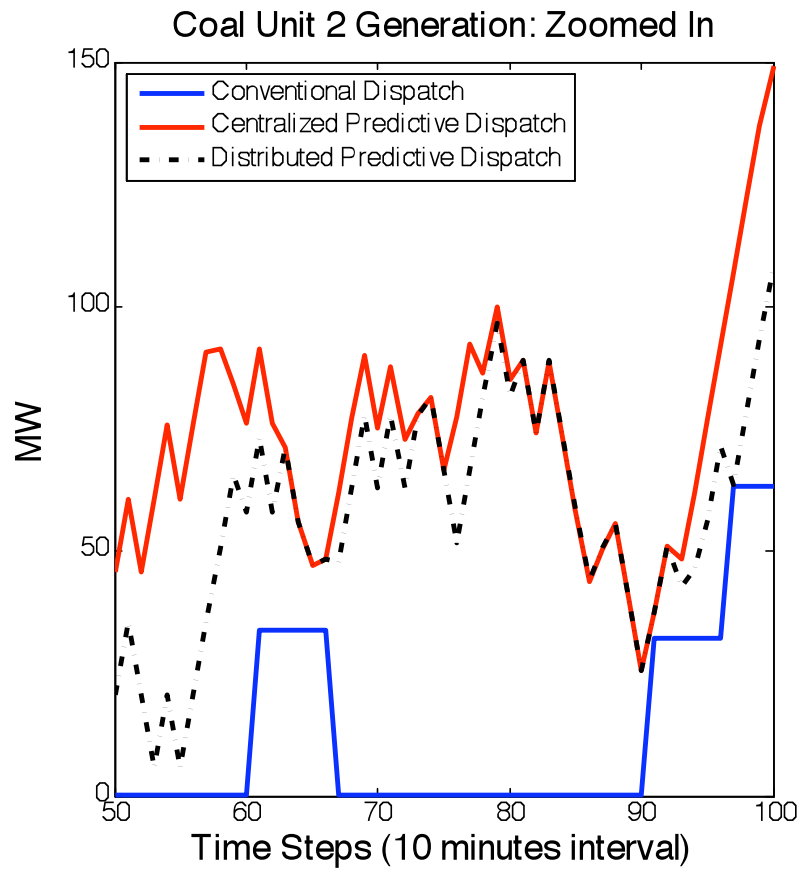
Table 1: Generator parameters of the 12-bus system

Generator ID	Type	Min Generation	Max Generation	Generation Cost	Ramp Rate
1	Gas	20	500MW	350$/MWh	150MW/5 min
2	Coal	20	500MW	150$/MWh	15MW/ 5min
3	Wind	0	250MW	0$/MWh	150MW/5 min
4	PV	0	600MW	0$/MWh	200MW/5 min
5	Coal	10	500MW	100$/MWh	10MW/5 min



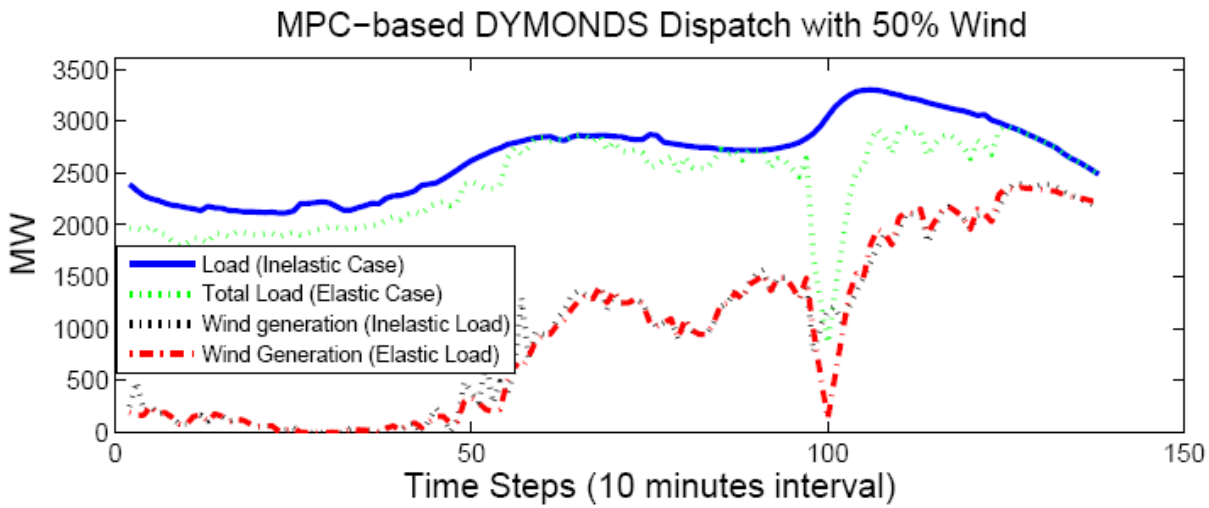
Compare the outcome of ED from both the centralized and distributed MPC approaches.

