



The Role of Network Systems Engineering in Reaching the Energy and Environment Dream

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October 7, 2008
PSERC Video-Talk

Acknowledgments

Based on the on-going work in the
Electric Energy Systems Group,
Carnegie Mellon University

Electric Energy



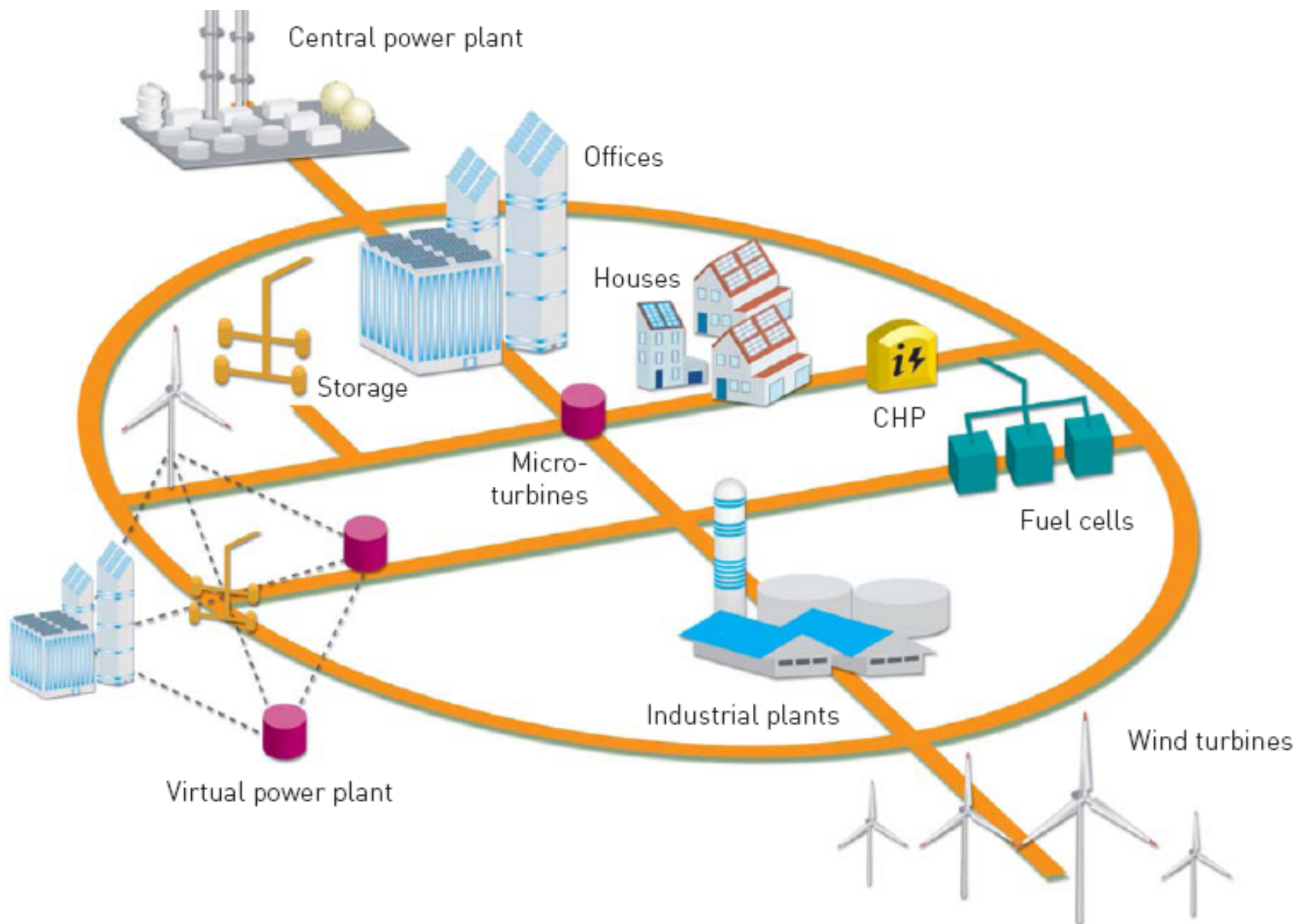
Systems Group

Outline

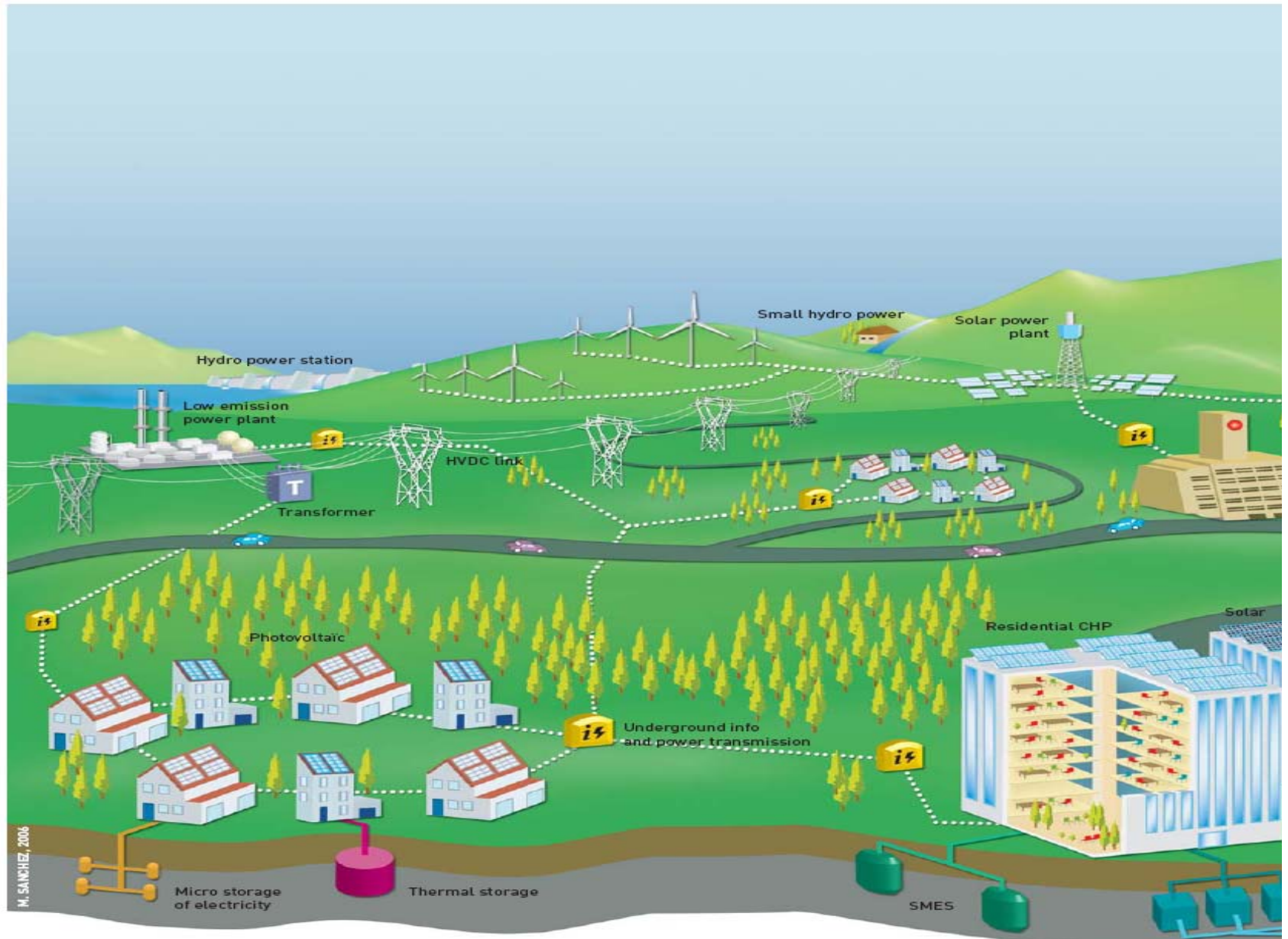
- Likely future energy systems structure
- What needs to be re-engineered? How to get from here to there?
- New network systems problems
- Related work at the CMU's EESG (<http://www.eesg.ece.cmu.edu>)
- Open fundamental questions

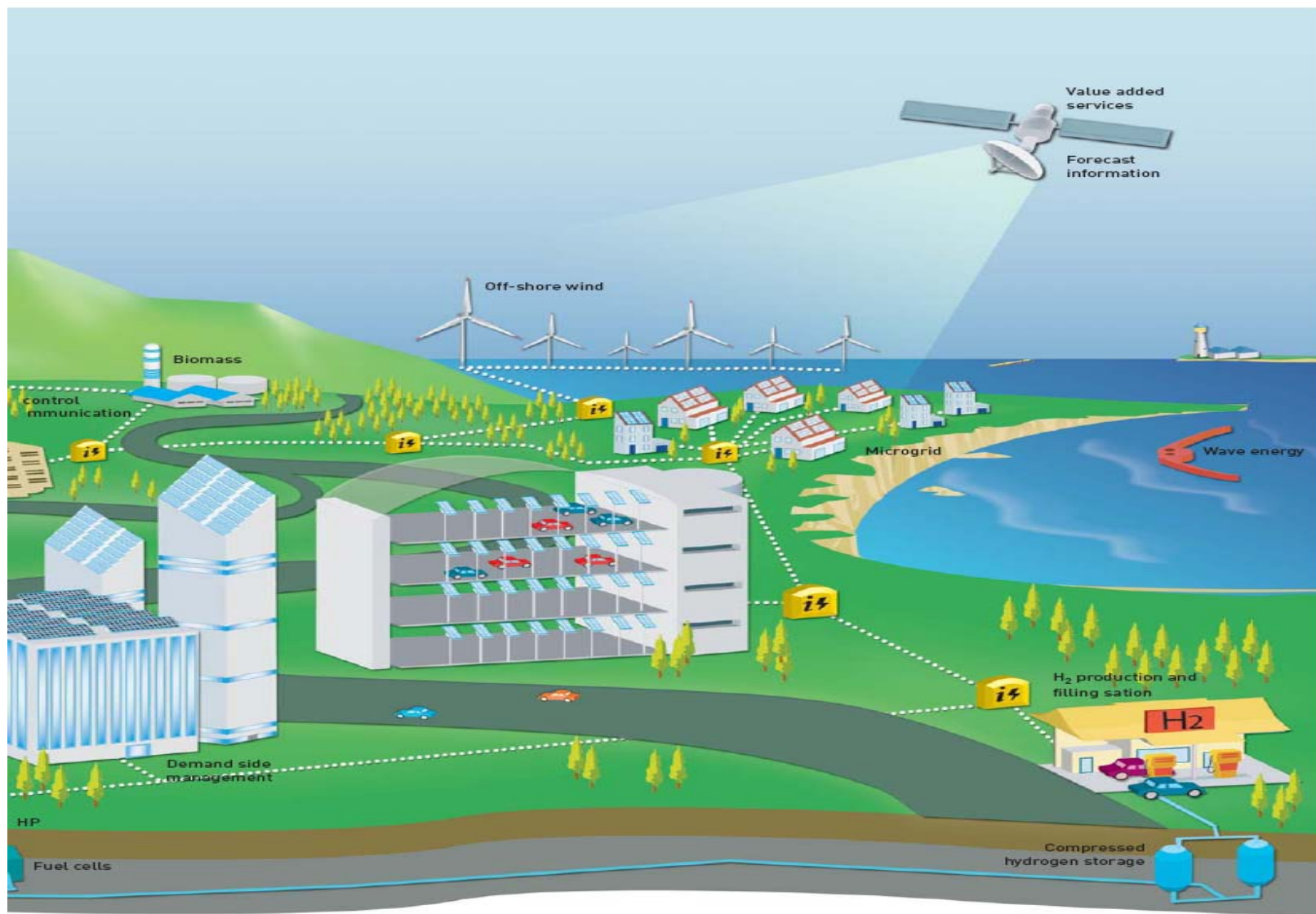
Some predictions of (long-term) energy network architectures

