A CYBER-ENABLED SMART GRID

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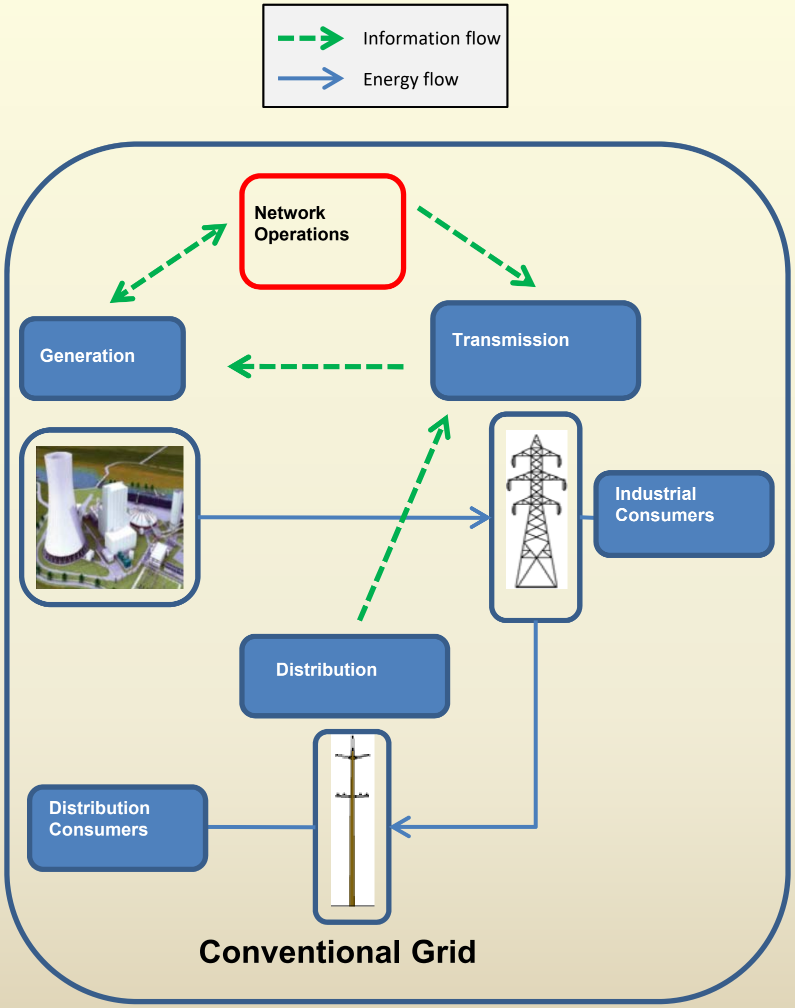
Massachusetts Institute of Technology

Current Power Grids and Control

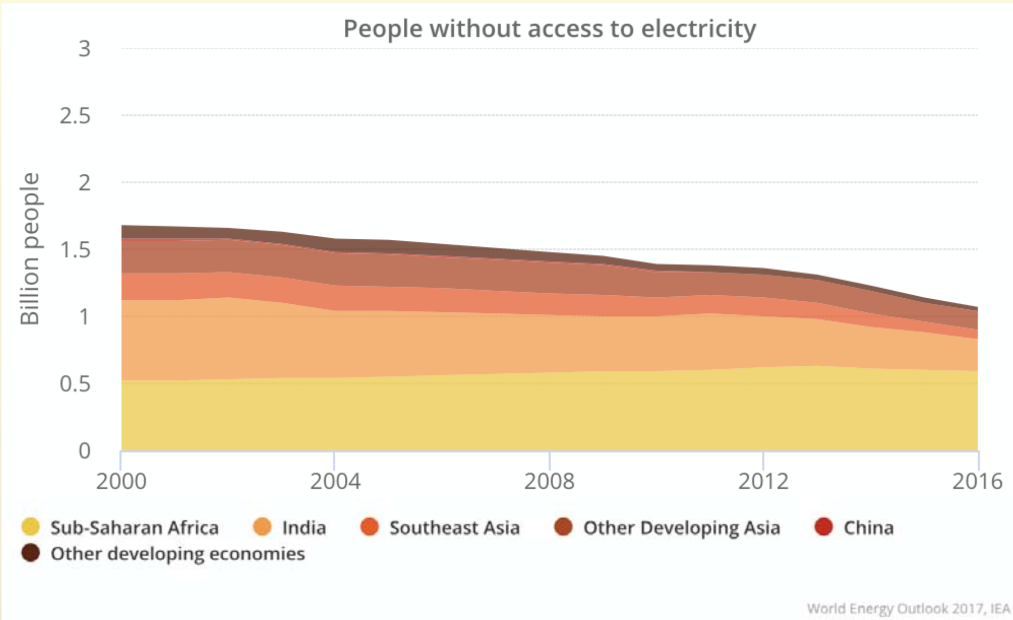


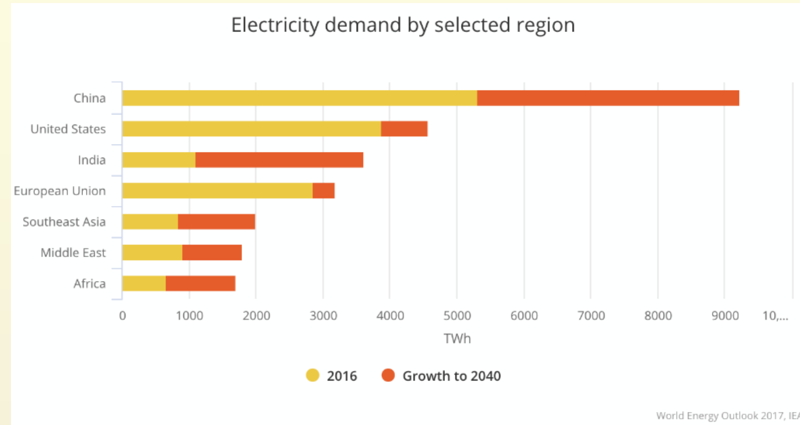
Control goals: Ensure

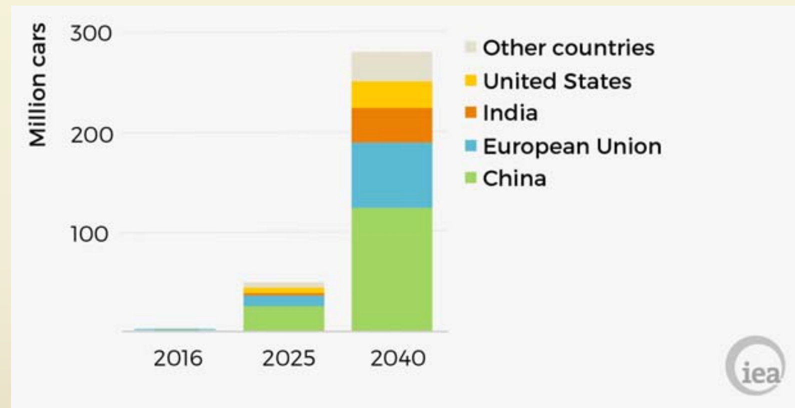
- Power balance
- Operating limits are maintained
  - Generators limit
  - Tie-lines limit
- Regulation of frequency (50 Hz or 60Hz)
- Regulation of voltage (110V or 220V)
- Maintain Transient Stability

