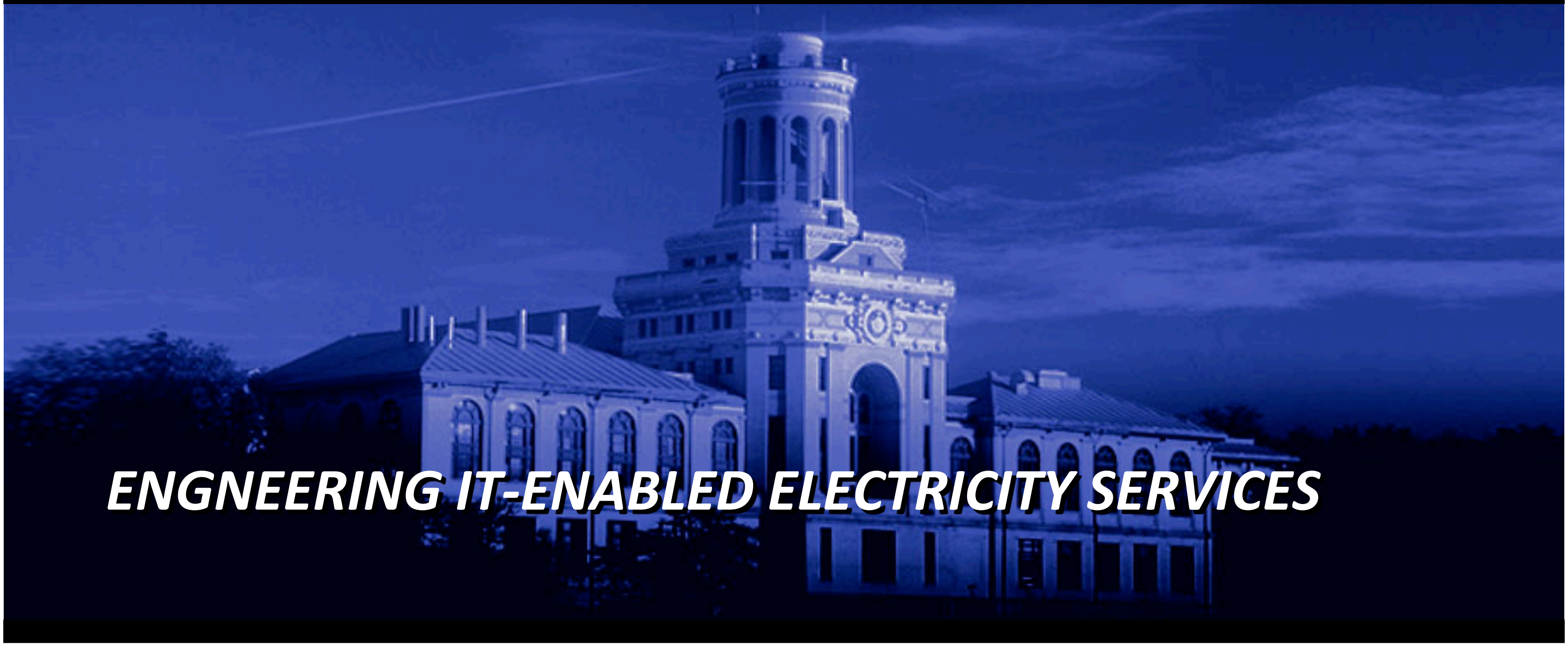

ENGNEERING IT-ENABLED ELECTRICITY SERVICES

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SRC SGRC http://www.src.org/program/eri/

Southern Cal Workshop, Caltech October 13,2011

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.***
- ***SRC Energy Research Initiative –Smart Grid Research Center*** http://www.src.org/program/eri/
- ***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.***

Electrical & Computer ENGINEERING

Outline

- ***Bringing Information (Communications) Technology (I(CT) to Power Systems***
- ***The general Socio-Ecological Systems (SES) framework [1] – basis for re-thinking what is possible in the electric energy systems and how can it be engineered (implications on candidate architectures)***
- ***The man-made electric power network, its governance system and the Information Communications Technology (ICT) --- key enablers of sustainable electric energy provision [2,3]***
- ***Common modeling framework for SES and ICT modeling and design—interaction variables***
- ***Dynamic Monitoring and Decision Systems (DYMONDS) framework—a possible ICT approach to managing temporal, spatial and contextual interaction variables***
- ***Proof of Concept Simulations for DYMONDS***
- ***Looking forward…***

Bringing ICT to Power Systems

- ***The creation of "smart grids" is the application of information technology to the power system while coupling this with an understanding of the business and regulatory environment***
- ***Smart grids as a means of managing uncertainties in more adaptive ways than in the past; aligning reliability and efficiency***
- ***Critical to the creation of "smart grids" is;***
  - *development of models of the power system*
  - *development of command and control algorithms and software*
  - *incorporation of security, communications, and safety systems*
  - *BEFORE hardware is deployed!*
  - *Our Approach to ICT design --Dynamic Monitoring and Decision Systems (DYMONDS)*

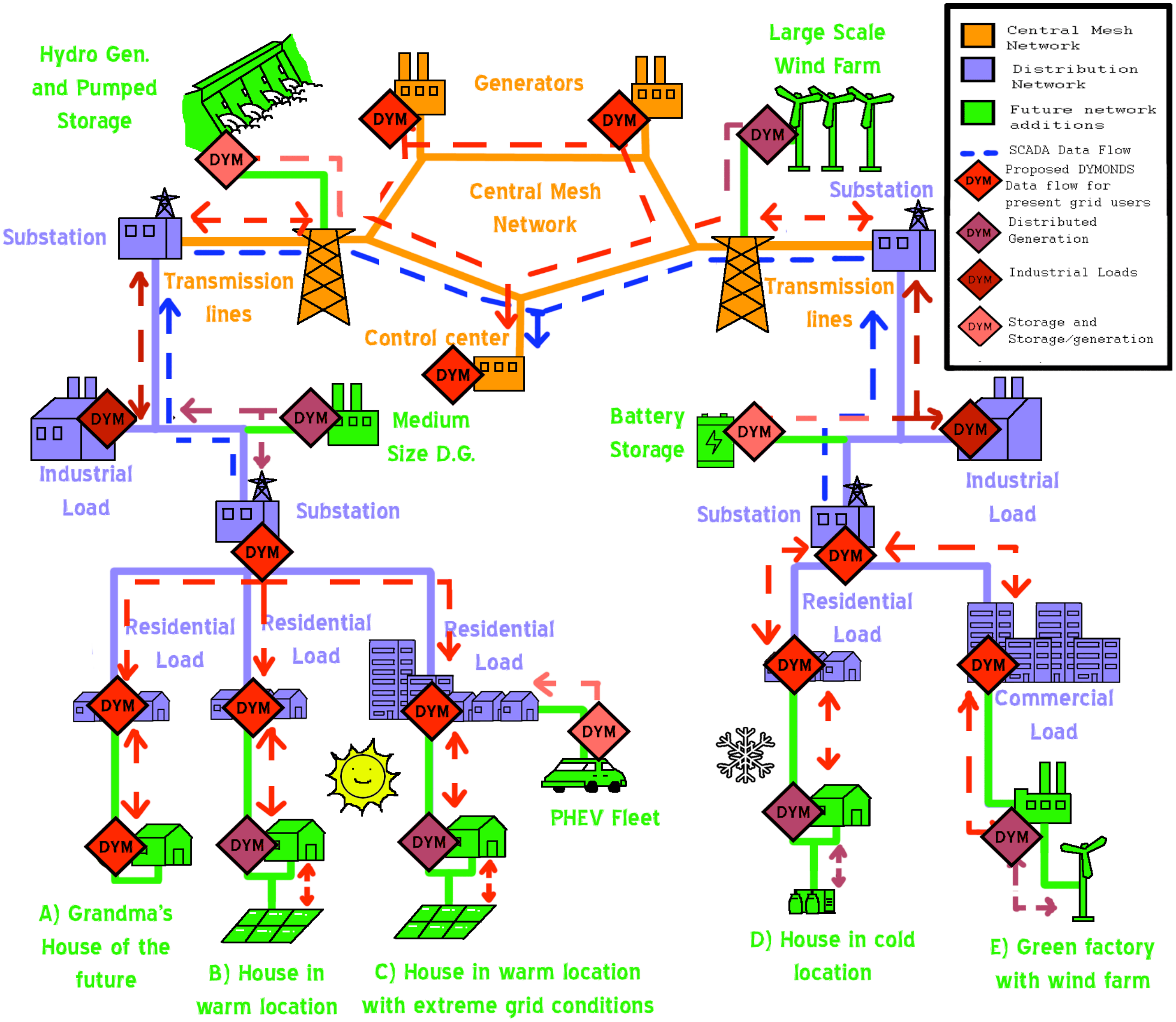
Uncertainties in Power Systems

- *System demand forecast*
- *Low probability high risk forced outages*
- *Difficult to manage*
- *Hierarchical control approach to the worst-case system management*
- *Very high cost of preventive approach*
- *(NEW) Distributed-decision making (restructuring) and intermittent resources (environment)*
- *The need for on-line decision making as conditions change for enhanced efficiency w/o loss of reliable service*

Transformational change in objectives of future energy systems

Today's Transmission Grid	Tomorrow's Transmission Grid
Deliver supply to meet given demand	Deliver power to support supply and demand schedules in which both supply and demand have costs assigned
Deliver power assuming a predefined tariff	Deliver electricity at QoS determined by the customers willingness to pay
Deliver power subject to predefined CO_2 constraint	Deliver power defined by users' willingness to pay for CO_2
Deliver supply and demand subject to transmission congestion	Schedule supply, demand and transmission capacity (supply, demand and transmission costs assigned); transmission at value
Use storage to balance fast varying supply and demand	Build storage according to customers willingness to pay for being connected to a stable grid
Build new transmission lines for forecast demand	Build new transmission lines to serve customers according to their ex ante (longer-term) contracts for service

DYMONDS-enabled Physical Grid [2,3]



Examples of Enhanced Asset Utilization with Better Dispatch

- ***Conventional system operation***
  - *Centralized decision making*
    - *ISO knows and decides all*
  - *Not proper for future electric energy systems*
    - *Too many heterogeneous decision making components : DGs, DRs, electric vehicles, LSEs, etc.*

- ***Dynamic Monitoring Decision-making System (DYMONDS)***
  - *Distributed decision making system*
    - *Distributed optimization of multiple components → computationally feasible*
  - *Individual decisions submitted to ISO (as supply/demand bids)*
    - *Individual inter-temporal constraints **internalized***
    - *Market clearance and overall system balanced by ISO*

Getting from here to there..
MORE THAN ONE WAY TO INTEGRATE

- ***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***
- ***Methods for managing dynamic response under uncertainties (just-in-time (JIT) and just-in-place (JIP) production, delivery and consumption)***

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

THE MOST DIFFICULT QUESTIONS IN DESIGNING SMART GRIDS

- *THE KEY CHALLENGES---HARDWARE AVAILABLE AND BEING DEPLOYED (SMART GRIDS) BUT VERY LITTLE KNOWN ABOUT HOW TO INTEGRATE; SYSTEMATIC DEPLOYMENT AT VALUE*

- *MUST UNDERSTAND THE KEY FUNCTION OF SMART GRID AND ITS INFORMATION CONMMUNICATIONS TECHNOLOGY (ICT) DESIGN*

- ***Establish sufficiently accurate (but not too complex) modeling framework which captures inter-dependencies between SOCIO-ECOLOGICAL ENERGY SYSTEM (SEES), physical grid, ICT and governance system***
- ***The key objective: Match attributes of SEES, physical grid, ICT and governance system by designing around a given energy SES***
- *All of our SRC SGRC evolves around this question*

Toward Reconciling Engineering and Environmental Objectives--SES Framework

- ***THE KEY DESIGN---***

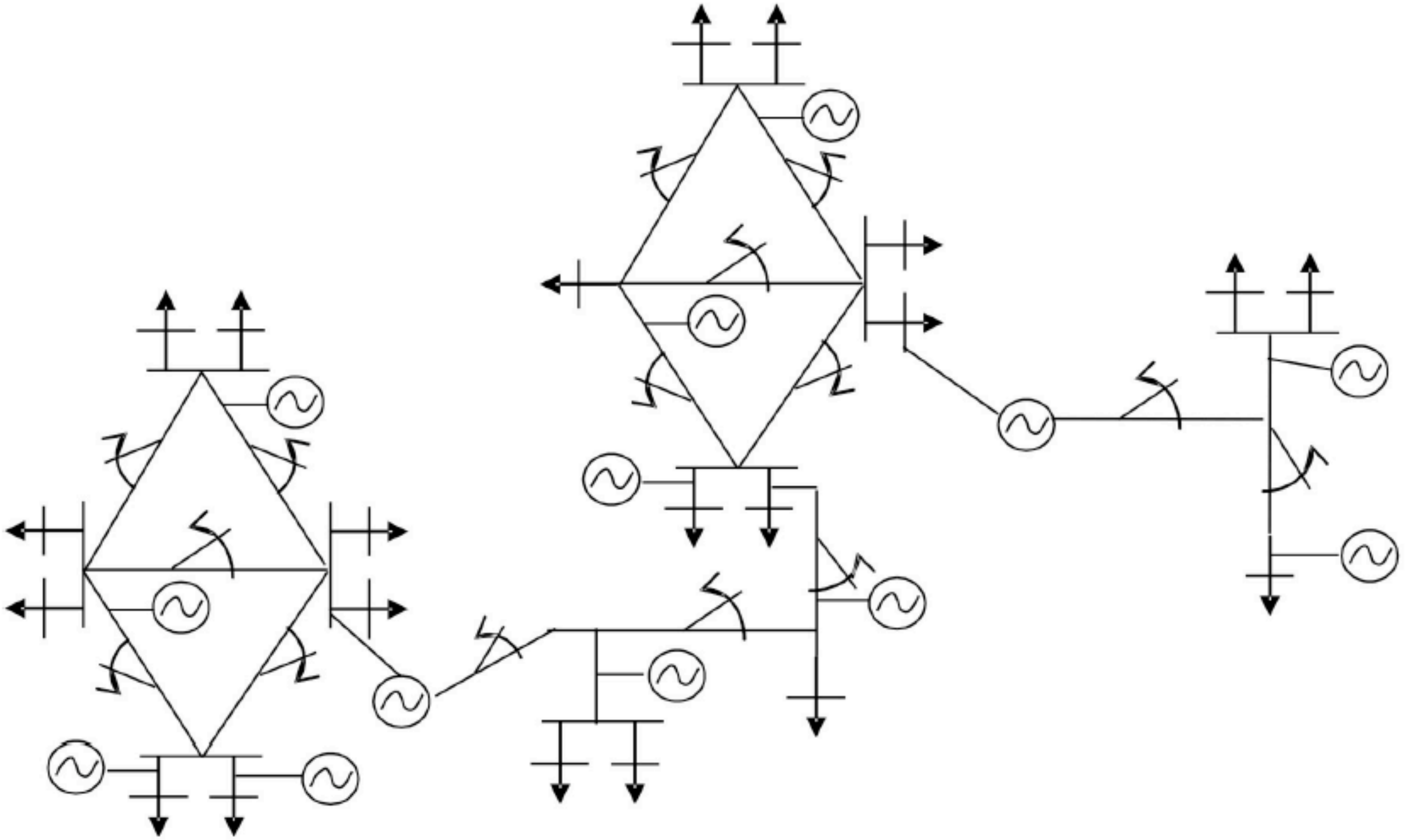
Fragmented coarse models of energy SES [7]

- ***Fragmented models the man-made power grids (for answering different questions, different temporal and spatial scales)***
- ***Fragmented approaches to ICT for "smart grid" modeling and design***
- ***POSSIBLE TO PURSUE AN SES-LIKE FRAMEWORK FOR DESIGNING SMART GRIDS [1]***
- ***Our approach---align modeling for SEES and objectives of smart grid and its ICT***

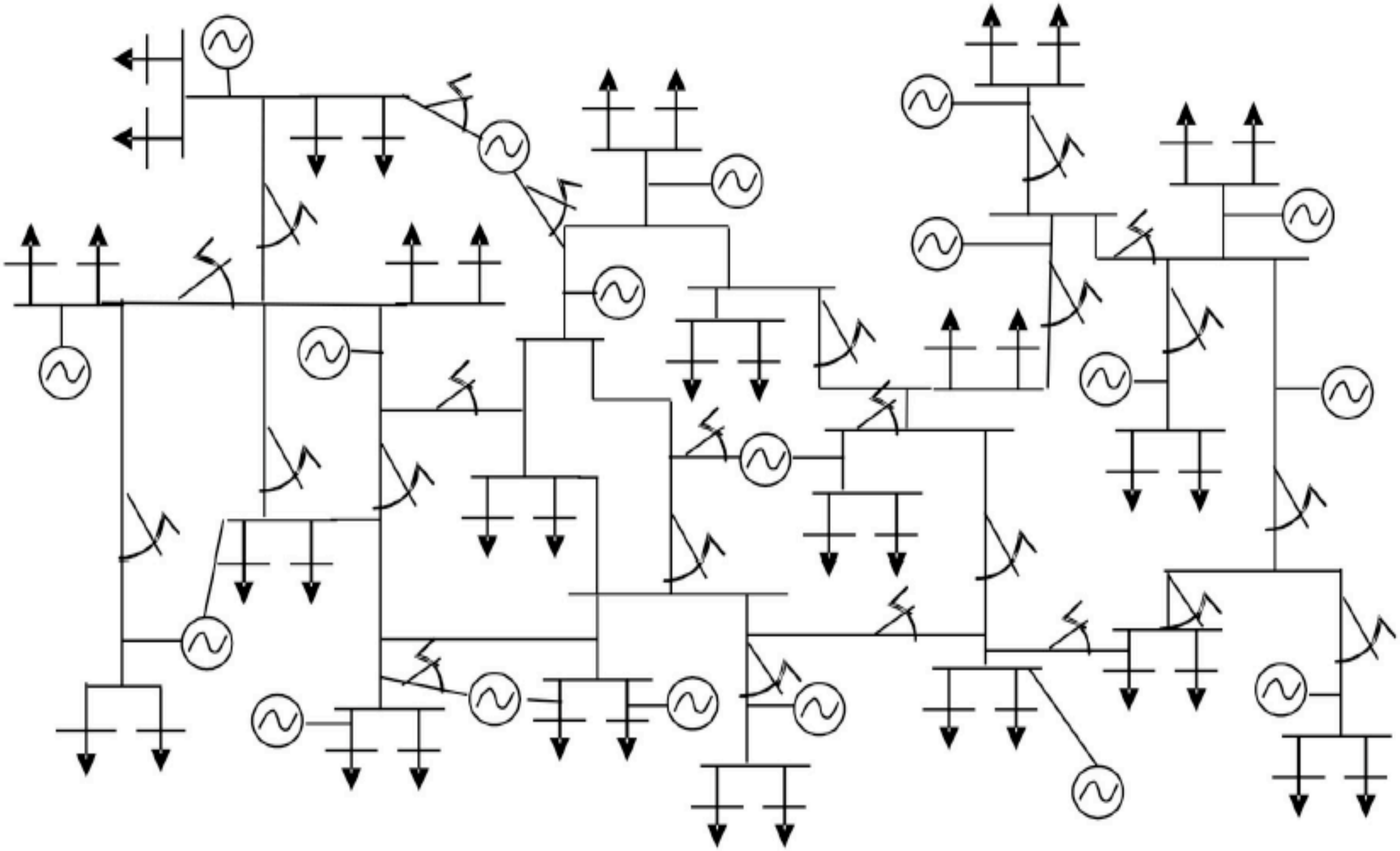
Interaction variables in bulk regulated energy systems-hindsight view

- ***Spatial, temporal and contextual interactions significant***
- ***This is particularly pronounced as the system is beginning to be used for more economic transfers and intermittent resources***
- ***Assumptions made for simplifications***
- ***Hard to reconcile reliability and efficiency***
- ***Different relevant interaction variables for different energy systems (Bulk power systems, hybrid, fully distributed)***

Hybrid Electric Energy System—How to model and manage interactions?

