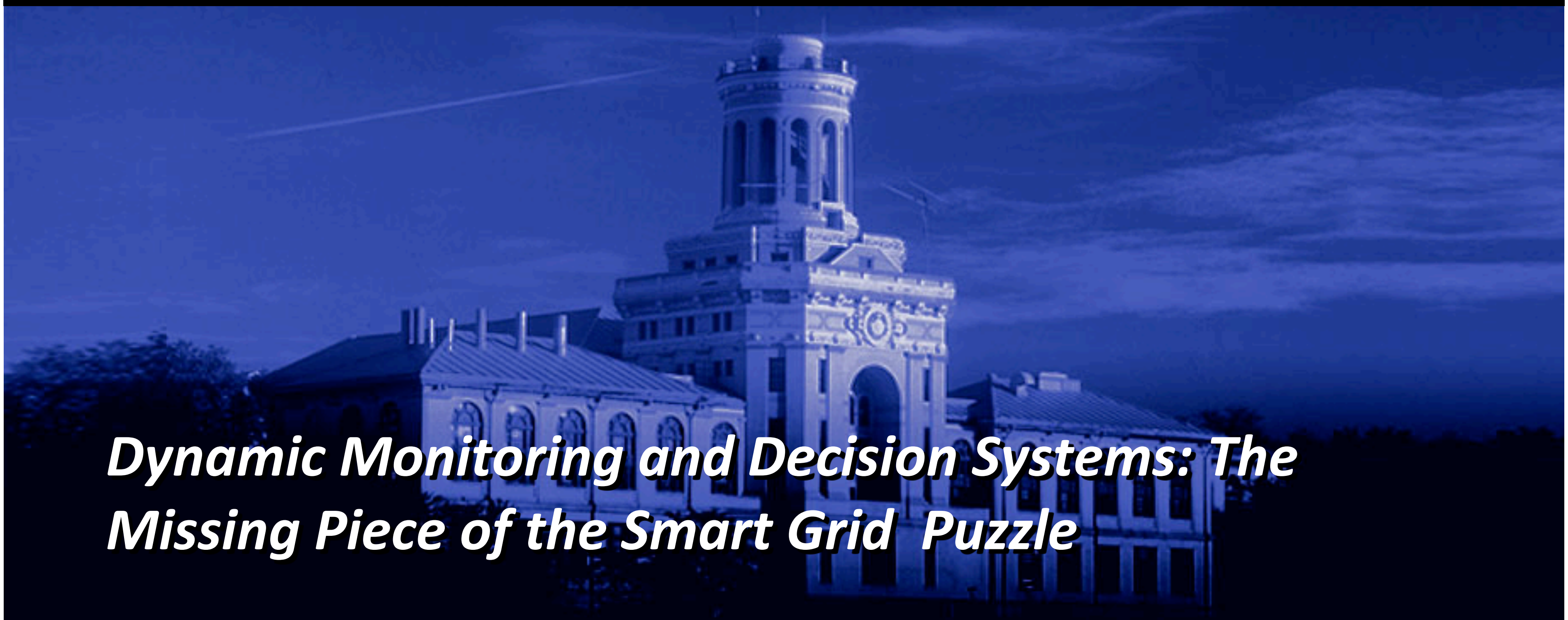

Dynamic Monitoring and Decision Systems: The Missing Piece of the Smart Grid Puzzle

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SAMSI Smart Grid Workshop, October 2 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.***

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Outline

- *Technical challenge; what needs fixing? Getting from here to there.*
- *Integration important. Many ways of ``integrating" — Dynamic Monitoring and Decision Systems (DYMONDS); change of paradigm*
- *Temporal and spatial uncertainties in power systems; ICT for managing these*
- *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*
- *The man-made electric power network, its governance system and the Information Communications Technology (ICT) --- key enablers of sustainable electric energy provision [2,3]*
- *Examples of DYMONDS*

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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 software*
  - *incorporation of security, communications, and safety systems*
  - *BEFORE hardware is deployed!*
  - *Our Main Approach--Dynamic Monitoring and Decision Systems (DYMONDS)*

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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

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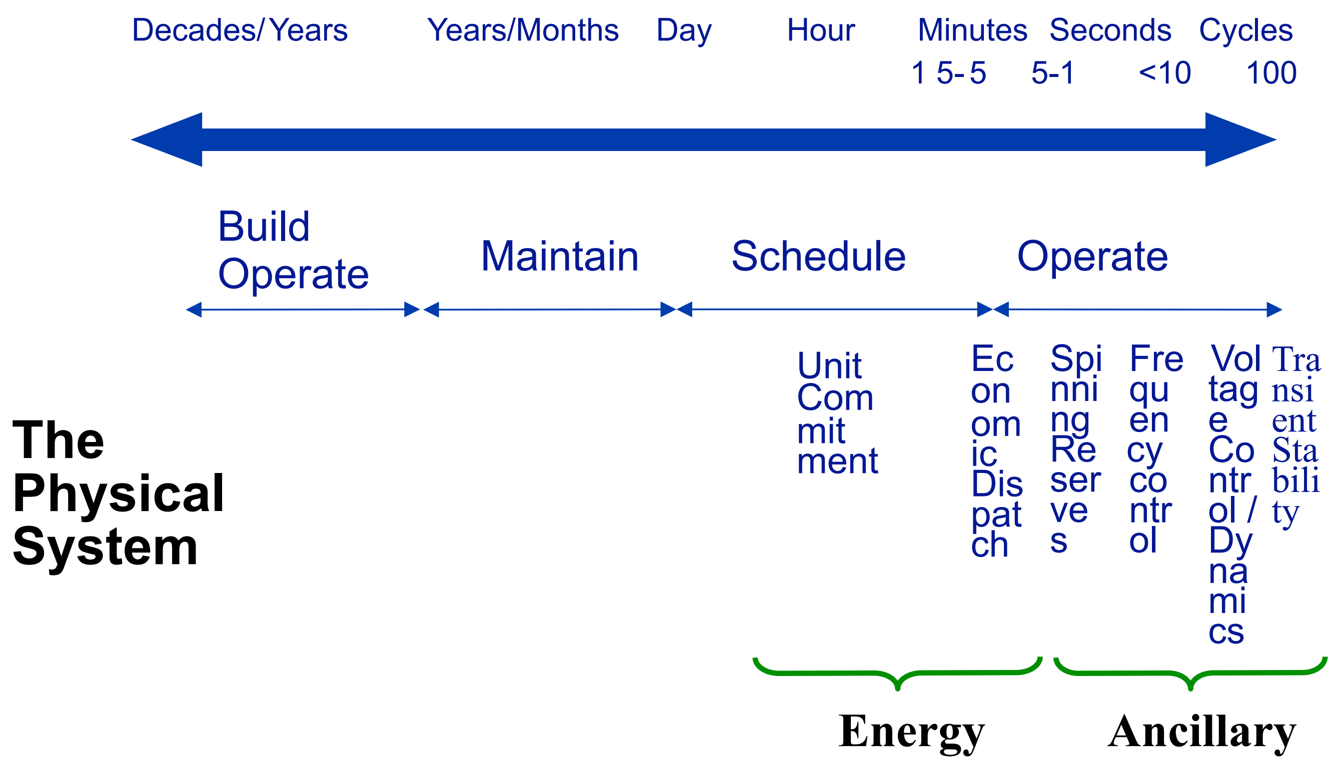
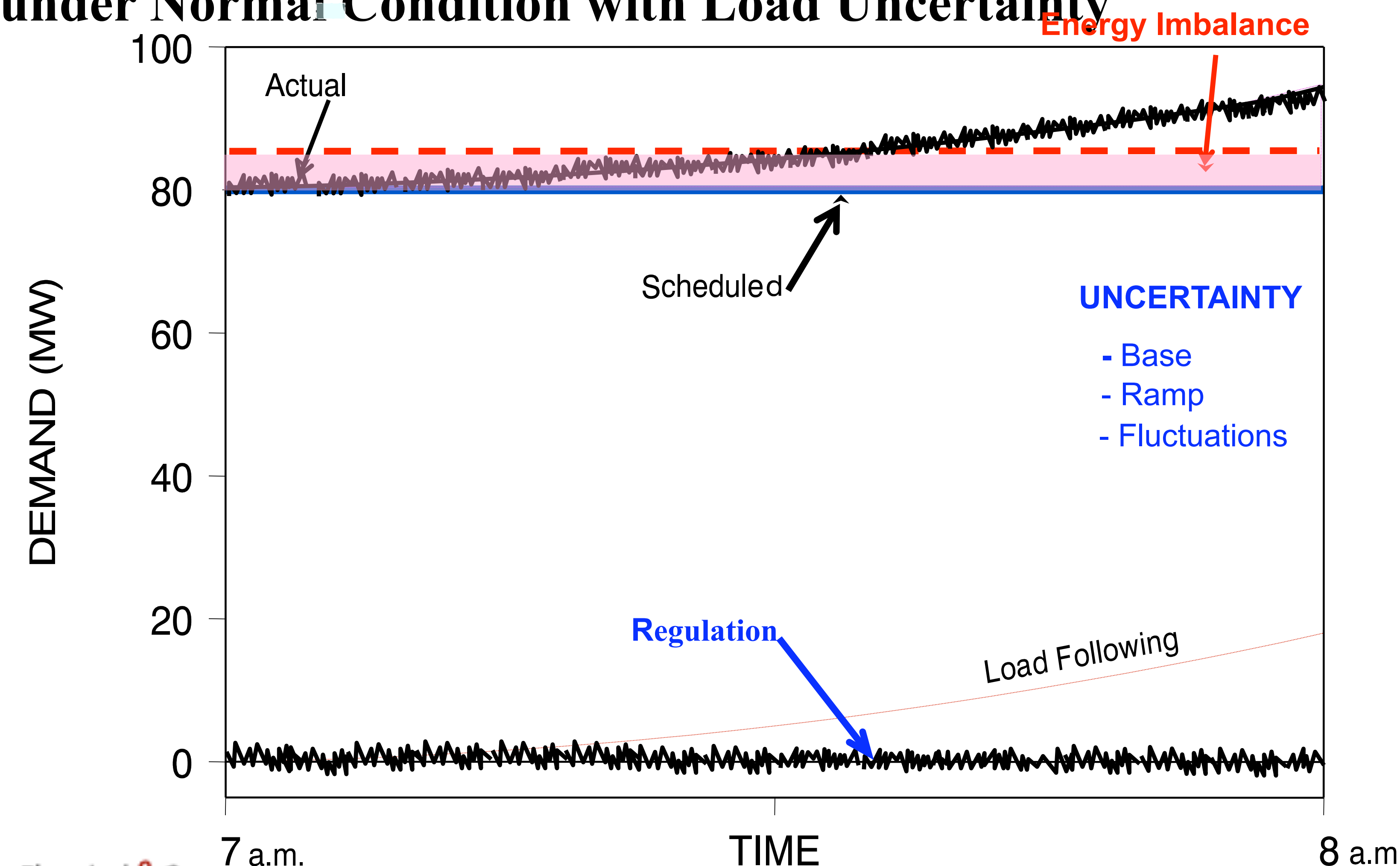
Temporal Complexity



- ***Objectives (in today's industry): Produce, Deliver and Consume Electricity Reliably under Normal Operating Conditions with Possible Occurrence of Plausible Contingency***
- ***We never relied on Just-in-Time (JIT) and Just-in-Place (JIP) adaption---high price on both reliability and cost***
- ***Continual Balance of Supply and Demand***
  - *Lack of Practical Means of Storage*
  - *Long Distance Transmission*
  - *Uncertainties in Load and Equipment*