Significant drivers are causing drastic changes in the Power Grid landscape

Driver 1: Increased Demand

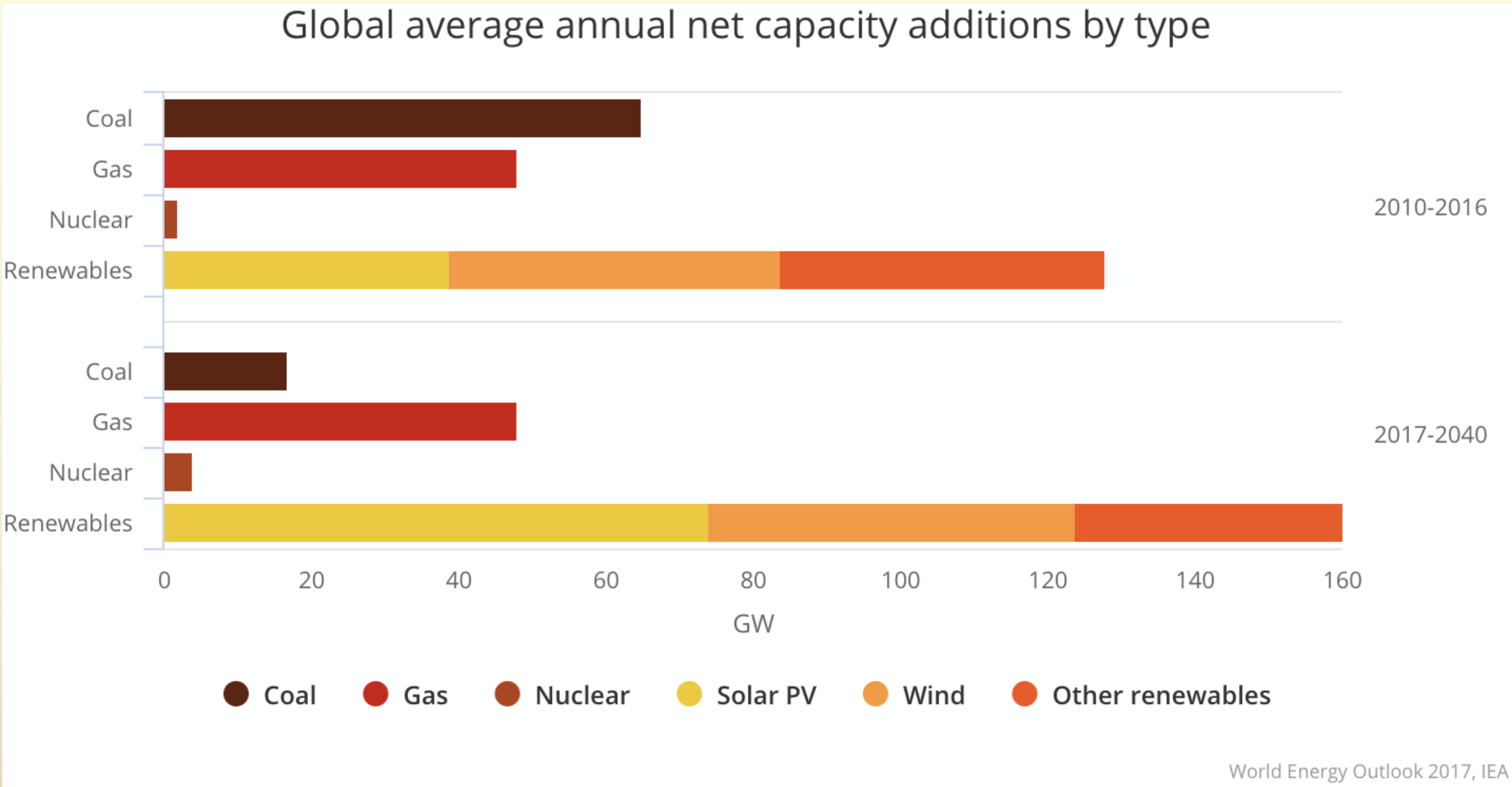






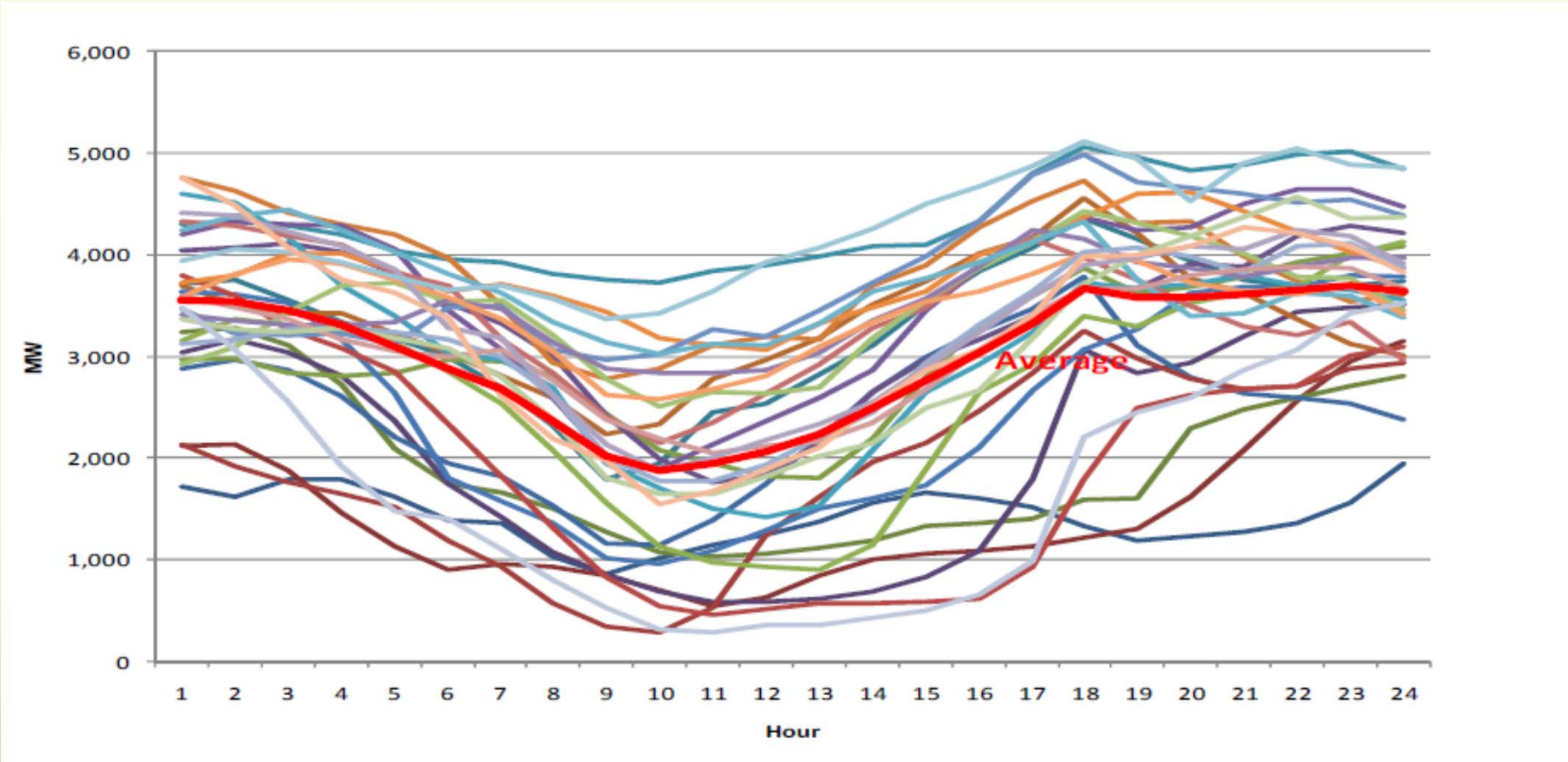
- Significant improvements in electrification are expected to halve number of people without access to electricity by 2030 from 2016 levels
- Over the next 25 years, electricity will play an increasing role in the transportation industry

Driver 2: Decarbonization



- Renewables meet 40% load growth through 2040
- Coal net additions are following a decreasing trajectory with absence of CCS
- By 2040, 40% installed generation will be renewable

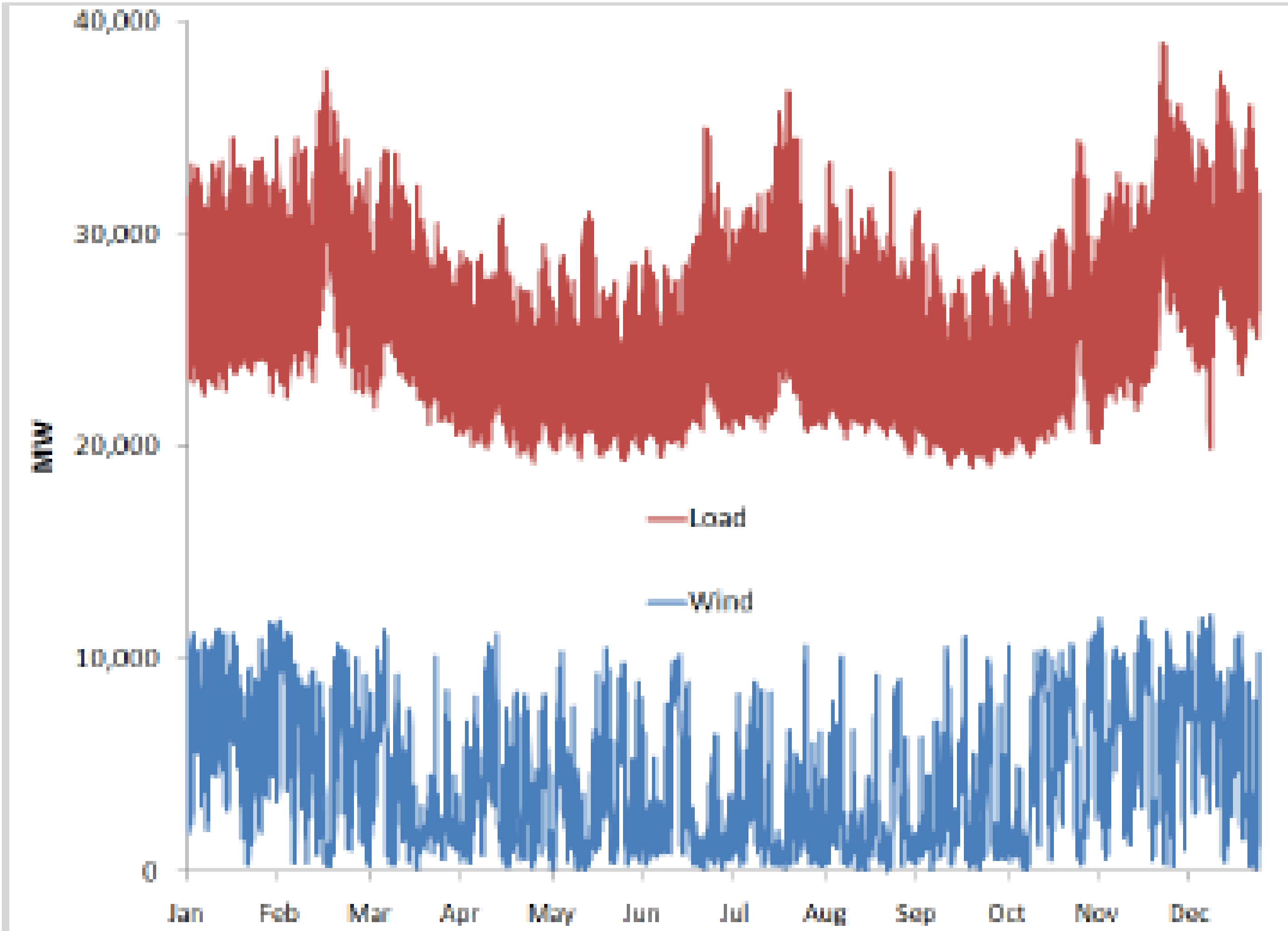
Intermittency: Wind Energy



From Integration of renewable resources, CA ISO Report, Aug. 2010.

"In almost every operating hour, wind could be producing across the full range of its potential production, from close to zero to almost maximum output."

Uncertainty: Wind and Load



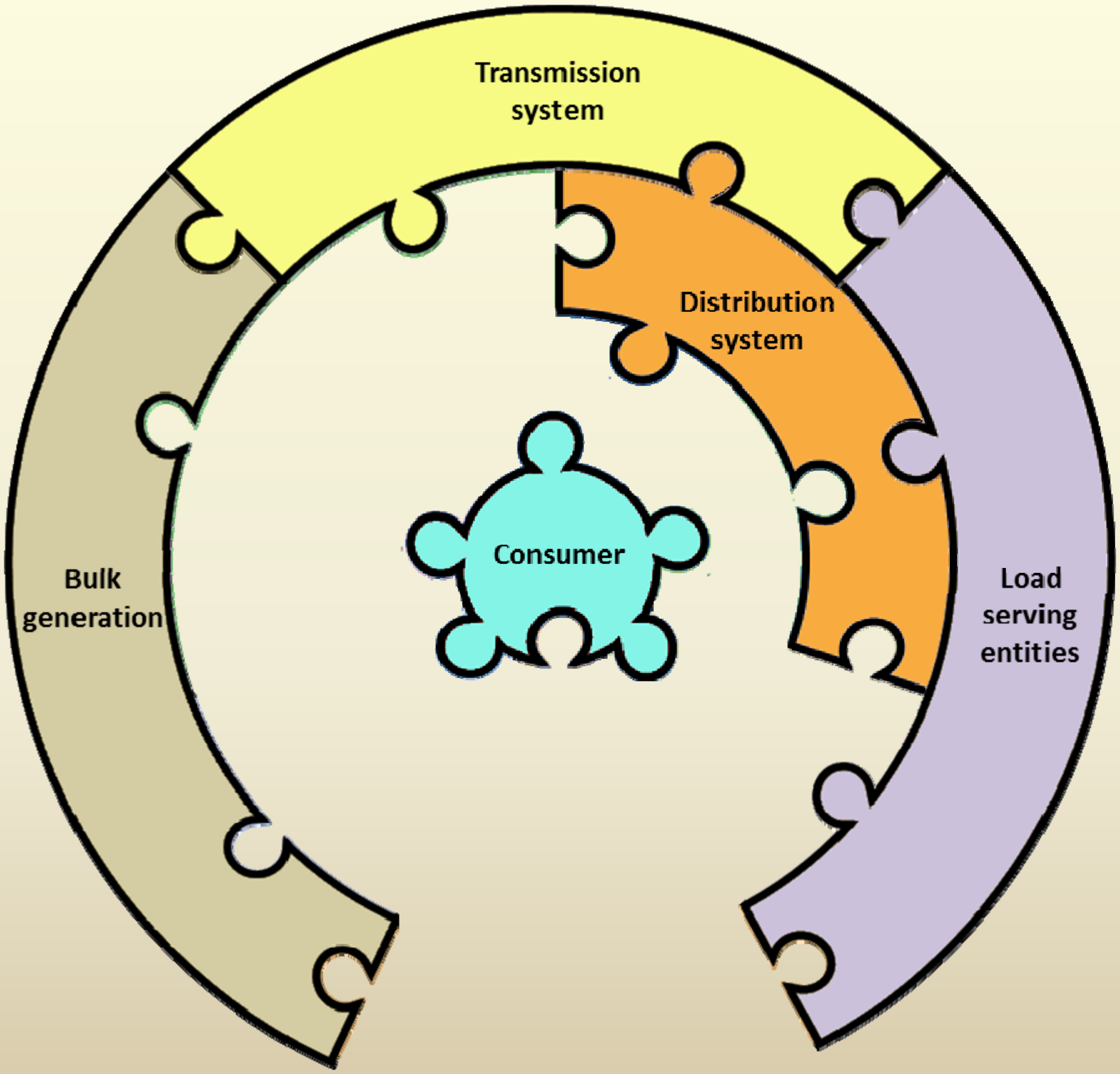
Wind uncertainties are almost as large as the load variations!