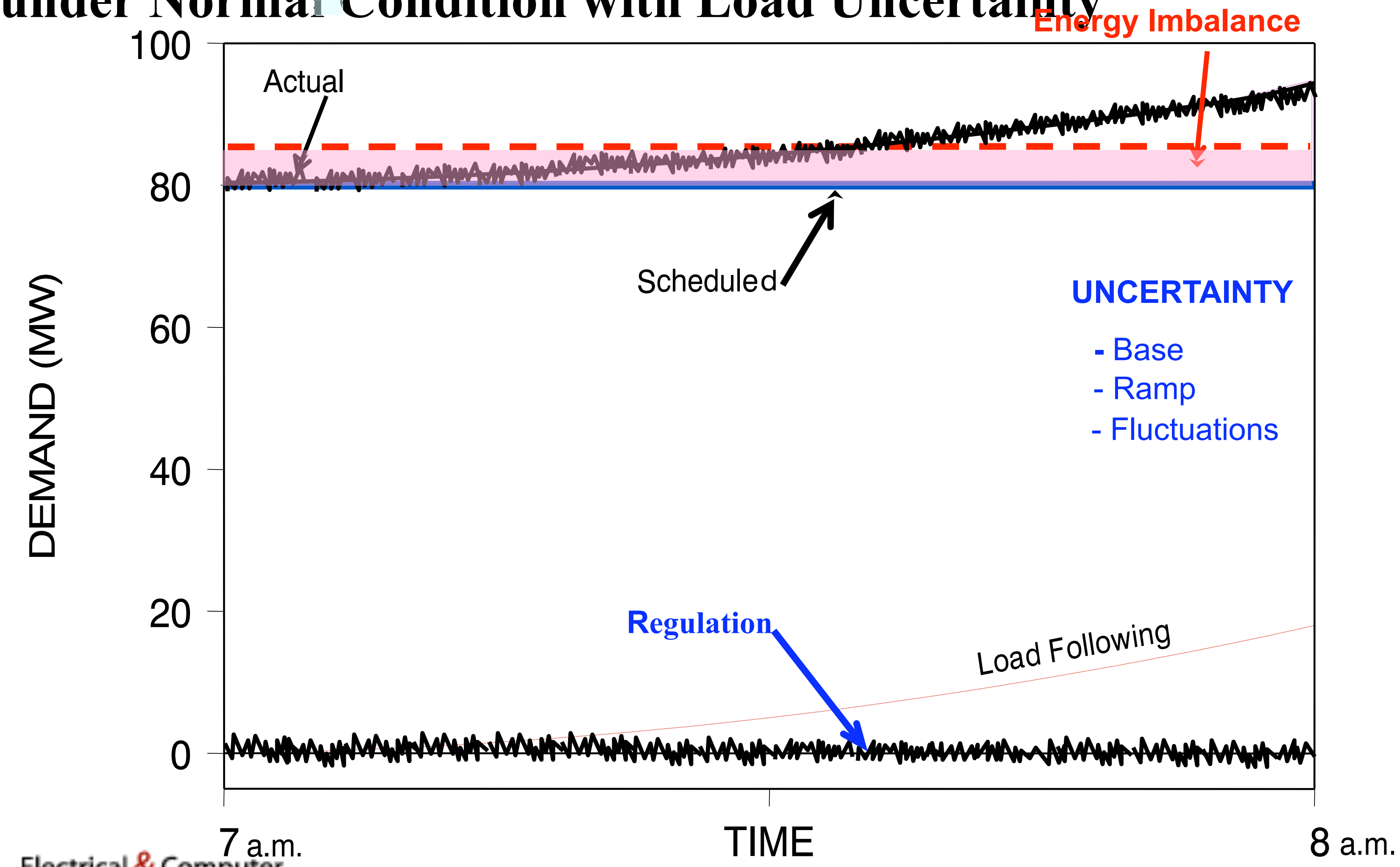


Fully distributed small-scale systems—Are there any interactions or it is all more or less distributed?



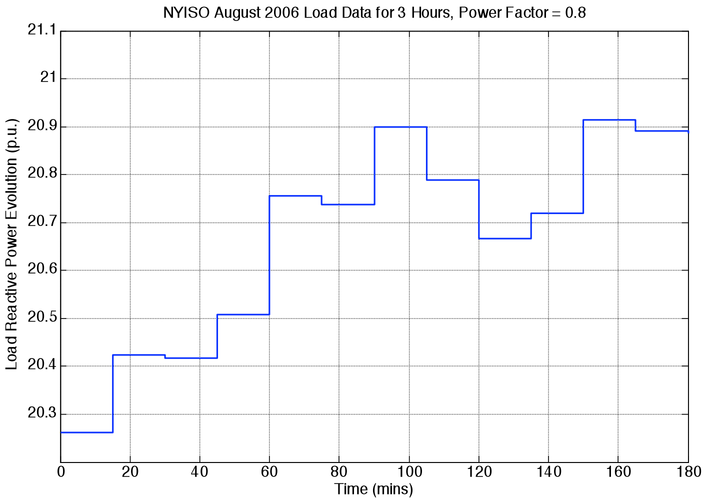
Temporal Complexity –COULD AND SHOULD BE MANAGED MORE ADAPTIVELY

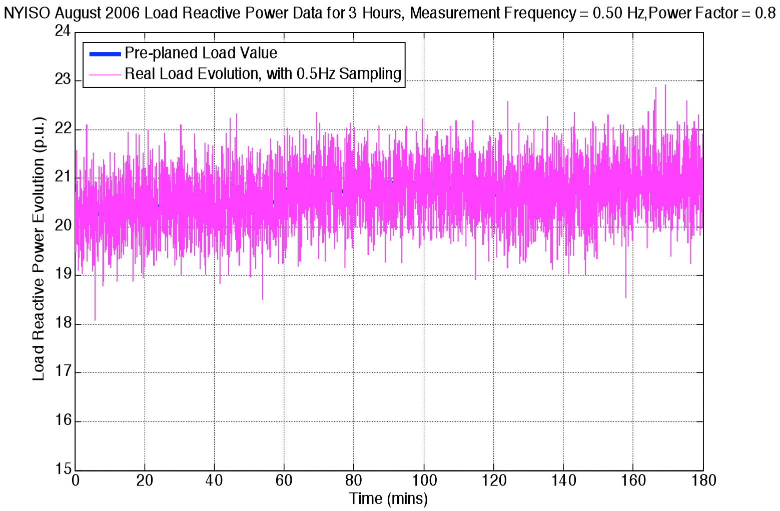
Continual Balance between Supply and Demand under Normal Condition with Load Uncertainty



Load Disturbance Around Scheduled Value

Scheduled load value and the disturbance around the value





Interaction Variables within a Socio-Ecological Systems [1]

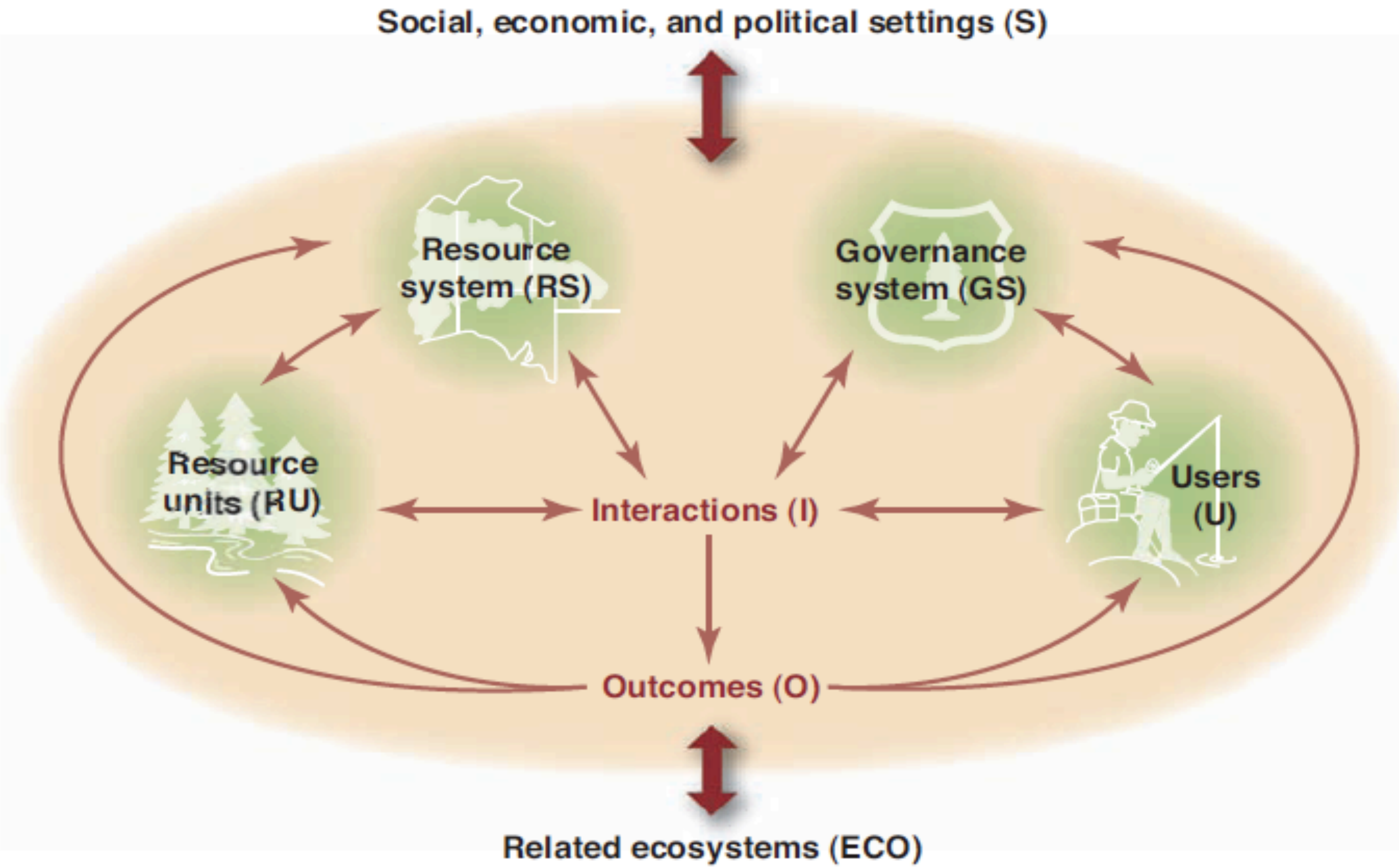


Fig. 1. The core subsystems in a framework for analyzing social-ecological systems.

"Smart Grid" ←→ electric power grid and IT for sustainable energy SES [2,3]

Energy SES

- Resource system (RS)
- Generation (RUs)
- Electric Energy Users (Us)

Man-made Grid

- Physical network connecting energy generation and consumers
- Needed to implement interactions

Man-made ICT

- Sensors
- Communications
- Operations
- Decisions and control
- Protection

Design for SEES—must manage uncertainties

- *Our proposed approach:*

  Step 1- Start with the core- and second-level variables to characterize the energy SES

  Step 2—Define deeper-level variables for capturing inter-dependencies between energy SES, physical grid, ICT and governance system

  Step 3– Design physical grid, IT and governance system to induce sustainability

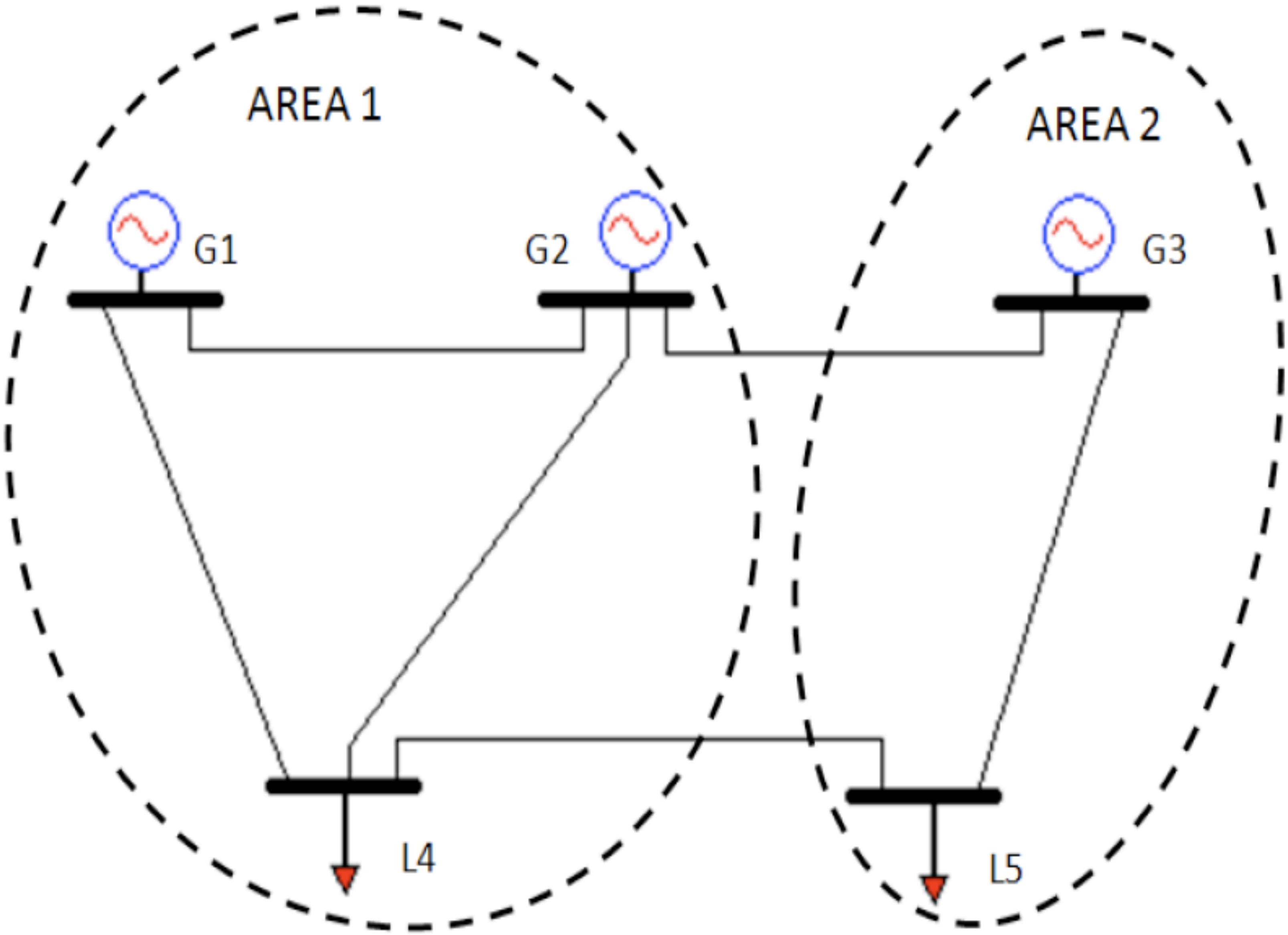
A Smart Grid design framework [2,5]

- Core variables the same in each system
- Second-level variables the same– very telling of how different energy SES [1] are
- OUR CONJECTURE --- design of a “Smart Grid” -- (not any) man-made power grid, ICT and governance system requires introduction of deeper-level variables for more effective differentiating among the electric energy system types [3]

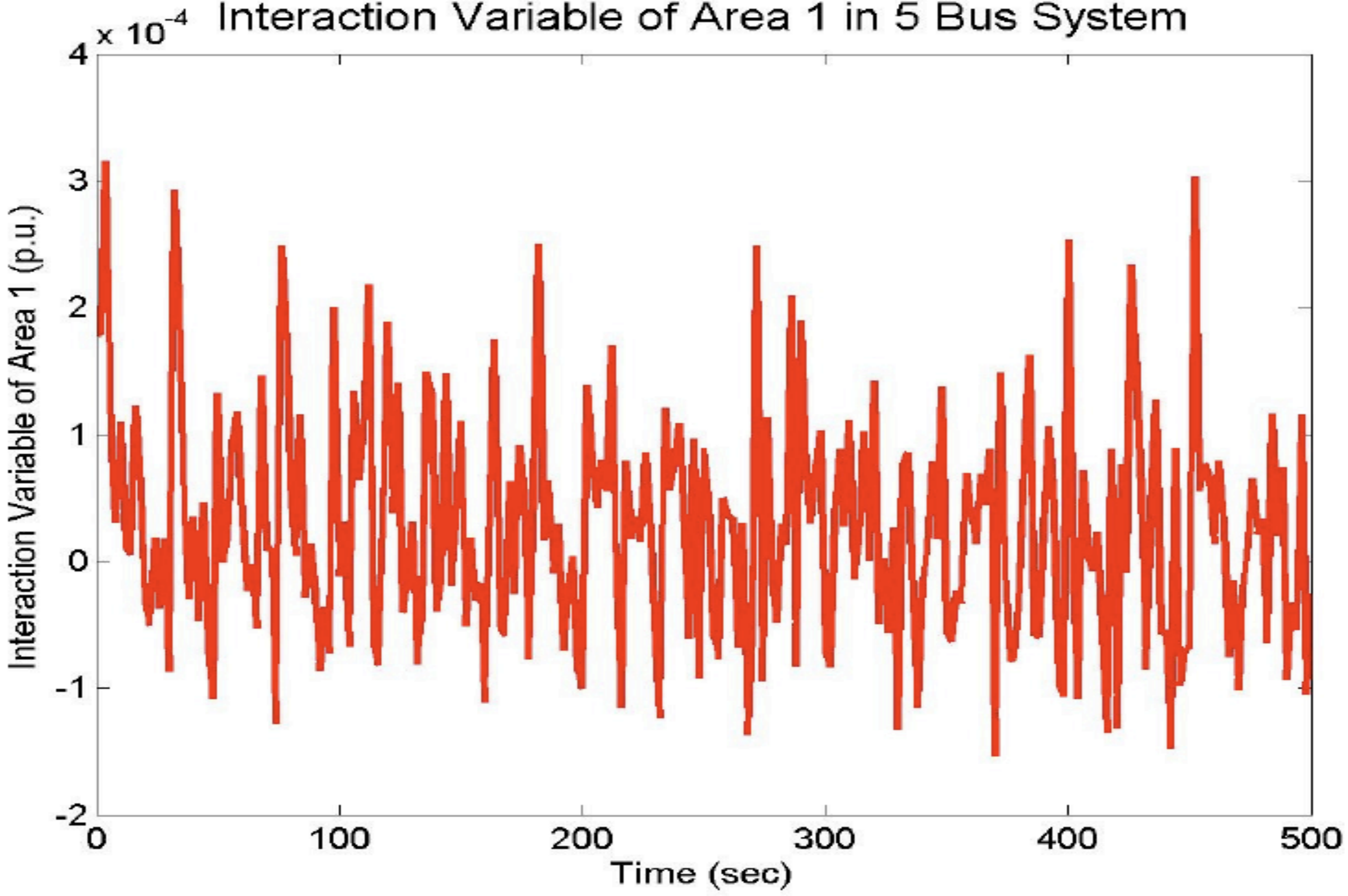
Proposed deeper-level variables— interaction variables