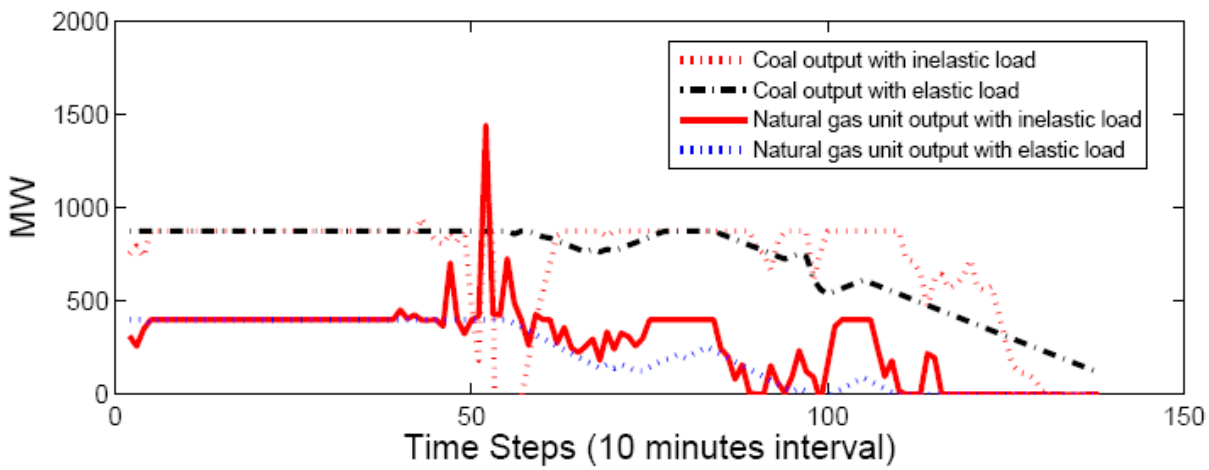




BOTH EFFICIENCY AND RELIABILITY MET

Preliminary Results: 50% Wind





[5] Marija Ilic, Le Xie, and Jhi-Young Joo, "Dynamic Monitoring and Decision Systems (DYMONDS) for Efficient Integration Wind Power and Price-Responsive Demand:
Proof of Concept on the IEEE RTS System", EESG WP 2009.