A Cyber-enabled Smart Grid

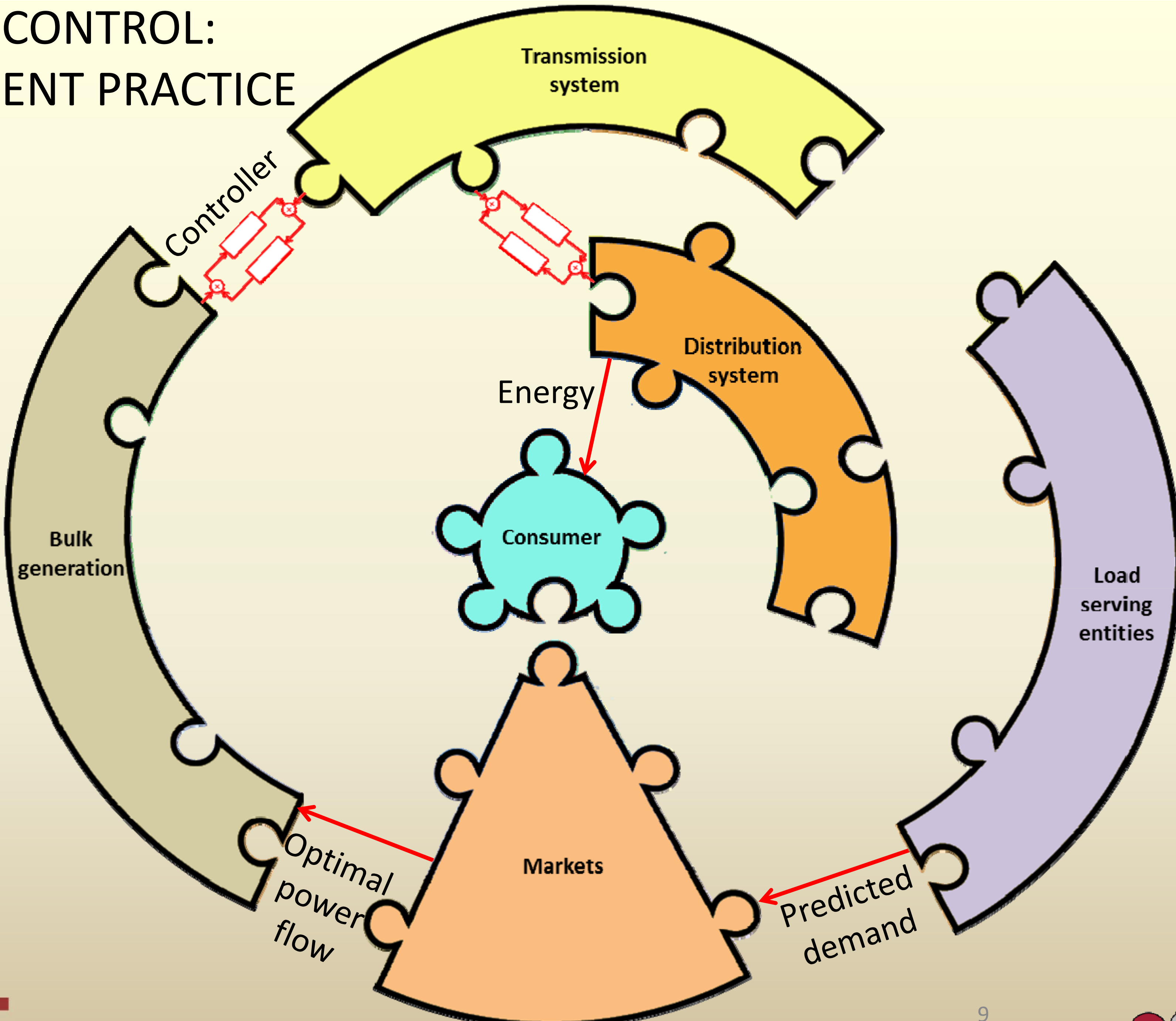
An end-to-end cyber-enabled electric power system, with bi-directional power flow, that

- Decarbonizes and integrates green energy resources
- Enables efficiency, effective demand-side management, and customer choice
- Operate resiliently against cyber and physical attacks

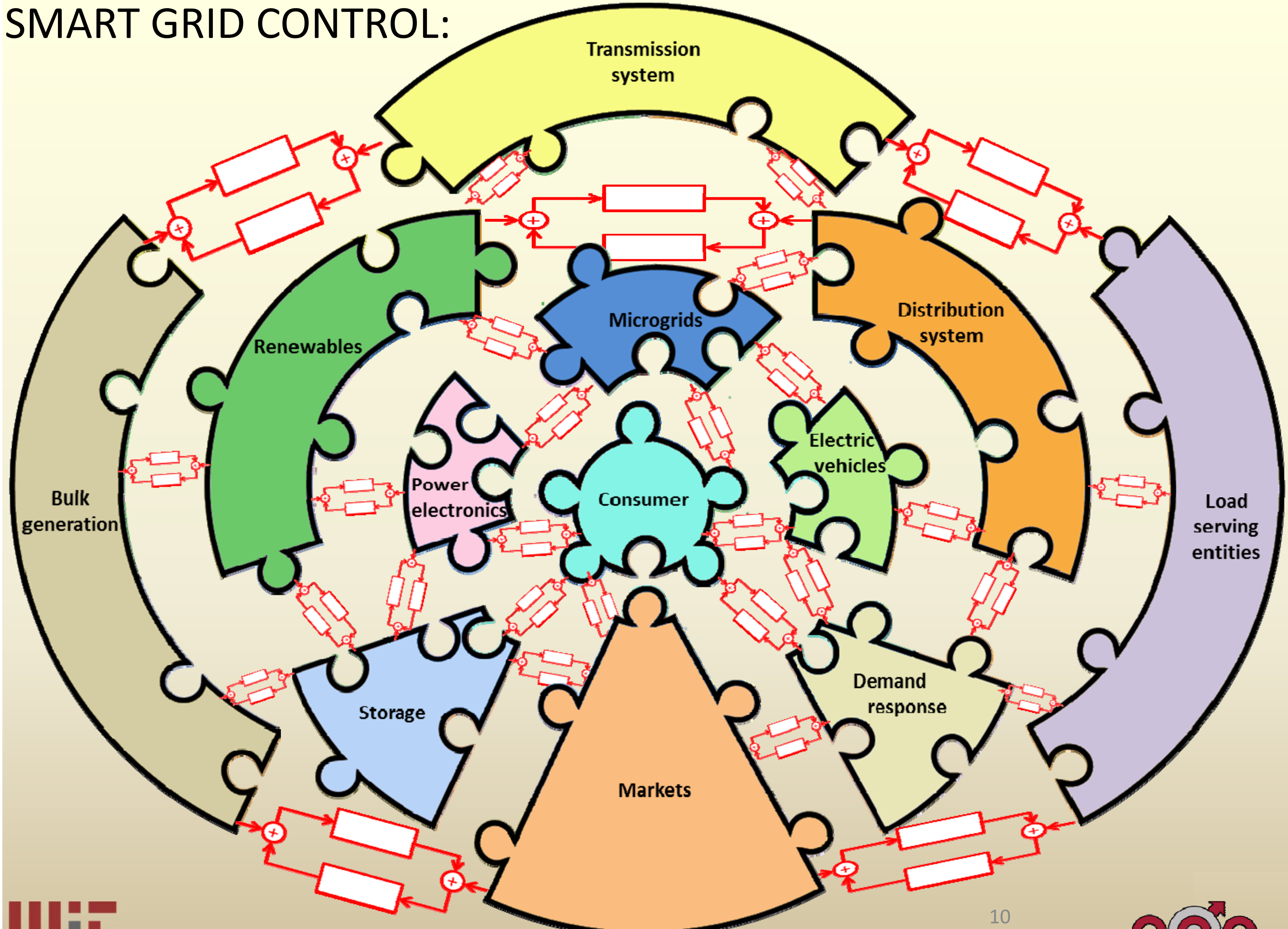
GRID CONTROL: CURRENT PRACTICE



GRID CONTROL: CURRENT PRACTICE



SMART GRID CONTROL:



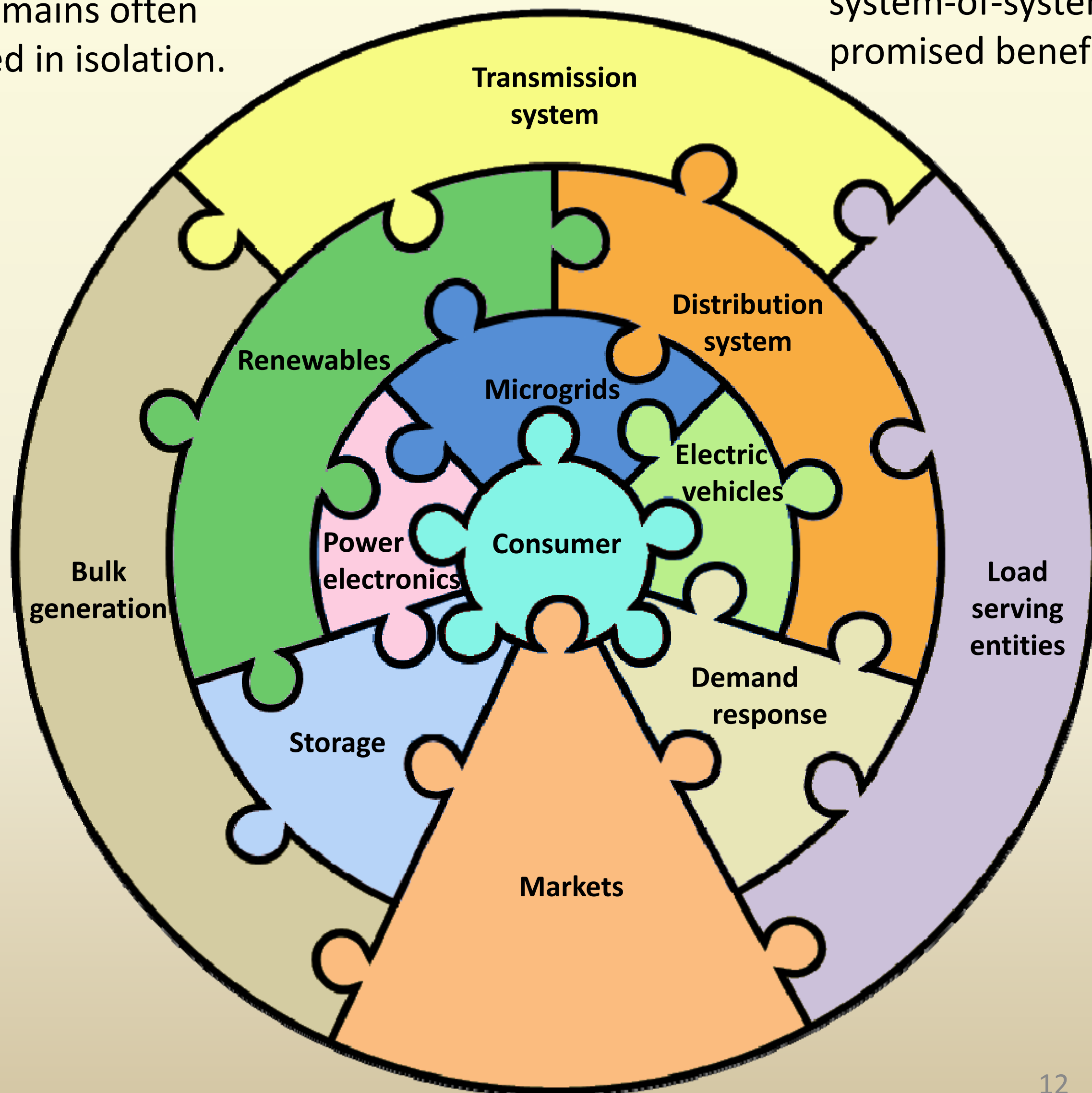
New Tools

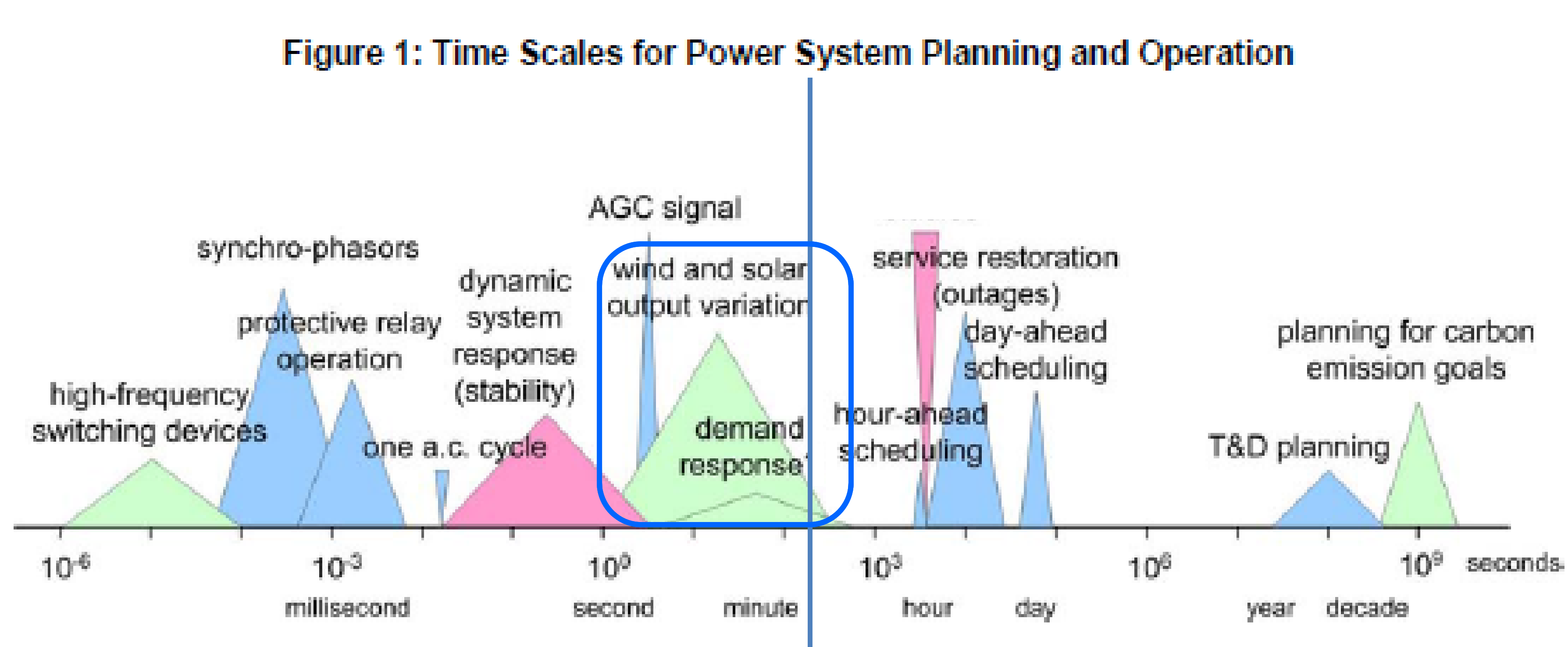
- Demand Response – Flexible Consumption
- Advances in Storage Technologies
- Advances in Sensors (ex. PMUs)
- Advances in Power Electronics (ex. Smart Inverters)
- Advances in Actuators (ex. FACTS)
- Advances in theory – distributed optimization and control

Vision for Smart Grid Controls

Smart grids are expanding the traditional notion of a power system, enabling the interconnection of domains often traditionally considered in isolation.

Control systems will be essential in closing the numerous loops in the new system-of-systems and in realizing the promised benefits of smart grids.





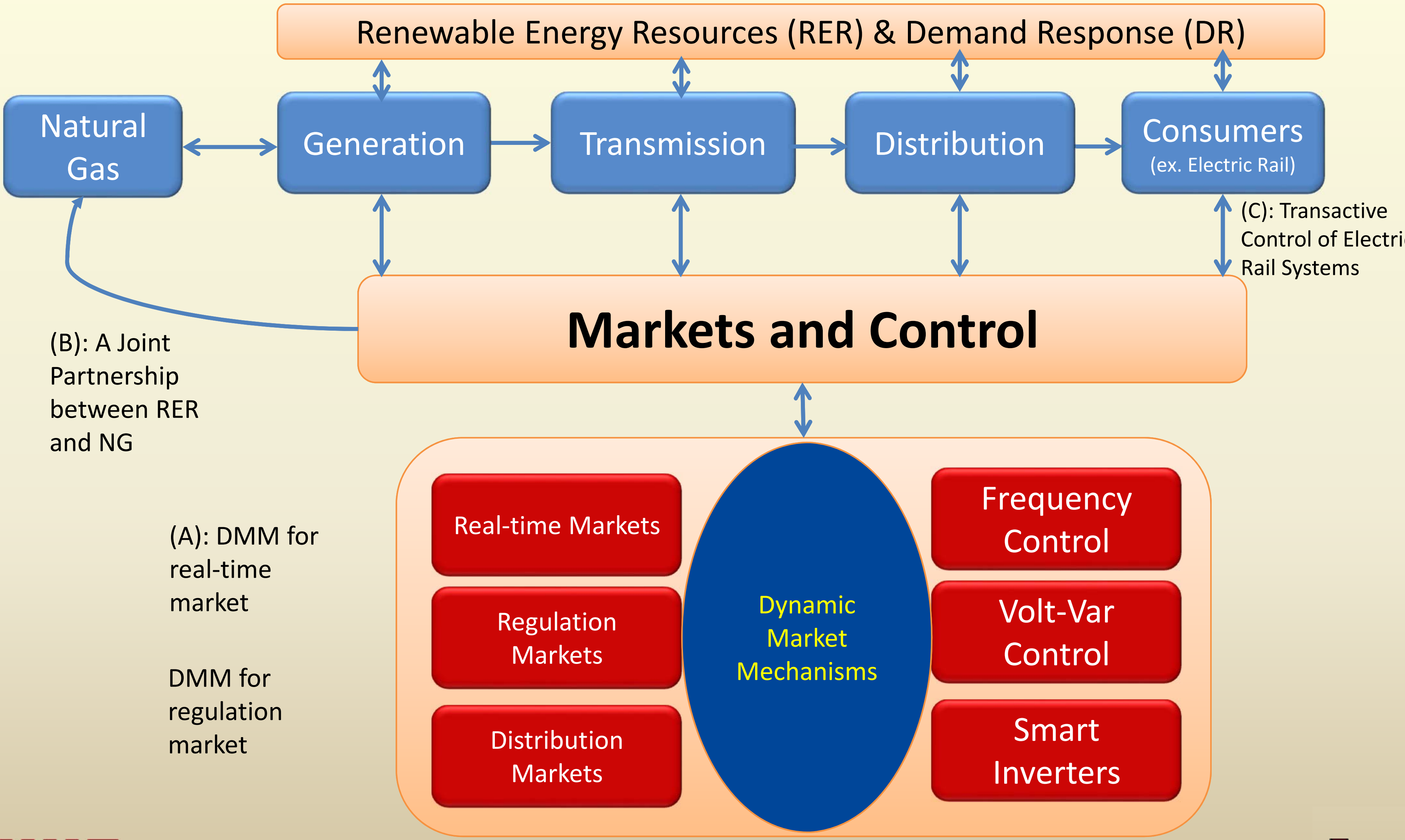
(Source: California Energy Commission California Institute for Energy and Environment MAY 2014)

Operation
- Control for stability
  - Rotor angle
  - Frequency
  - Voltage
- Optimization
  - Power losses
  - Reactive power

Planning
- Markets – SCUC, DAM,RTM
- Regulatory concerns
- Policies

Reorganization of time-scales in markets and control is needed

A Cyber-enabled Smart Grid



Dynamic Framework for Smart Grids

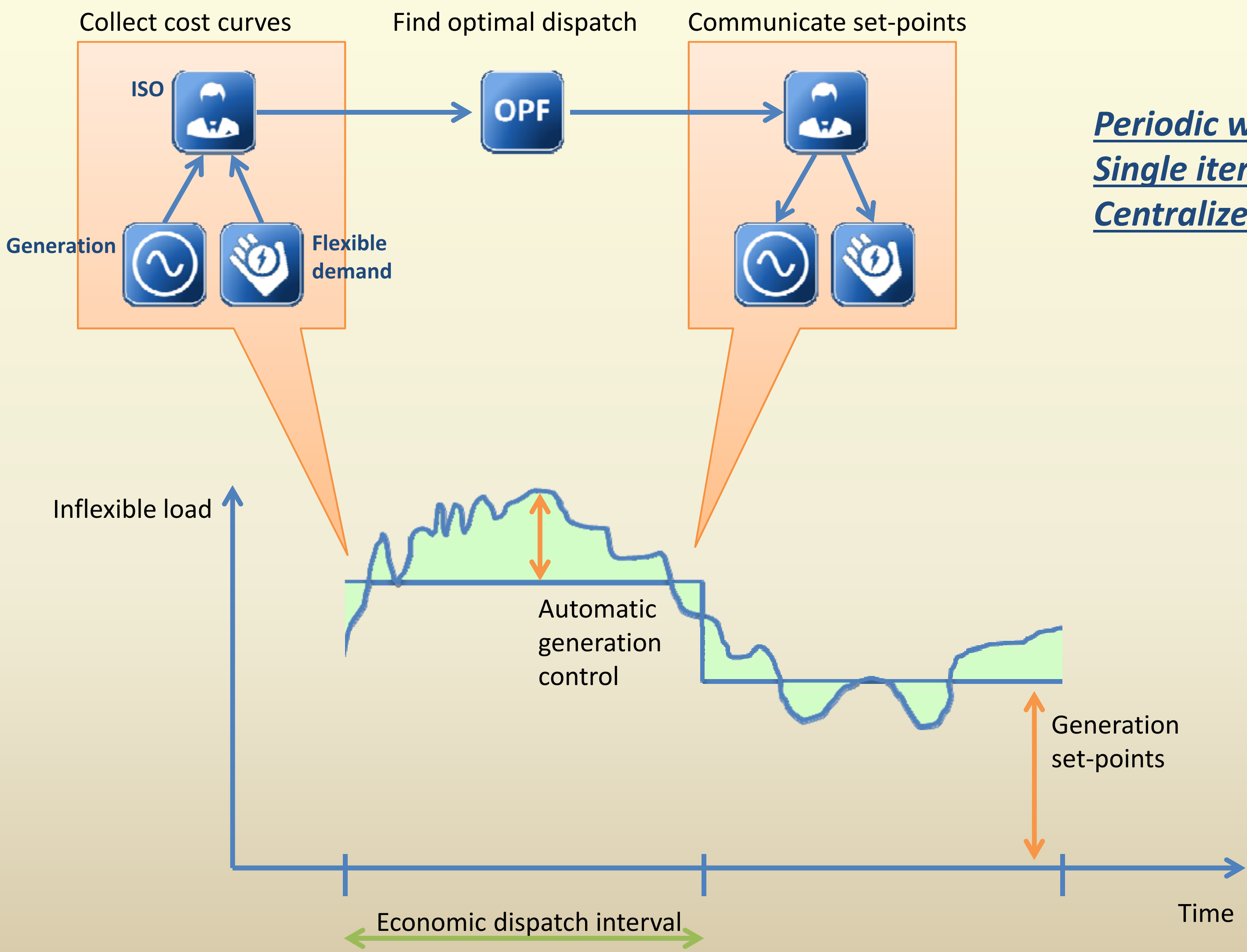
Outline

- **Bulk Energy and Transmission**
  - Dynamic Market Mechanisms for Real-time Markets
- **Natural Gas and Electricity Infrastructures**
  - Gas Prices and Gas Bid-volatility
  - Joint partnership between Wind and Natural Gas producers
- **Transportation and Electricity Infrastructures**
  - Electric Rail Network & Transactive Control
- **Road Ahead**

BULK ENERGY AND TRANSMISSION:

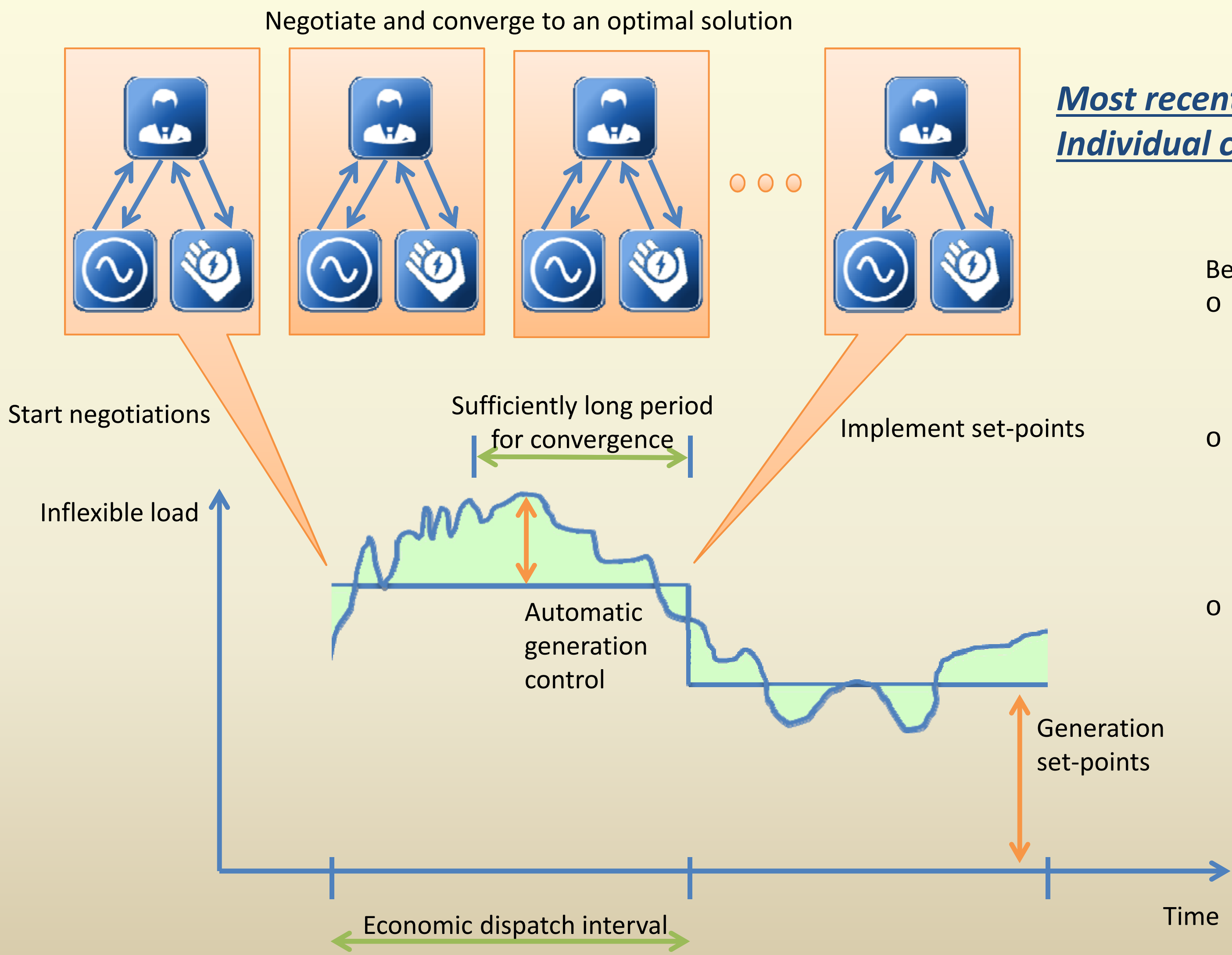
(A) DMM FOR REAL-TIME MARKETS

Economic dispatch today



Periodic with a regular interval.
Single iteration process.
Centralized computation.

Our solution: Dynamic Market Mechanism (DMM)

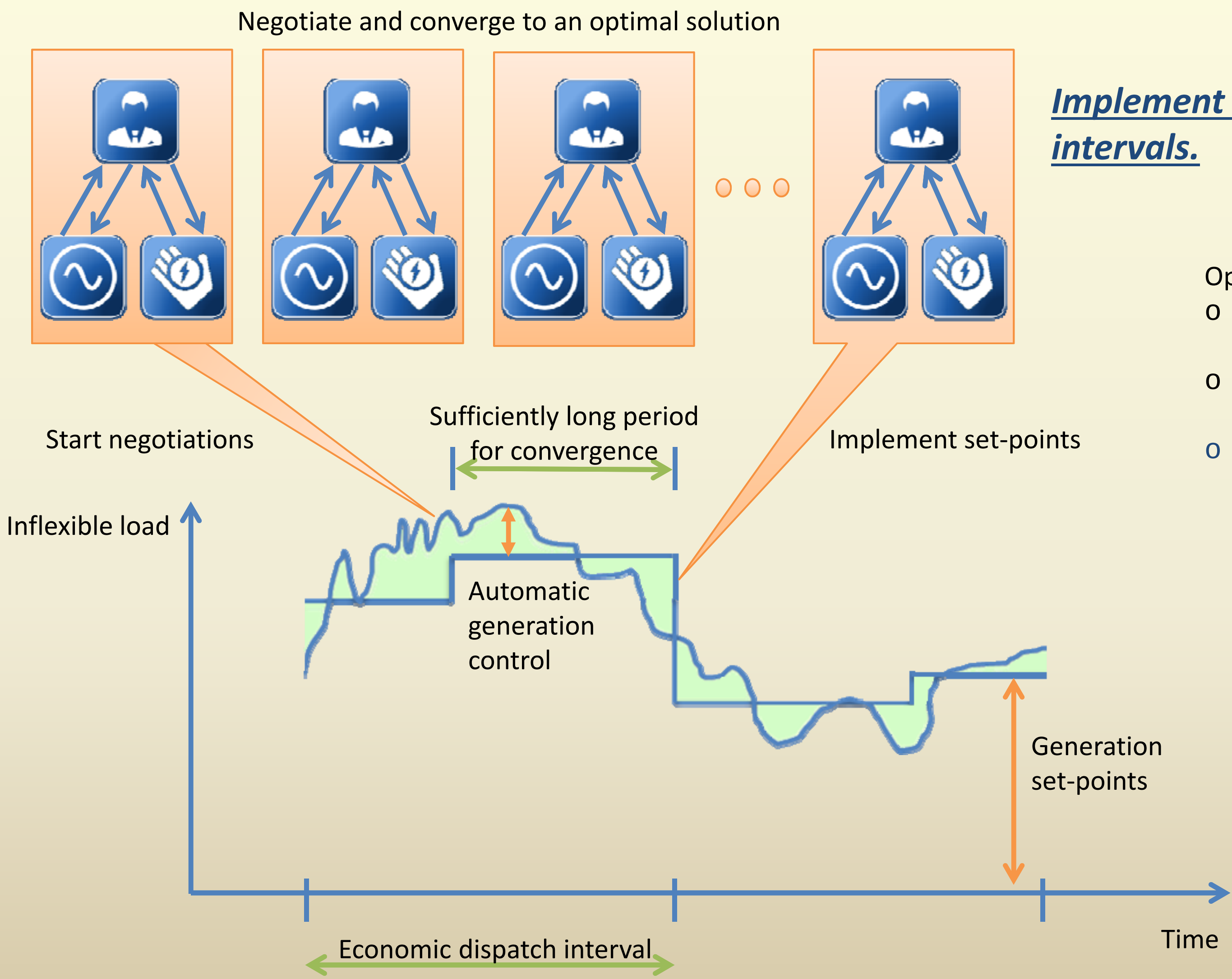


Most recent information is included.
Individual constraints remain private.

Benefits when addressing:

- Fuel uncertainty
  - Wind
  - Solar
  - Natural gas
- Change in operating conditions of components
  - Saturation limits
  - Protection tripping
  - Emergency conditions
- Dynamic price response
  - Lower real-time prices before dispatching
  - Close-loop price control

DMM and shorter dispatch interval



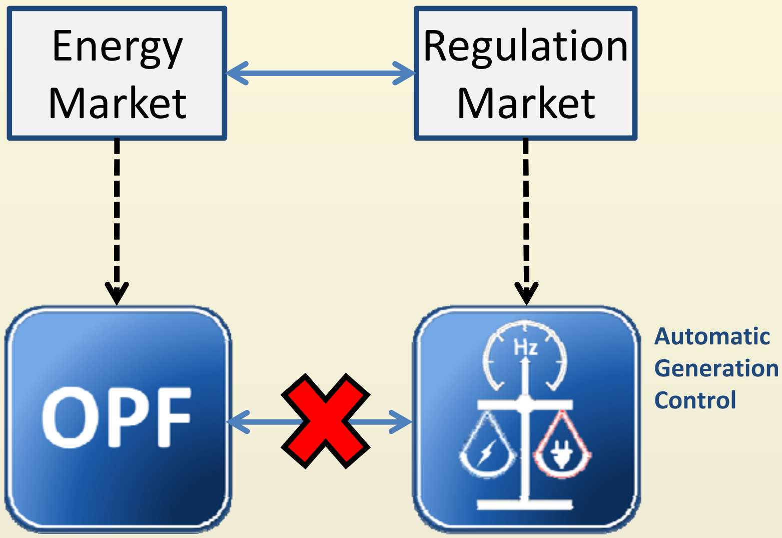
Implement dispatch on shorter intervals.

Opportunities for addressing:

- Significant and unpredicted penetration of renewables
- Non-zero mean volatility of renewable generation
- **High regulation requirements in presence of renewables**

Integrated DMM (economic dispatch + AGC)

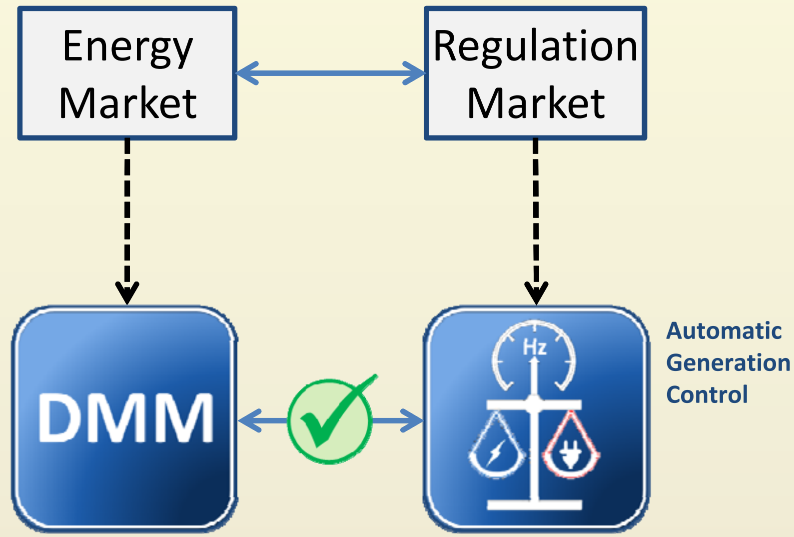
Conventional architecture



Assumption of magnitude and time-scale separation between OPF and AGC.

Large penetration of intermittent energy represents a challenge.

Proposed approach

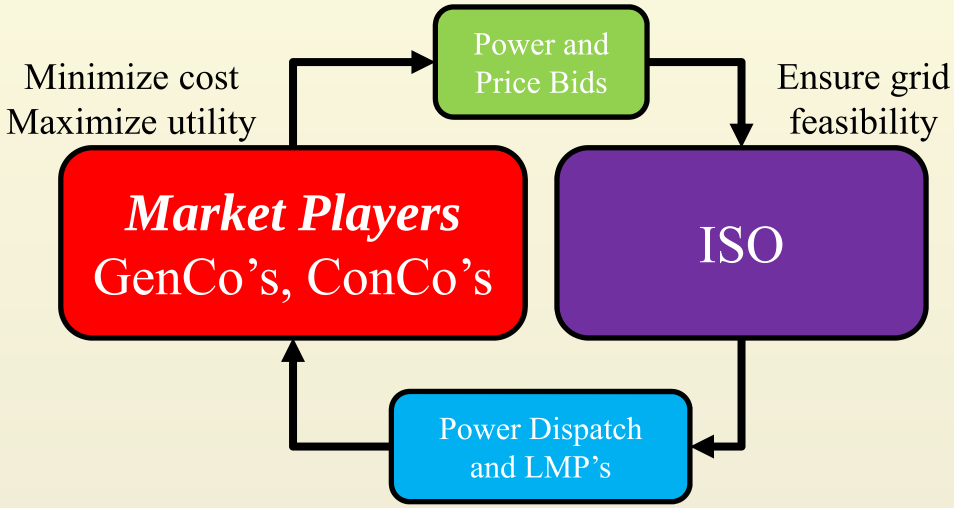


Aggregated feedback from AGC

Simultaneous decisions at both markets.