- Interaction variables [4]--- variables associated with sub-systems which can only be affected by interactions with the other sub-systems and not by the actions taken at the sub-system level
- Dynamics of physical interaction variables zero when the system is disconnected from other sub-systems [4]
- Temporal, spatial and/or contextual (governance and policy dependent)

Interaction Variable Simulation for Real Power Problem in 5 Bus System



Vast temporal and spatial inter-dependencies (deeper-level)



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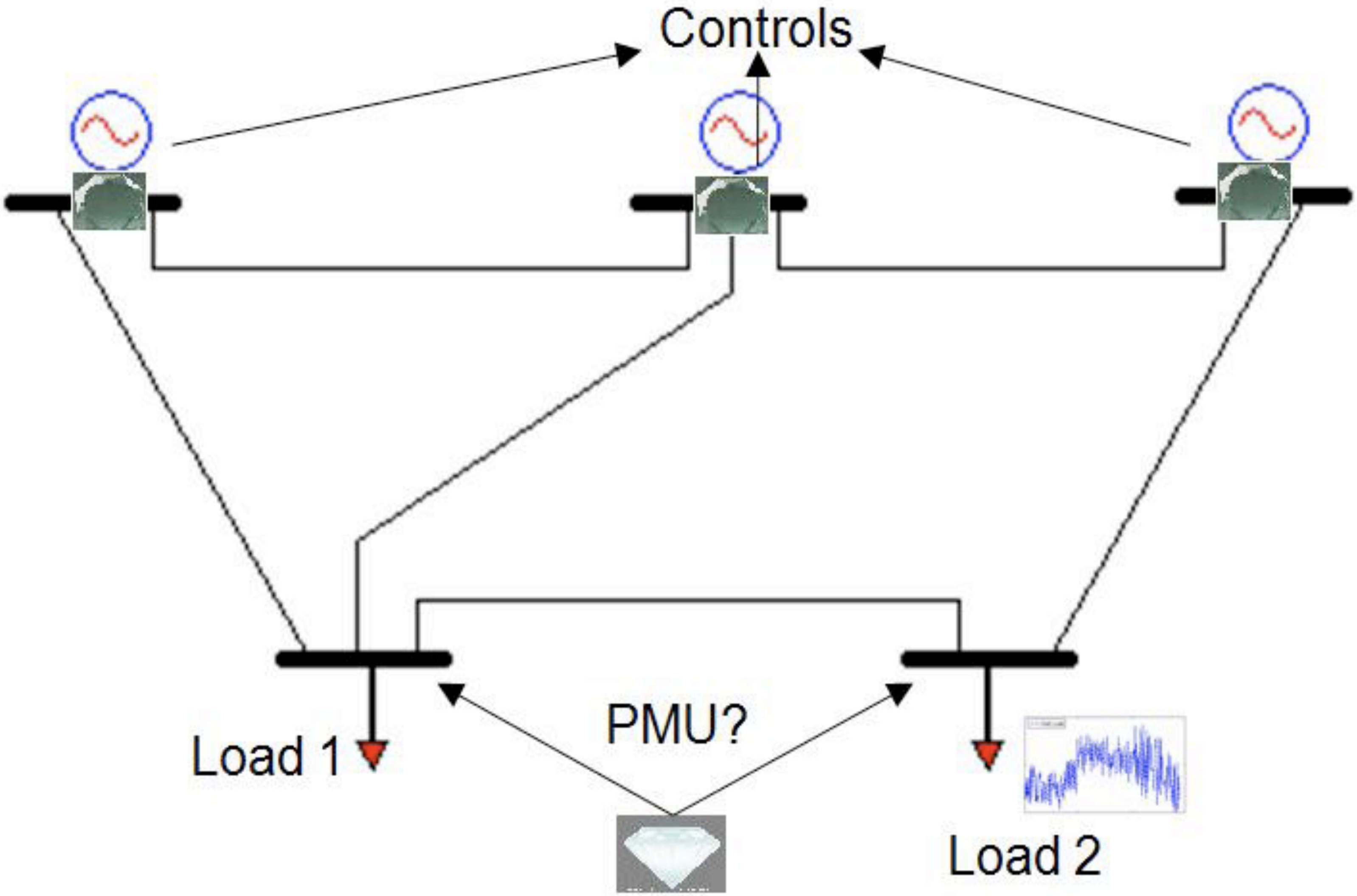
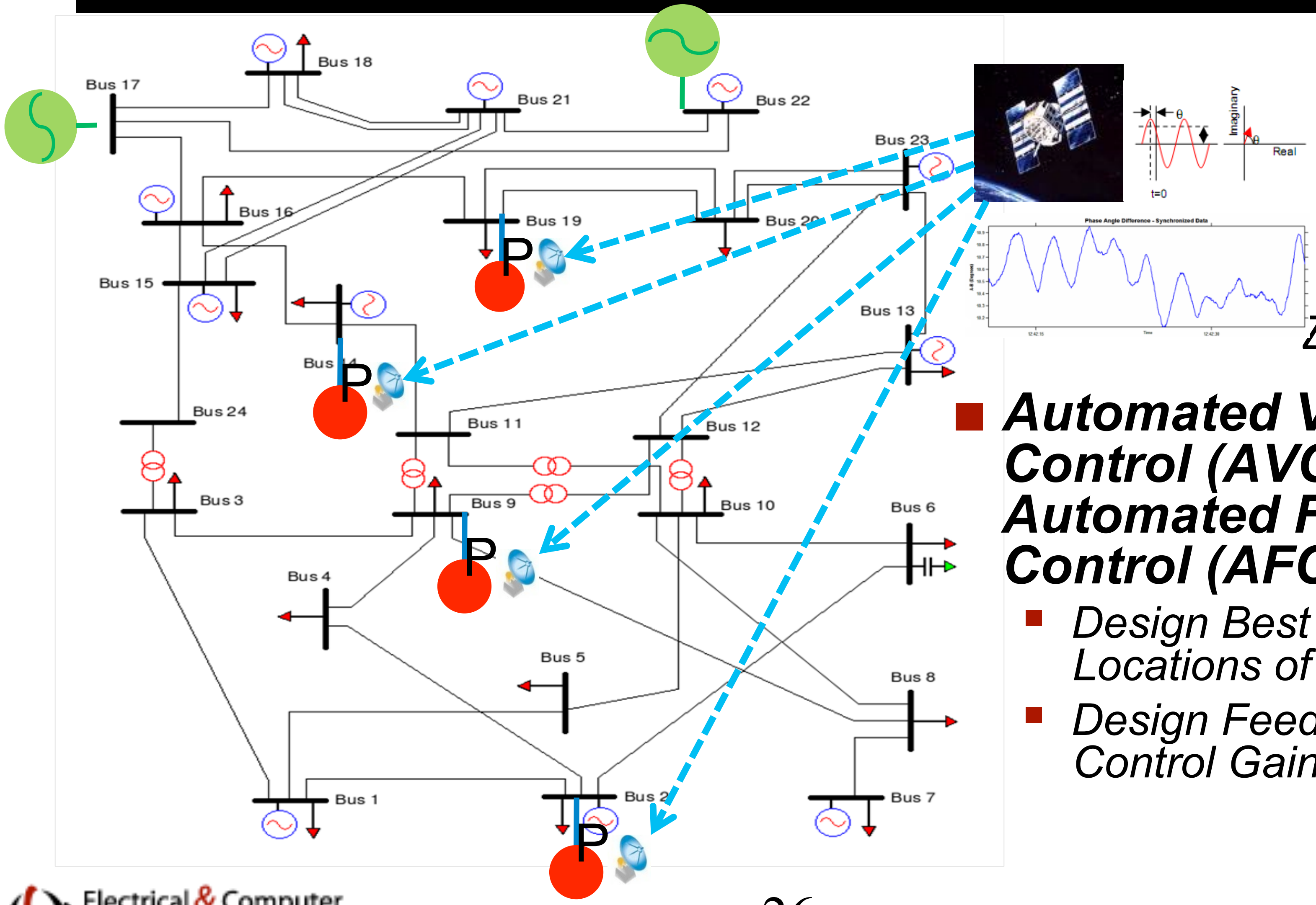
ICT design to monitor and control interaction variables



DYMONDS Simulator
PMU-Based Robust Control [7]

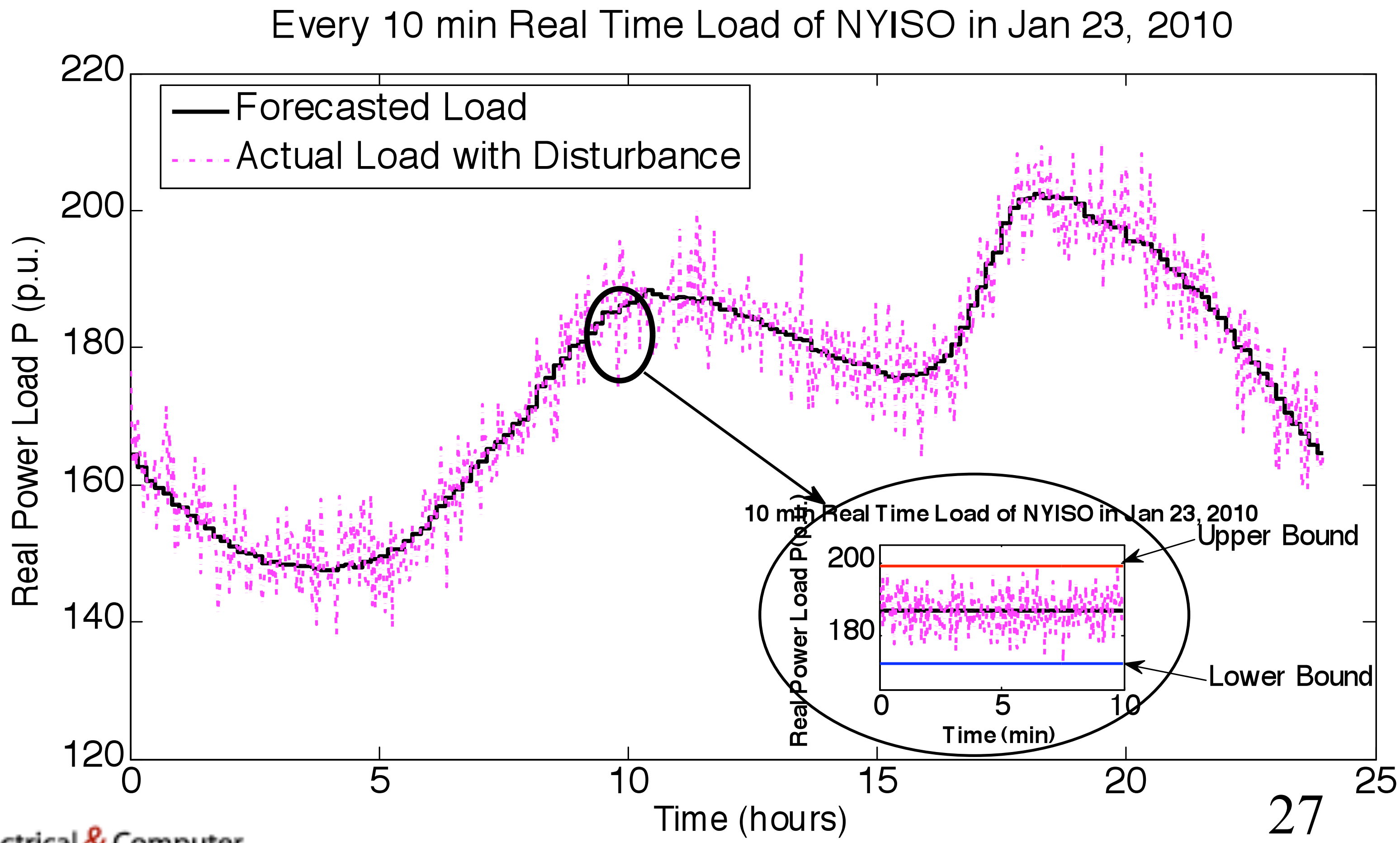


Zhijian Liu

- ***Automated Voltage Control (AVC) and Automated Flow Control (AFC)***
  - *Design Best Locations of PMUs*
  - *Design Feedback Control Gains*

Illustration on the NPCC 36 Equivalent System [8]

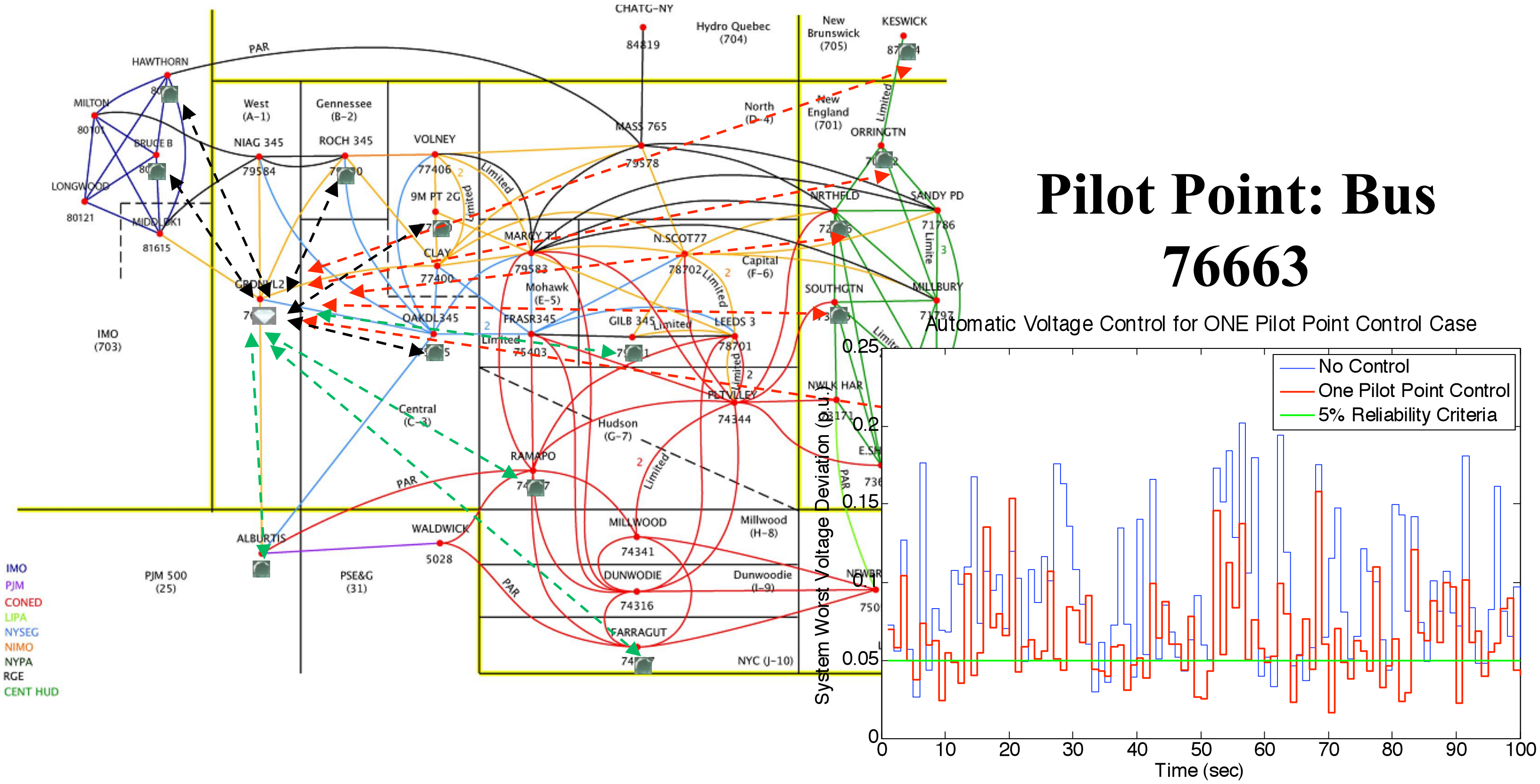
- **System Load Curve**



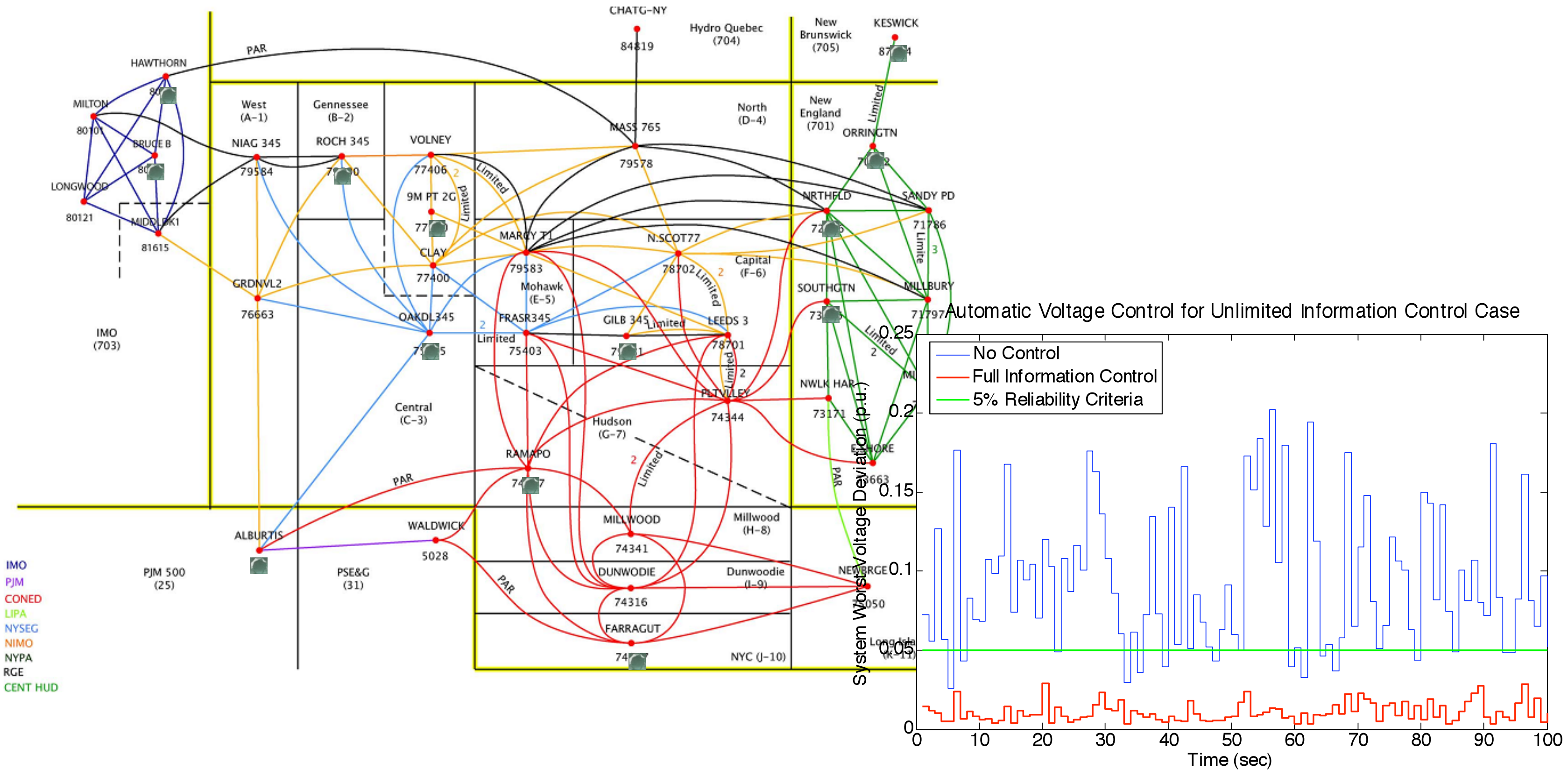
Robust AVC Illustration in NPCC System-single ''best' load bus monitored [7,8]