- Interstate EHV DC delivery system connecting large nuclear power plants (backbone network)
- Closer to the end users a mix of
 - highly distributed micro-grids with their own back-up small power plants and/or connections to the backbone
 - medium-sized fossil fuel/gas power plants
 - distributed energy resources (DERs)
- Significant penetration of IT:
 - Making local grids highly flexible (BOTH reliable/secure and efficient!) with the end user actively participating;
 - Facilitating on-line coordination of the backbone network and the local grids.

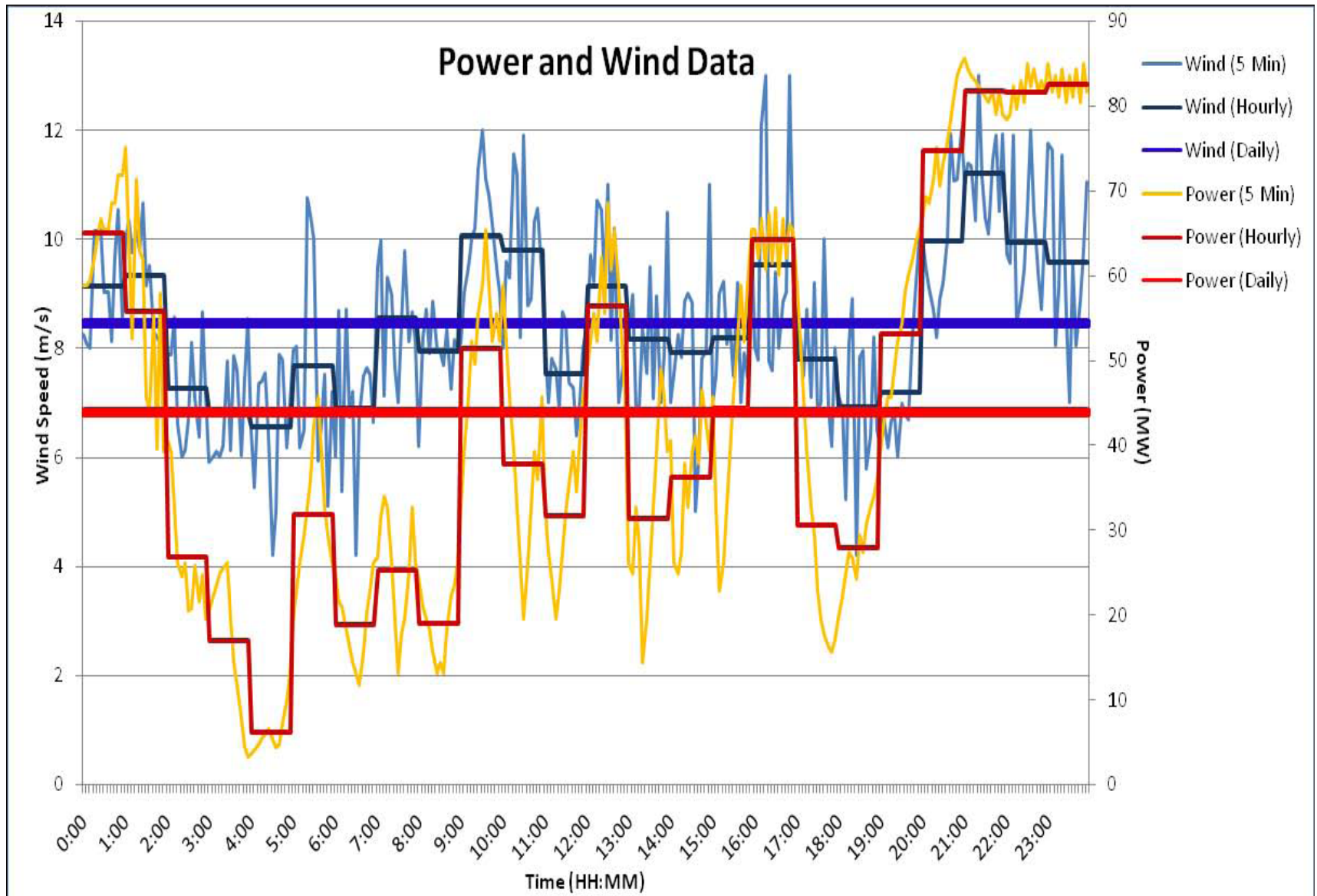


Future Network Vision

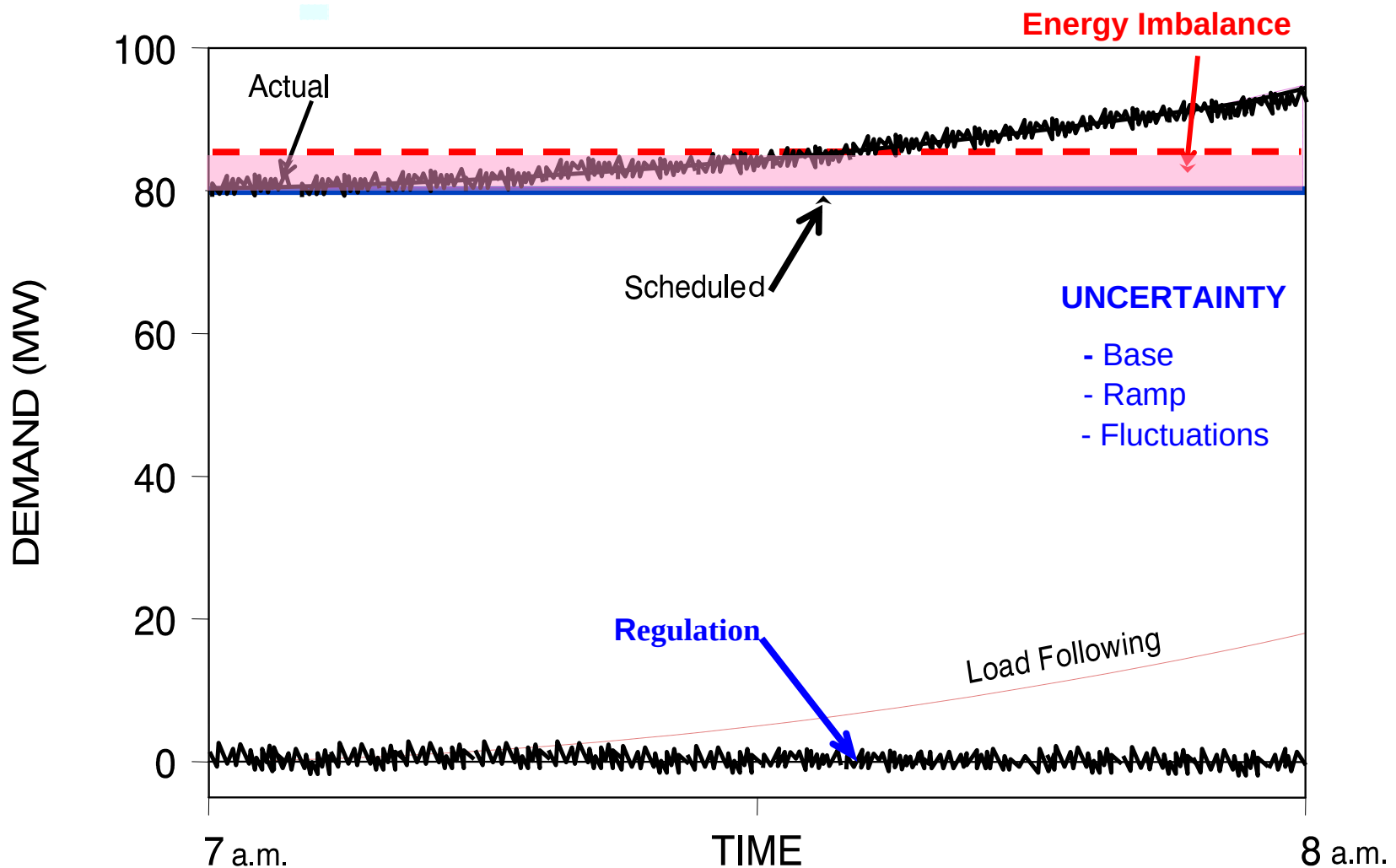




Typical system input (load, wind)



Continual Balance between Supply and Demand under Normal Condition with Load Uncertainty



Complexity of the Evolving Industry Architectures

- The industry challenge is much more complex than ever before as a result of variety of reasons:
 - the needs for more energy are growing, but it is no longer possible to build according to the existing planning and operating criteria (there is simply not enough resources to provide the same energy density per capita as at present; right of ways hard to obtain; greenhouse effects major concern);
 - it has become inevitable that we must make the “most” out of what is available (even at the expense of violating once sacred principles of unconditional service provision to the customers);
 - the “most” not a single criterion subject to constraints (instead, the notion of the “most” has become multi-dimensional and must be viewed as a result of reconciling major tradeoffs)

Challenge to the old assumptions—as seen by the **system operators**

- Much action at many more network nodes than in the past
 - demand is much harder to predict
 - intermittent resources are “negative load” (new forecast, modeling and scheduling challenge)
 - economic exchange between utilities driven by power plant/LSE decisions (strong, and not coordinated by the operators); seams issue
- Disruptive technologies attempting to connect to the existing grid
- Temporal separation not obvious
 - rate of response, start-up, shut-down, must-run specifications of new technologies;
 - much more distributed, small local actions than in the past; storage effects.