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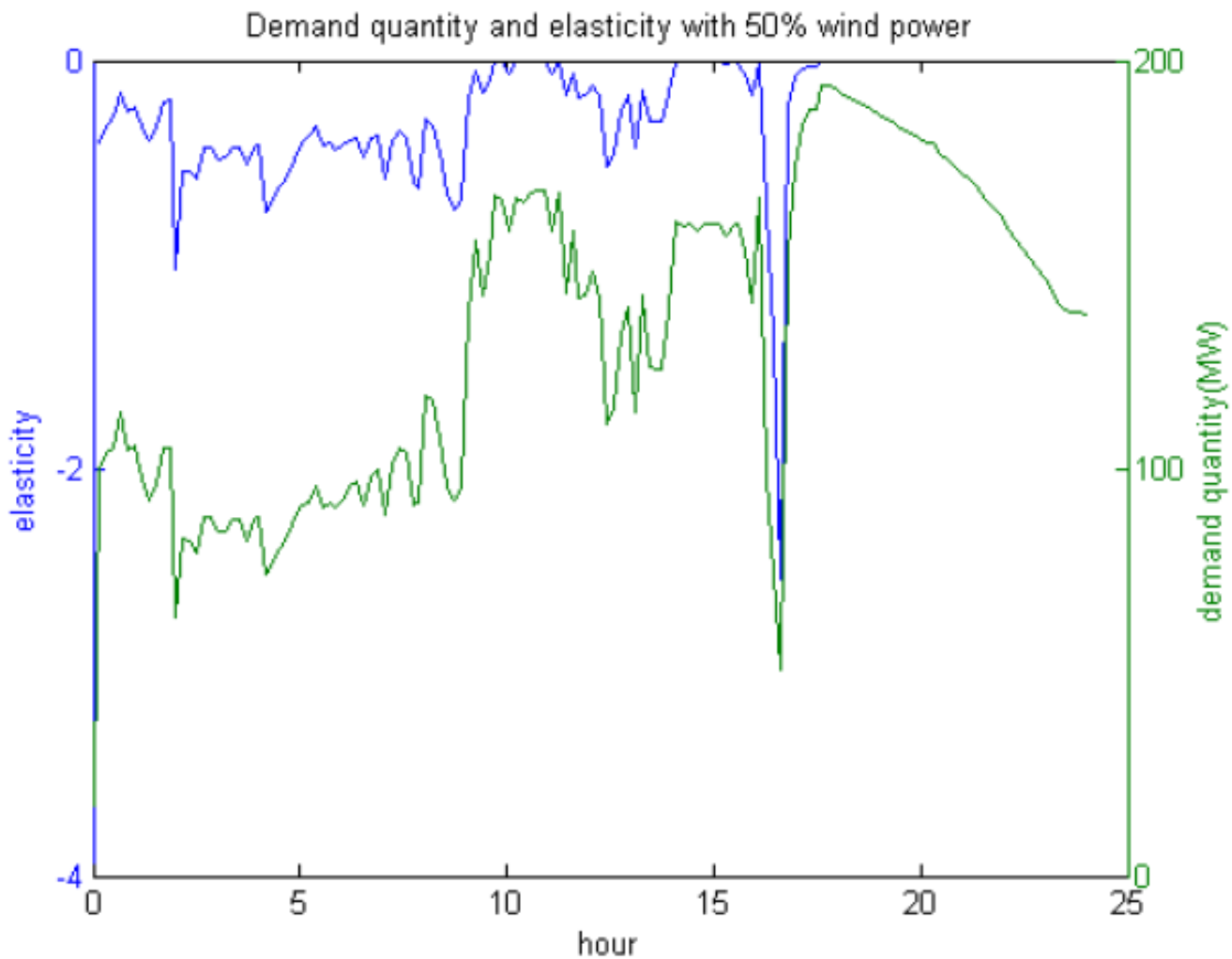