-

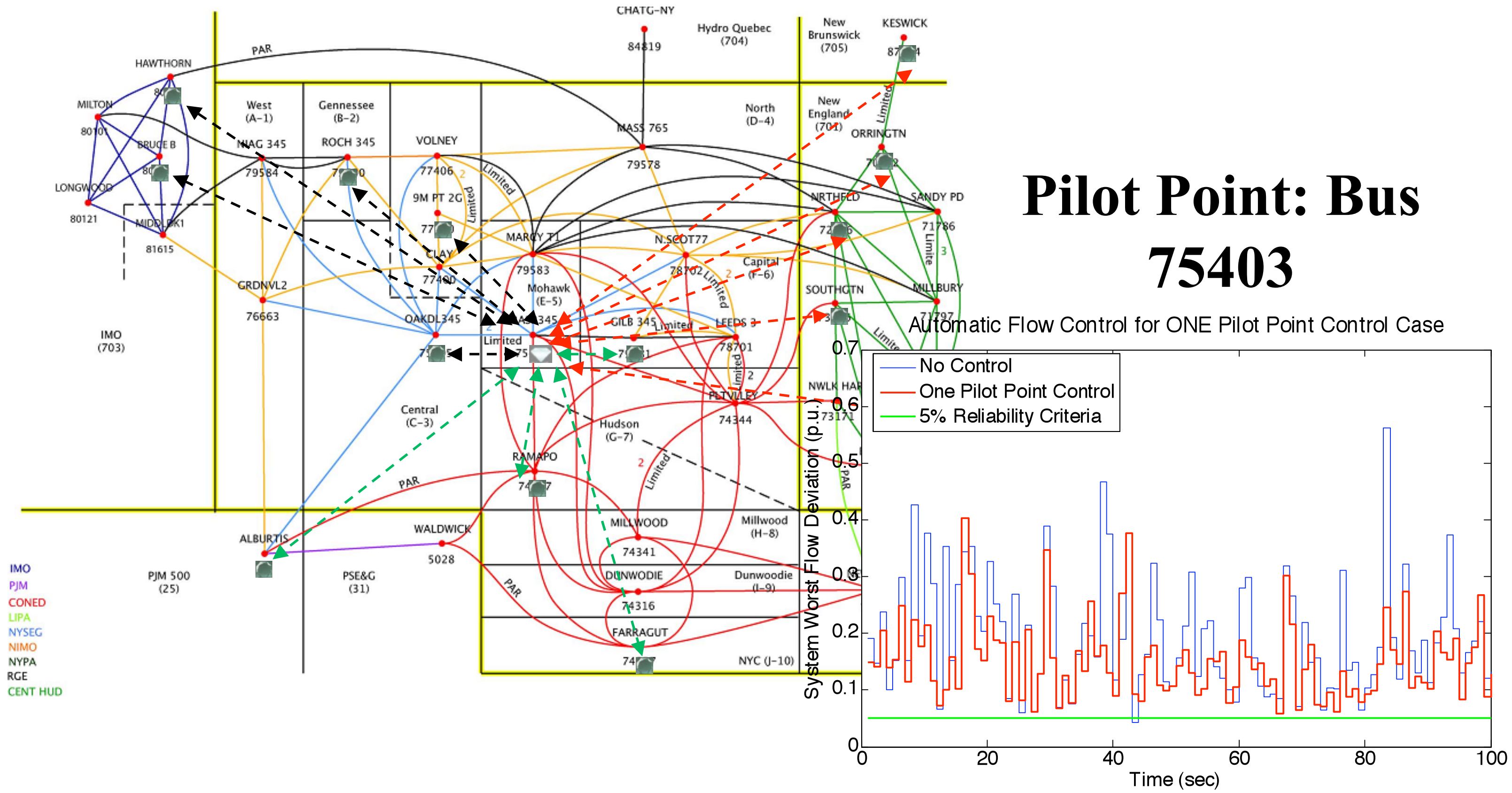
Pilot Point: Bus 76663



Robust Automatic Voltage Control (AVC)- all loads monitored



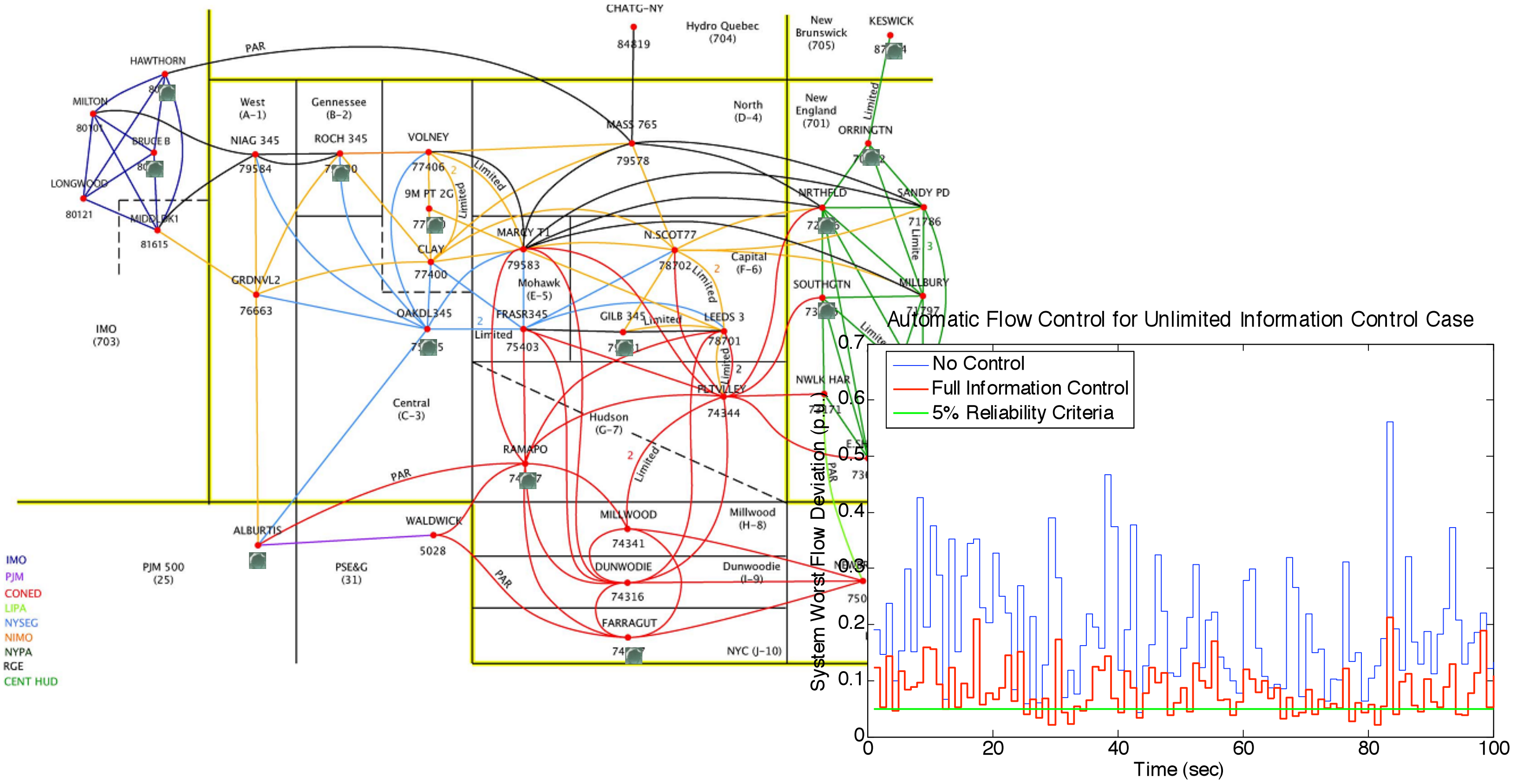
Robust Automatic Flow Control (AFC) [7,8]



Pilot Point: Bus 75403

Robust Automatic Flow Control (AFC)-all loads monitored [7,8]

- **Robust AFC Illustration in NPCC System**



Interesting architecture questions

- Decompose and then design AVC?
- More distributed architecture
- Less complicated communications
- Different quality of performance
- In the case of AVC better

- Design AVC for the system as a whole?
- More centralized communications
- Perhaps more complicated
- Must design so it is robust
- In the case of AFC better

Work in Progress-Architectures for Enhanced -AGC (E-AGC) [9,10]

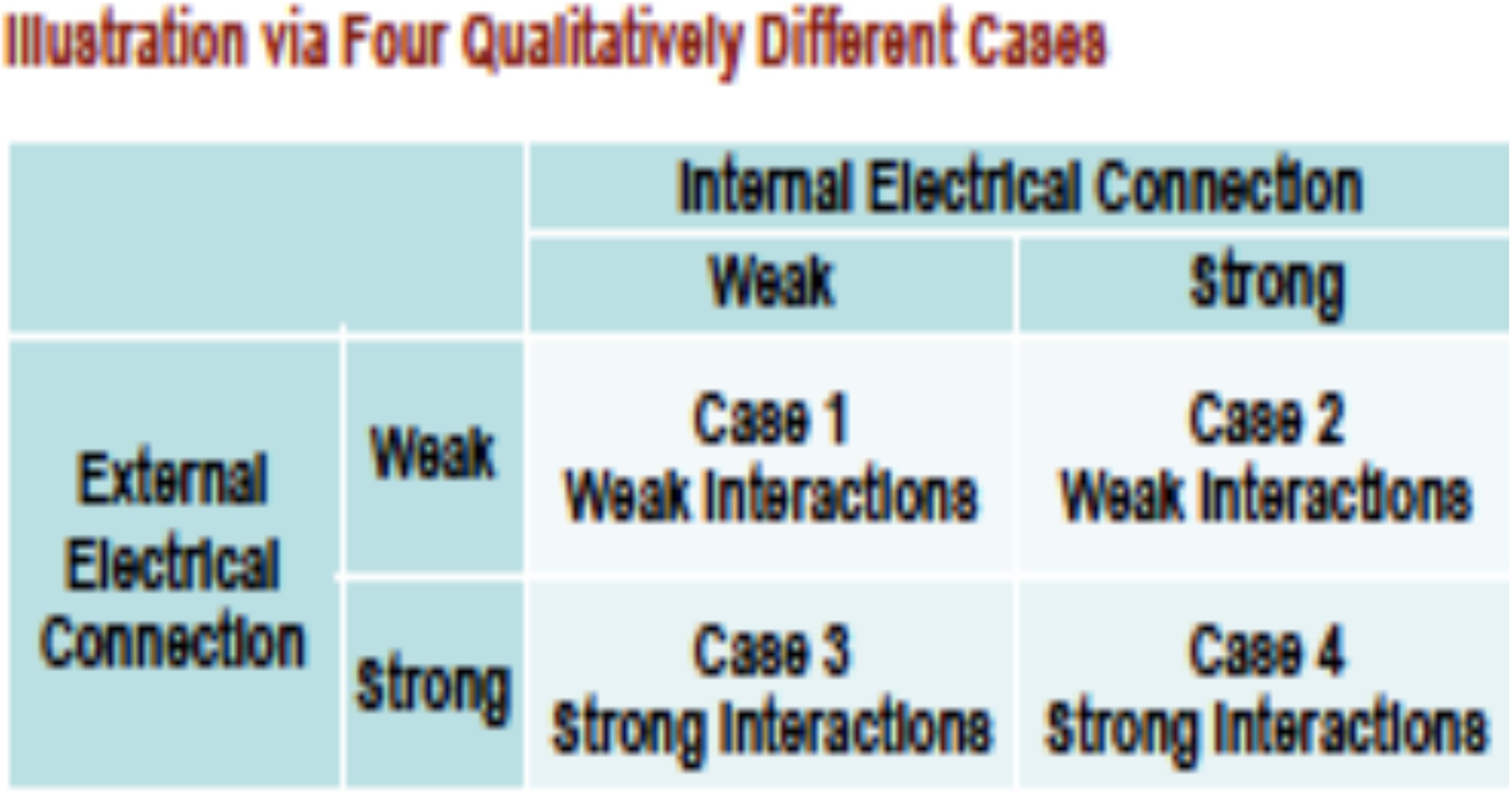
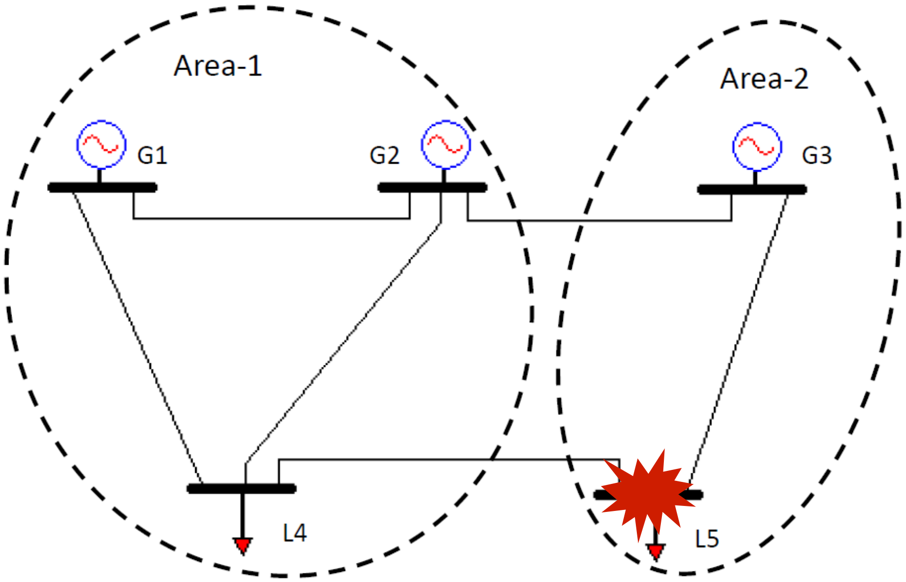


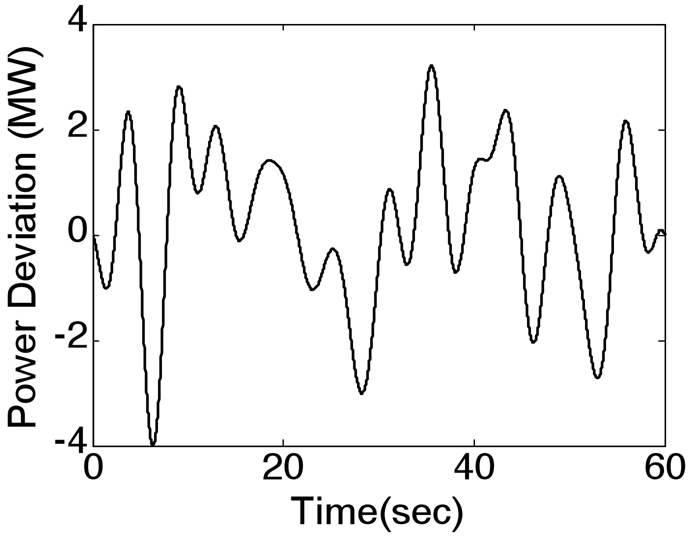
Illustration via Four Qualitatively Different Cases

		Internal Electrical Connection	
		Weak	Strong
External Electrical Connection	Weak	Case 1 Weak Interactions	Case 2 Weak Interactions
	Strong	Case 3 Strong Interactions	Case 4 Strong Interactions

Wind Perturbations

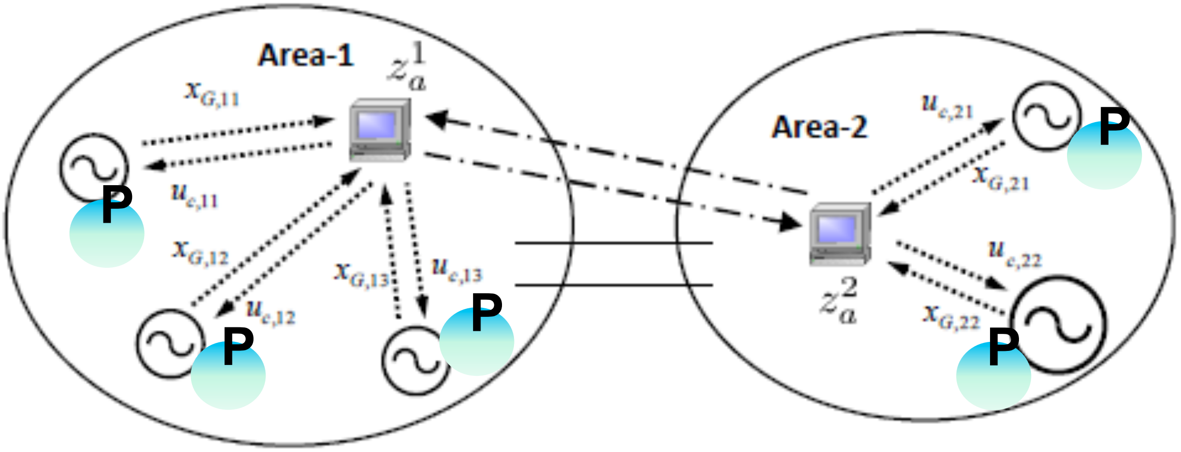
- **Case: Two-area system with strong interconnection**



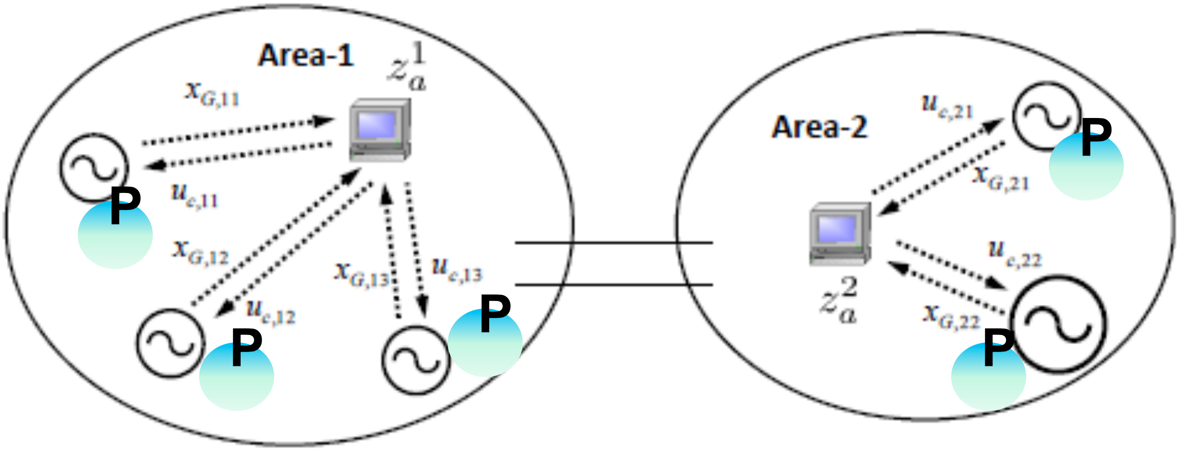


IntV-based Output Feedback Control [9]