Challenge to the old assumptions created by the DERs

- DERs (DGs, demand-side, transmission and distribution providers)
 - Technical specifications for interconnecting
 - Decision making to sell/buy
 - Local sensing and control technology choice
 - Communications and coordination with the others (large portfolios—hydro+wind?)
 - Even more complex (clusters of plug-in-vehicle stations + wind+PEV)?
 - Valuation of their unique characteristics

Qualitatively new dynamics of the evolving electric energy systems

- Interactions between the transmission (bulk) and distribution (local) networks significant ; increased spatial interactions among the utilities
- Large number of DERs located at various network nodes; vastly heterogeneous dynamics (wind, solar, storage, demand-side feedback); increased temporal interactions among different system modules.
- Network dynamics not negligible compared to the fast dynamics of small resources.
- Much beyond electromechanical and electromagnetic conversion dynamics.

What needs to be engineered? Getting from here to there..

- Need for new infrastructure to support change
- Moving from the worst-case deterministic hierarchical control design to the **multi-layered protocols in support of multiple tradeoff decision making [6,8]**
- Methods for managing dynamic response under uncertainties (**just-in-time (JIT) and just-in-place (JIP) production, delivery and consumption [6,9]**)

Need for new infrastructure to support change

- Some key examples
 - empower customer choice
 - implement demand side response
 - integrate renewable resources (distributed energy resources –DERs-)
 - implement differentiated reliability and Quality of Service (QoS)
- ALL OF THESE REQUIRE TRANSFORMATION OF TODAY'S ELECTRIC POWER GRID TO AN ACTIVE ENABLER
- CHANGE OF PARADIGM FROM BUILDING PASSIVE LARGE POWER LINES TO SELECTIVELY BUILDING WHERE TRULY NECESSARY; INSTEAD, COMPLETELY RE-DESIGNING THE GRID INTELLIGENCE

Need for managing dynamic response of various technologies

- **System load factor** can be significantly increased by deploying just-in-time (JIT) and just-in-place (JIP) technologies. The load factor in the US utilities has worsened in a major way recently. This is not sustainable.
- These technologies range from individual components through extracting economies of scope and economies of systems [10]
- Impossible to integrate effectively (with provable benefits to the end users) large scale intermittent resources and demand side response without transforming the grid intelligence.
- Major tradeoffs in performance dependent on how are these technologies utilized.

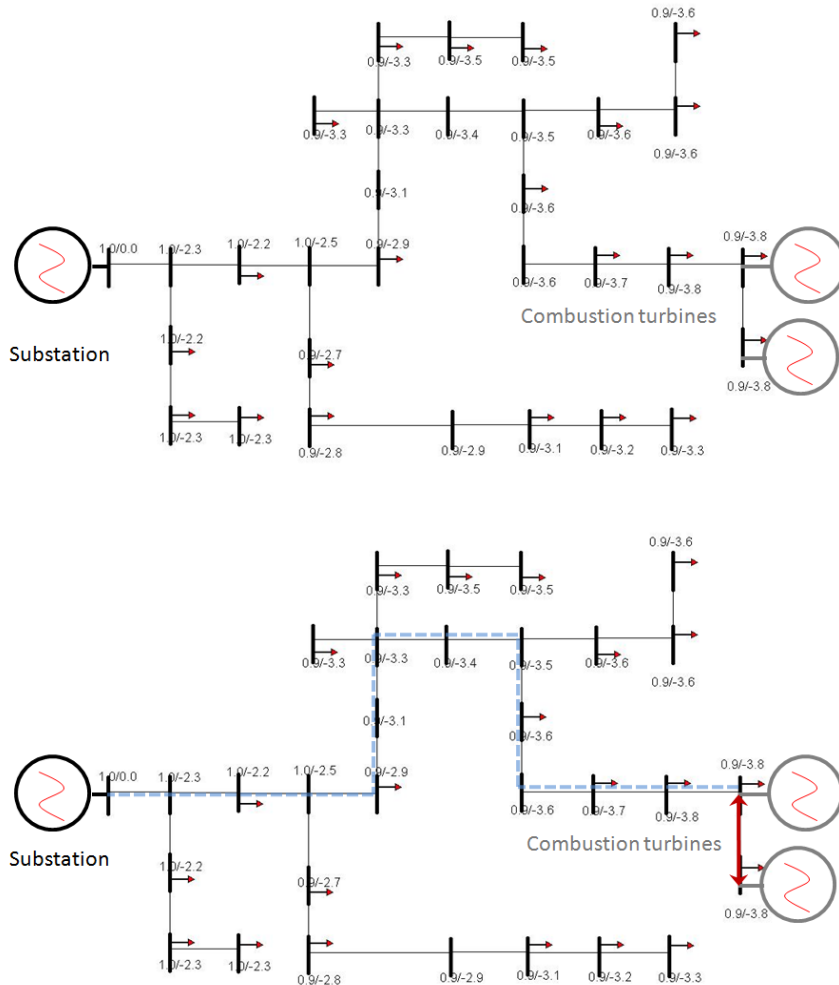
New network systems problems

- Systematic modeling, monitoring and control framework for open-access energy systems
- Stability analysis of electric networks whose nodes are embedded modules characterized by the dynamic conversion from non-traditional forms of energy to the electric energy.
- Design of cyber (sensing and communications) architectures for predictable performance
- Beyond generator control. Of particular interest **methods for fast switching to ensure pre-specified performance (frequency and voltage control)**. Perhaps the key problem.

Our work at CMU

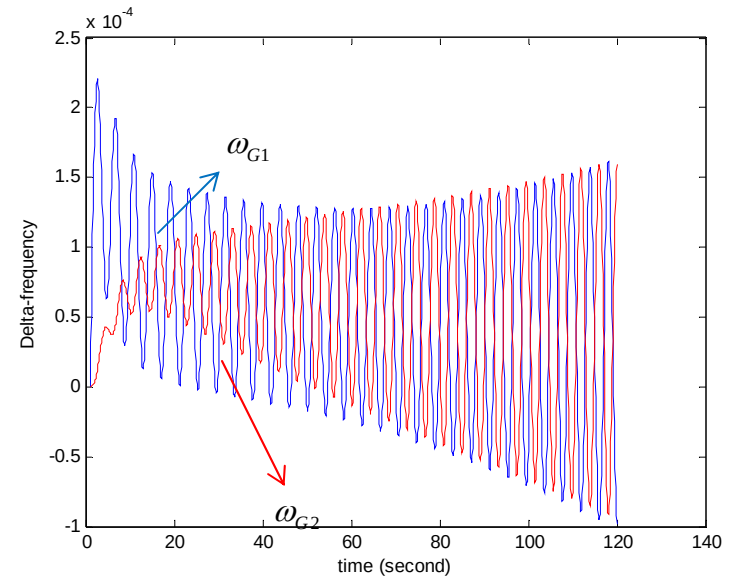
- Examples of unstable local (distribution) networks caused by interactions of DERs.
- New structure-preserving model cyber-physical model of future energy systems; basis for dynamic multi-layered (distributed) monitoring and control.
- Sufficient conditions for stable modular integration of new DERs (wind).
- Preliminary work on information structures.
- Model Predictive Control (MPC) for empowering customers and integration of intermittent resources.
- Dealing with blackouts in qualitatively different ways: Implementing differentiated reliability and QoS by means of dynamic islanding.

Example of instabilities caused by the DERs interactions

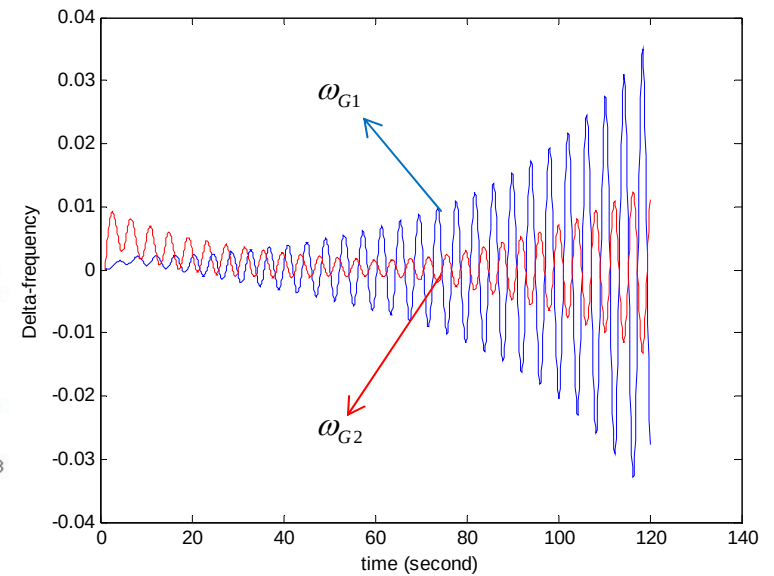
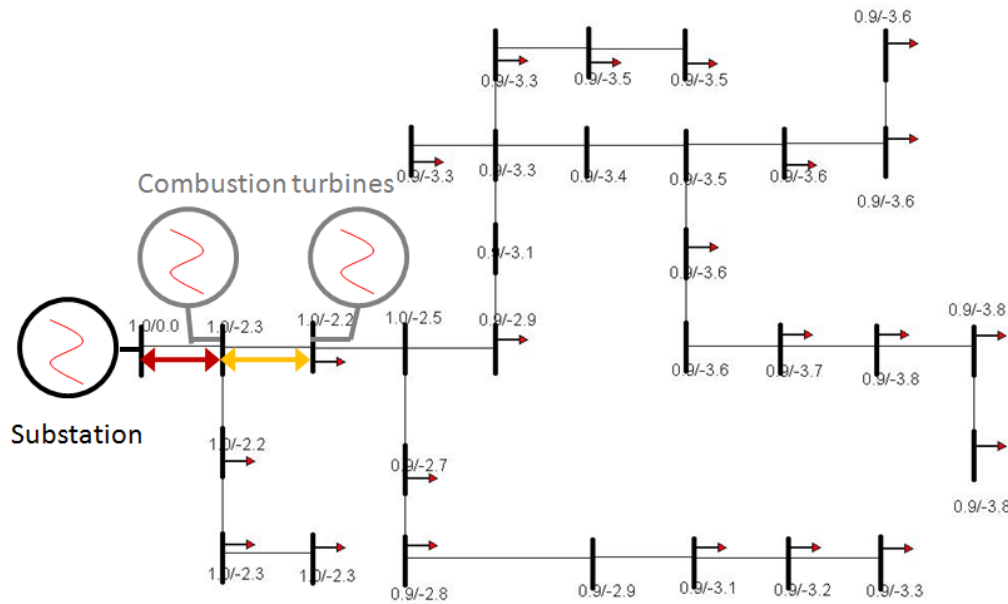