Temporal Complexity –COULD AND SHOULD BE MANAGED MORE ADAPTIVELY

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



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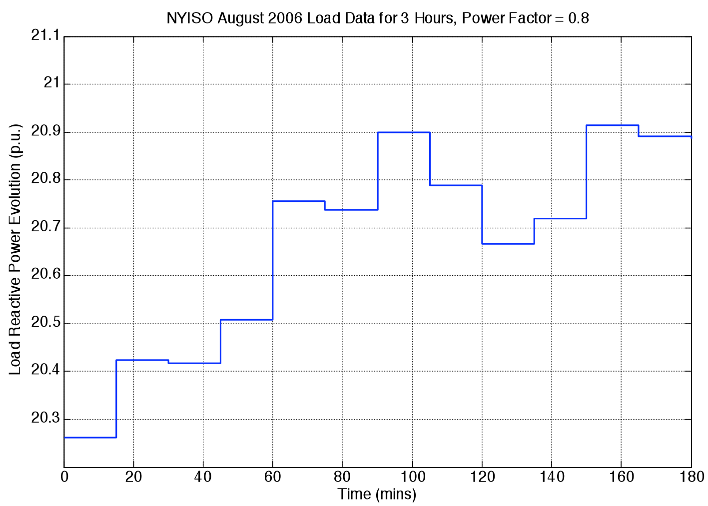
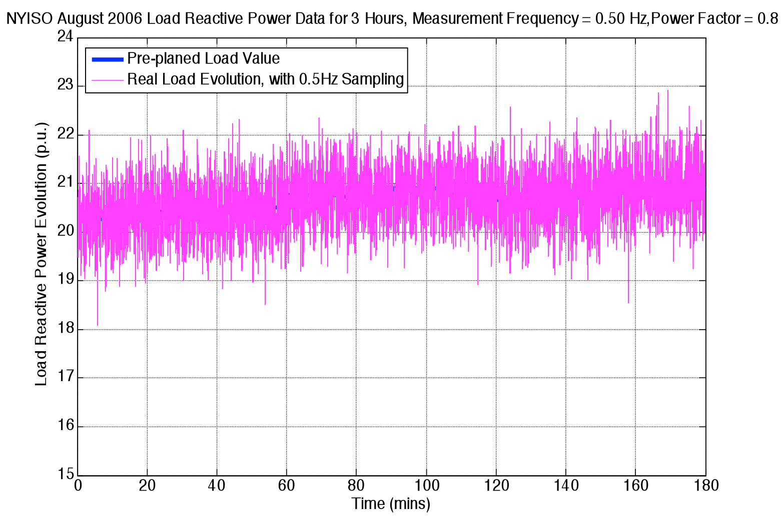
Load Disturbance Around Scheduled Value

Scheduled load value and the disturbance around the value





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Technical 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 operator; seams issue

- ***Spatially and functionally nested hierarchies***
- ***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.

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Challenge to the old assumptions created by the DERs (decision driven)

- ***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 (portfolios—hydro+wind?)

  -Valuation of their unique characteristics

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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.***

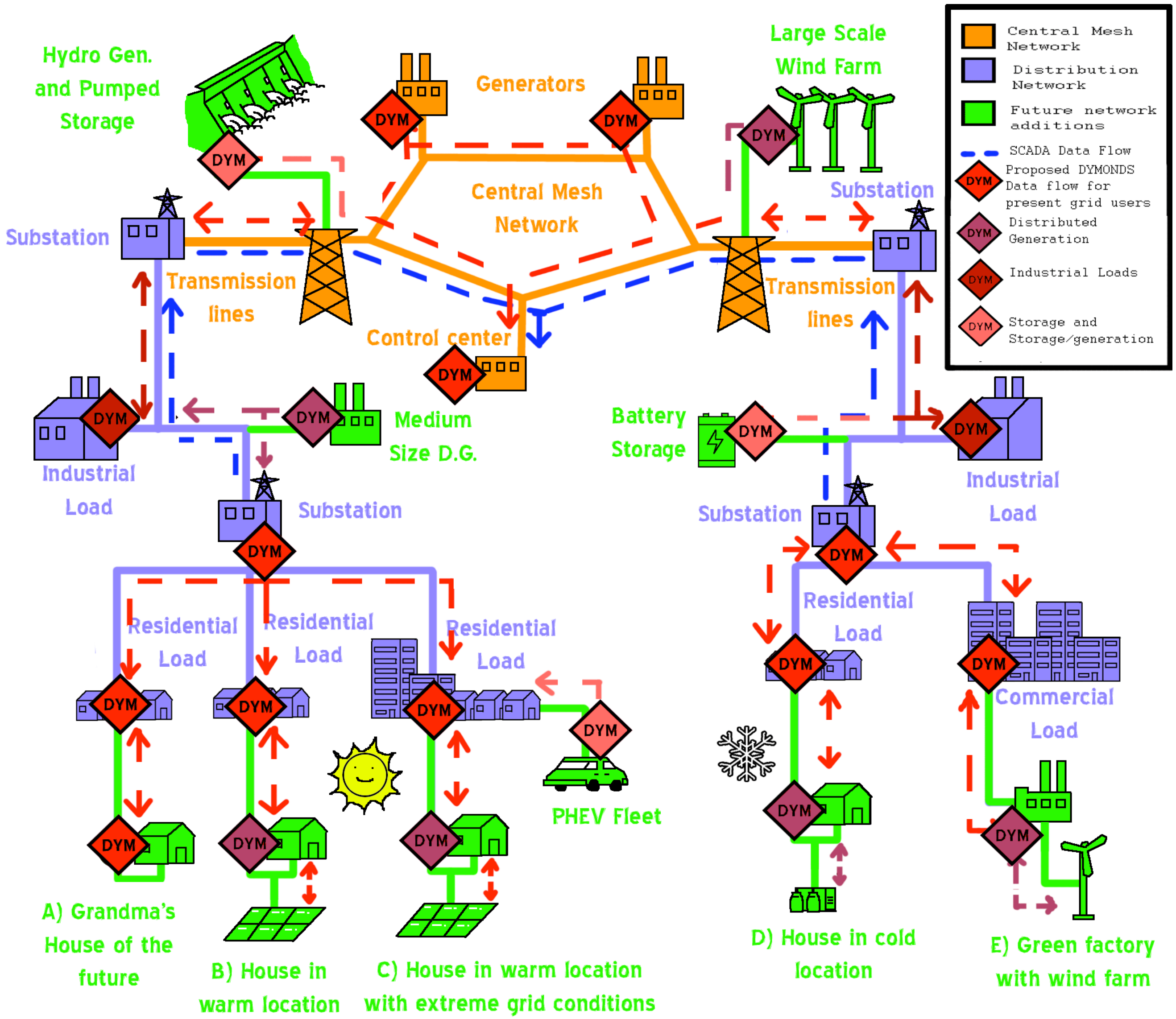
Need for managing dynamic response of various technologies

- *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*
- *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.*

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]



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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***

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Meeting of Traditional Disciplines and the 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*
- *Our approach---align modeling for SEES and objectives of smart grid and its ICT*

The SEES framework [1] --Summary

- ***Define core sub-system variables of an SEES***
- ***Define second- (and deeper)-level variables key to answering questions of interest***
- ***Establish measures (qualitative and quantitative) of second- and deeper-level variables***
- ***Use these to determine key factors for assessing the likelihood of the given SES to be sustainable and for policy design***
- ***INTERACTION-VARIABLES BASED—Ostrom approach and engineering modeling for spatial and temporal complexity aligned***

Five Representative Electric Energy Systems [2-3]

Bulk Electric Energy Systems -Regulated	Bulk Electric Energy Systems -Restructured	Hybrid Electric Energy Systems	Fully Distributed Electric Energy Systems—Developed Countries	Fully Distributed Electric Energy Systems-Developing Countries

Table 2 Five Representative Types of Electric Energy Systems

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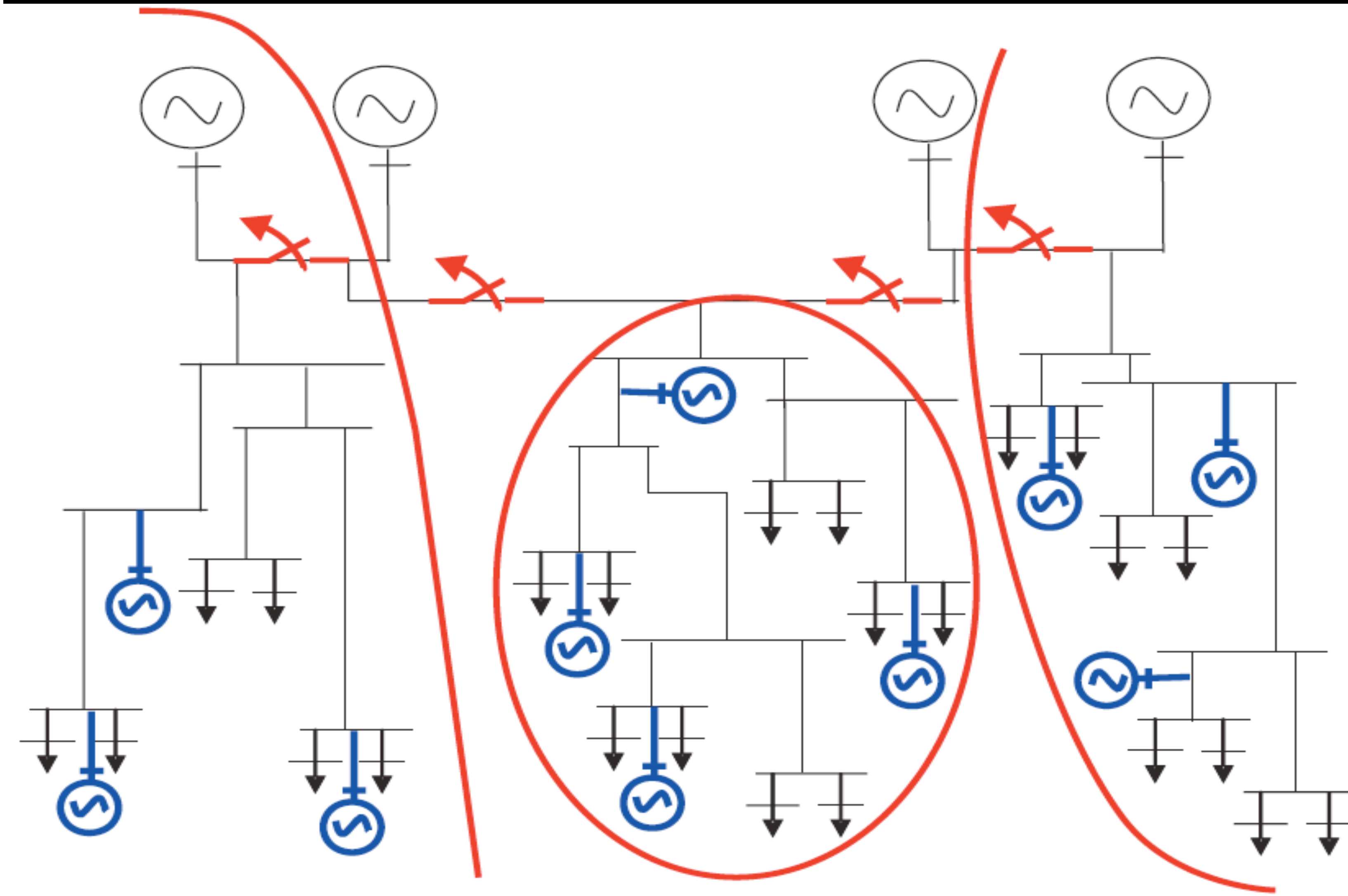
Fully regulated bulk electric energy system