- **Infrastructure of the cyber-physical system**

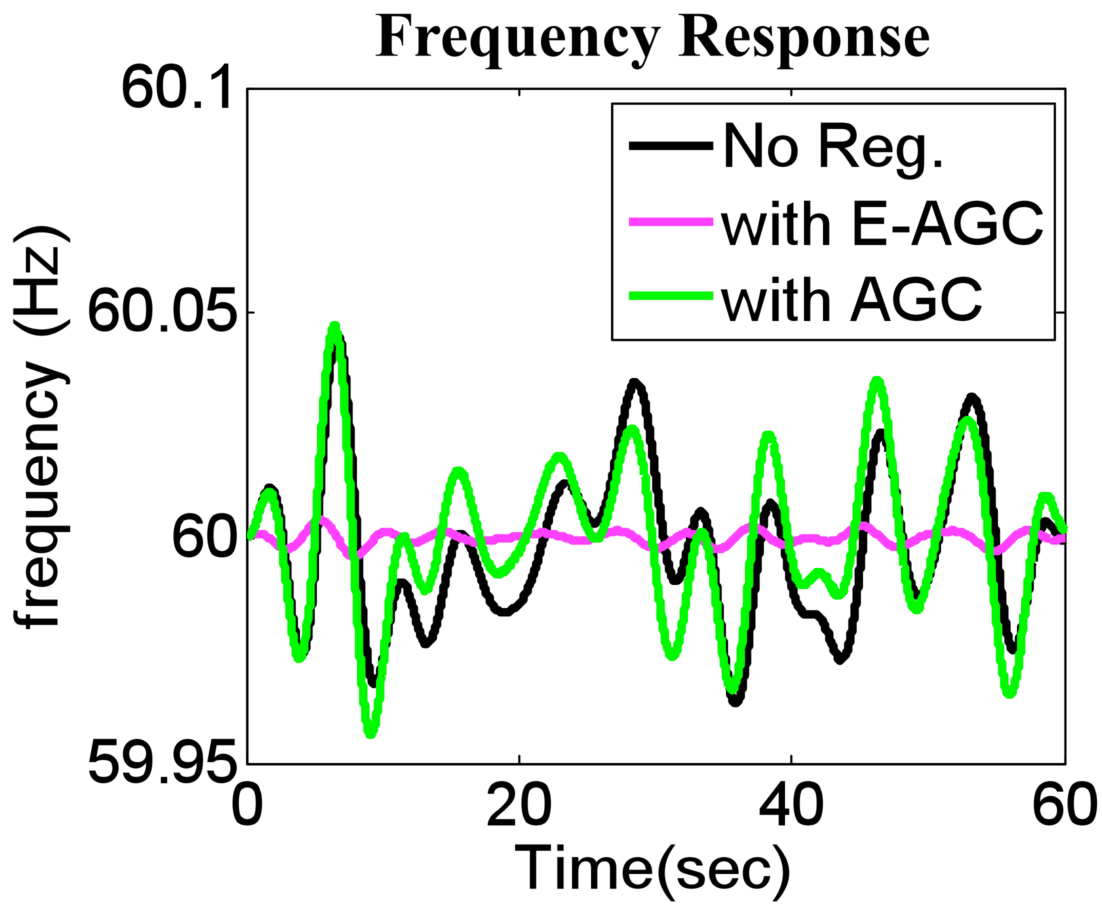


Strong Interconnection



Weak Interconnection

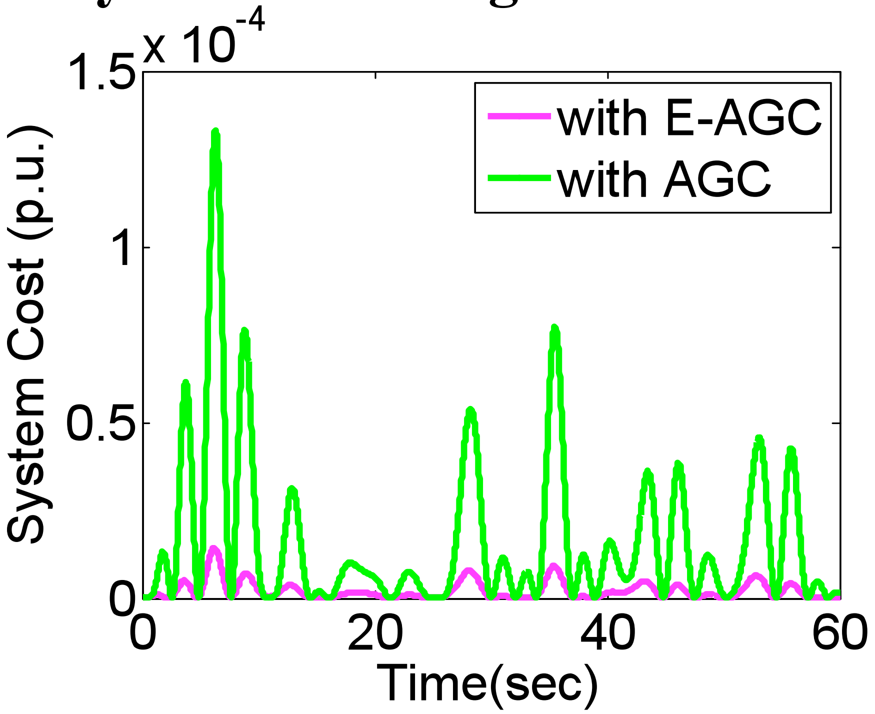
Two-area system with strong interconnection



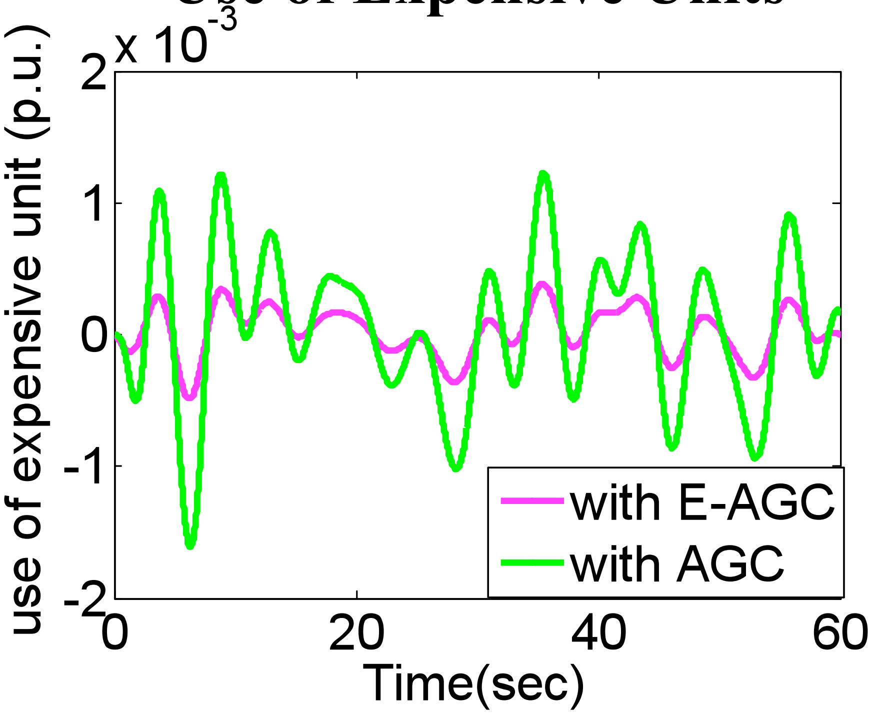
TODAY’S AGC DOES NOT WORK!

AGC-Cost Dependence on Embedded Smarts

System-level Regulation Cost



Use of Expensive Units



CAREFUL WITH FULL DISTRIBUTION!

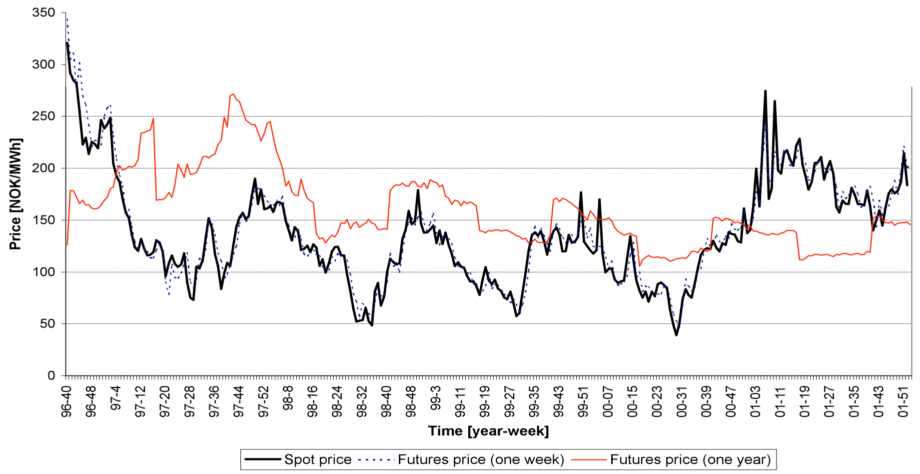
Managing temporal interactions interactively

- ***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.***

Managing wind power—smarter way

- ***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).***
- ***Implicit value of storage***

Key value of managing inter-temporal risks—major uncertainties



NORDPOOL FUTURE AND SPOT PRICES [13]

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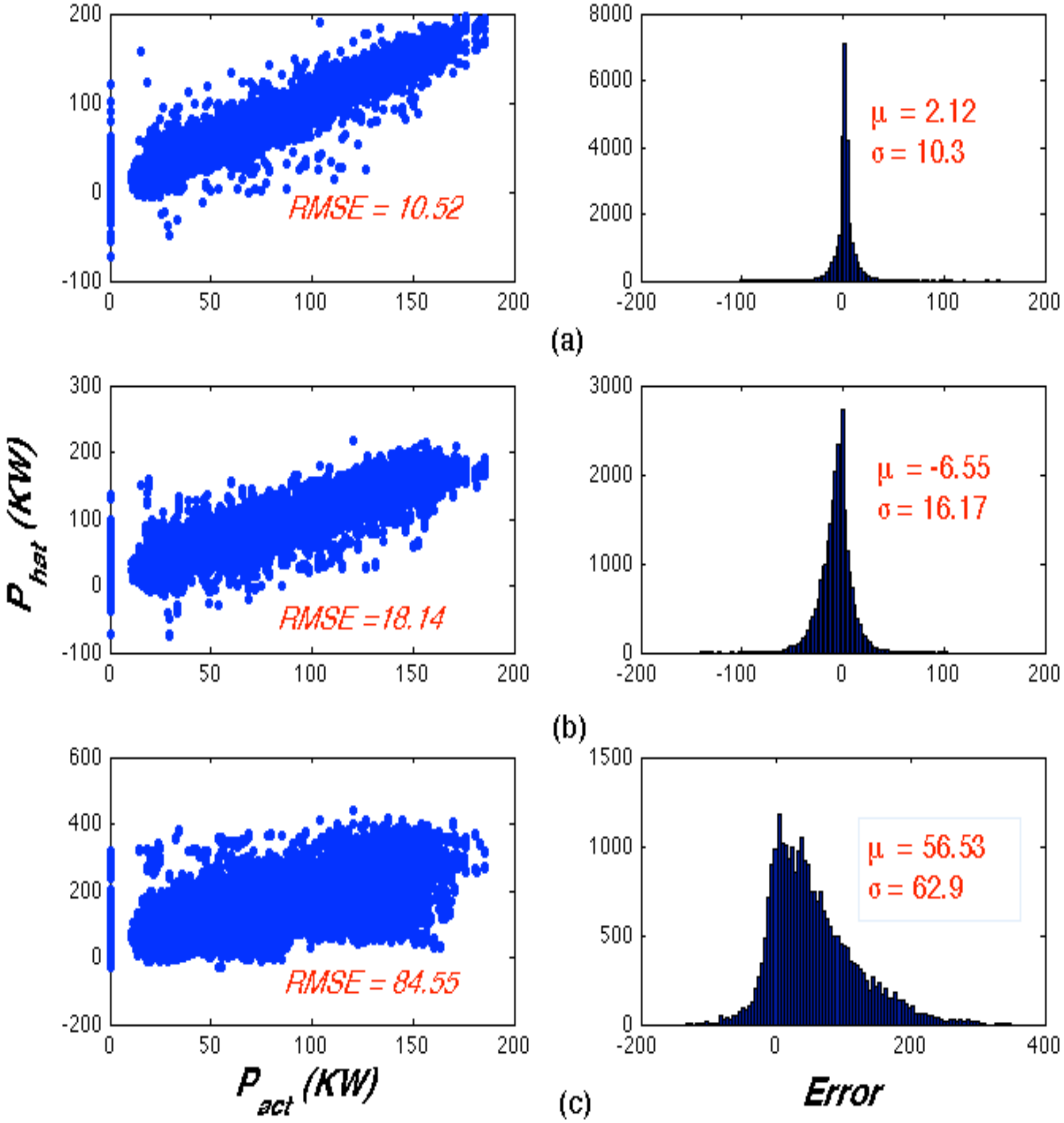
Load Forecast [14]



It goes that forecast errors defined as

$$e(n) = \hat{x}(n) - x(n)$$

follow normal distribution

$$E(t) \sim N(\mu, \sigma)$$

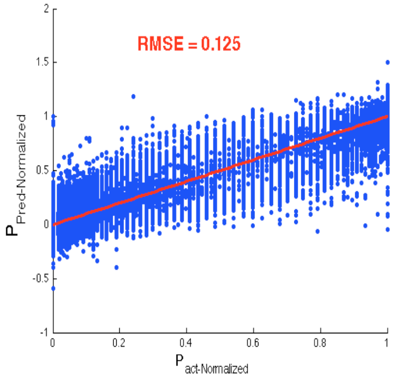
The Figure shows three look ahead time horizon forecasting results, 10 minute, 1 hour, and 24 hours. On the LHS of the plot, actual and predicted MW loads and their associated root mean square errors (RMSE) are presented on the RHS of the plot

Error distributions for longer look ahead time forecast show more disturbance from normal distribution and longer tails. This is expected without updating forecasting signal to include new available measured values.

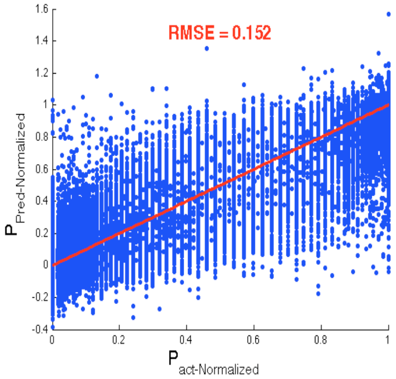
Wind Forecast

Scatter plots for predicted versus actual normalized wind power signals for 10 minute, 1 hour and 24 hours look ahead forecast are shown in the LHS. The RMSE increases as the look ahead time forecast increase.

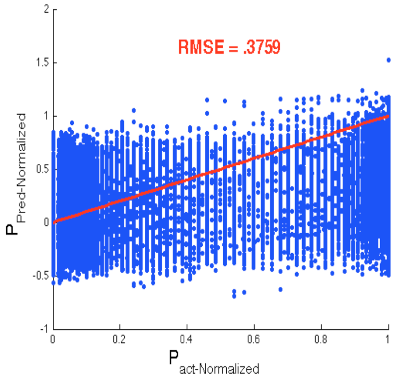
The distribution of forecast error is deviated from normal distribution as look ahead forecast time increases, (RHS of the plots) and depicts forecast error histograms for the three 10 min , one hour and 24 hours look ahead time horizons of normalized wind power.



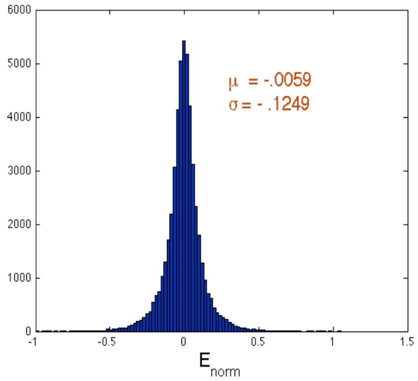
(a)



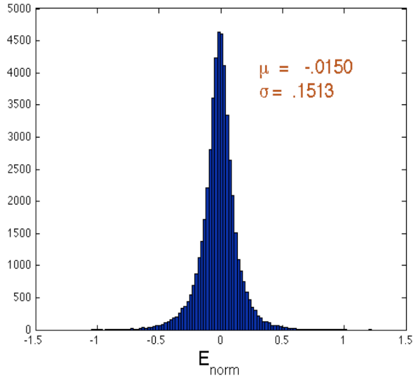
(b)



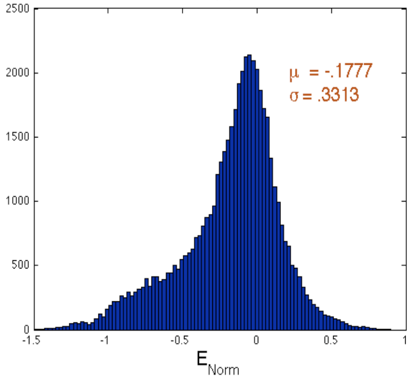
(c)



(a)

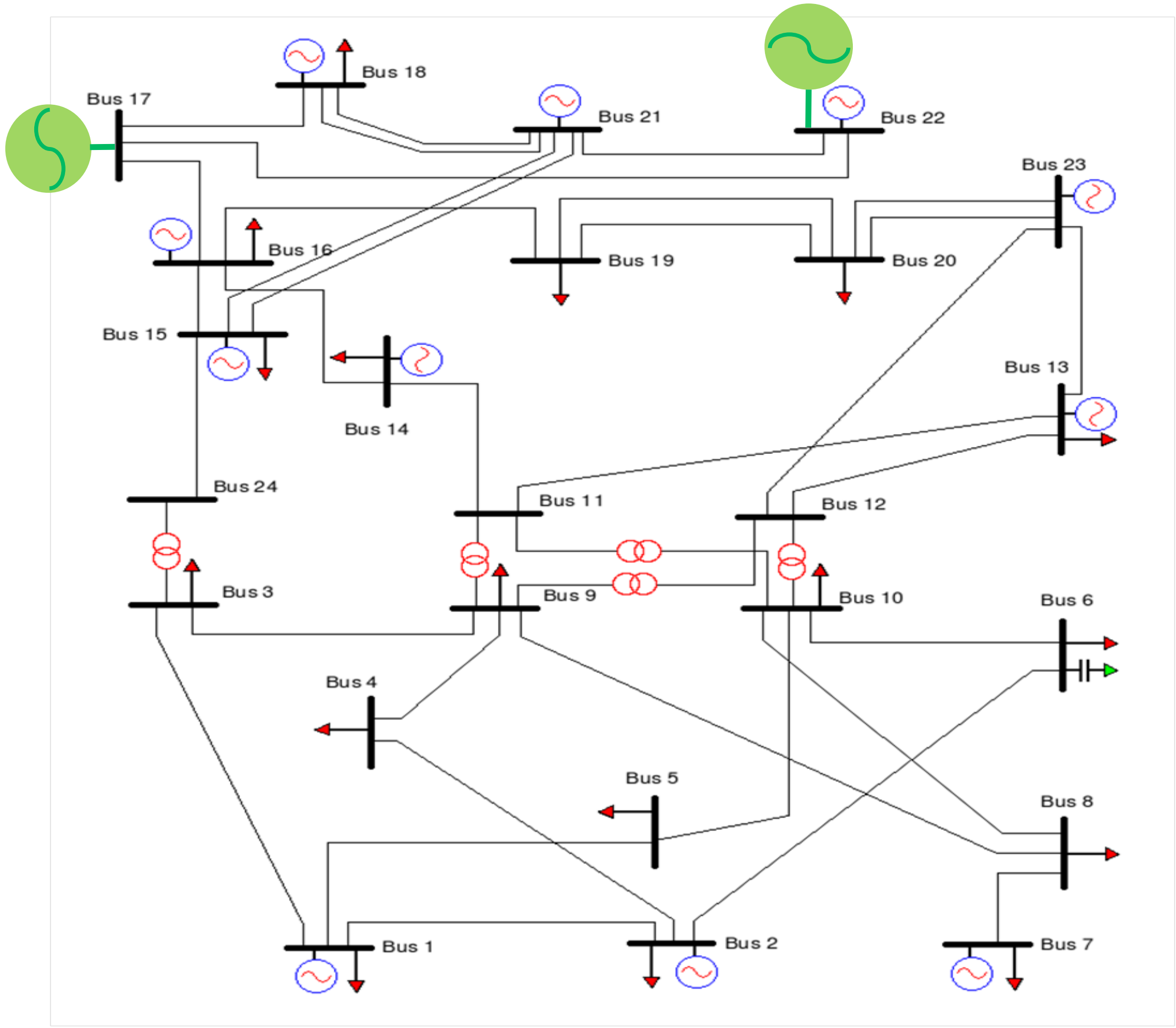


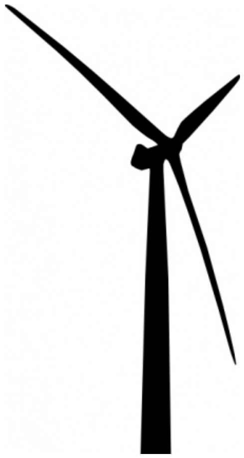
(b)