DMM structure

- Approach: ***Iterative negotiations*** over a wide area network*



$$x^{k+1} = x^k + \Delta x^k$$

$$\lambda^{k+1} = \lambda^k + \Delta \lambda^k$$

x: states of players and ISO
λ: Lagrange multiplier (LMP)

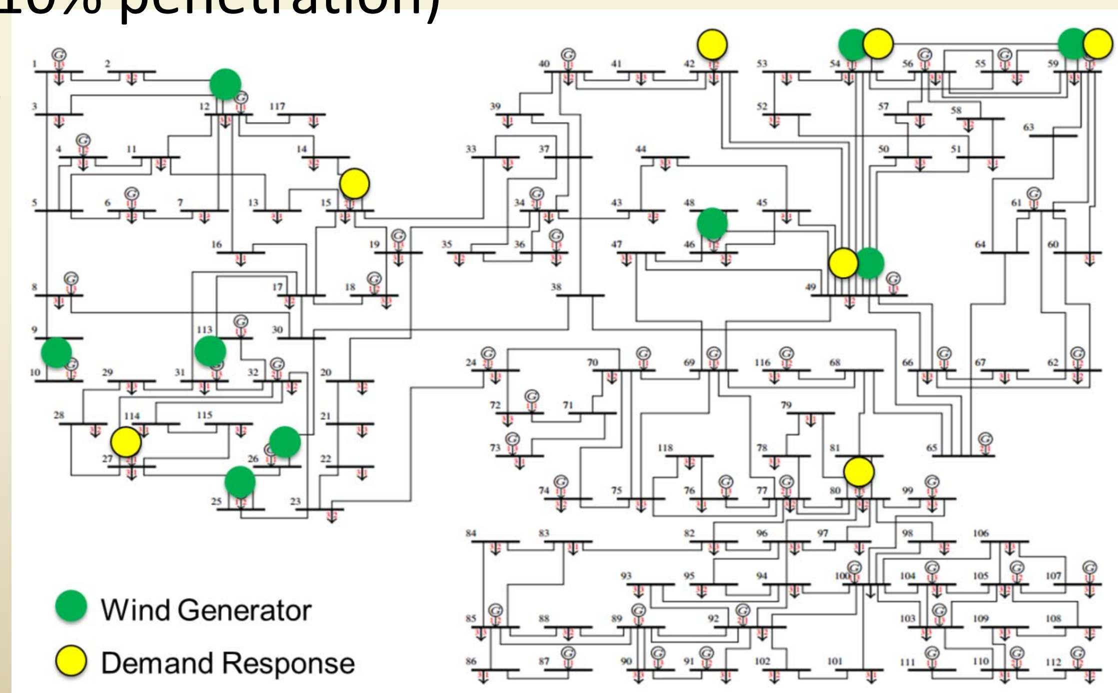
- Challenges addressed:
  - Computation time
  - Most information must be kept private
  - Stability

$$x^k = \begin{bmatrix} P_{Gc}^k \\ P_{Gr}^k \\ P_{Dr}^k \\ \delta^k \end{bmatrix} \begin{matrix} \text{Conventional generation} \\ \text{Renewable generation} \\ \text{Demand response} \\ \text{Voltage angles} \end{matrix}$$

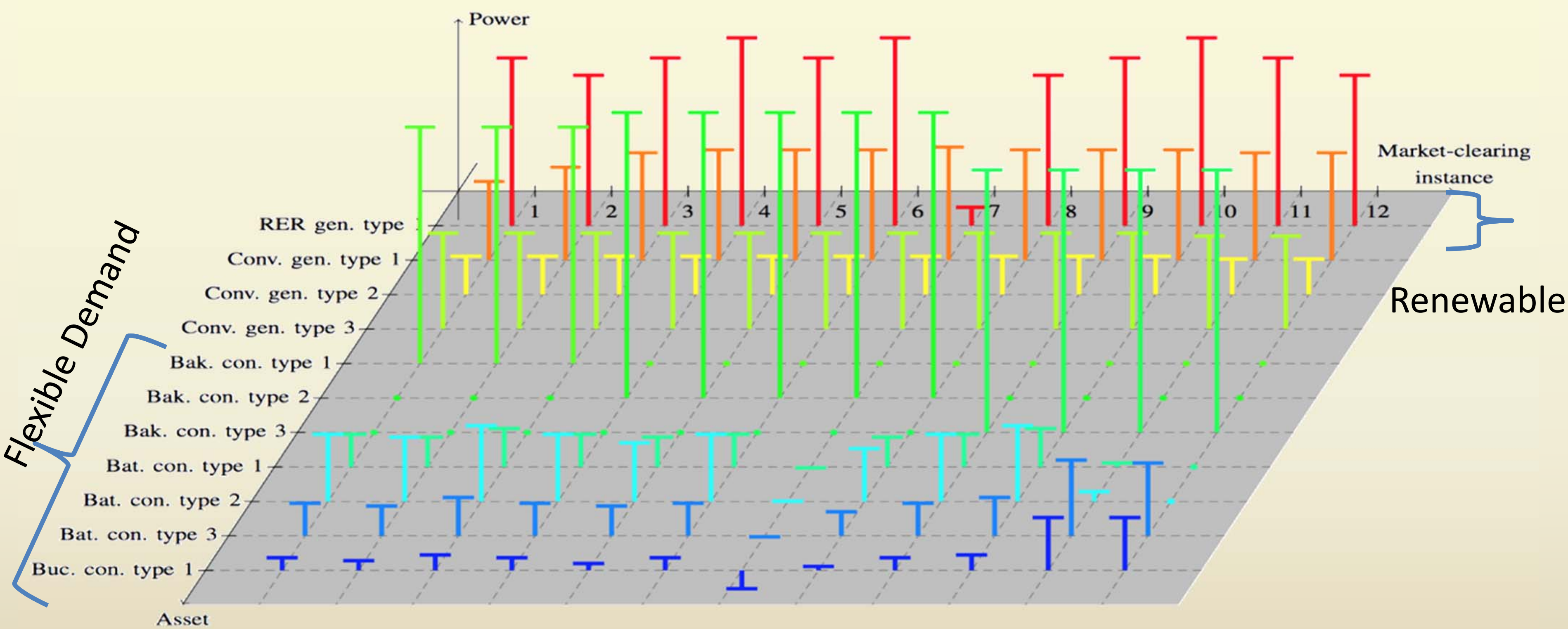
Modified IEEE 118 Bus Test Case

Bus consists of:

- 45 conventional generators
- 9 renewable generators (30% penetration)
- 7 flexible consumers (10% penetration)
- 186 transmission lines

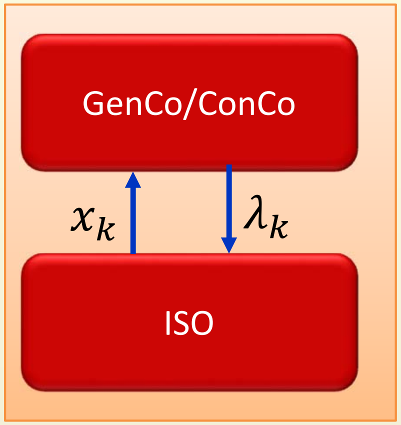


Results: IEEE-118 bus

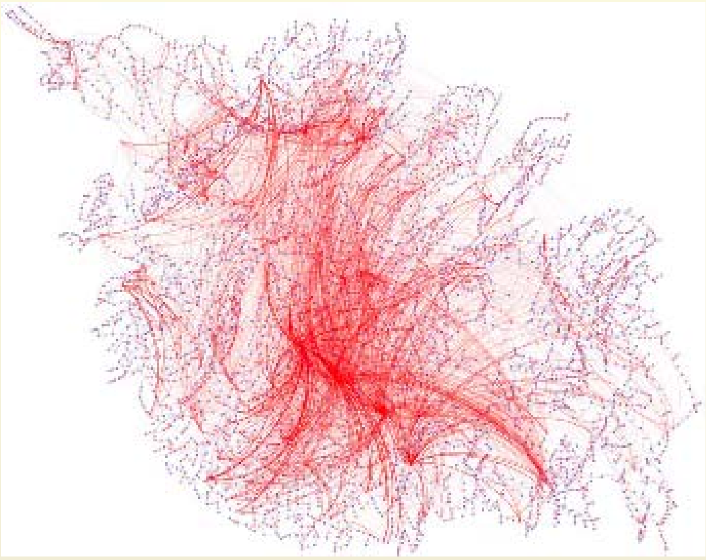


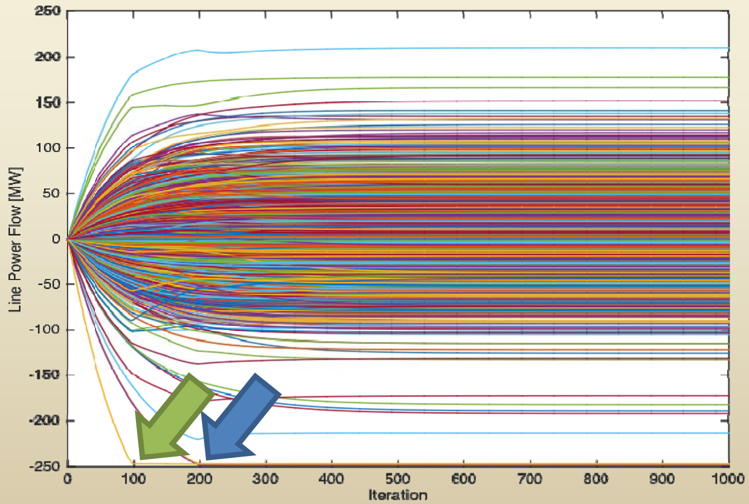
(A): Validation in IEEE 3120 bus

- Wholesale markets:



Validation in IEEE 3120 bus:

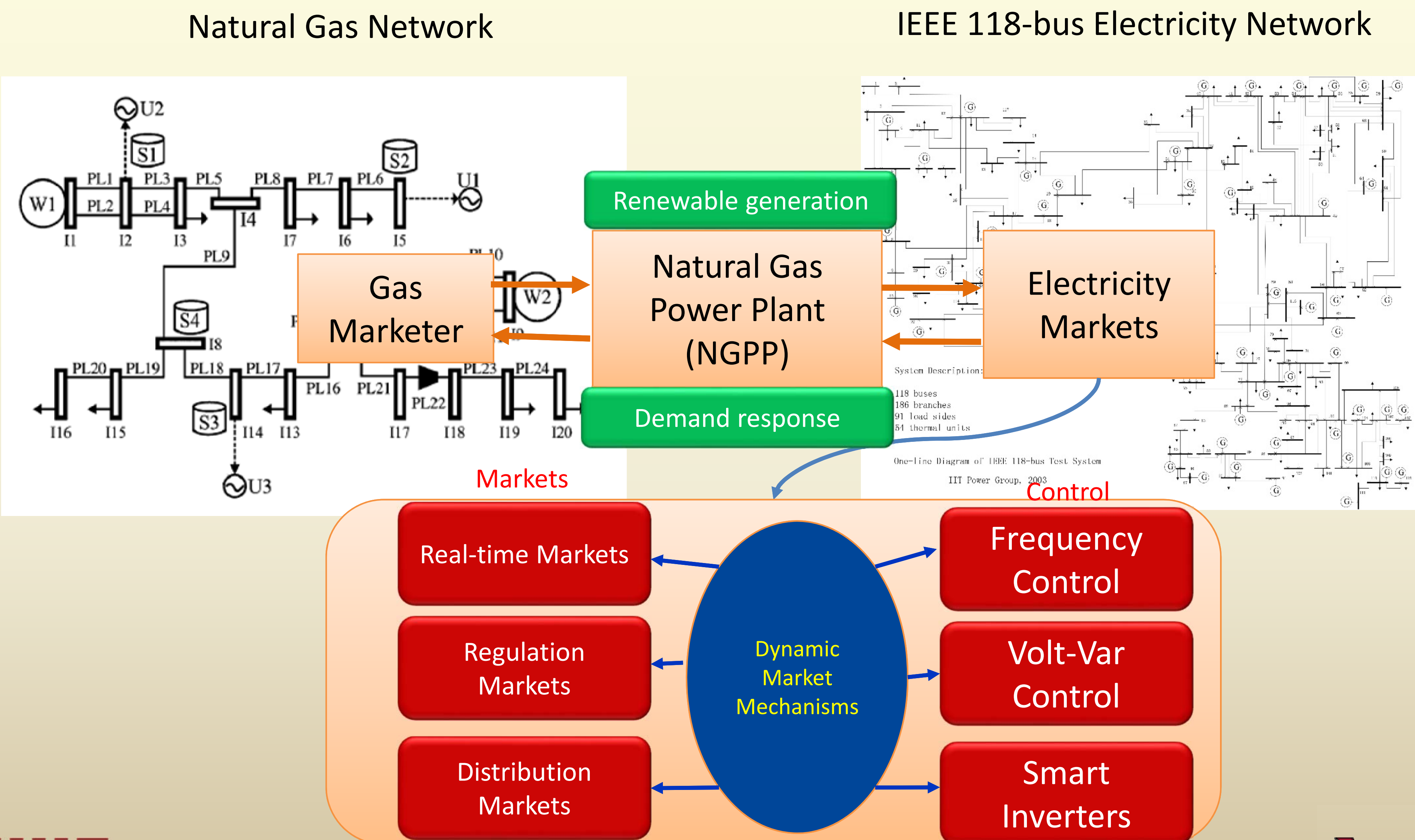




NATURAL GAS AND ELECTRICITY INFRASTRUCTURES

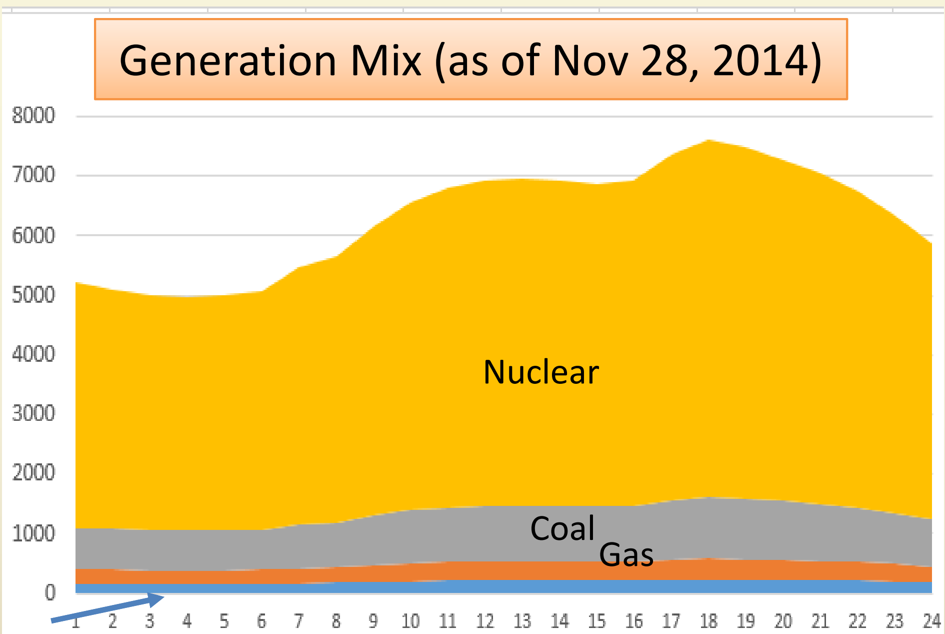
(B): MODELS FOR ESTIMATION OF GAS PRICES AND GAS BID-VOLATILITY

Role of Markets and Control in Smart Grids

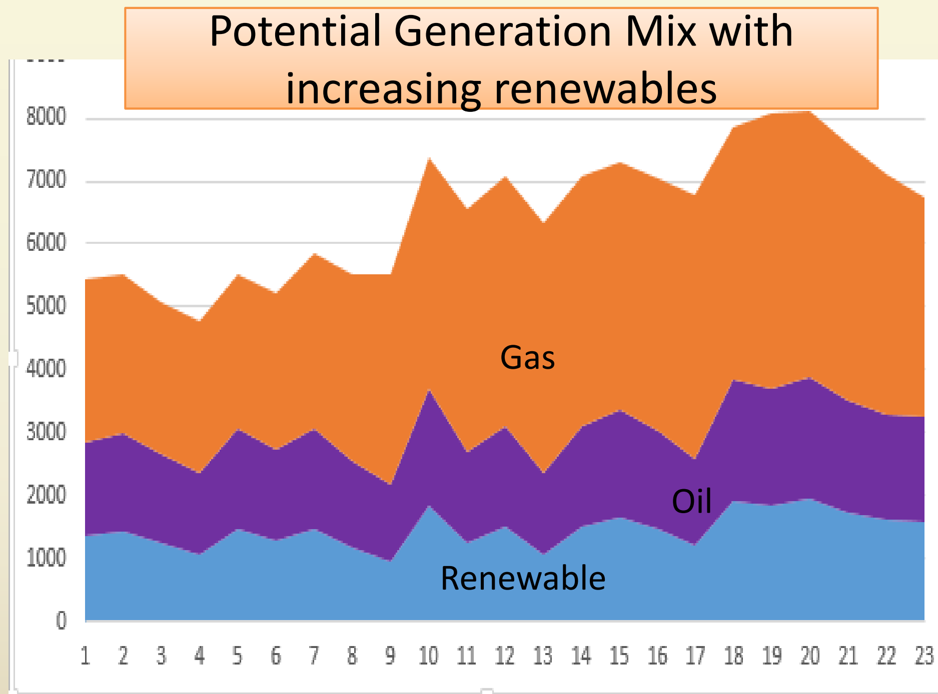


Implications of Renewable Generation

$$demand\ G_d = \cancel{G_{coal}} + \cancel{G_{nuclear}} + G_{oil} + \boxed{G_{gas}} + G_{hydro} + \boxed{G_{solar} + G_{wind}}$$



Renewable

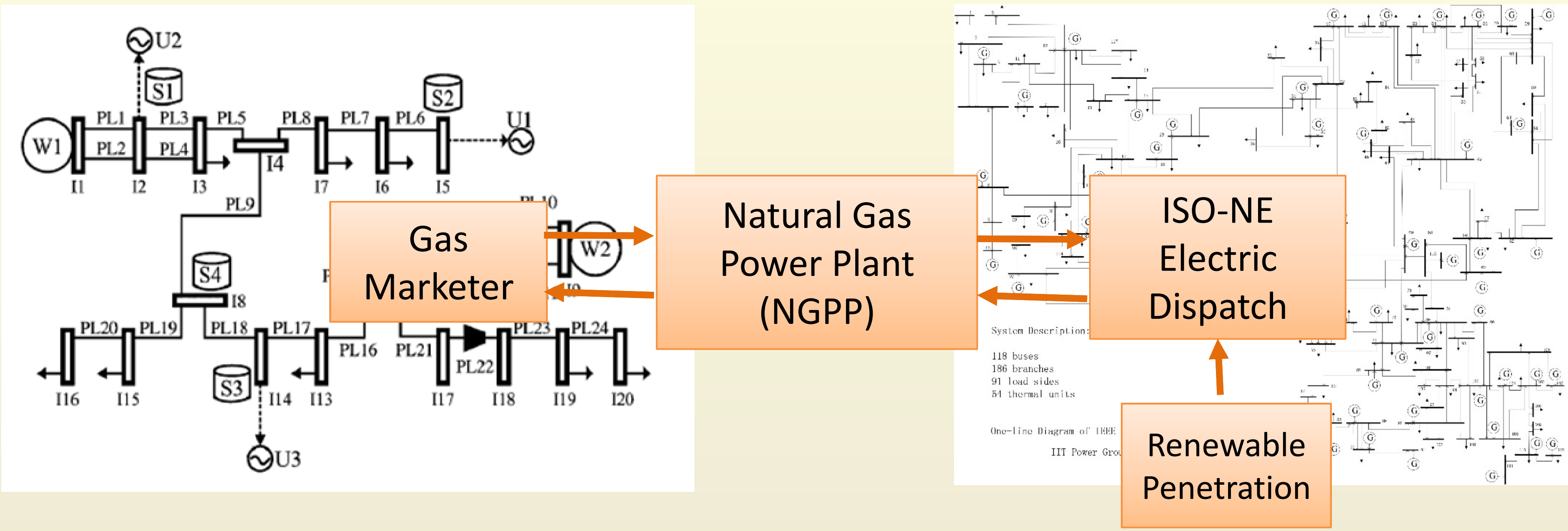


- Goal: To validate the figure on the right using a computational model

Interdependency between NG and Electricity Networks – Market Flow

Natural Gas Network

IEEE 118-bus Electricity Network



NGPP bids to ISO

NGPP gets dispatched amount to produce

Bilateral transaction between marketer and NGPP

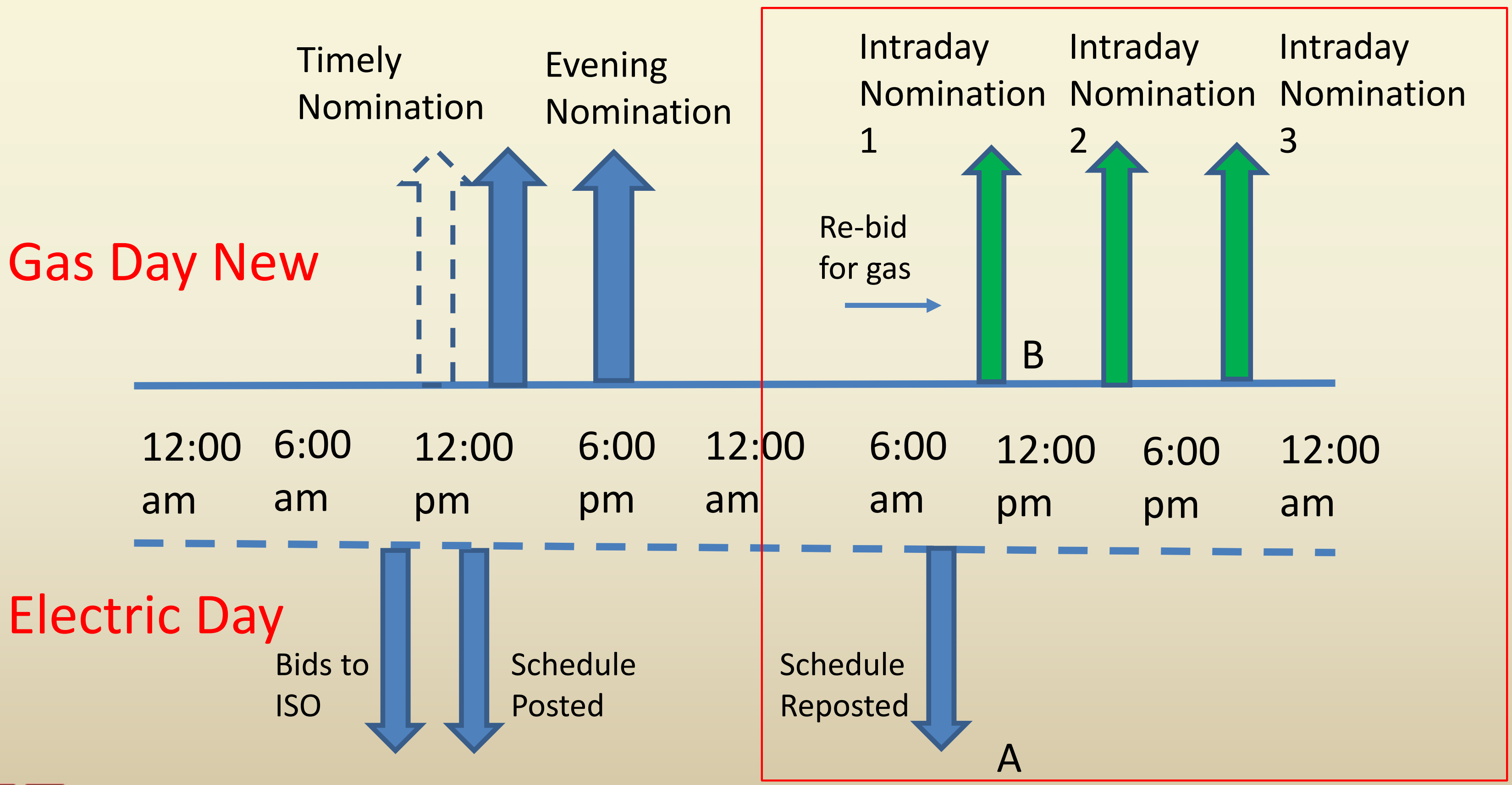
Adjustments to dispatch in real time markets