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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***

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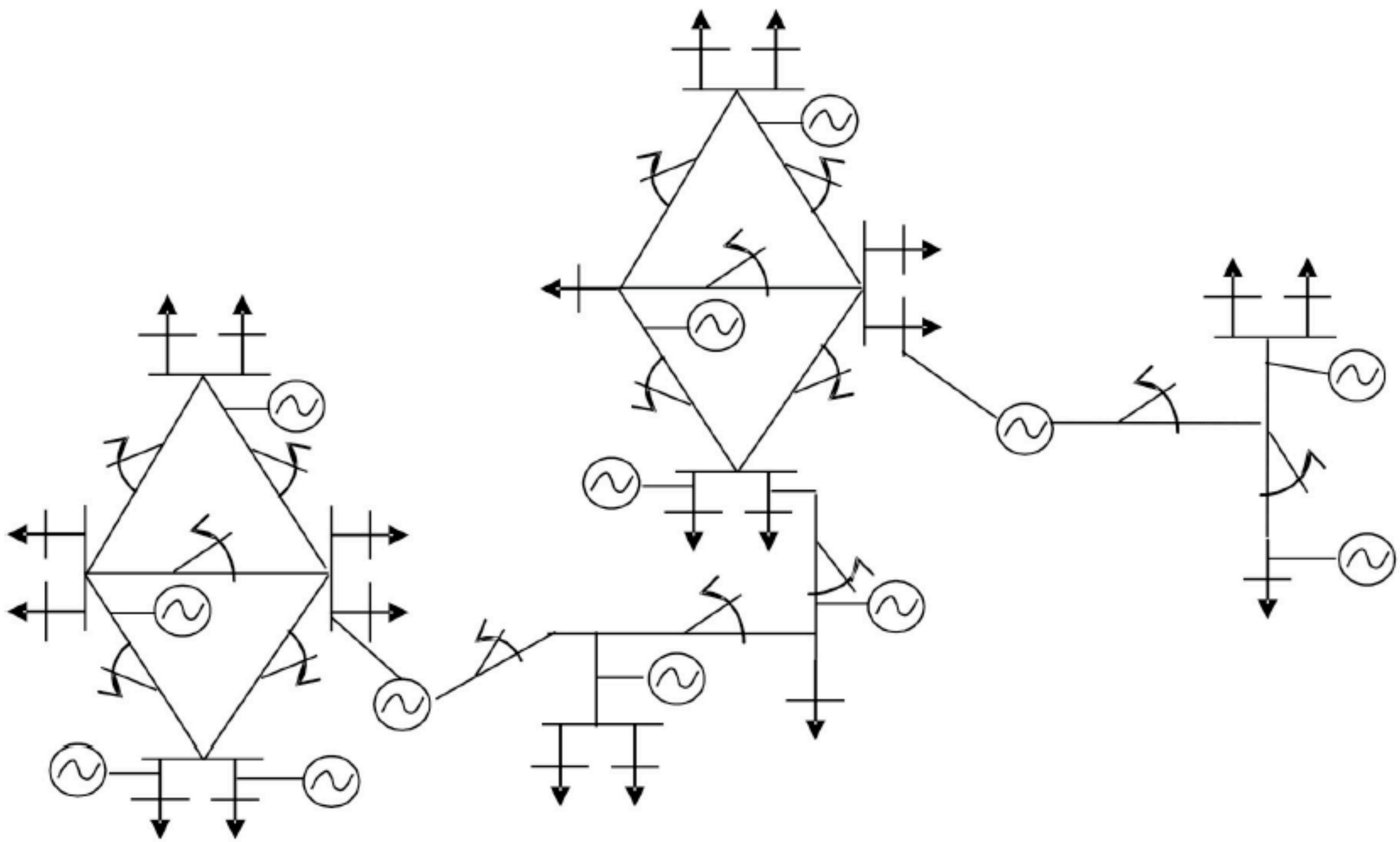
Hybrid Electric Energy System—How to model and manage interactions?



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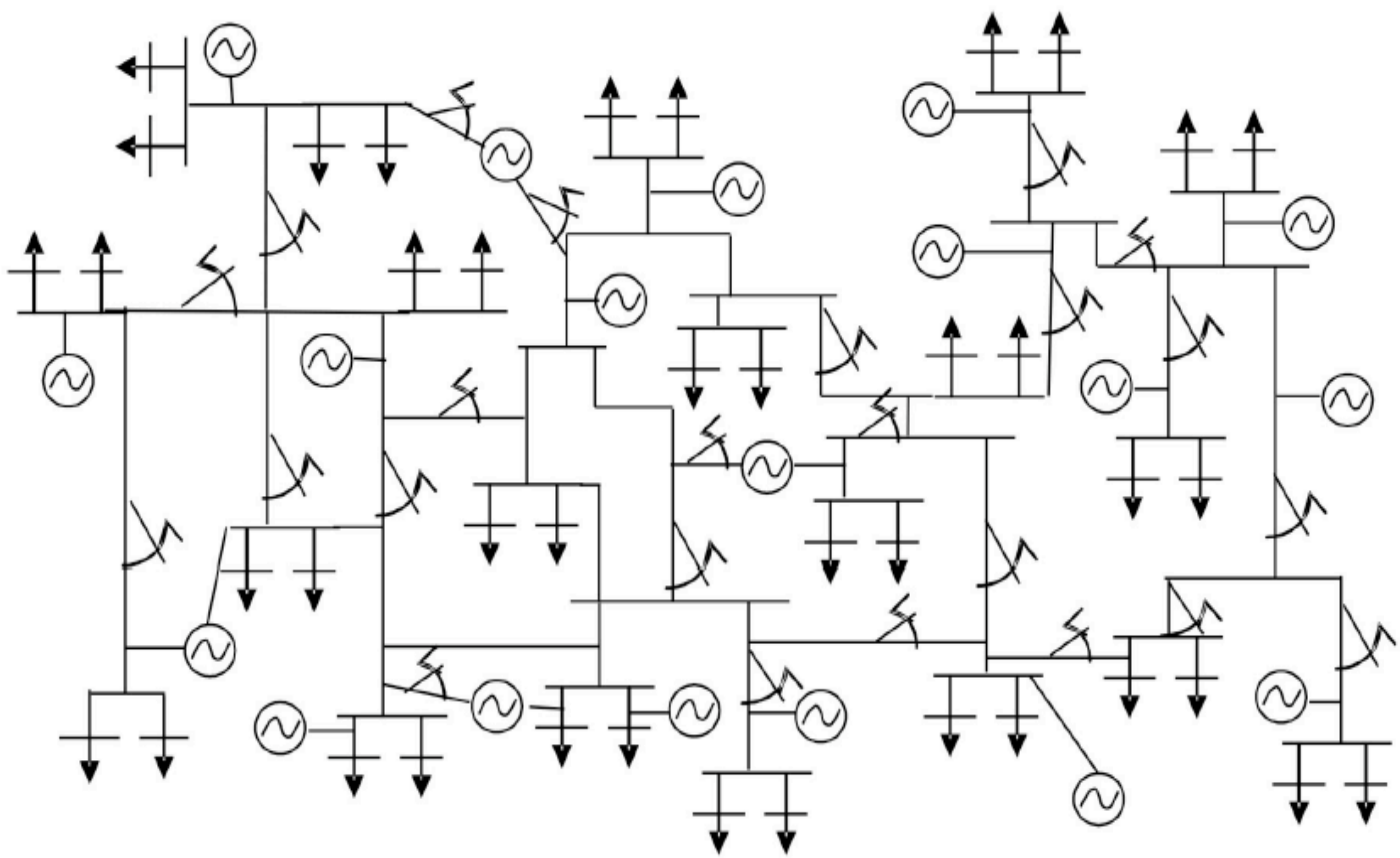
Fully distributed small-scale systems—Are there any interactions or it is all more or less distributed?



Interaction Variables within a Socio-Ecological Systems

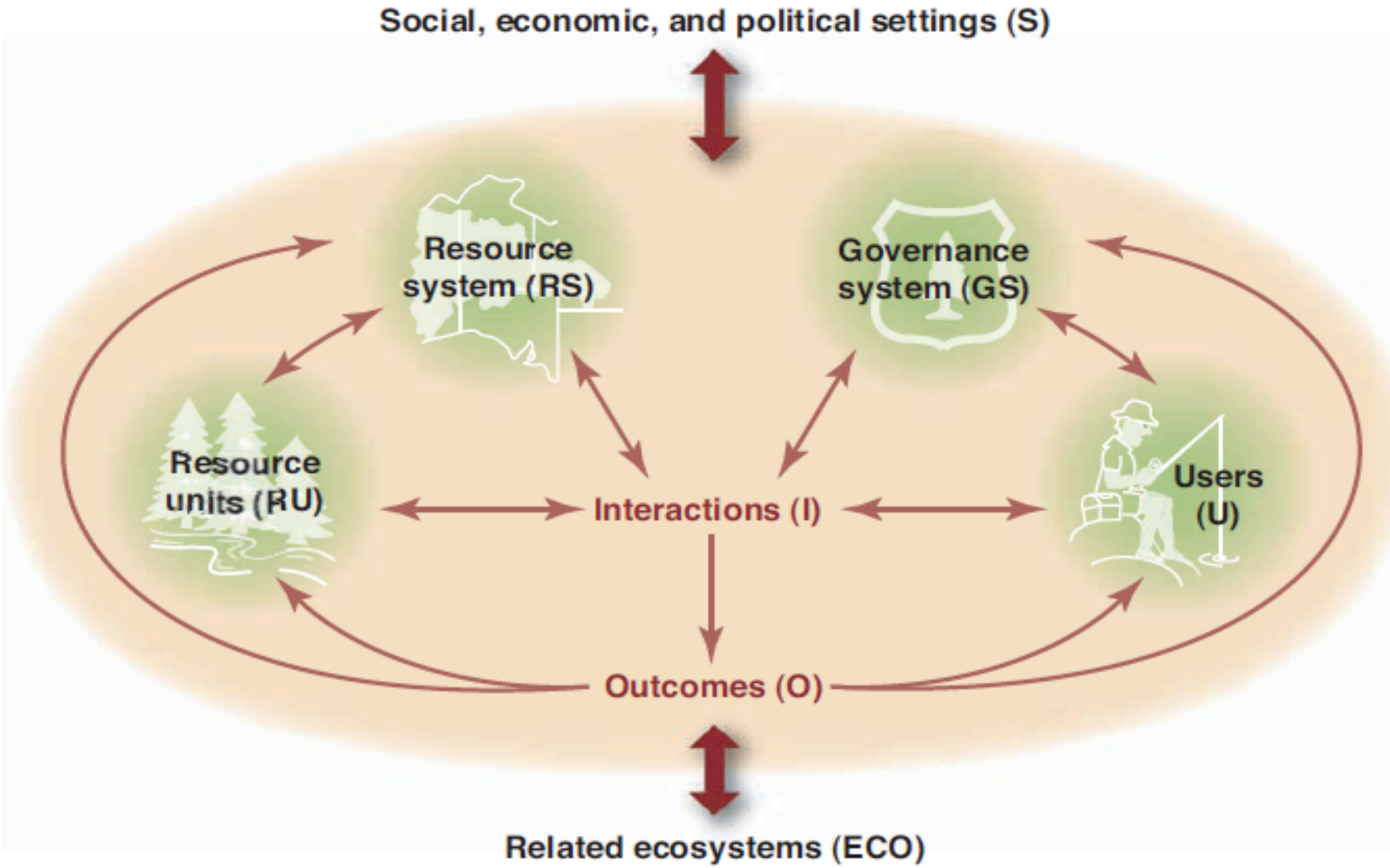


Fig. 1. The core subsystems in a framework for analyzing social-ecological systems.