- 10% of total power from DGs (1.5 MW)
- 50% power loss reduction by optimum placement (0.7 MW)

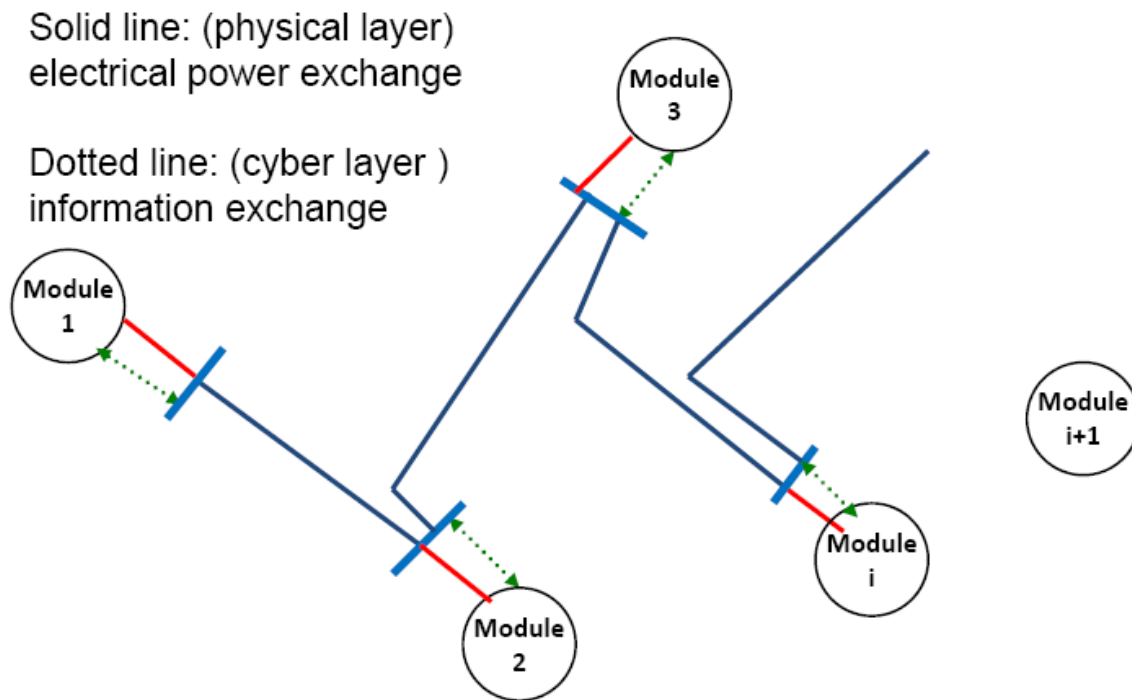
Frequency instability at optimum loss location



Interaction of DGs with a large generator (substation)



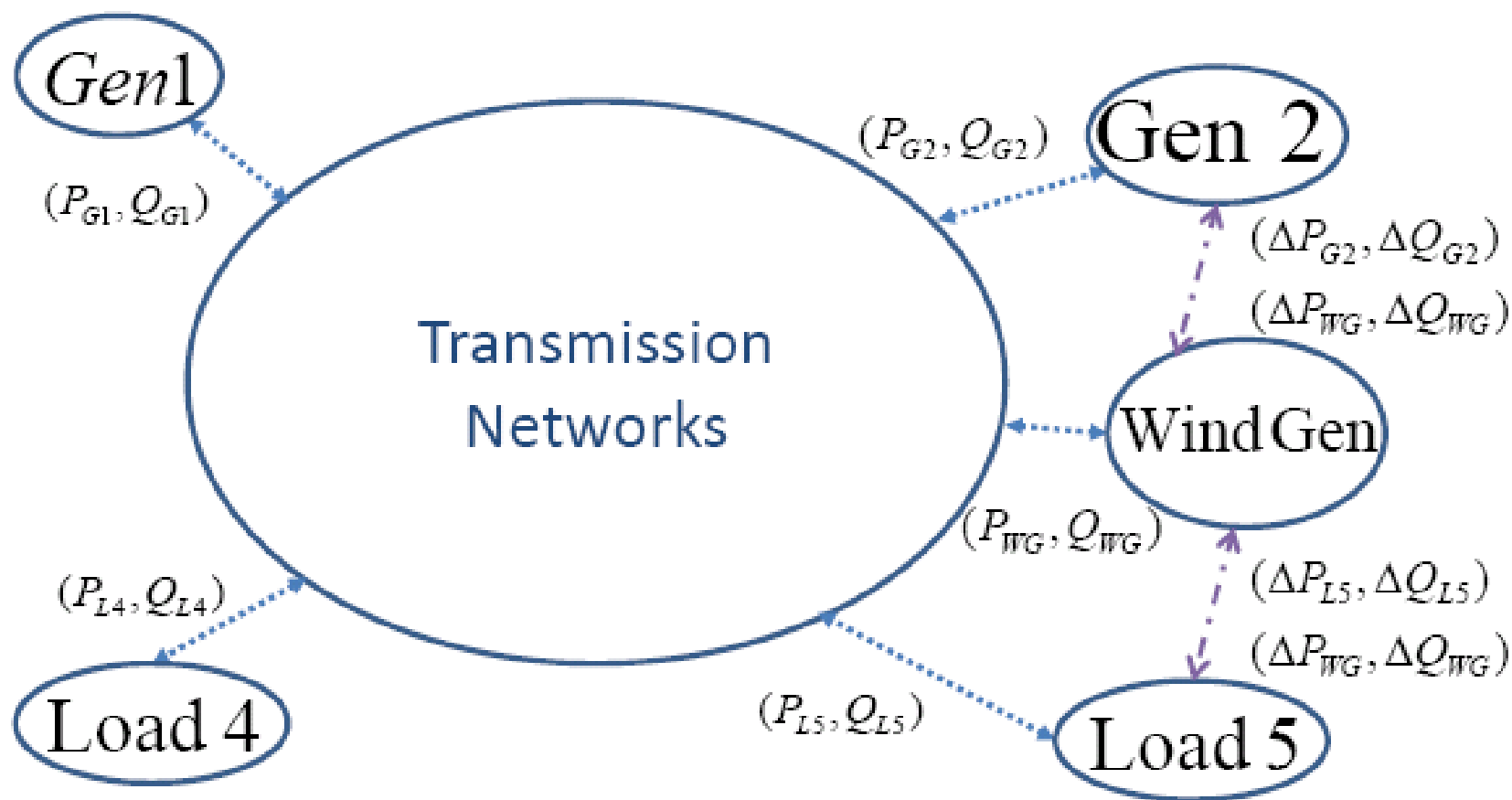
New cyber-physical modeling for future energy systems



- Modules:
 - Generators (Coal, Gas, Wind, etc.)
 - Loads
- Modules are interconnected via transmission lines

Cyber-physical model using new state space

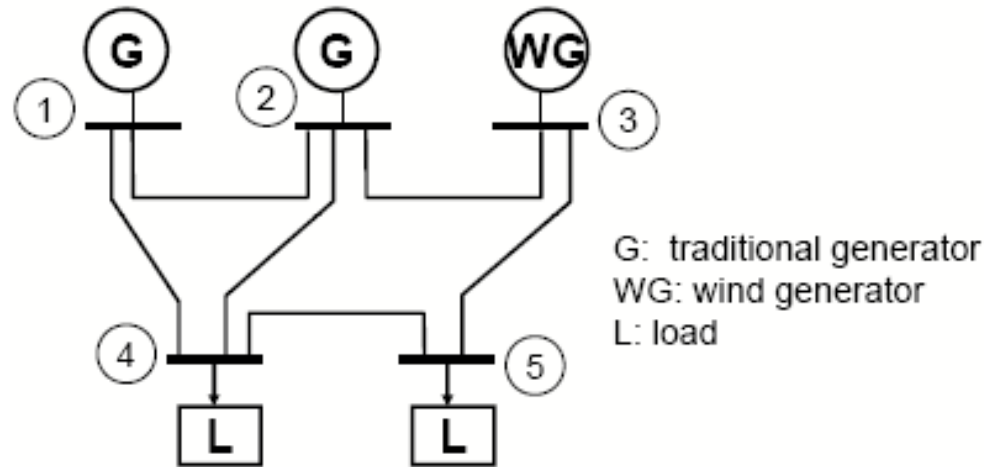
- **New structure-preserving** model: represent all components as modules (both loads and generators) inter-connected through a **sparse electric network**.
- **Mix of physics-based models** (power plants) and **cyber models of system modules** (load—a city).
- **New state variables** which allow for an ODEs model without losing structure.