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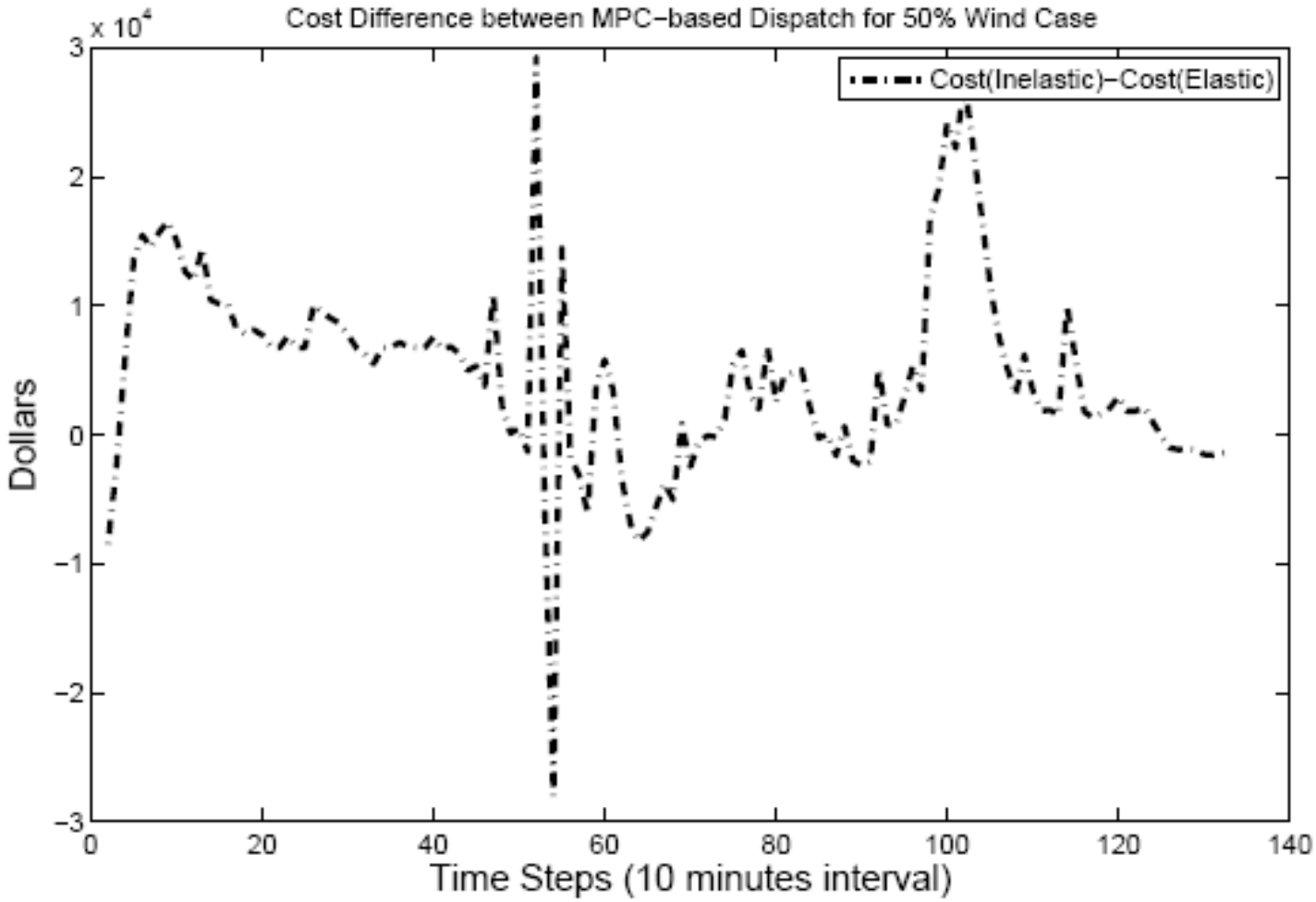
Potential Savings