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Core and Second-Level Variables

RESOURCE SYSTEM (RS)	RESOURCE UNITS (RU)	GOVERNANCE SYSTEM (GS)	USERS (U)
SIZE	MOBILITY	COLLECTIVE CHOICE RULES	NUMBER
PRODUCTIVITY			LEADERSHIP
PREDICTABILIT Y			SOCIAL NORMS
			SES KNOWLEDGE

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

Energy SES	Man-made Grid	Man-made ICT
• Resource system (RS) • Generation (RUs) • Electric Energy Users (Us)	• Physical network connecting energy generation and consumers • Needed to implement interactions	• Sensors • Communications • Operations • Decisions and control • Protection

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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 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 five electric energy system types*

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Design for Smart Grids

- ***Our proposed approach:***

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

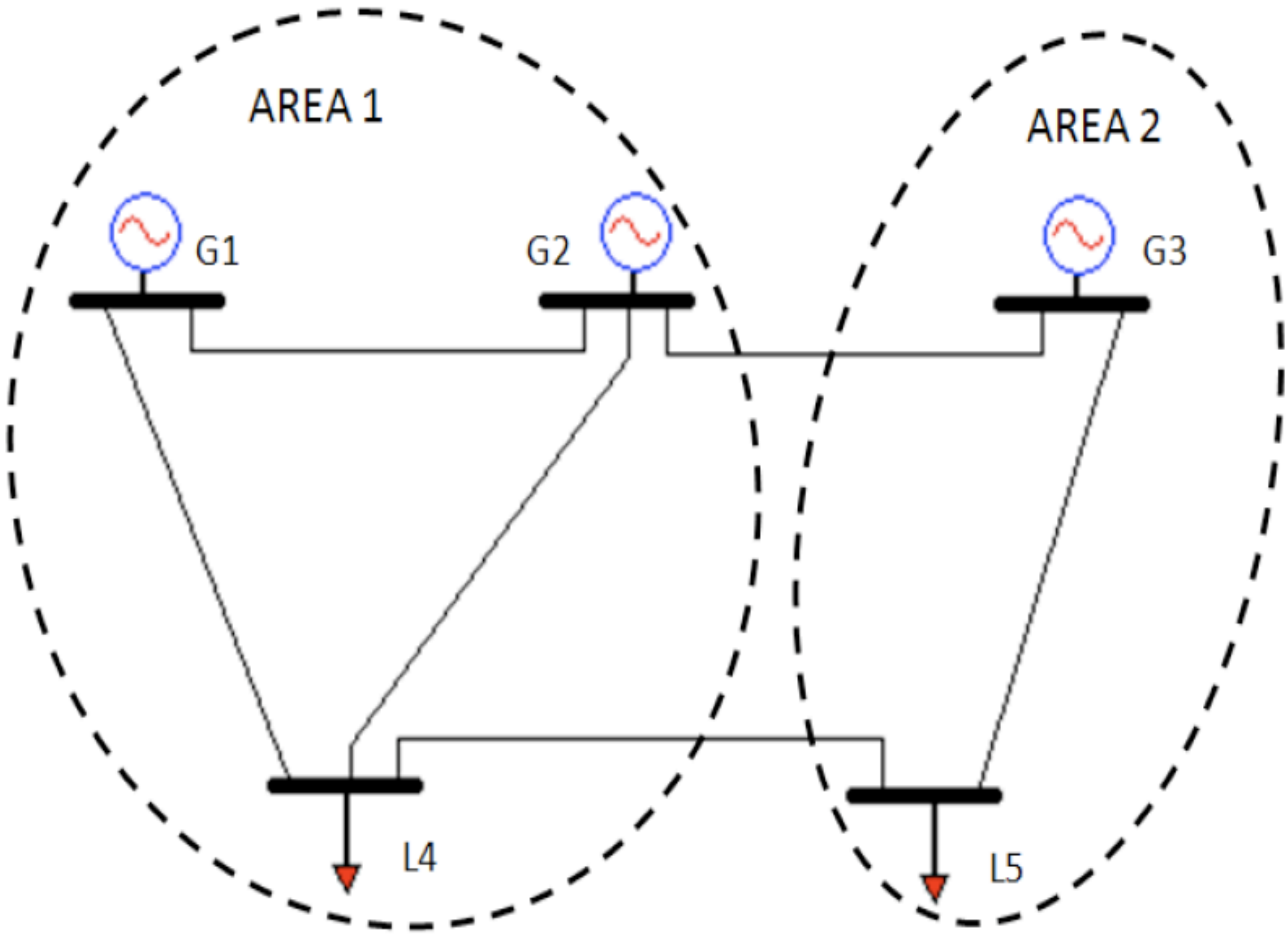
  Step 2—Define deeper-level variables for capturing inter-dependencies between energy SES, physical grid, ICT and governance system

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

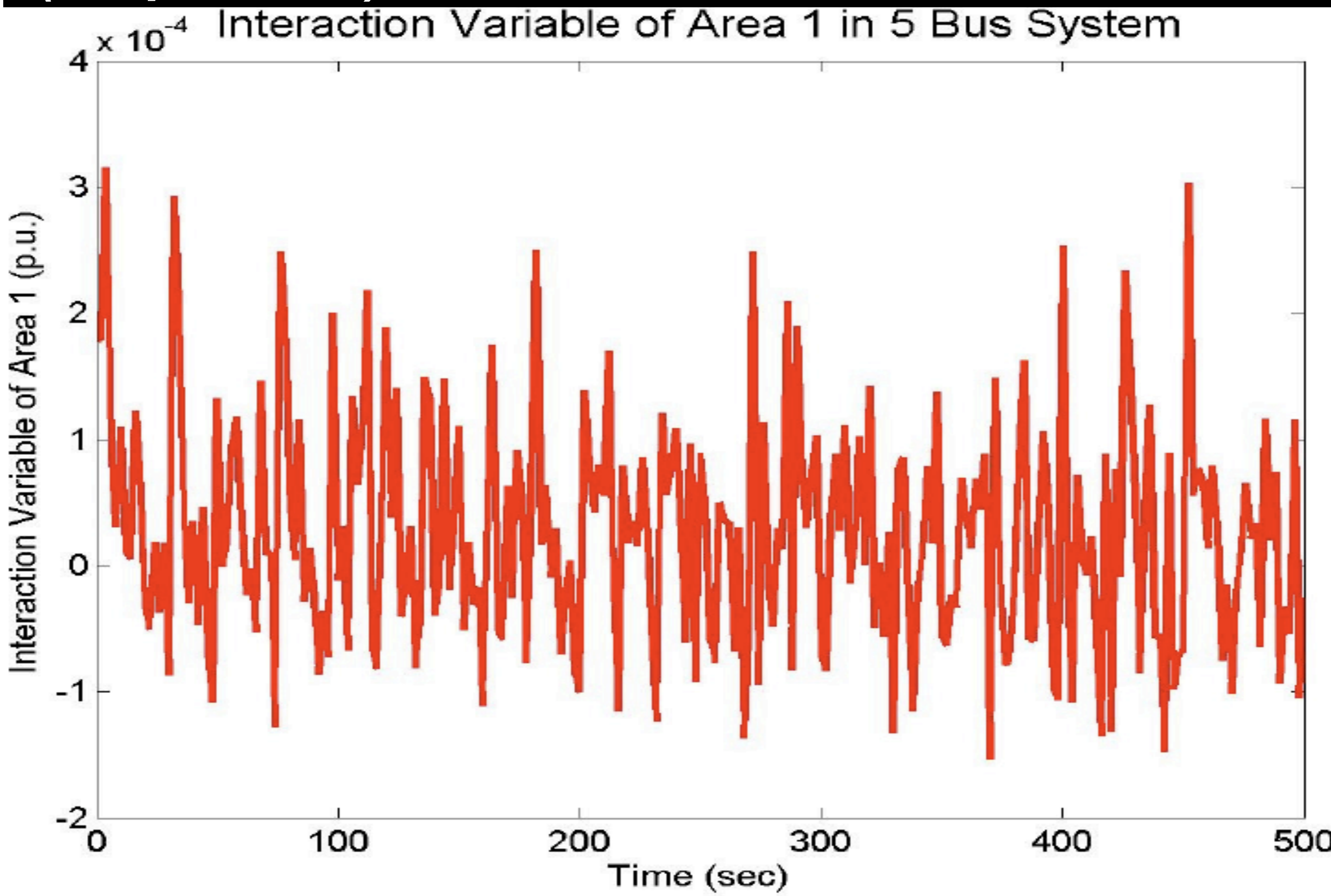
Proposed deeper-level variables

- ***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]***

Interaction Variable Simulation for Real Power Problem in 5 Bus System



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



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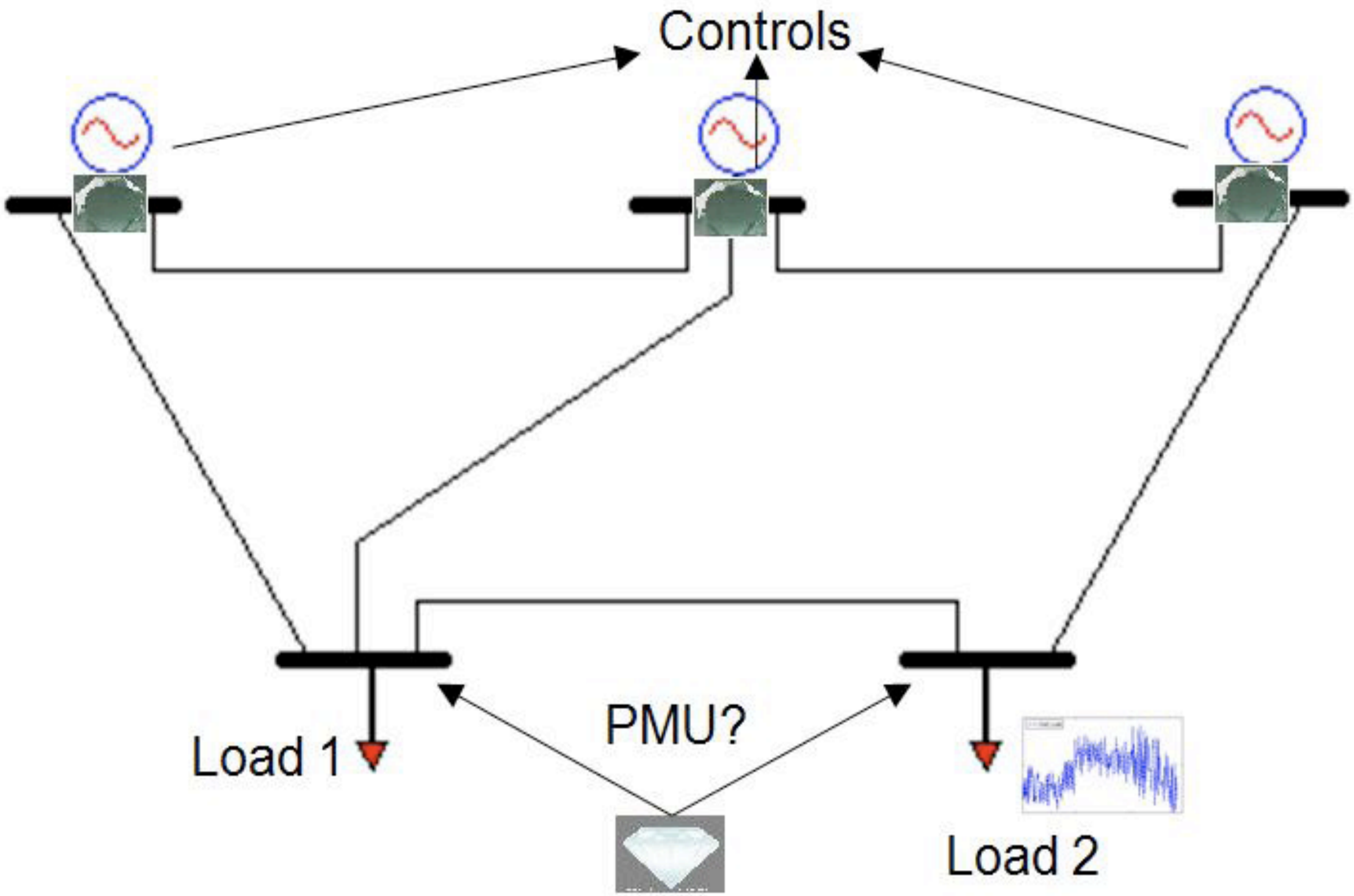
ICT design to monitor and control interaction variables