(c)

DYMONDS Simulator
IEEE RTS with Wind Power

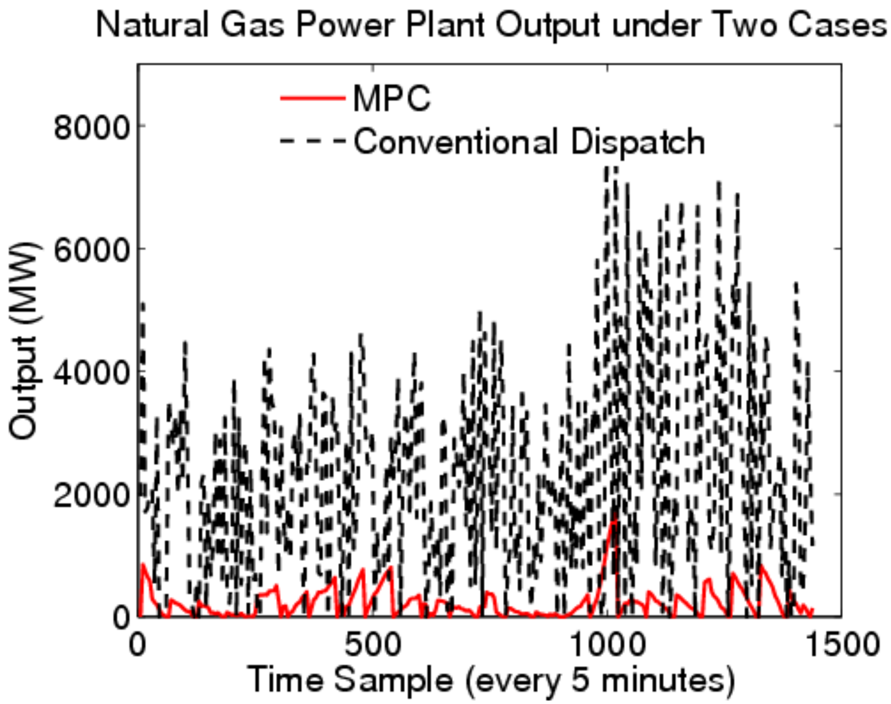


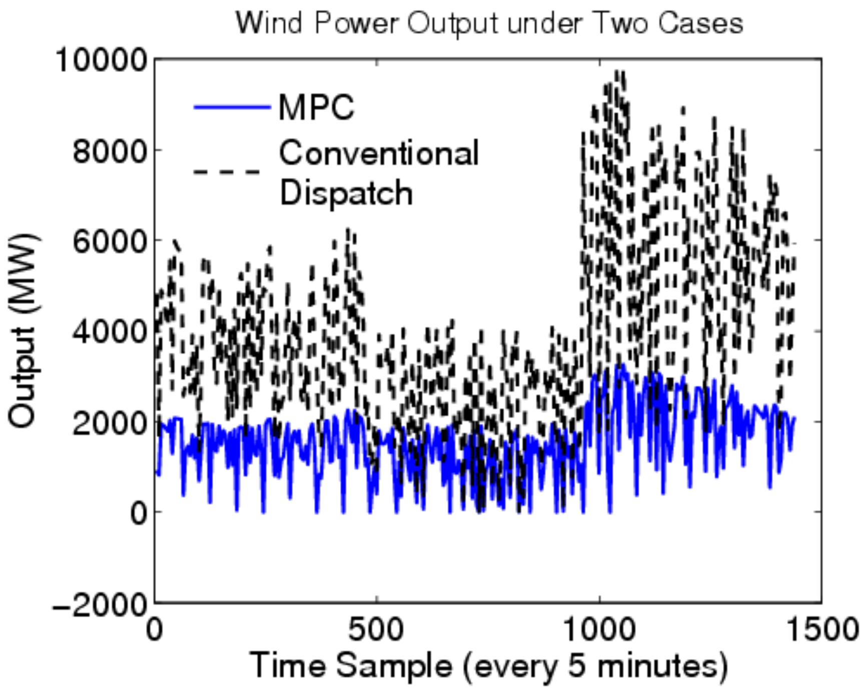


Le Xie

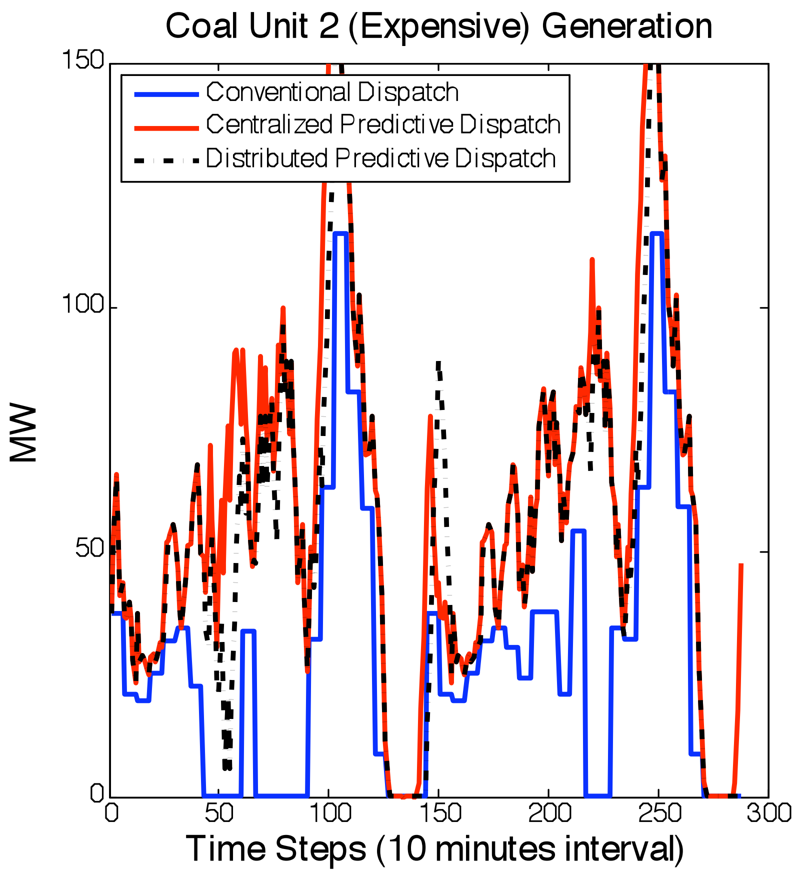
- ***20% / 50% penetration to the system [2]***

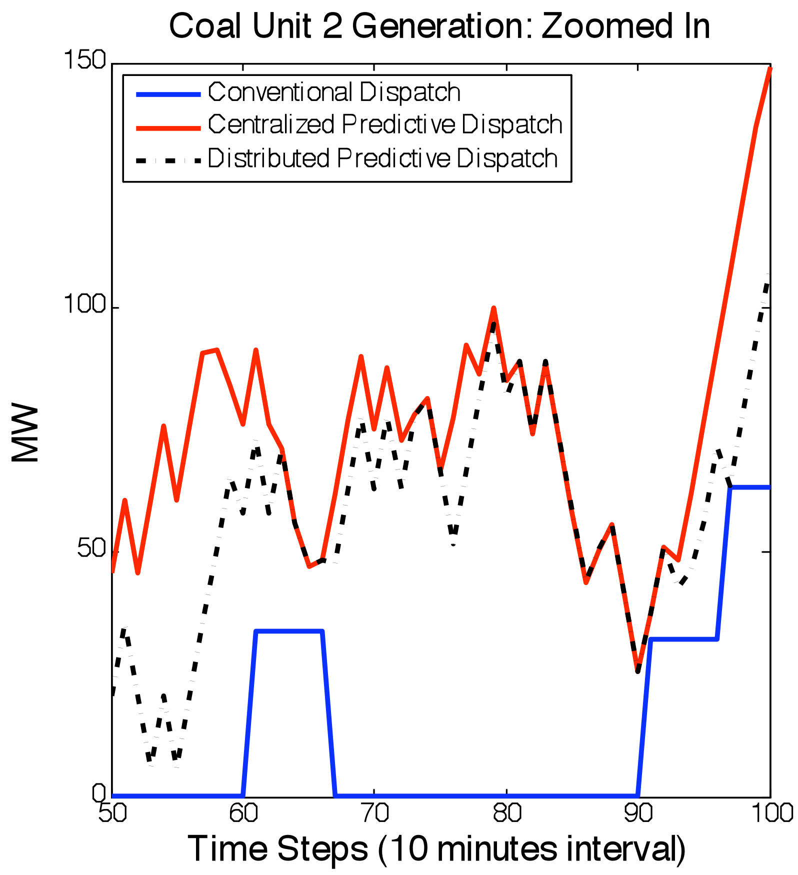
Conventional cost over 1 year *	Proposed cost over the year	Difference	Relative Saving
$ 129.74 Million	$ 119.62 Million	$ 10.12 Million	7.8%





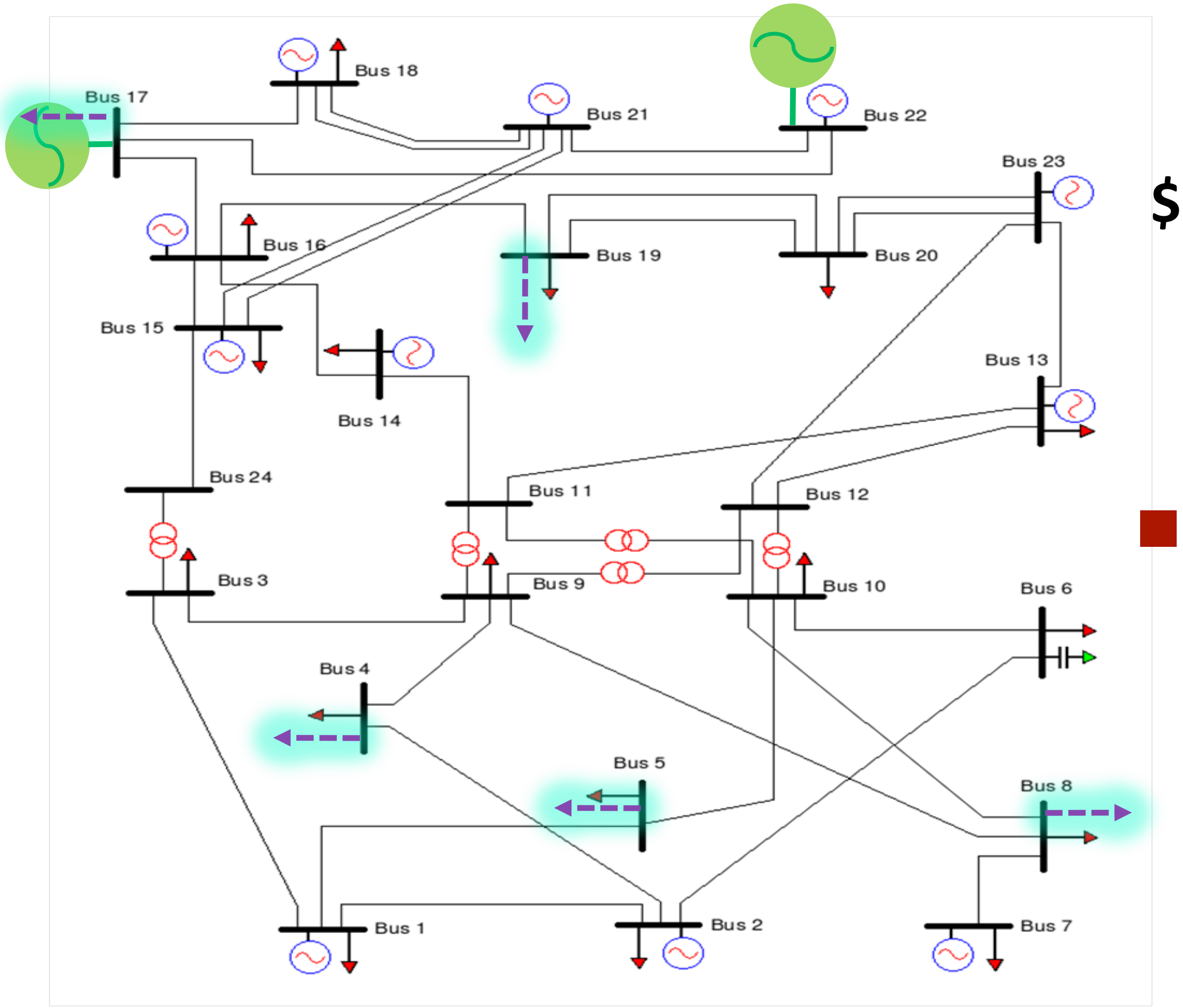
*: load data from New York Independent System Operator, available online at http://www.nyiso.com/public/market_data/load_data.jsp

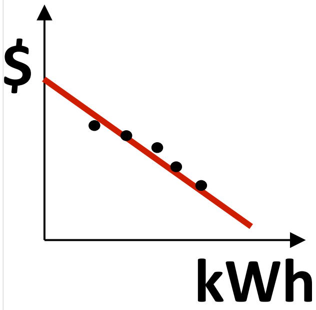

Coal Unit 2 (Expensive) Generation


Coal Unit 2 Generation: Zoomed In

BOTH EFFICIENCY AND RELIABILITY MET

DYMONDS Simulator
Impact of price-responsive demand





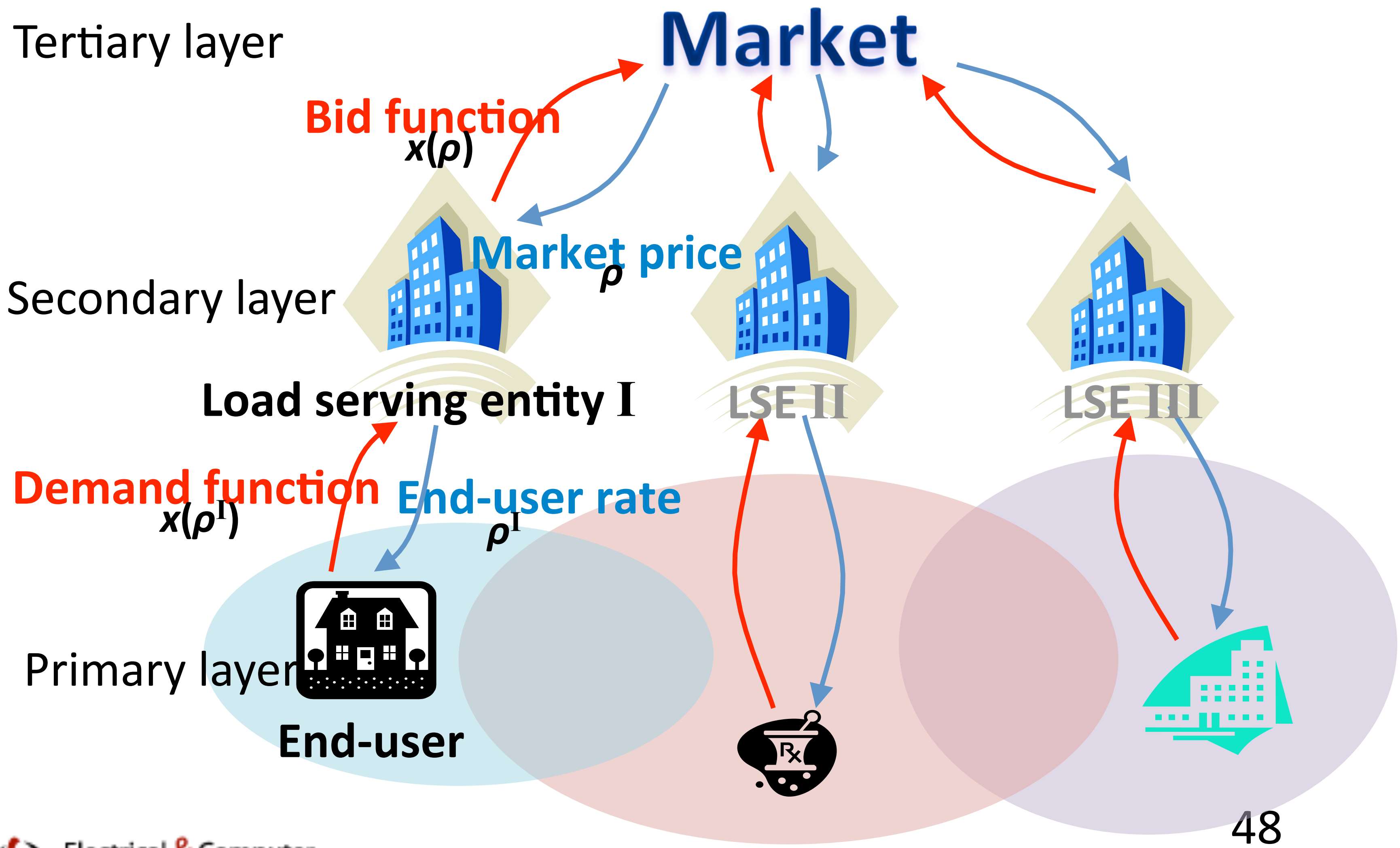
J.Y. Joo

- ***Elastic demand that responds to time-varying prices***

What is ALM?