↔ Module-network communication (centralized)

↔ Module-module communication (decentralized)

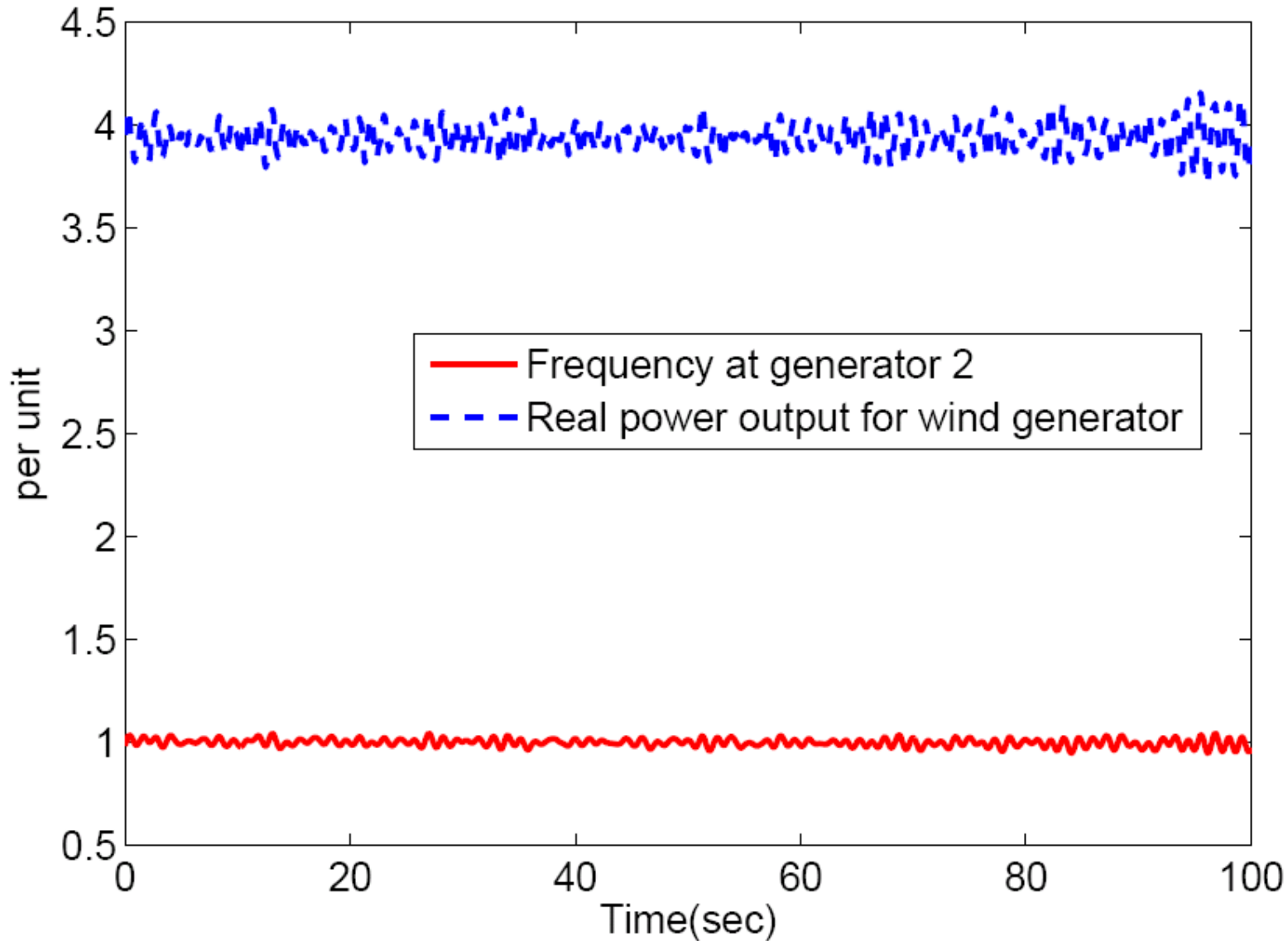
Example of wind power integration



- Five bus system
- Wind capacity is 20% of the system total capacity
- Transmission lines assumed lossless

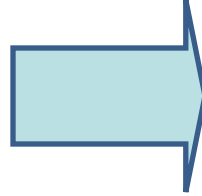
Dynamical Response

Trajectory of wind gen real power output and frequency of gen 2



Motivation

Better Prediction of
Intermittent Resources?



More efficient utilization of
intermittent resources

More reliable operation of
intermittent resources

Problem Statement

- Economic Dispatch (ED): given a mixture of energy resources, how to determine the output of individual energy resources so that (1) power supply always balances demand

(2) total generation cost is minimized?

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

$$s.t. \sum_i P_{G_i}(k) = \hat{L}(k), i \in G, k = 1, 2, \dots, K;$$

$$P_{G_i}^{\min} \leq P_{G_i}(k) \leq P_{G_i}^{\max}, k = 1, 2, \dots, K;$$

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

Total Gen
Cost

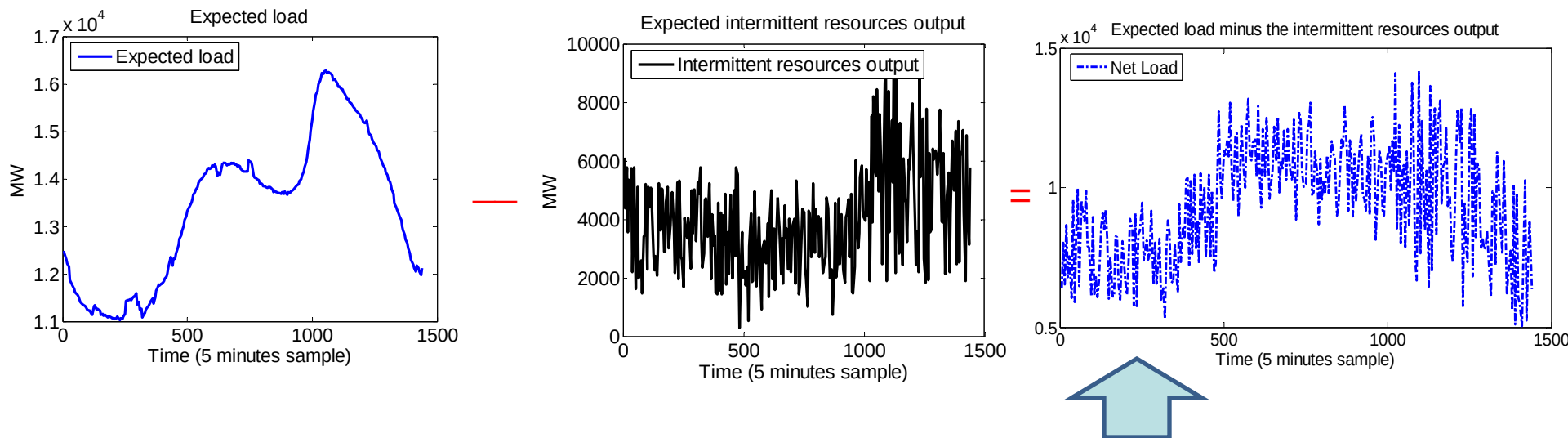
Supply=E(Dema
nd)

Gen Constraints

Ramp rate
constraints

Conventional Approach to ED

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

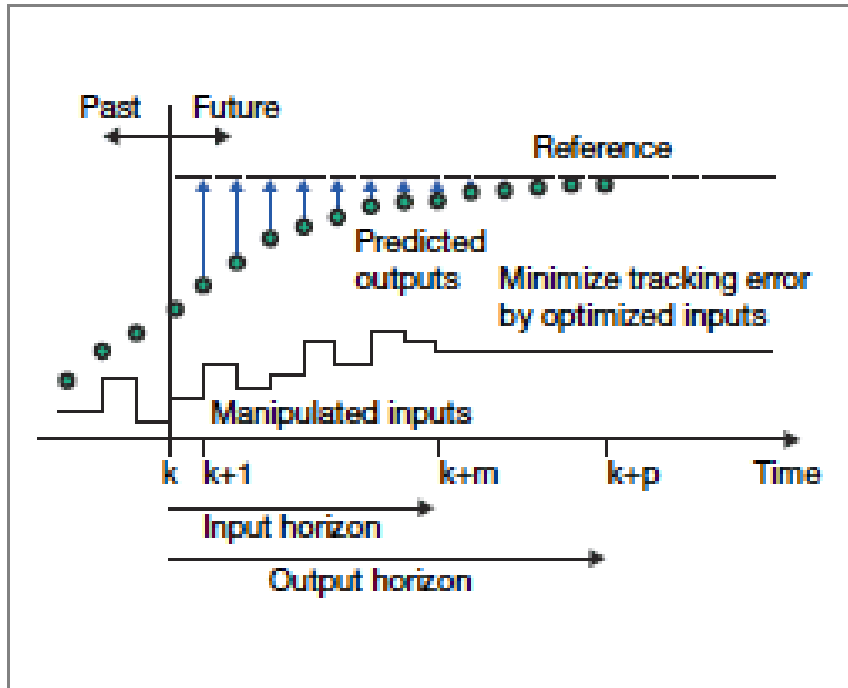


Economic Dispatch (ED): Choose output levels from conventional power plants to meet the “net load” at minimum cost.

Proposed Approach

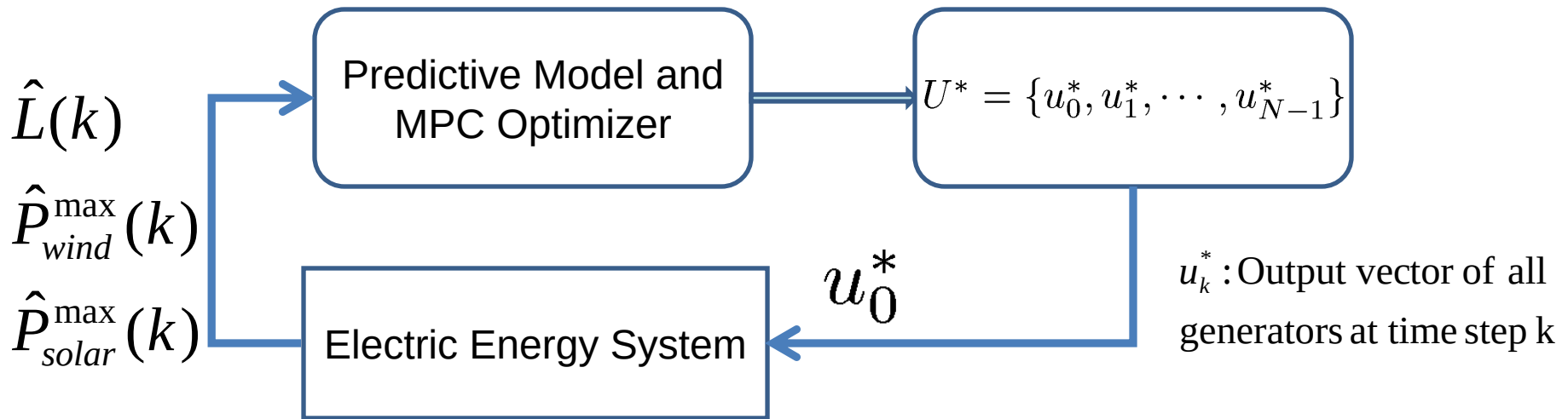
- Actively control the output of available intermittent resources to follow the trend of time-varying loads.
- By doing so, the need for expensive fast-start fossil fuel units is reduced. Part of the load following is done via intermittent renewable generation.
- The technique for implementing this approach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

Model Predictive Control: Concept



- 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.