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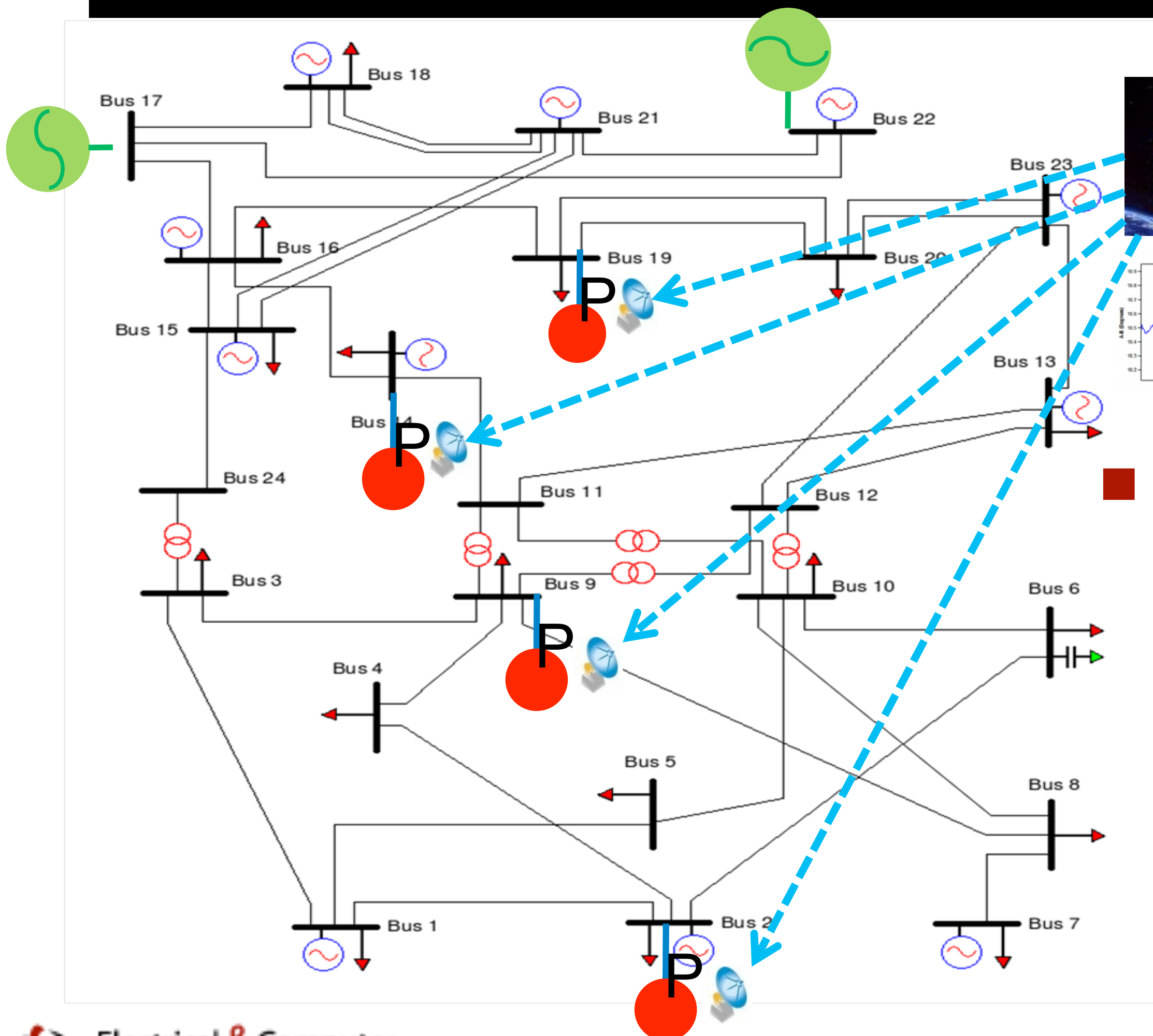
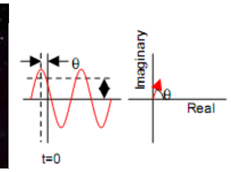
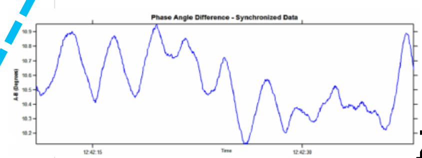
DYMONDS Simulator
PMU-Based Robust Control







Zhijian Liu

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

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.*

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*

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***

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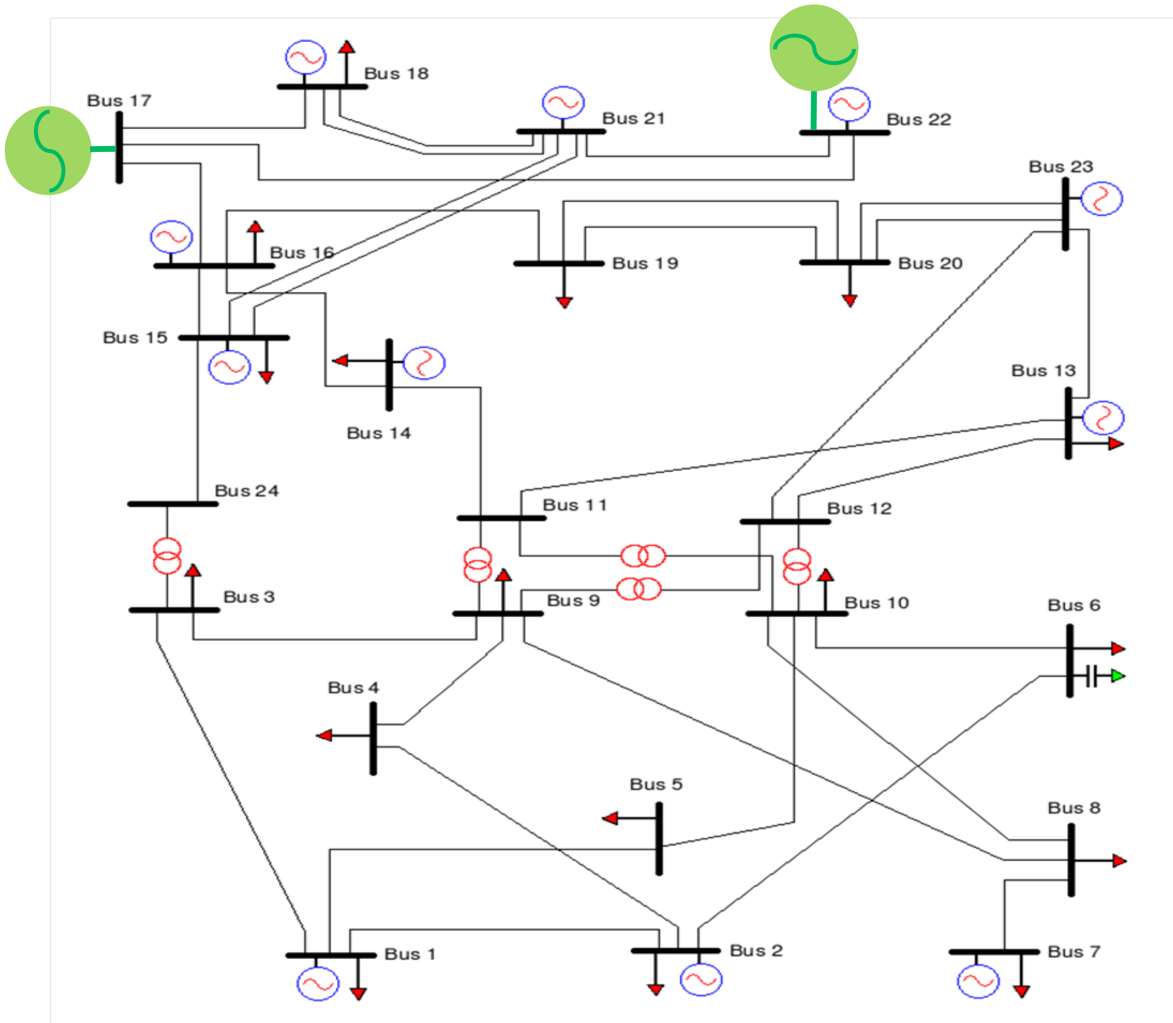
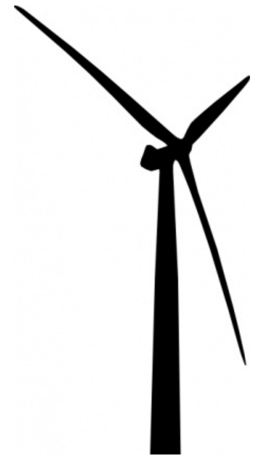
DYMONDS Simulator
IEEE RTS with Wind Power