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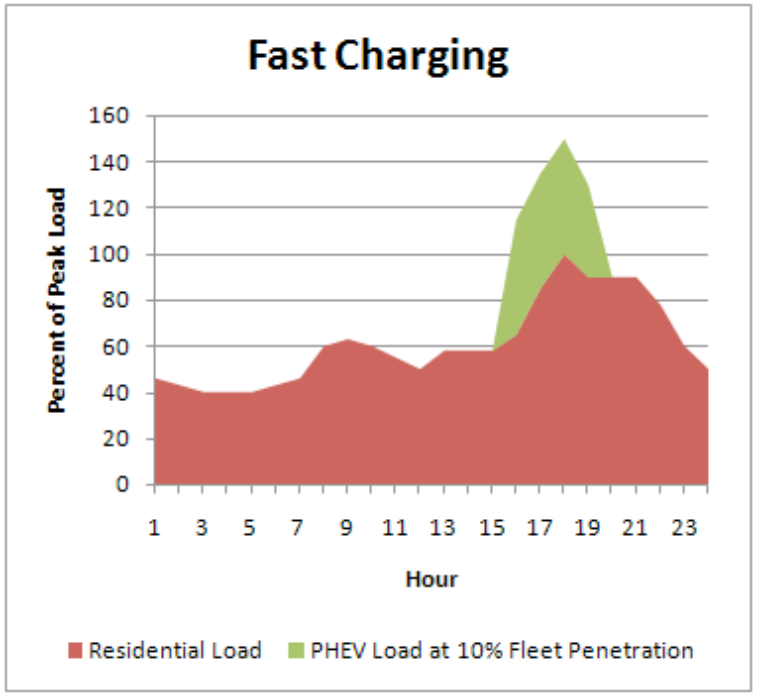
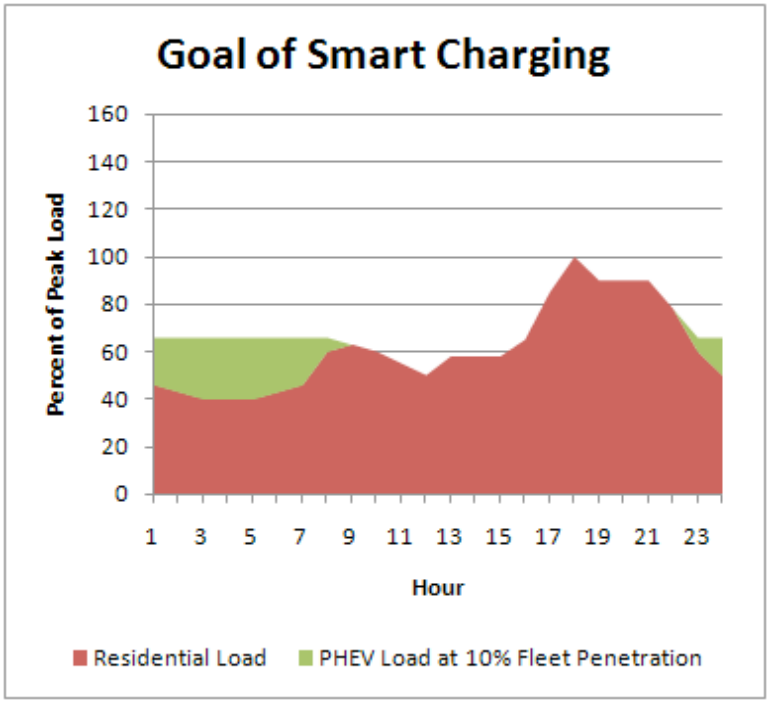
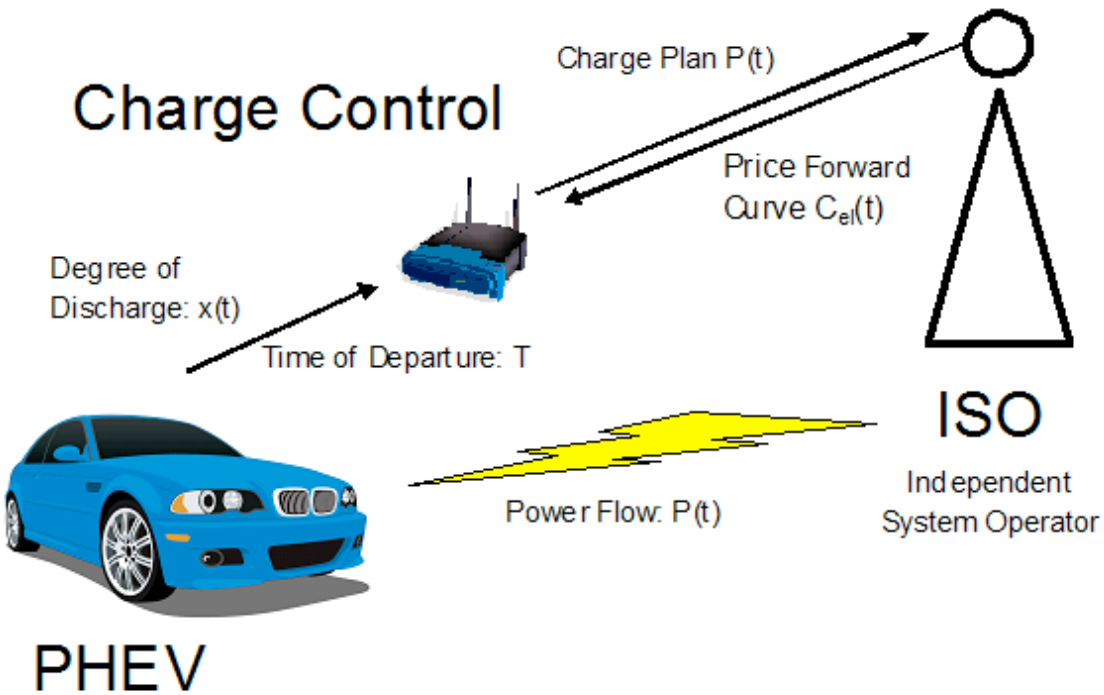
Optimal Control of Plug-in-Electric Vehicles: Fast vs. Smart