Proposed Approach: Algorithm

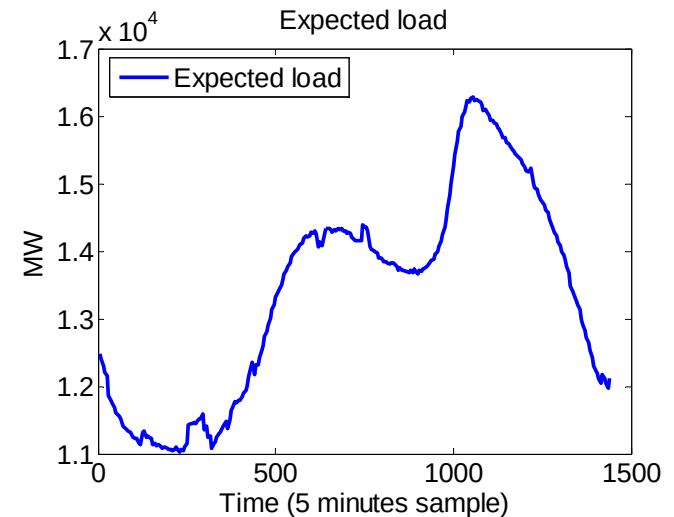
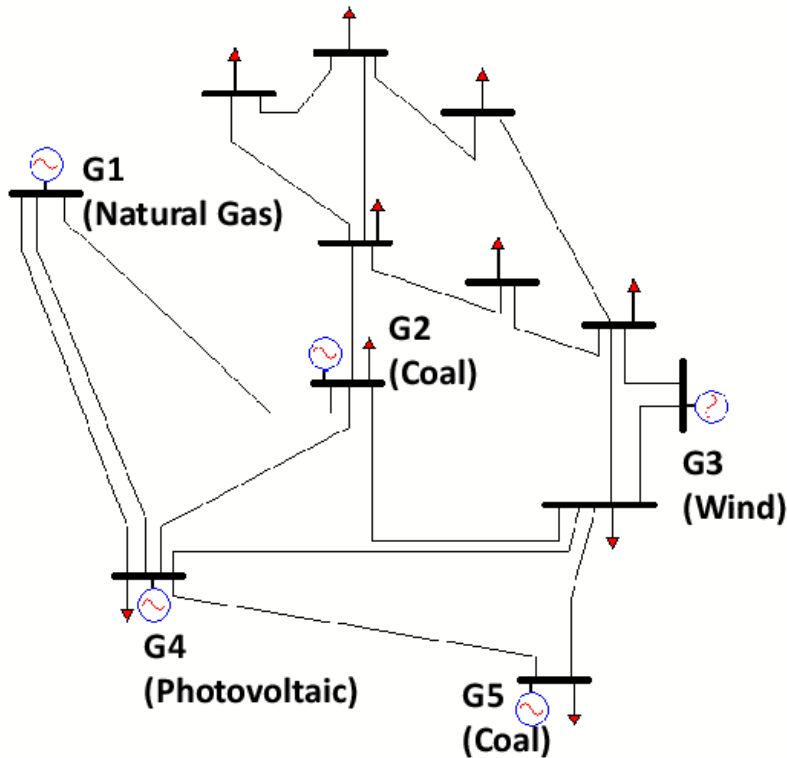


- Predictive model of load and intermittent resources are necessary.
- Optimization objective: minimize the total generation cost.
- Horizon: 24 hours, with each step of 5 minutes.

Numerical Experiment

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

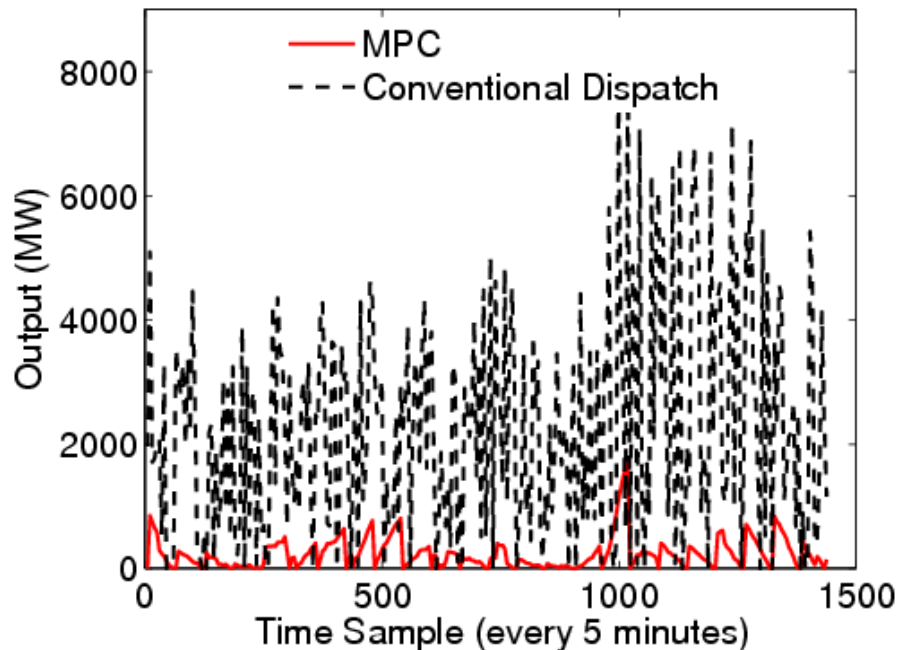


Compare the outcome of ED from both the conventional and proposed approaches.

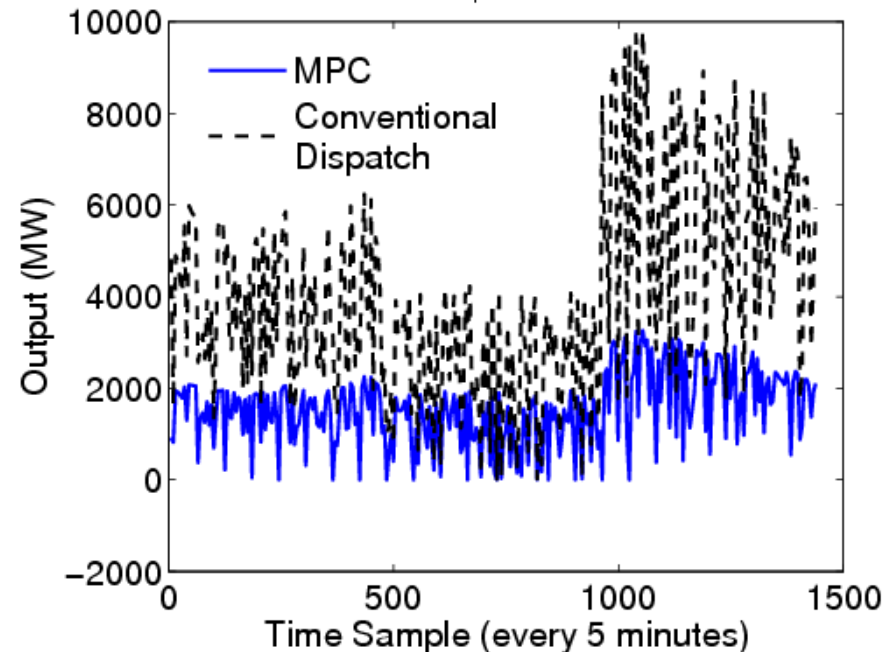
Numerical Experiment

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

Natural Gas Power Plant Output under Two Cases



Wind Power Output under Two Cases



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

Lessons learned

- Look-ahead model predictive dispatch of future energy system is proposed.
- Combined with good short-term prediction of intermittent resource outputs, the proposed method can lower the total generation cost.
- Smarter is less: more intelligent utilization of intermittent resources can actively follow the load variation trend, thus lower the total generation cost.

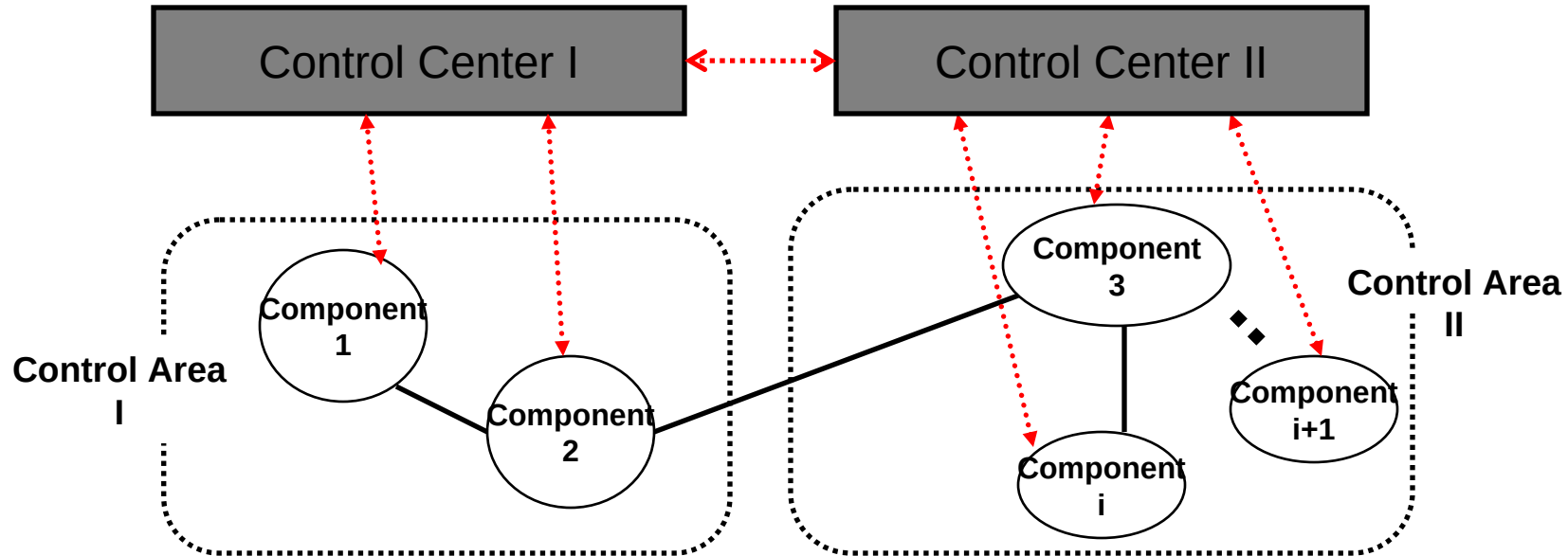
Future Work

- Scale issue: how to make this algorithm fast enough in large-scale systems?
- Multi-objective problem: how to generalize the algorithm to study the tradeoff between environmental and economic costs?
- More realistic model: how to include more realistic factors (e.g. transmission constraints) into the predictive dispatch model?