Le Xie

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

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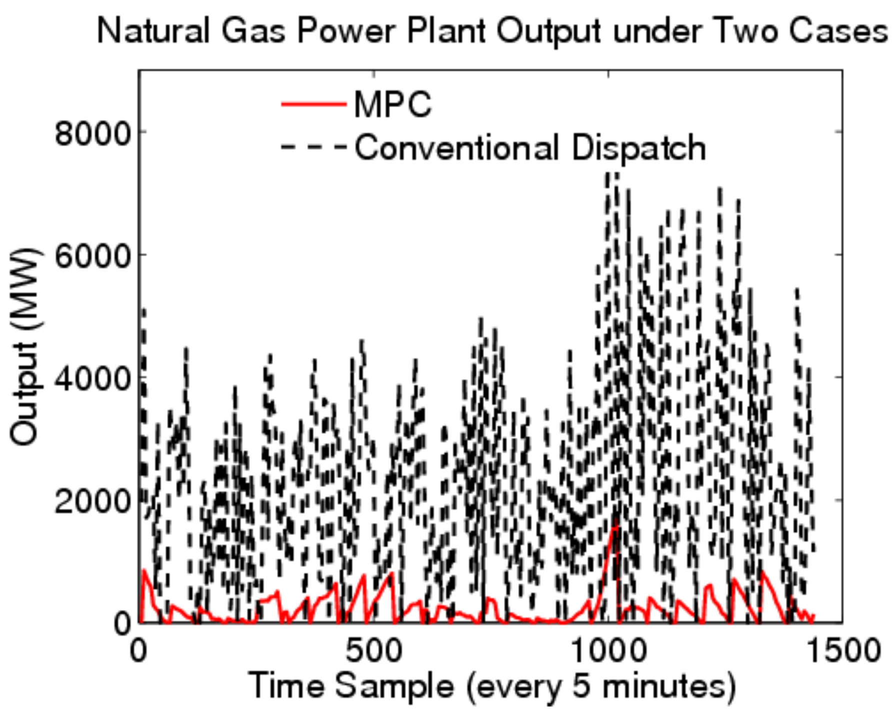
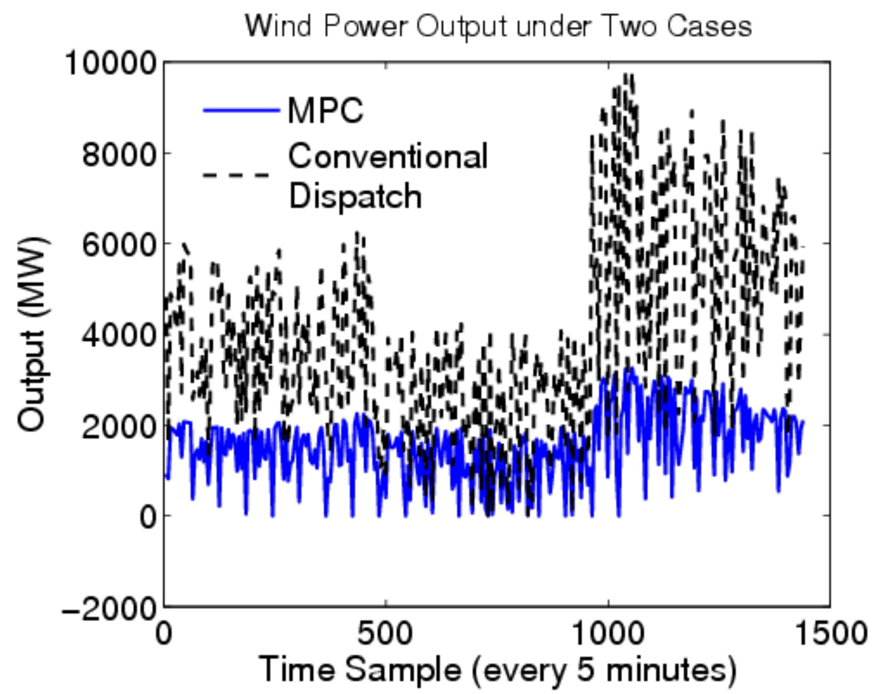
Conventional cost over 1 year *	Proposed cost over the year	Difference	Relative Saving
$ 129.74 Million	$ 119.62 Million	$ 10.12 Million	7.8%





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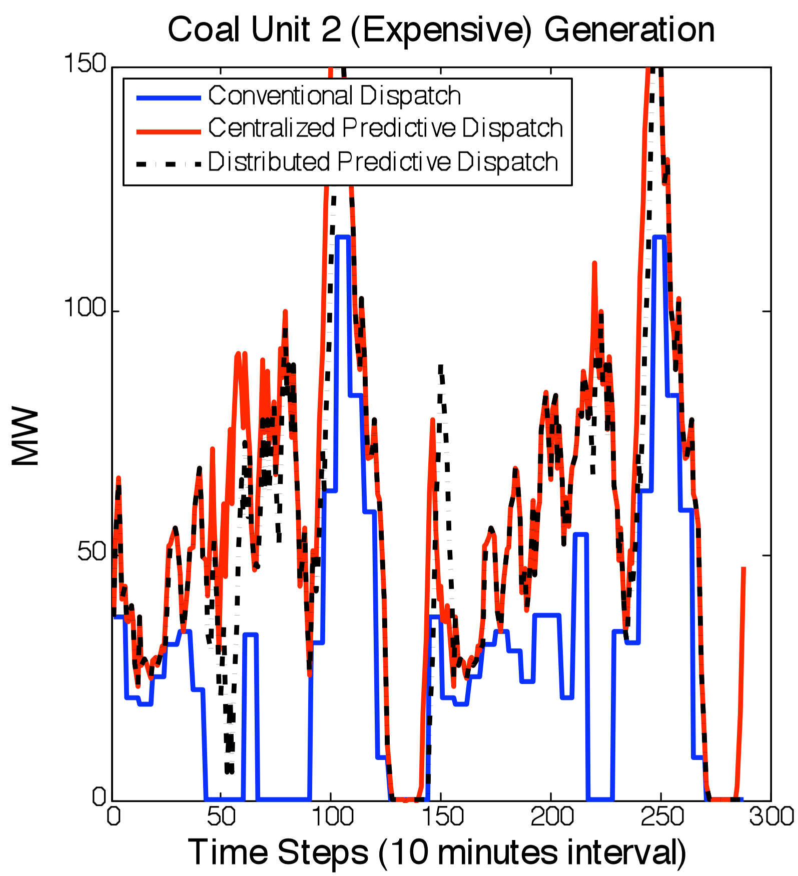
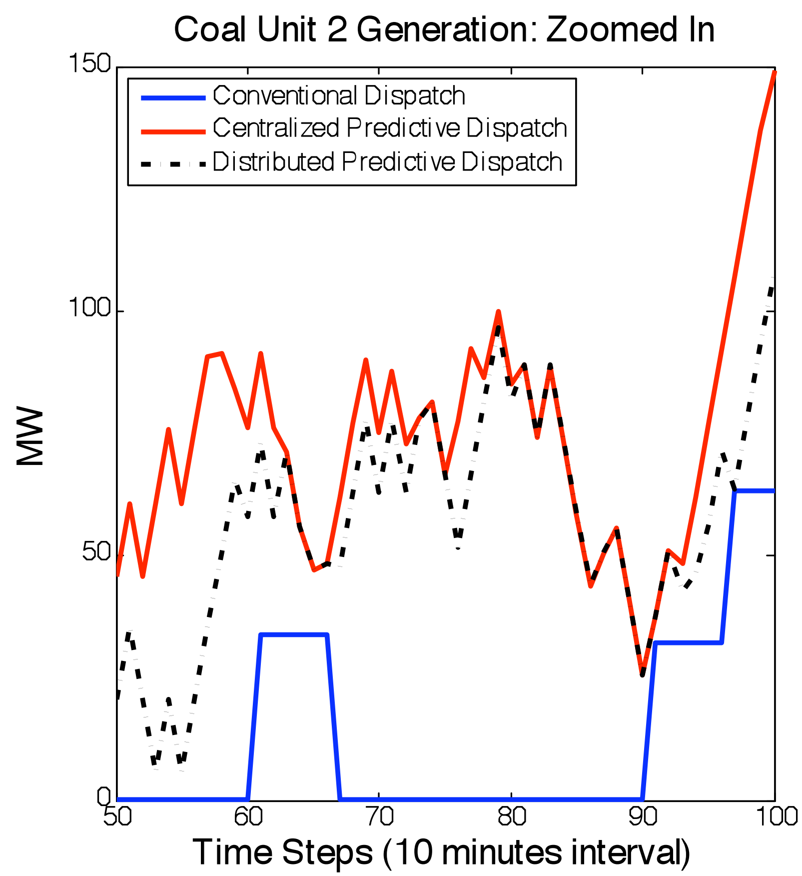
*: load data from New York Independent System Operator, available online at http://www.nyiso.com/public/market_data/load_data.jsp





BOTH EFFICIENCY AND RELIABILITY MET

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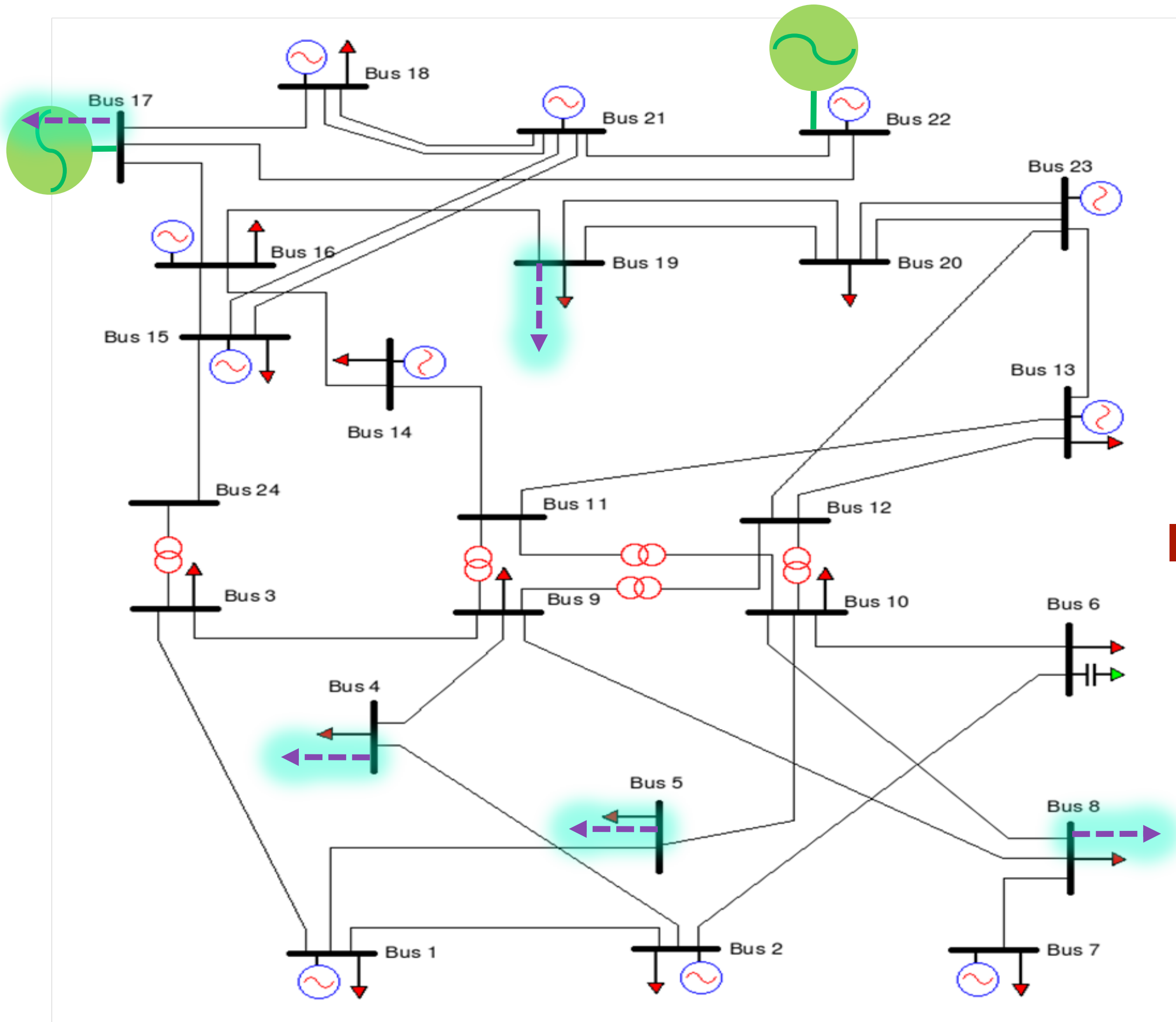
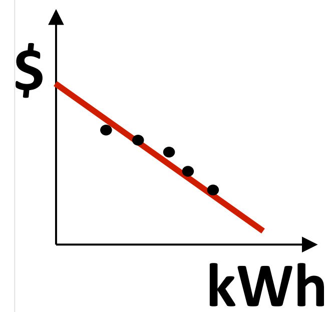
DYMONDS Simulator
Impact of price-responsive demand