- **Balancing the end-users' needs** (e.g. keep desired indoor temperature) and **the system's operational conditions** (e.g. spill less wind, reduce emission, minimize cost, etc.)
- **Through interactive information exchange** between the end-users and the system operator, and the load serving entities (LSEs)
- While **managing the risk** from the uncertain market conditions and the demand

Information flow of ALM



Tertiary layer

Market

Bid function

$x(\rho)$

Market price

ρ

Secondary layer

Load serving entity I

LSE II

LSE III

Demand function

$x(\rho^{\mathrm{I}})$

End-user rate

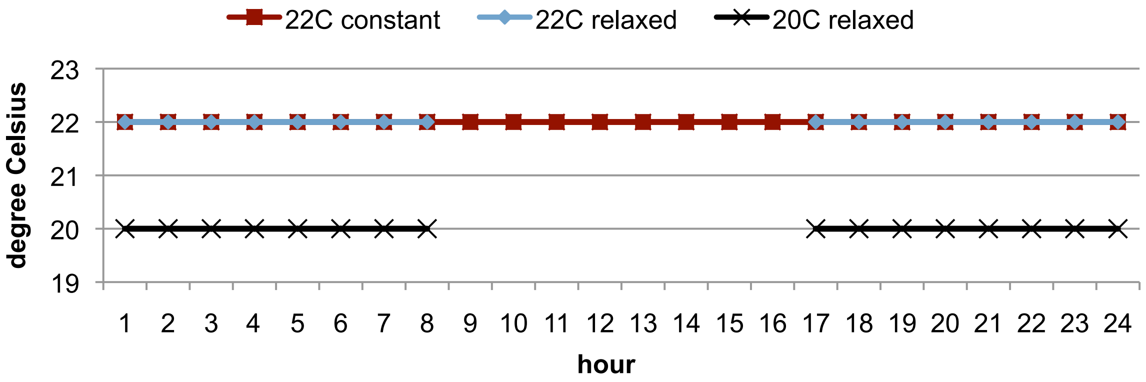
ρ^{I}

Primary layer

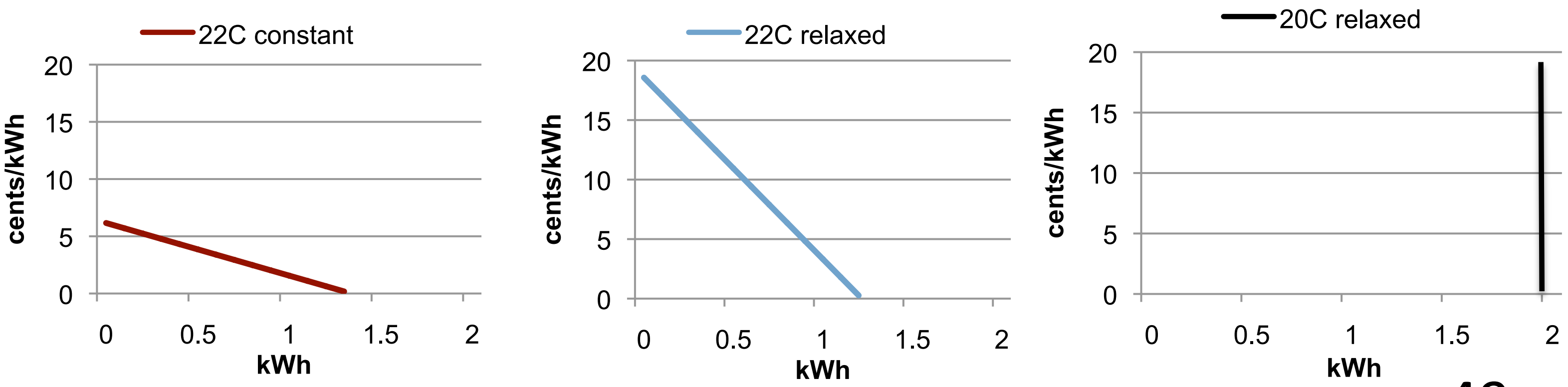
End-user

Demand function

- **Different needs on energy usage result in different demand functions!**



Demand functions at hour 10 with different temperature setpoint settings



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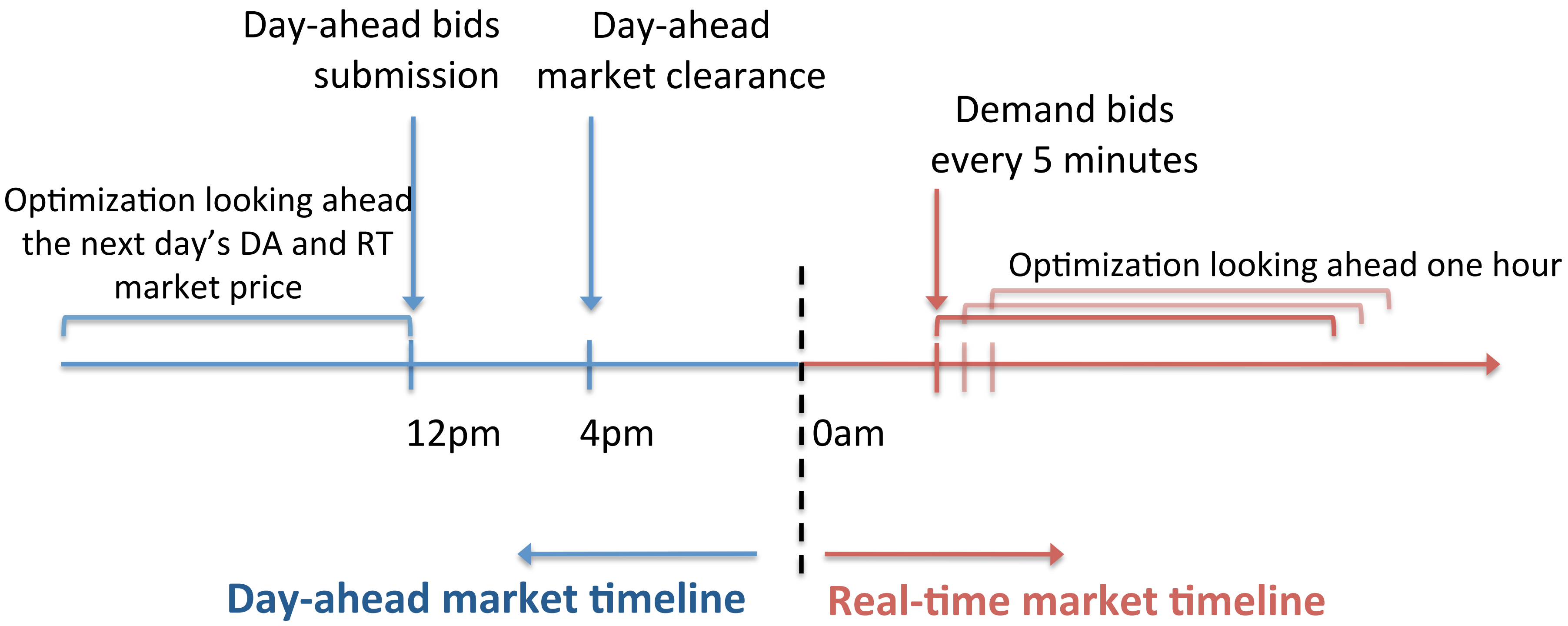
Time line of ALM (day-ahead and real-time)



Day-ahead bids submission

Day-ahead market clearance

Demand bids every 5 minutes

Optimization looking ahead the next day's DA and RT market price

Optimization looking ahead one hour

12pm

4pm

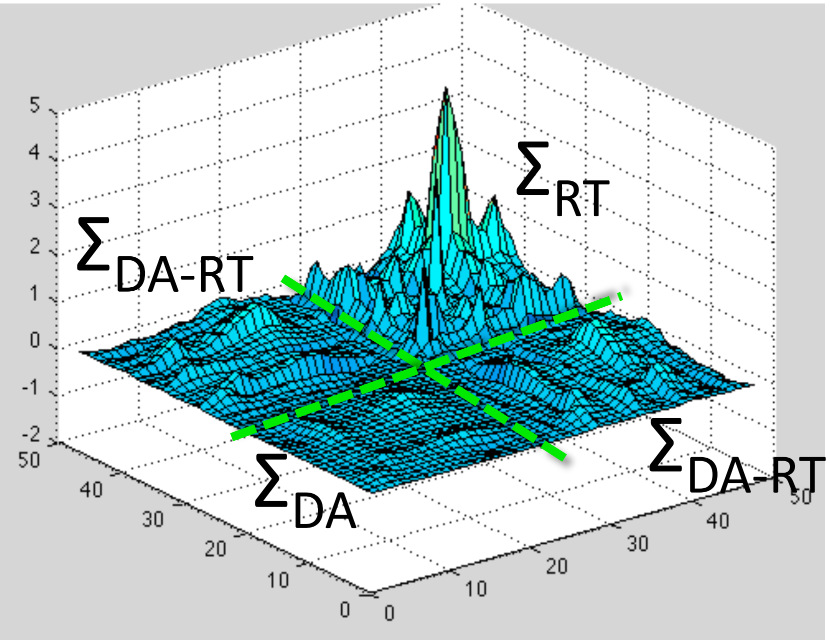
0am

Day-ahead market timeline

Real-time market timeline

Covariance matrix of DA & RT hourly prices

- *An element shows* ***correlation between two (different) random variables***
  - *48 random variables → 48x48 matrix*
- *Variance of* ***real-time market price*** *much higher*
- *Hourly day-ahead and real-time prices of the last n days*



$$\overset{\text{Day 1}}{\begin{bmatrix}\rho_{DA}[1]\\ \vdots \\ \rho_{DA}[24]\\ \rho_{RT}[1]\\ \vdots \\ \rho_{RT}[24]\end{bmatrix}} \quad \cdots \quad \overset{\text{Day } n}{\begin{bmatrix}\rho_{DA}[1]\\ \vdots \\ \rho_{DA}[24]\\ \rho_{RT}[1]\\ \vdots \\ \rho_{RT}[24]\end{bmatrix}} \quad \Rightarrow \quad \overset{\text{Average}}{\begin{bmatrix}\bar{\rho}_{DA}[1]\\ \vdots \\ \bar{\rho}_{DA}[24]\\ \bar{\rho}_{RT}[1]\\ \vdots \\ \bar{\rho}_{RT}[24]\end{bmatrix}} \quad \overset{\text{Covariance matrix}}{\left[\begin{array}{cc|cc}\sigma_{DA1\text{-}DA1} & \cdots & & \sigma_{DA1\text{-}RT24}\\ \vdots & \ddots & & \vdots \\ \hline \vdots & & \ddots & \vdots \\ \sigma_{RT24\text{-}DA1} & & \cdots & \sigma_{RT24\text{-}RT24}\end{array}\right]}$$

LSE's short-term risk management [12]

- ***Day-ahead and real-time market optimization : Markowitz optimization***
  - *Minimizing the risk of return*
  - *With respect to the physical temperature constraints (example of air conditioning load)*

$$\begin{aligned} \min_{x} \quad & \underline{w_r x^T \enclose{circle}{\Sigma_p} x} + w_c \bar{p}^T x + (T - T_{\text{set}})^T W_T (T - T_{\text{set}}) \\ \text{subject to} \quad & T[k+1] = \varepsilon T[k] + (1-\varepsilon)(T^{\text{out}}[k] + \gamma x[k]) \\ & x_{\min} \le x[k] \le x_{\max} \quad \forall k \end{aligned}$$

$$\text{where } \Sigma_p = \left[\begin{array}{c|c} \Sigma_{\text{DA}} & \Sigma_{\text{DA-RT}} \\ \hline \Sigma_{\text{DA-RT}} & \Sigma_{\text{RT}} \end{array}\right]$$

$x = [\, x[1], \ldots, x[24] \,]^T$

: energy consumption within each hour

$T = [\, T[1], \ldots, T[24] \,]^T$

: indoor temperature at each hour

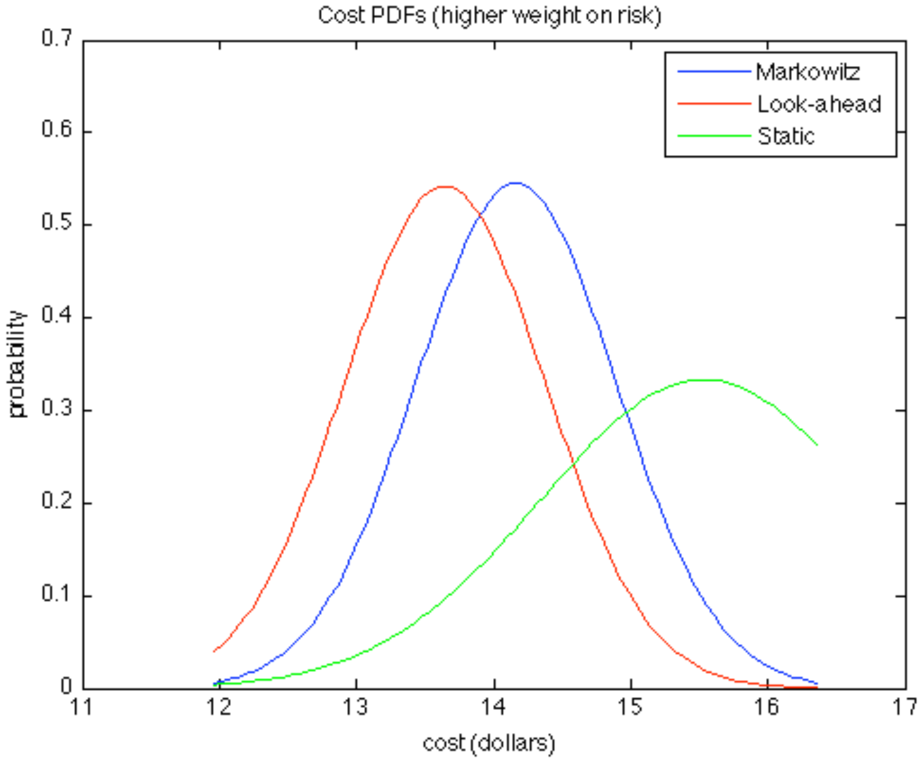
w_c, w_T, w_r: weights on cost, temperature, and risk