Dependence of Information Architecture on The Objectives

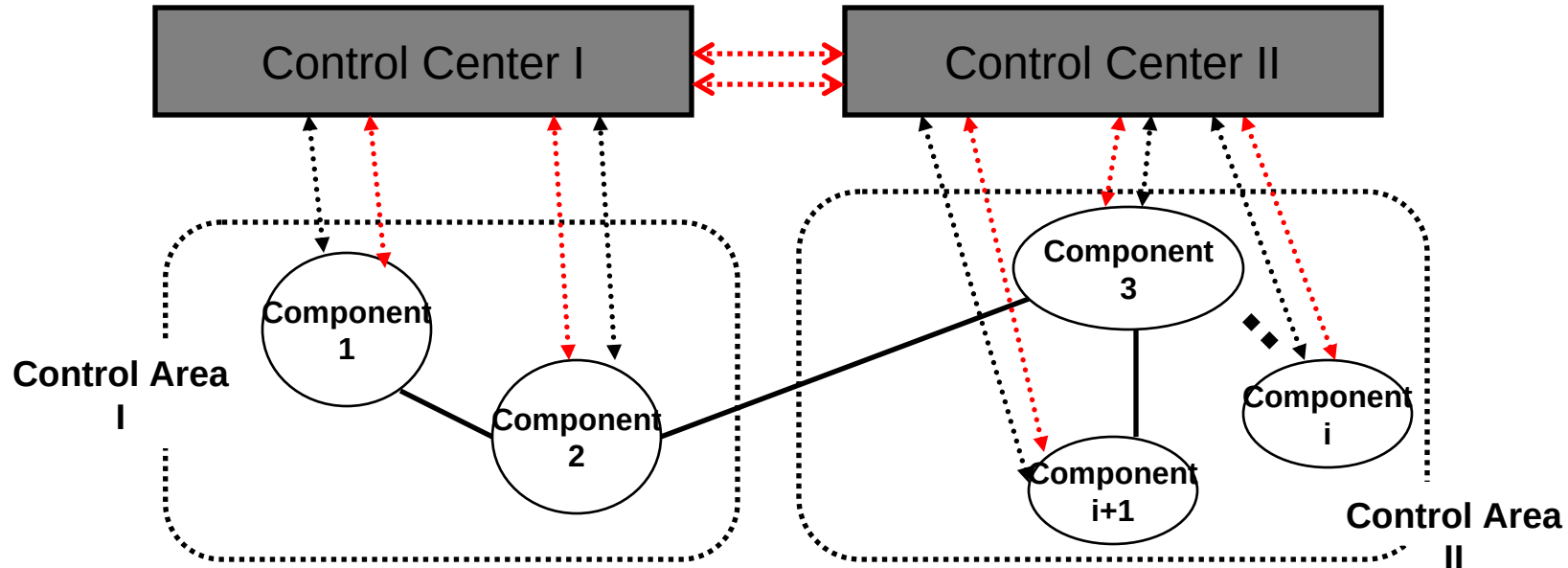
- Qualitatively **different IT infrastructures** required to support different physical architectures and objectives.
- Complexity and cost of **cyber** for physical systems such as future energy systems can be significant.
- Lack of well-defined incentives for converting today's power grid to a user-friendly enabler of future energy systems.
- In what follows, some illustrations of current and evolving energy system architectures and possible IT architectures.

Today's SCADA



Slow-centralized IT for scheduling
No fast communication for stabilization
No Adaptive local control

Modular Integration of New Resources (Wind) Within Today's SCADA



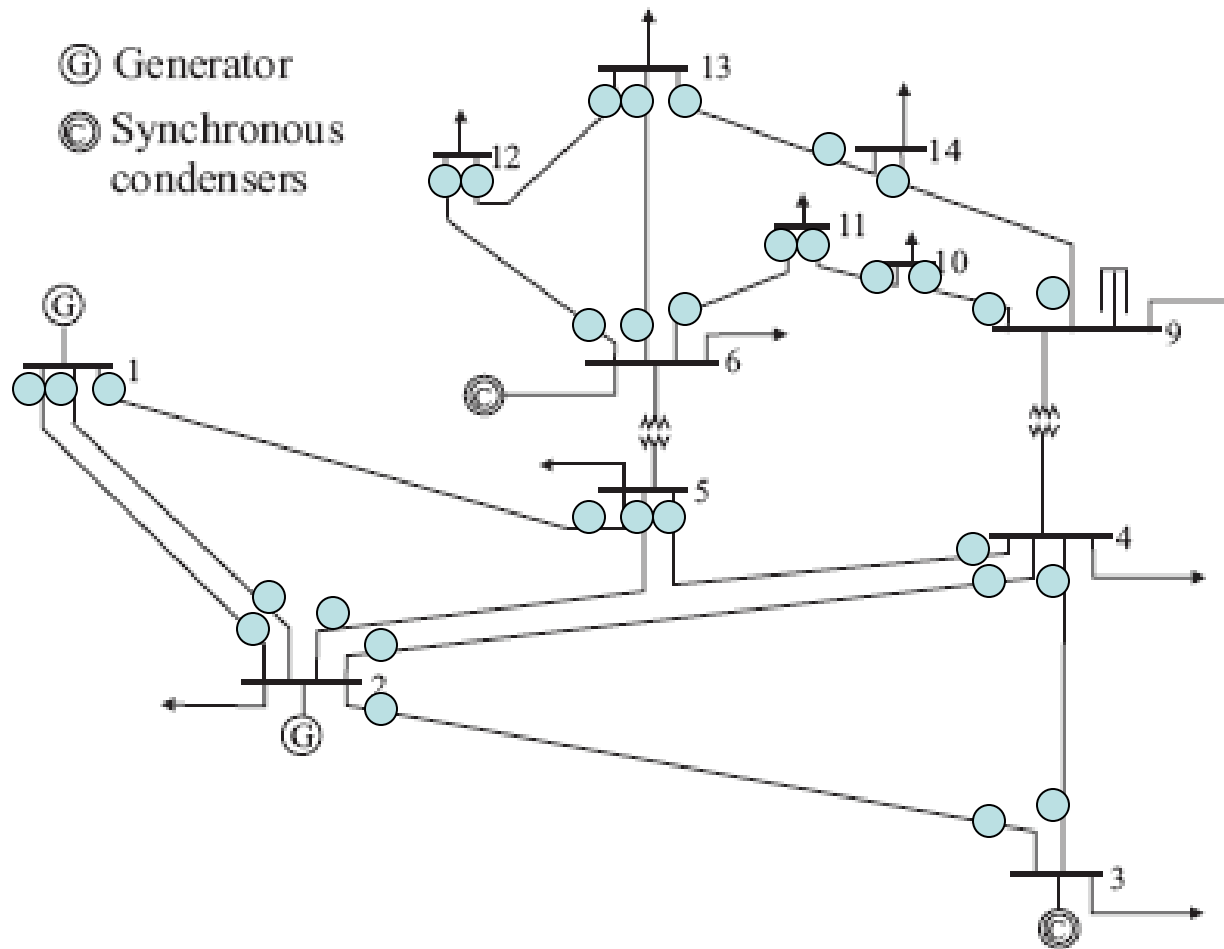
Interaction

— Physical

..... Cyber for scheduling (SCADA, slow)