J.Y. Joo

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

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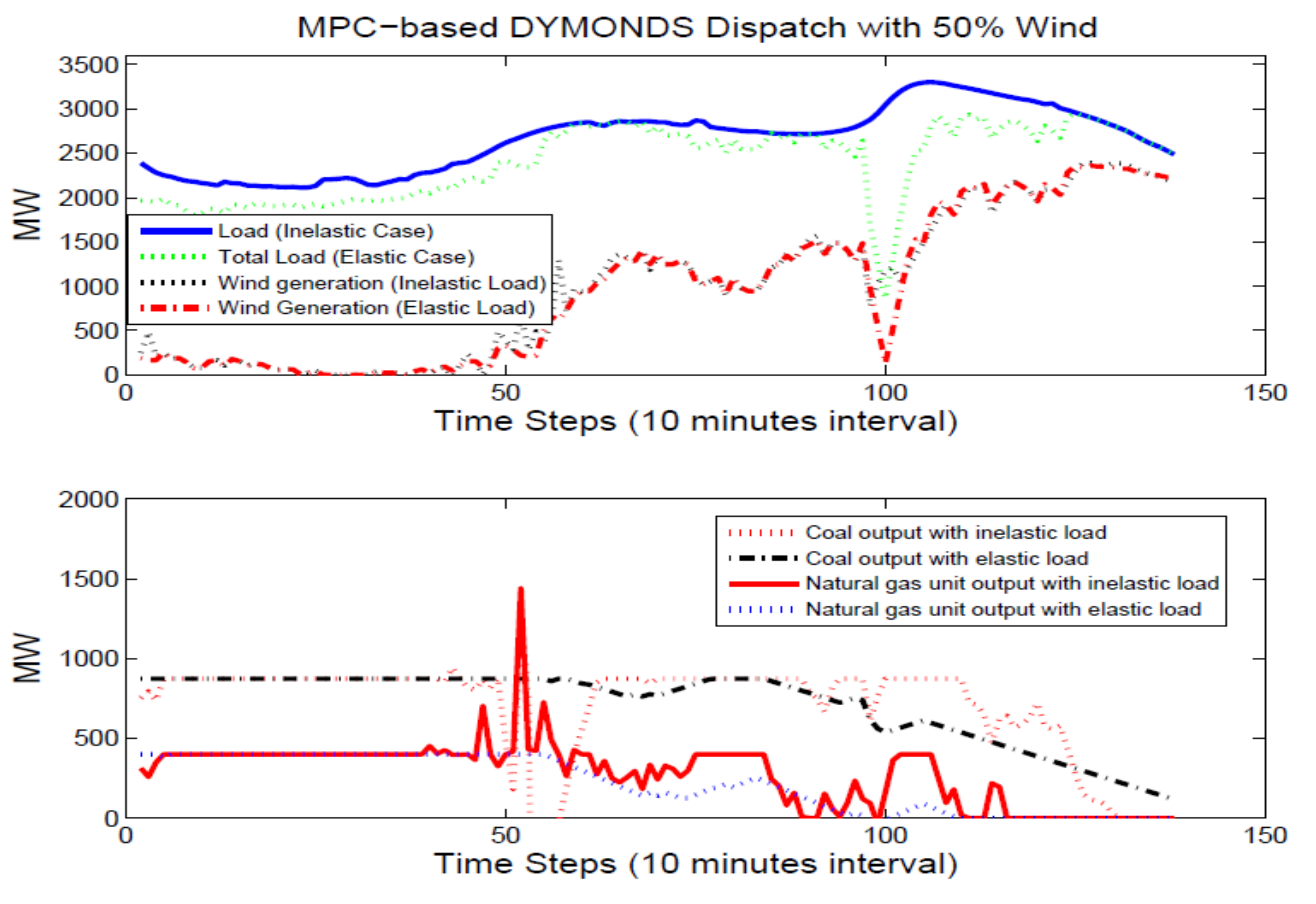
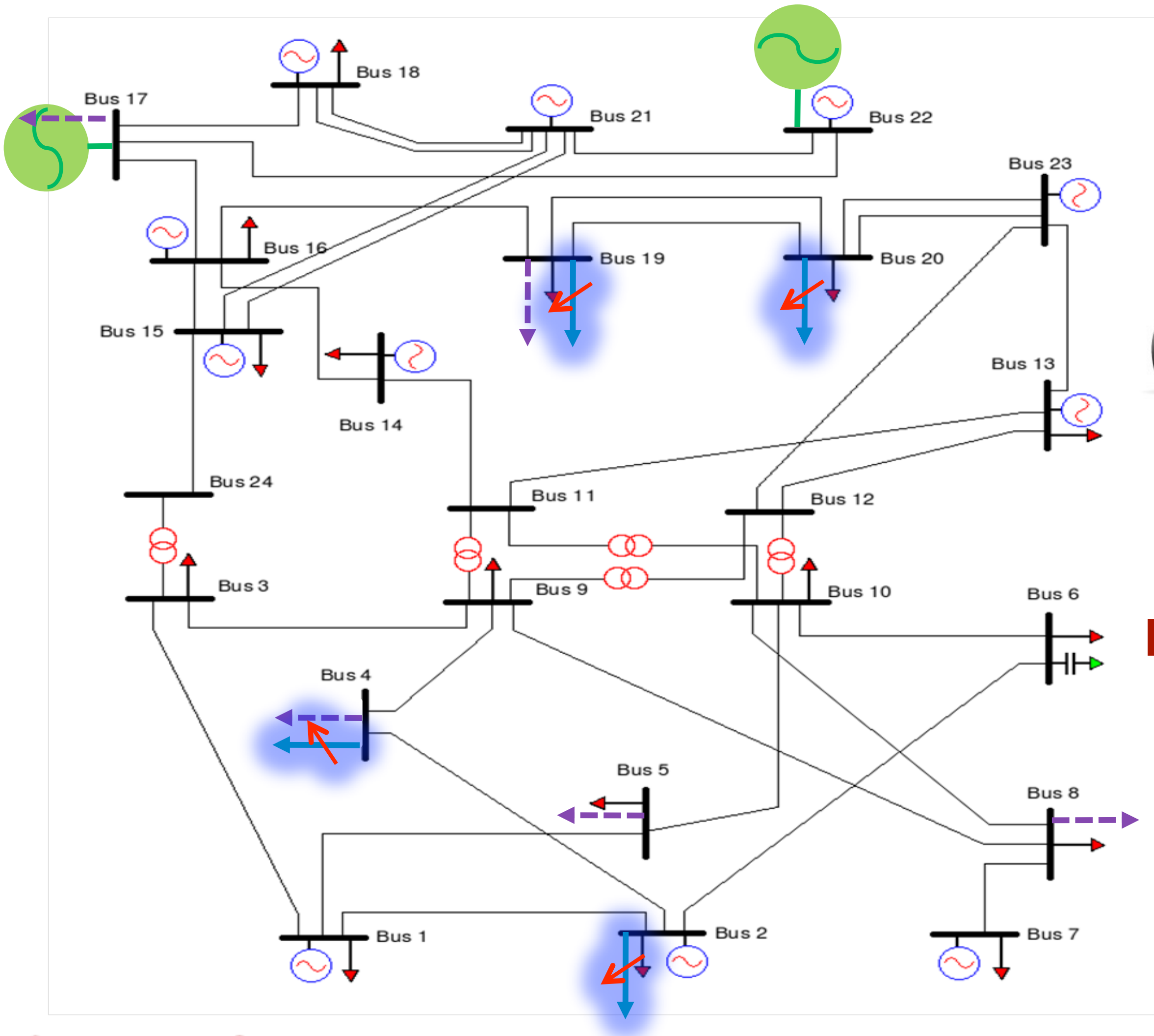
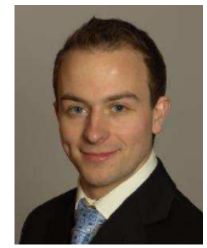

MPC−based DYMONDS Dispatch with 50% Wind
MW
Time Steps (10 minutes interval)
Load (Inelastic Case)
Total Load (Elastic Case)
Wind generation (Inelastic Load)
Wind Generation (Elastic Load)
0
500
1000
1500
2000
2500
3000
3500
0
50
100
150
MW
Time Steps (10 minutes interval)
Coal output with inelastic load
Coal output with elastic load
Natural gas unit output with inelastic load
Natural gas unit output with elastic load
0
500
1000
1500
2000
0
50
100
150

DYMONDS Simulator
Impact of Electric vehicles





NiklasRotering

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

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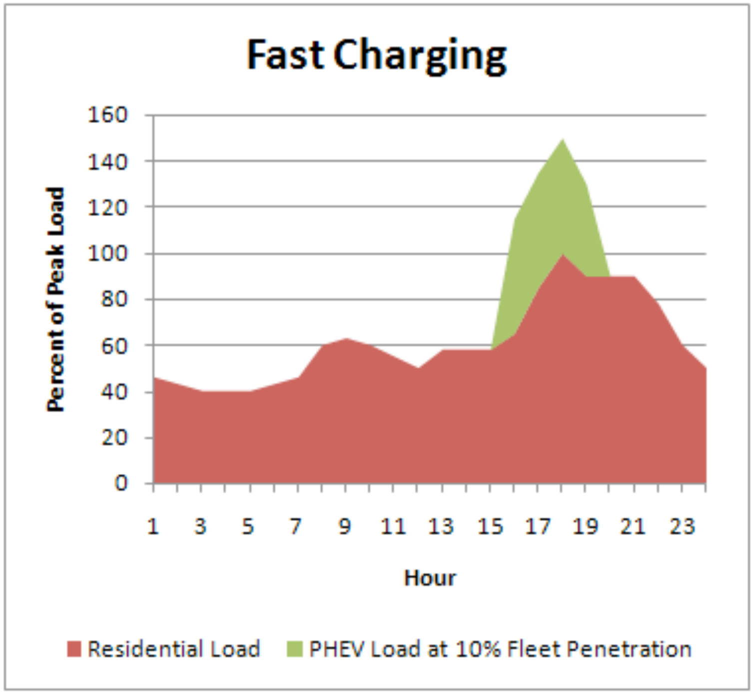
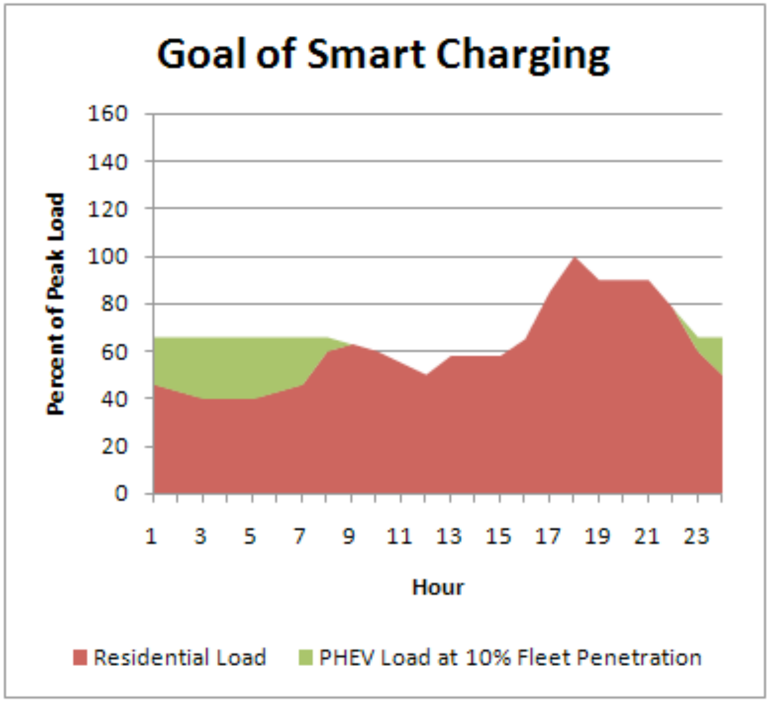
Optimal Control of Plug-in-Electric Vehicles: Fast vs. Smart