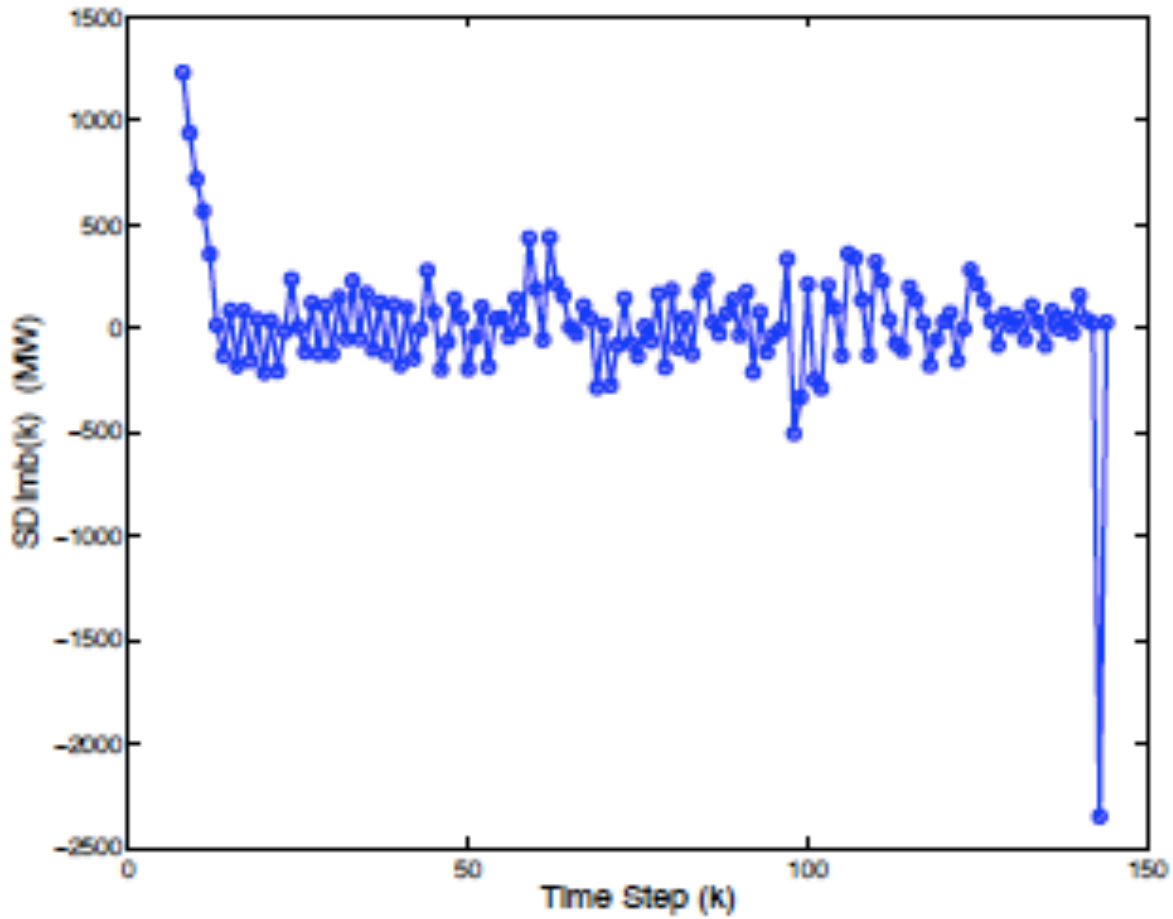




Information flow—Fantastic Use of Multi-layered Dynamic Programming

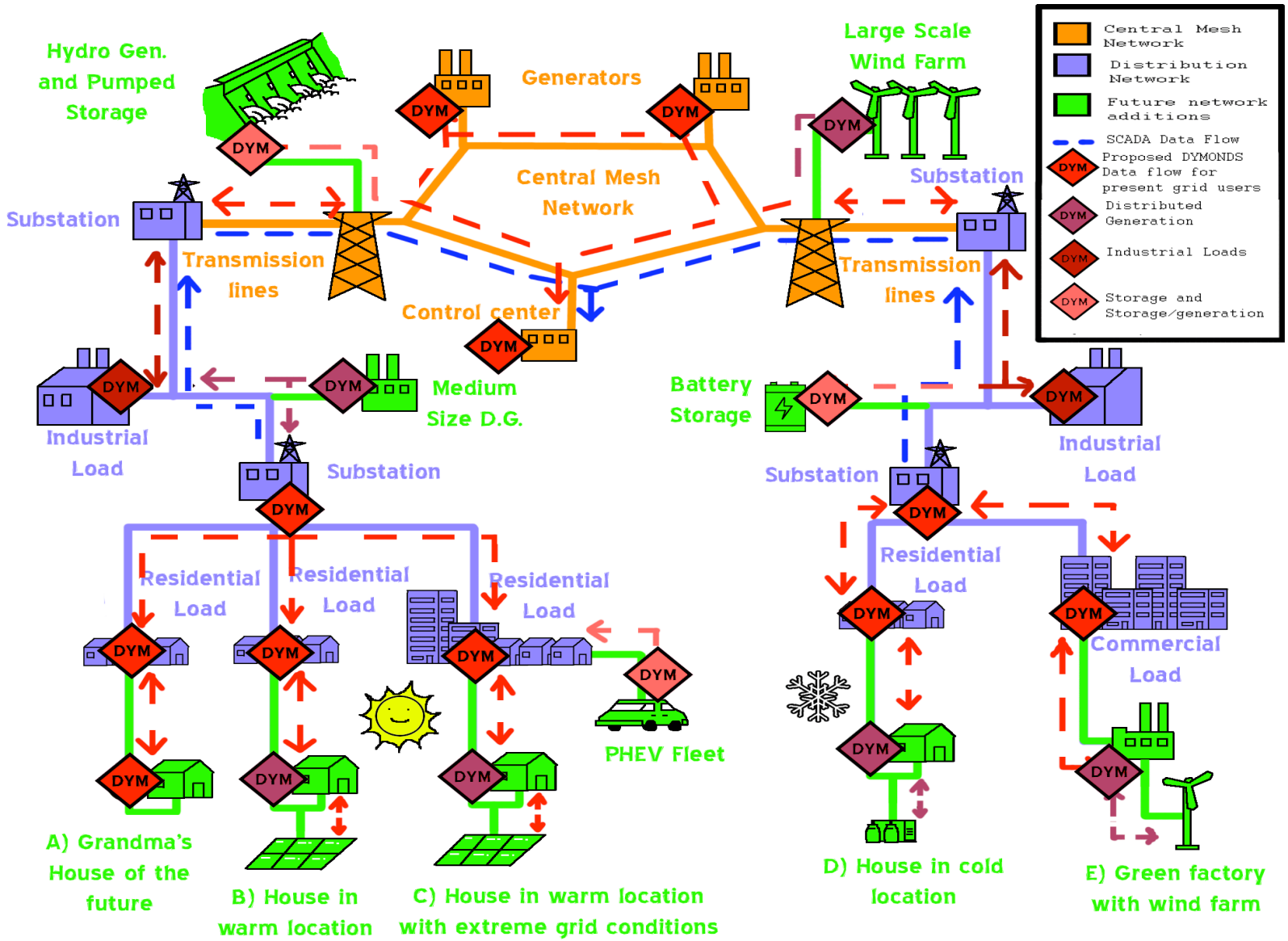


Plug-and-Play (No Coordination)?



Total generation and total demand imbalances in 50% wind case

Smart Grid [1]


Hydro Gen. and Pumped Storage
Generators
Large Scale Wind Farm
Central Mesh Network
Substation
Transmission lines
Control center
Medium Size D.G.
Battery Storage
Industrial Load
Residential Load
Commercial 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
DYM
Central Mesh Network
Distribution Network
Future network additions
SCADA Data Flow
Proposed DYMONDS Data flow for present grid users
Distributed Generation
Industrial Loads
Storage and Storage/generation

Distributed Interactive UC--DIUC

- Allow different technologies to optimize in anticipation of system conditions while taking into account their unique inter-temporal constraints and sub-objectives;
- The distributed optimization done in a look-ahead dynamic way at the resource level to create cost functions (bidding functions for both supply and demand)
- Result: Lower electricity prices and higher efficiency; minimized overall UC cost

Our general framework

- Use adequate performance measures
- Perform meaningful spatial decomposition and aggregation (zoned, portfolios)
- Iterate to ensure that the inter-dependencies are accounted for by inter-actively exchanging information

  -Even coordinated software must account for the information that is iteratively updated from the non-utility resources

  - In the market environment it becomes necessary to reconcile choice and system-wide objectives

  -Use predictions create bid functions (instead of numbers) to control software performance

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