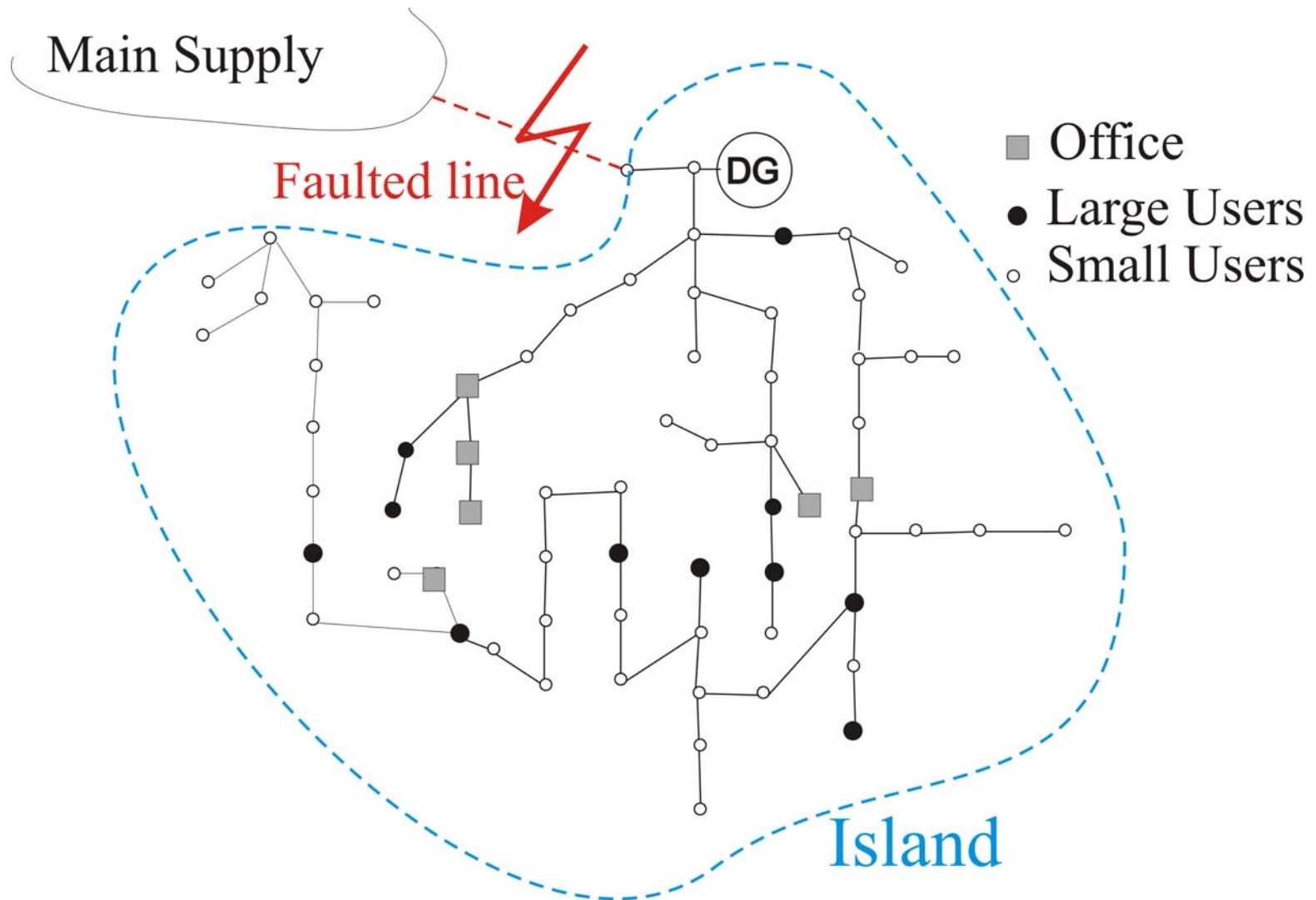
..... Cyber for control (SCADA, slow)

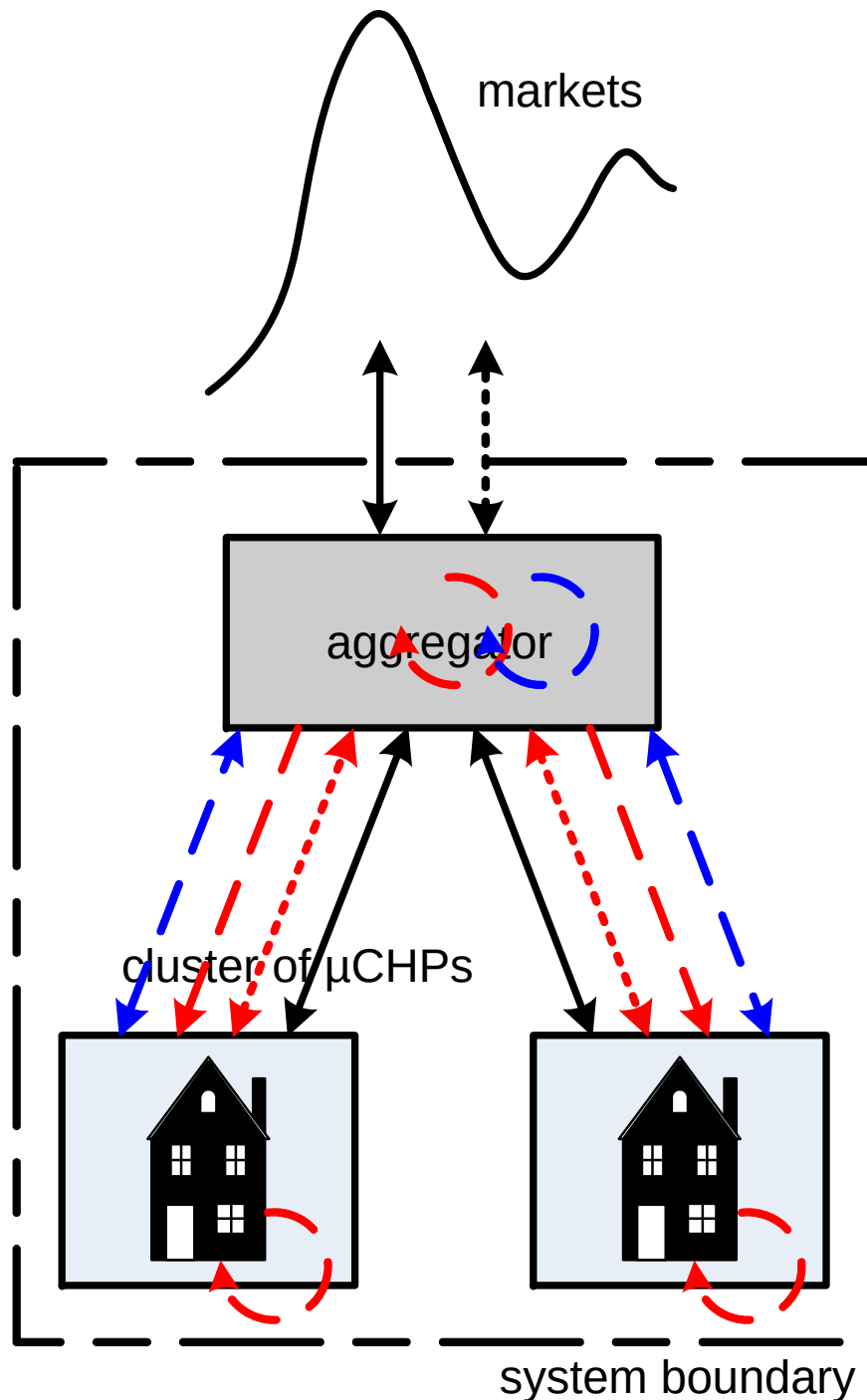
Local Protection Intelligence for Preventing Blackouts



● stands for the location of Support Vector Machine (SVM) Classifier-based protection relays

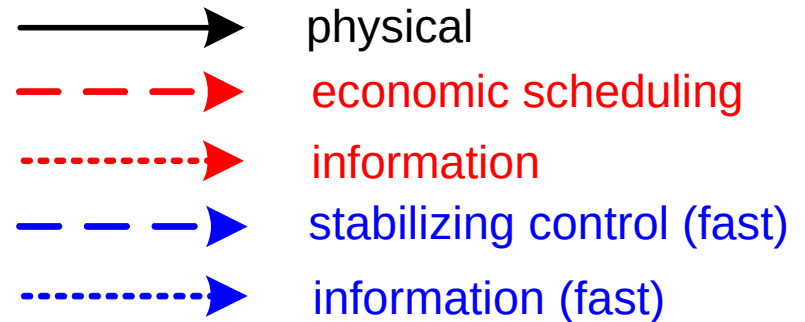
Maximizing Reliable Service by Coordinated Islanding and Load Management

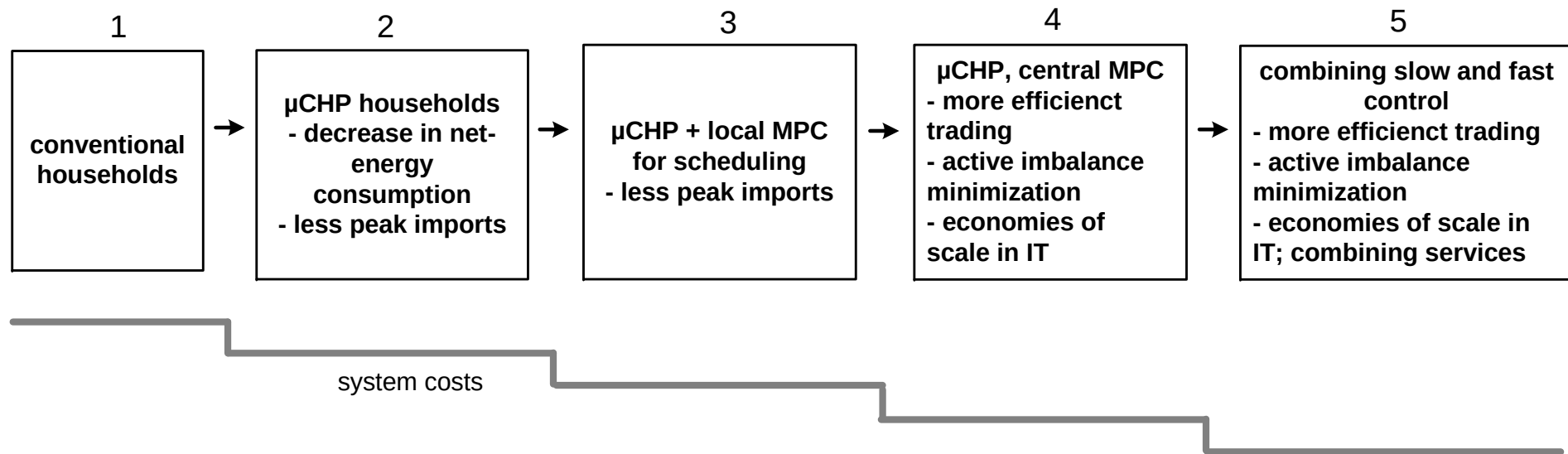




EMPOWERING THE END USERS

- μ CHP; 'plug-n-play'
- Local MPC
- Central MPC for trading
- Combining slow/fast control





- Economies of system in coordination and ICT

Open systems engineering problems

- Dynamics of the evolving electric energy systems needs to be modeled (simply not present in today's models)
- Must understand pros and cons of distributed intelligent sensing and control vs. extensive on-line coordination and communications
- Provable distributed sensing and control requires structure-preserving network representation
- Define technical specifications for (“plug-and-play”) embedding DERs and for designing protocols for multi-layered interactions between DERs and the rest of the system.
- Rather than the worst-case study, it is possible to have provable system stability performance by module-based design.
- None of the above exist today; there are only sporadic demos and/or brute-forcing of old industry standards.

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