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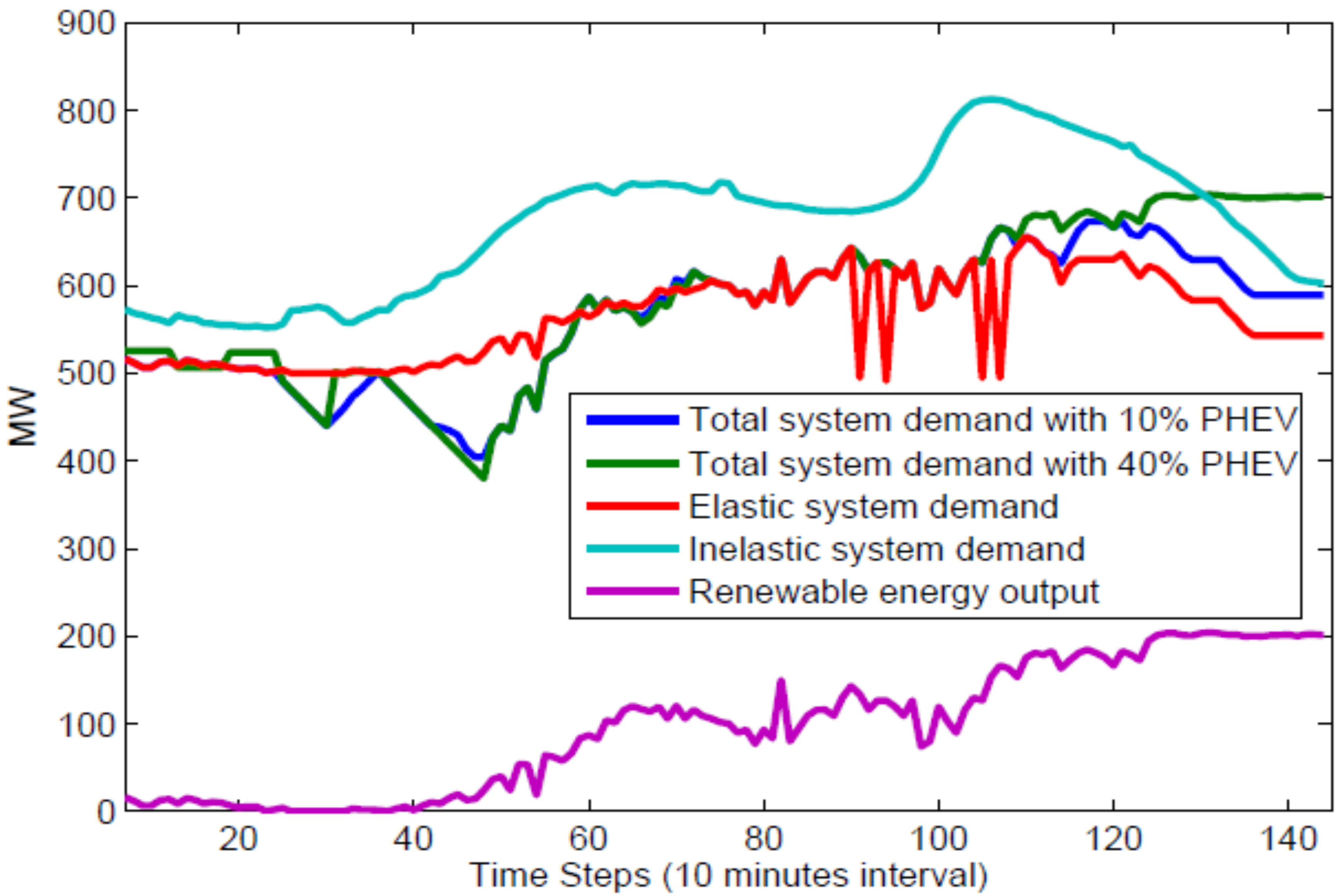
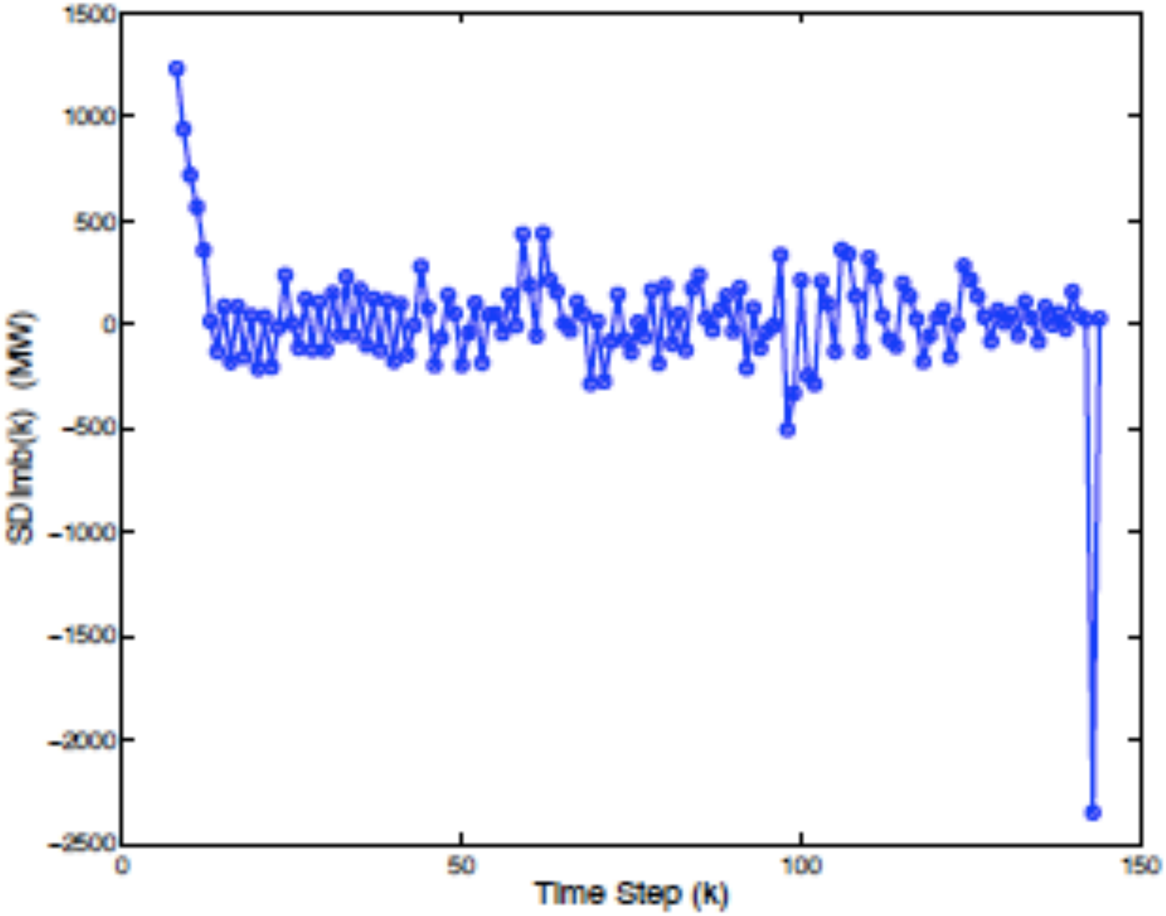
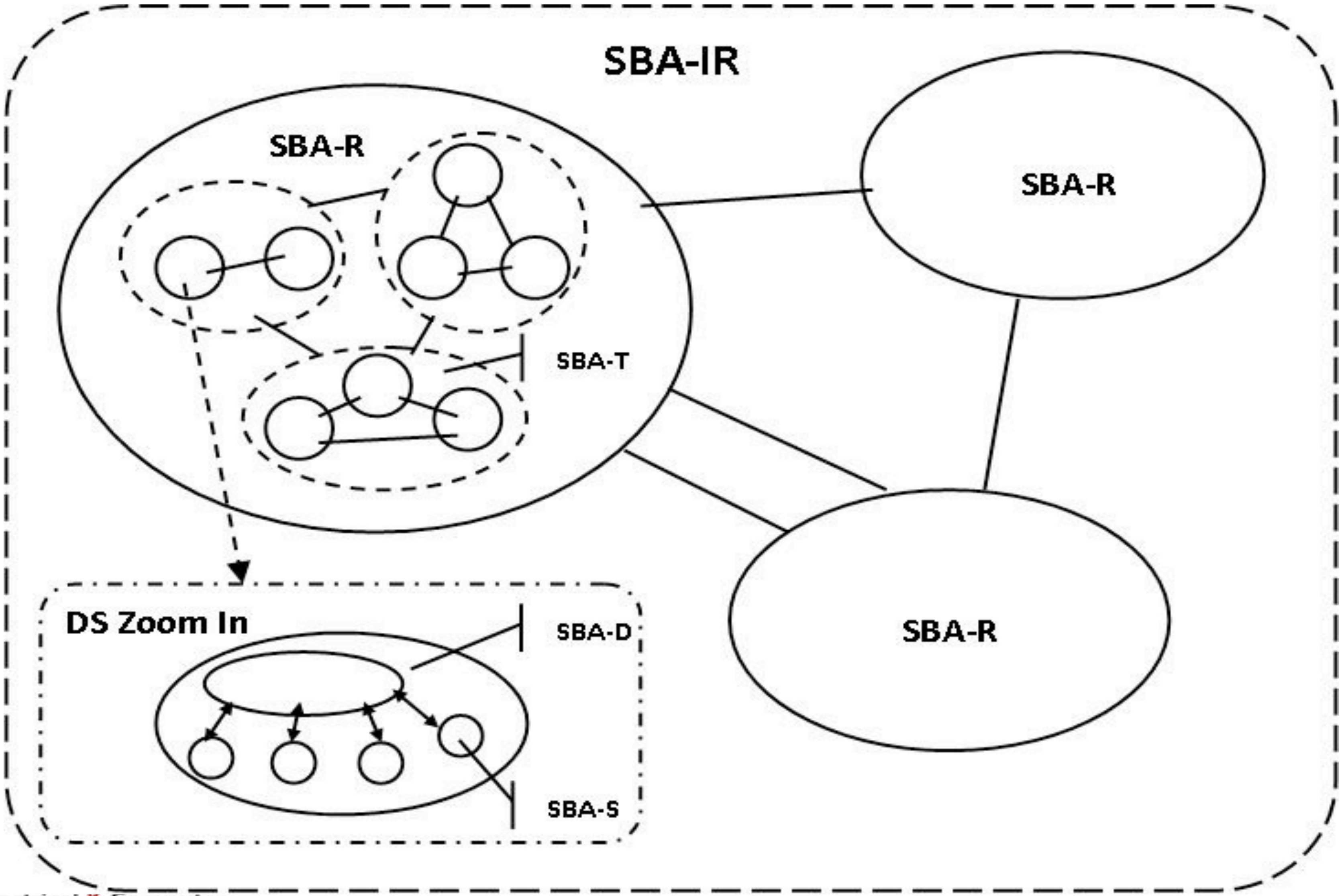

900
800
700
600
500
400
300
200
100
0
MW
20
40
60
80
100
120
140
Time Steps (10 minutes interval)
Total system demand with 10% PHEV
Total system demand with 40% PHEV
Elastic system demand
Inelastic system demand
Renewable energy output

Plug-and-Play (No Coordination)?



Total generation and total demand imbalances in 50% wind case

Aggregation and interactions for sustainability



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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