$p = [\, p[1], \ldots, p[24] \,]^T$

: anticipated hourly day-ahead market price

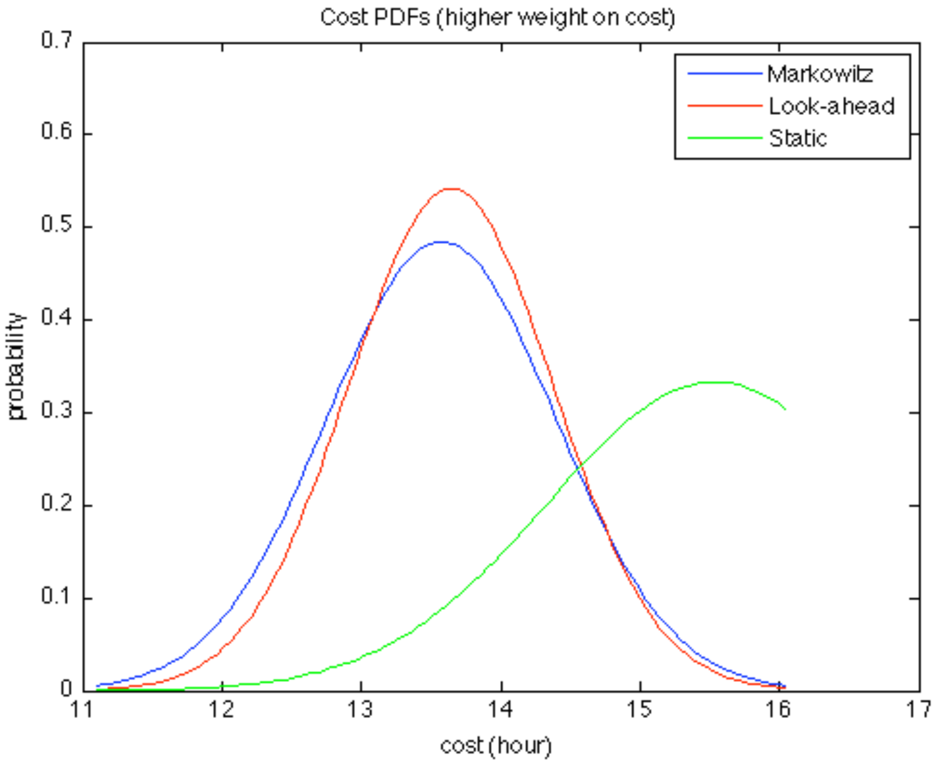
Tradeoff between risk and cost

risk > cost

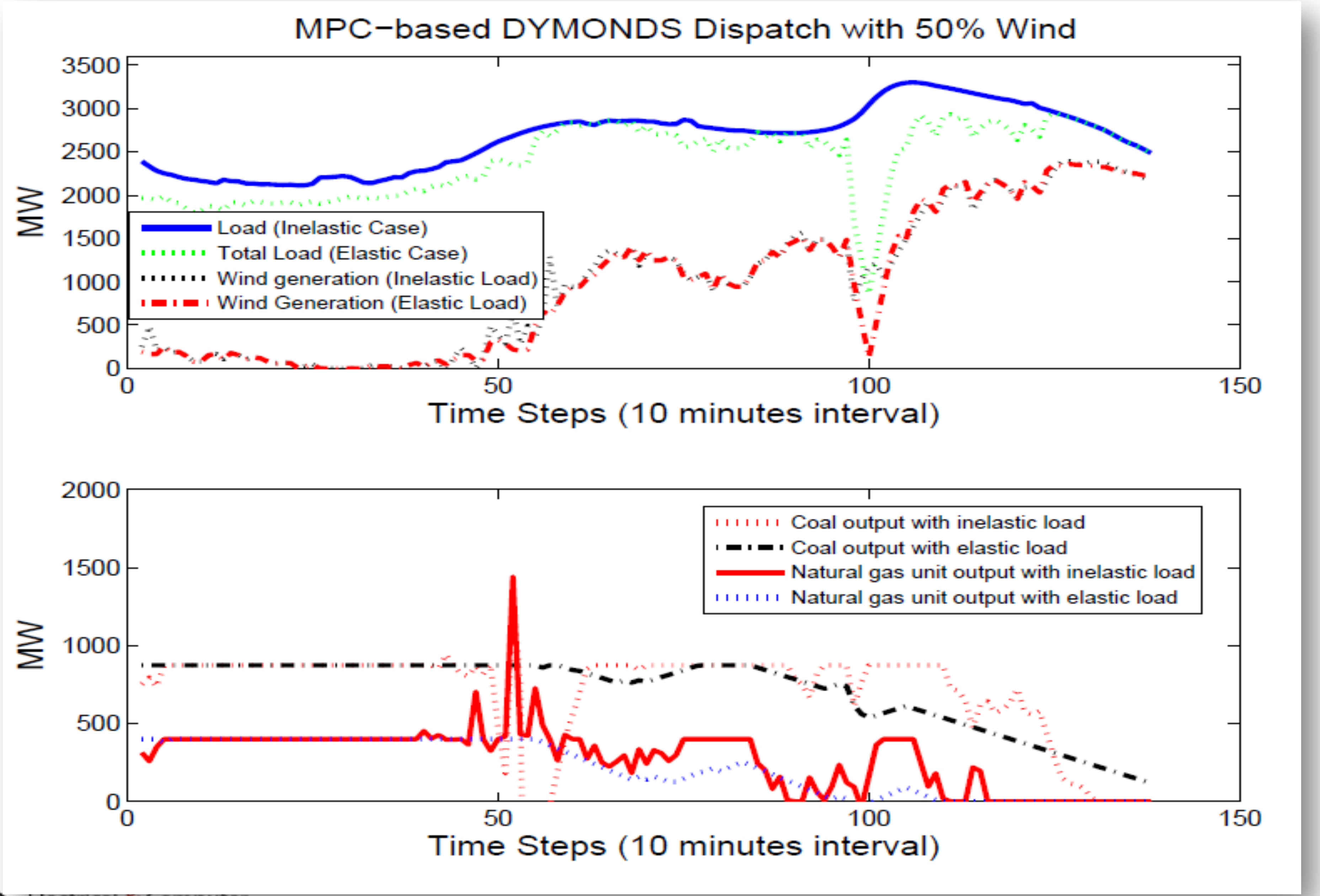


Mean: 14.16, variance: 0.54

risk **< cost**



Mean: 13.56, variance: 0.68



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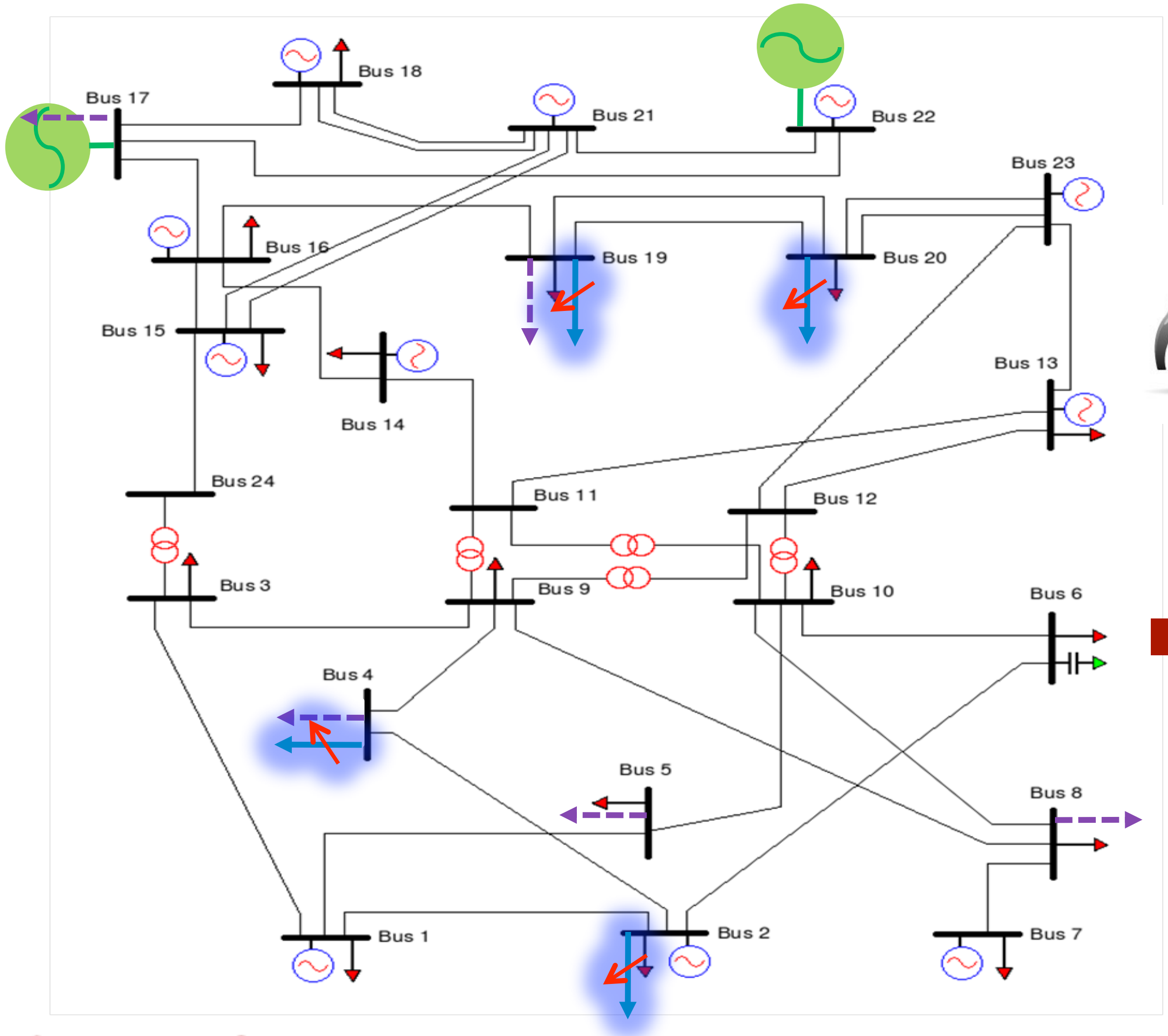
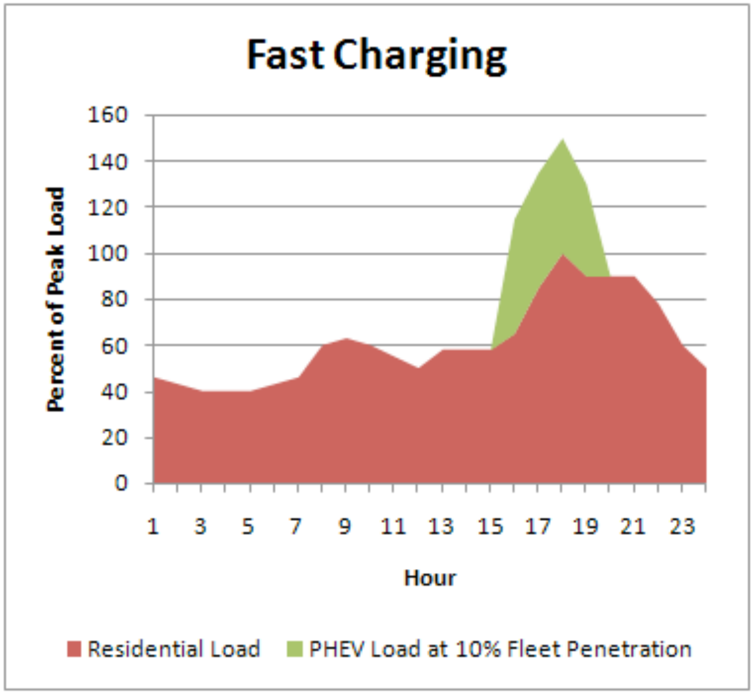
DYMONDS Simulator
Impact of Electric vehicles

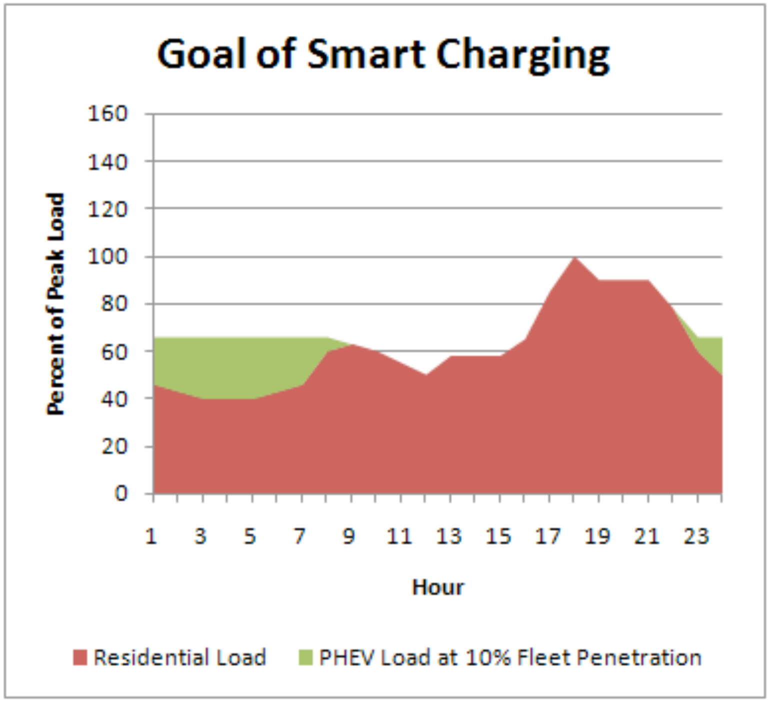


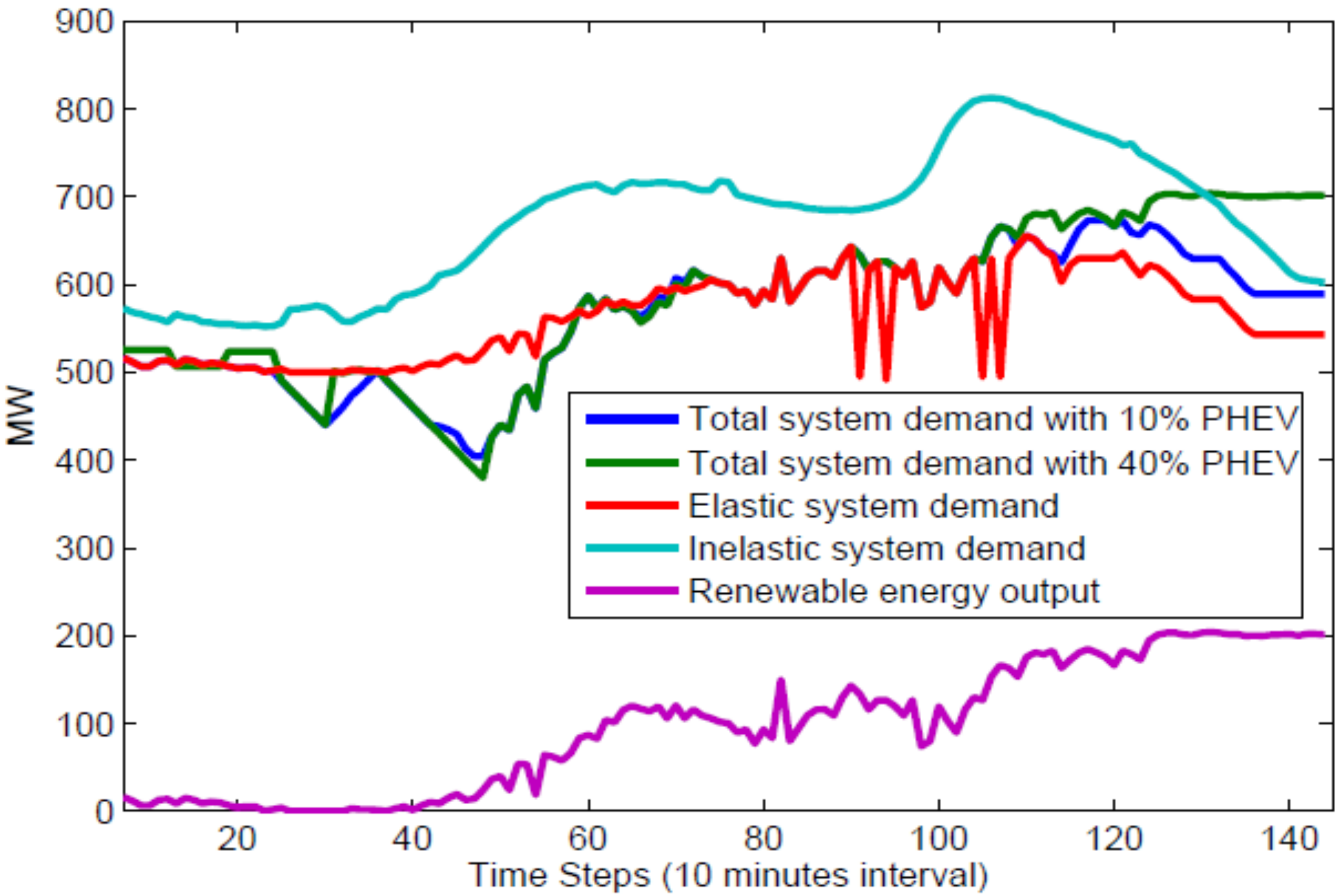
NiklasRotering

- ***Interchange supply / demand mode by time-varying prices***

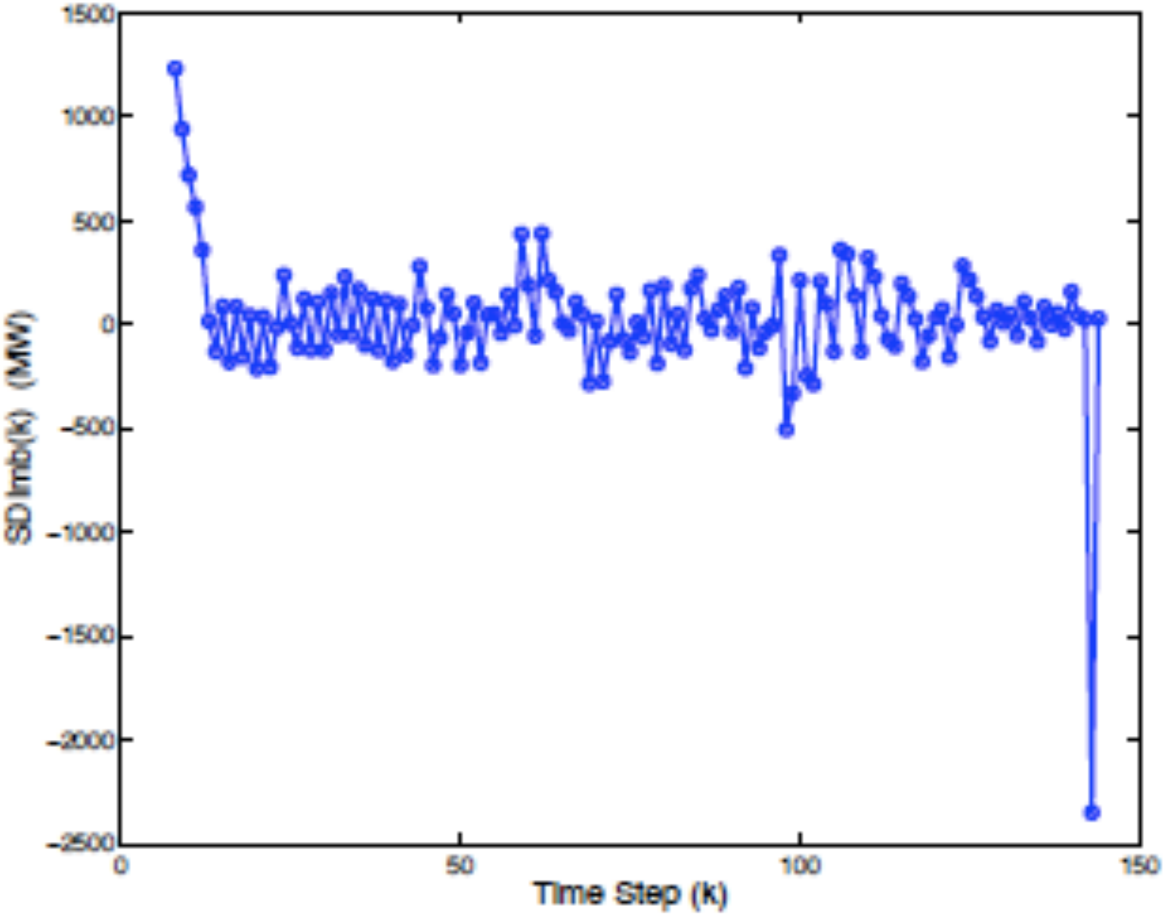
Optimal Control of Plug-in-Electric Vehicles: Fast vs. Smart






900
800
700
600
500
400
300
200
100
0
MW
20
40
60
80
100
120
140
Time Steps (10 minutes interval)
Total system demand with 10% PHEV
Total system demand with 40% PHEV
Elastic system demand
Inelastic system demand
Renewable energy output

Plug-and-Play (No Coordination)?



Total generation and total demand imbalances in 50% wind case

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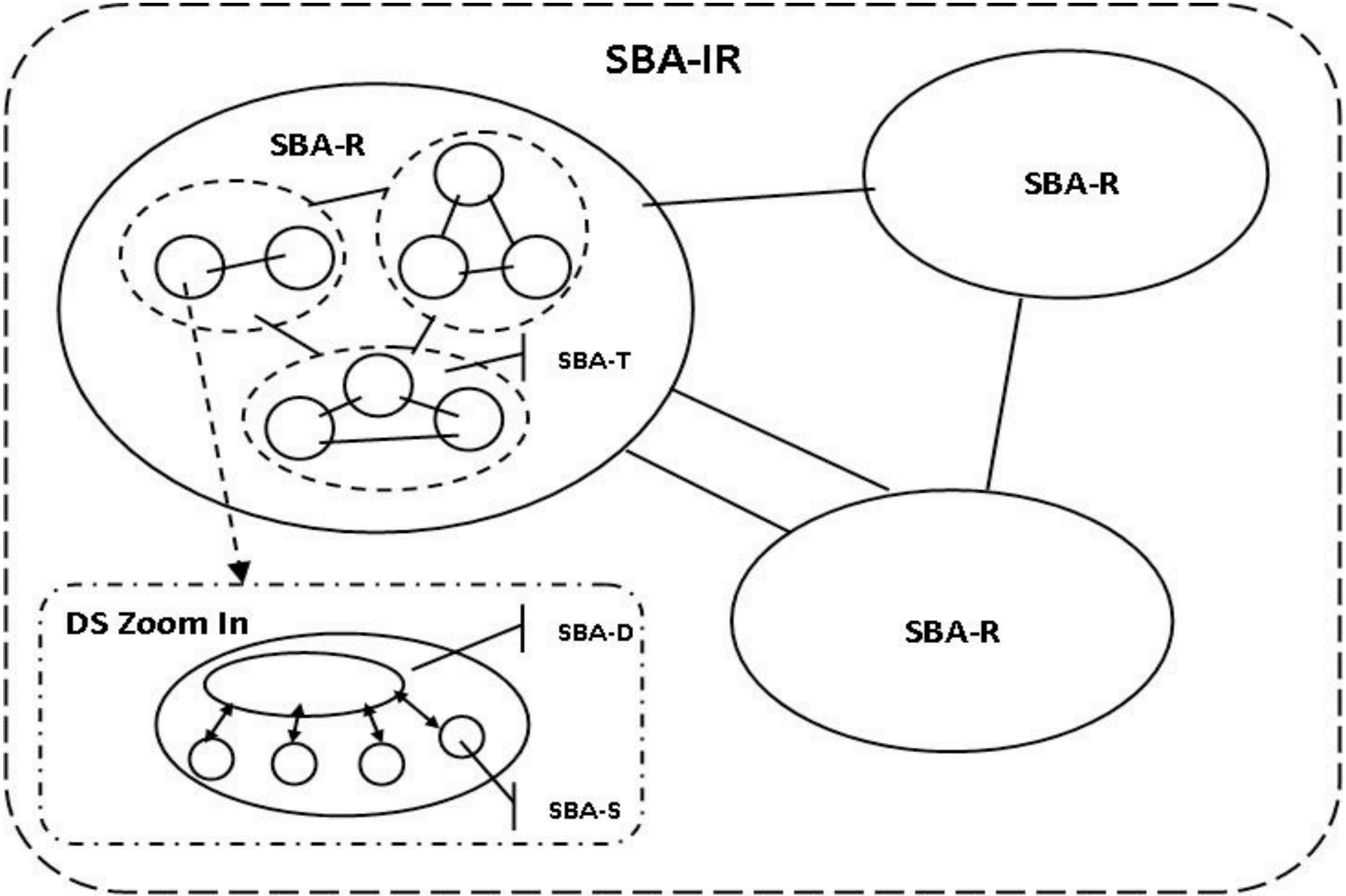
Aggregation and interactions for sustainability--nonunique



Summary:
Smart Grid Concept- Key Role of ICT

- ***Distributed decision making for anticipated system conditions (provided by means of minimal coordination to the users).***
- ***Predictions, adaptations, aggregation through cooperation and/or minimal aggregation***
- ***Large economic and environmental benefits***
- ***Need "smart regulation"—governance system to support its evolution***
- ***N.B. SUSTAINABLE (ELECTRIC) ENERGY SYSTEMS CAN NOT BE BASED ON SIMPLE BLUE-PRINTS***
- ***Smart grid should be designed to enable any energy SES to make it as sustainable as possible; much can be done by careful design of ICT (>20% efficiency low hanging fruit)***

Matching of Technical, Economic, and Governance Design –Future R&D

- Not the same physical grid, ICT and governance system for all of the five representative systems
- Design to manage sustainable multi-objective tradeoffs
- Need for "Smart Balancing Authorities" (SBAs) in Smart Grids
- ICT-related transactions costs and benefits need to be studied

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