Two main issues:

- Market misalignment
- Unequal access to gas between NGPPs (GenCos) and RCITs (LDCs)

Market misalignment in Real-time Market

- Only 3 instances when NGPPs find out if additional gas will be available
- Unequal access – gas is available only if RCITs release gas
- NGPPs may not be able to meet their dispatch



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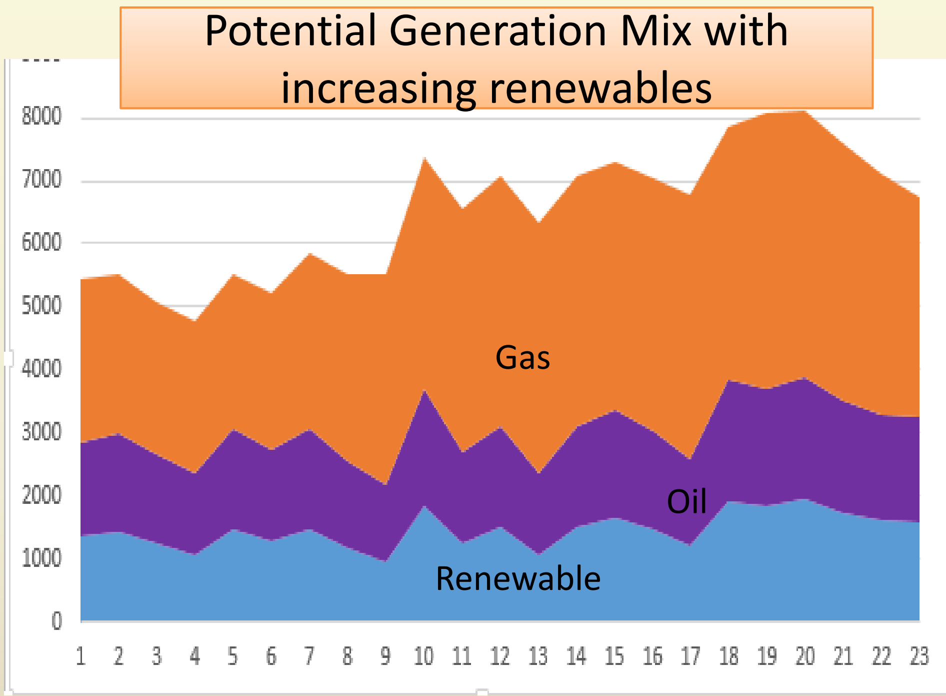
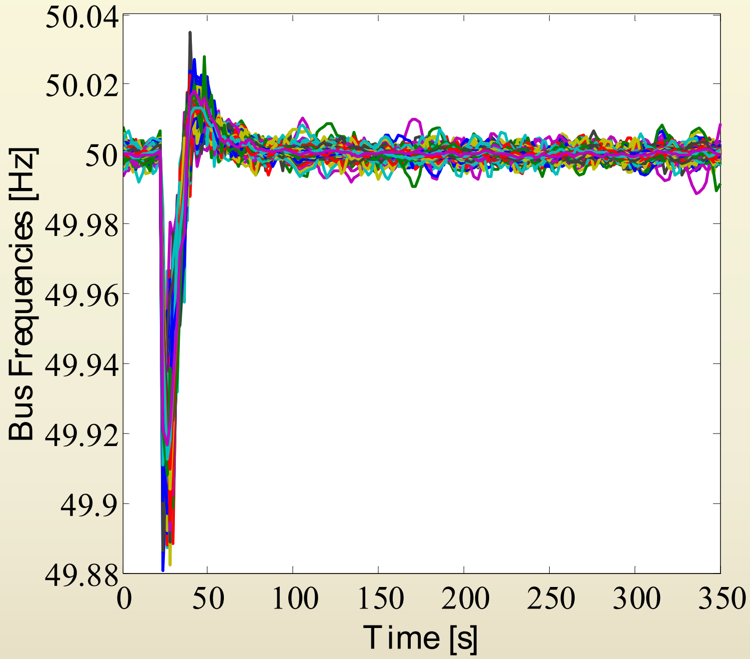


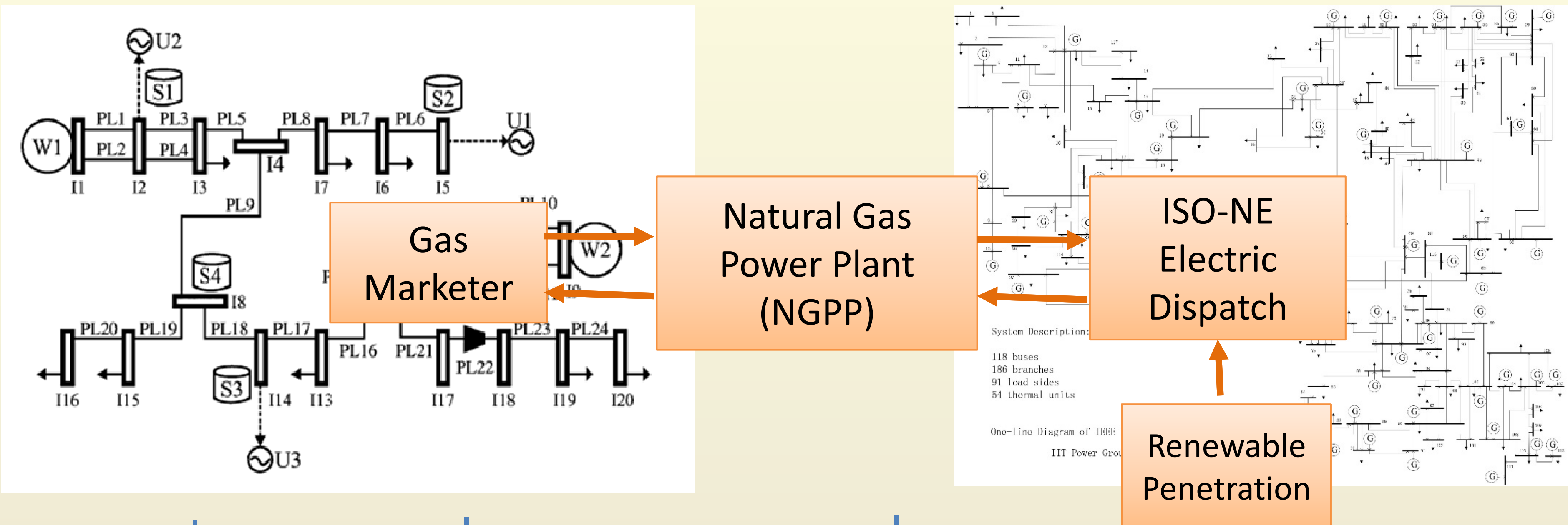


- If gas plants cannot meet their dispatch needs hourly and make up for renewable generation fluctuations, there can be a power imbalance, leading to frequency errors

Interdependency between NG and Electricity Networks – Unequal access

Natural Gas Network (MA)

IEEE 118-bus Electricity Network



NGPP bids to ISO

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Regression Model

$$P_k^{Gas} = 5.28 + 0.90 x_k^{v,WS} - 1.37 x_k^{Gas} + 1.22 x_k^{HHspot} - 0.09\, x_k^{storage}$$

P_k^{Gas}: Gas price paid by Gas Fired Generators (GFG)
$x_k^{v,WS}$: Normalized volatility in Wind and Solar Generation
x_k^{Gas}: Normalized Gas generation
$x_k^{storage}$: Normalized Gas storage
x_k^{HHspot} : Normalized Henry Hub spot price

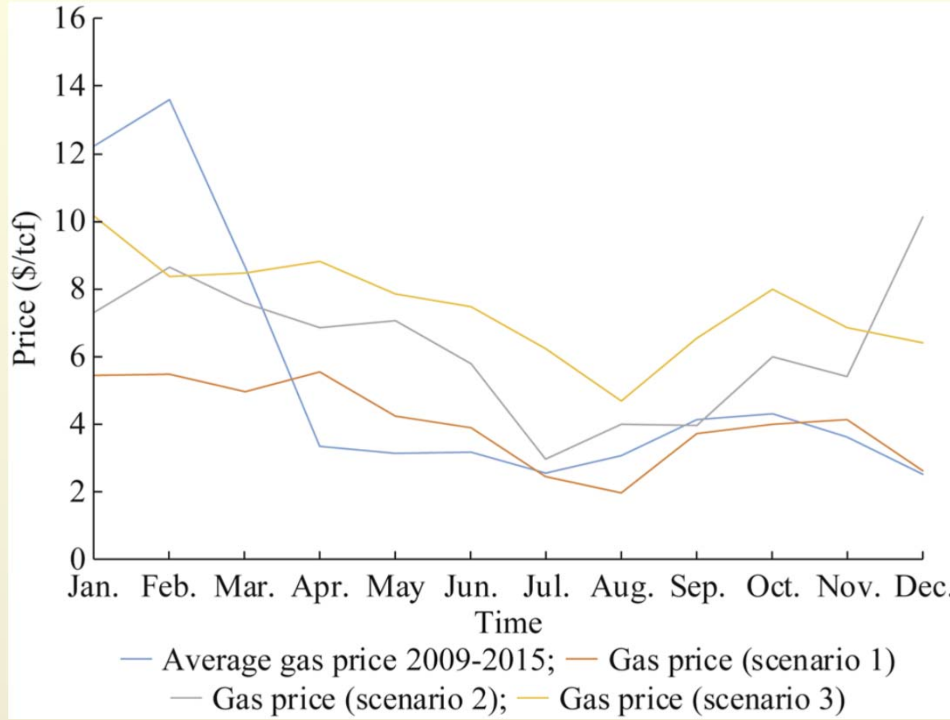
- Regression parameters identified using MA data from 2009 to 2015
- Extrapolated to predict gas-prices in 2030 and beyond

$$\hat{P}_k^{Gas} = 5.28 + 0.90 \hat{x}_k^{v,WS} - 1.37 \hat{x}_k^{Gas} + 1.22 \hat{x}_k^{HHspot} - 0.09\, x_k^{storage}$$

- $\hat{x}_k^{v,WS}$: Volatility in Predicted WS-Generation
- $\hat{x}_k^{Gas}$: Predicted Gas-Generation
- $\hat{x}_k^{HHspot}$: From \$2.63 in 2015 to \$5 in 2030
- $x_k^{storage}$: Assumed to remain the same

Prediction of Gas Prices

- Gas prices increase by 10%
  with 20% WS in the generation-mix
- Gas prices increase by 30%
  with 30% WS in the generation-mix
- Seasonal variations become less pronounced



Results of Gas Bids

Table 5 Average volatility in GFG bids

Scenario	Volatility
2015	~0
Scenario 1 (2.5 to 10%)	~0
Scenario 2 (2.5 to 20%)	0.002
Scenario 3 (2.5 to 30%)	0.1

- Main conclusion: With increasing penetration of WS, there is greater uncertainty for GFGs to obtain gas.
- Therefore they may be inclined to bid even less frequently in 2030 than 2015.

A possible solution: A joint partnership between Natural Gas Power Producers (NGPP) and Wind Power Producers (WPP)

Wind Integration – Volatility Management

Problem:

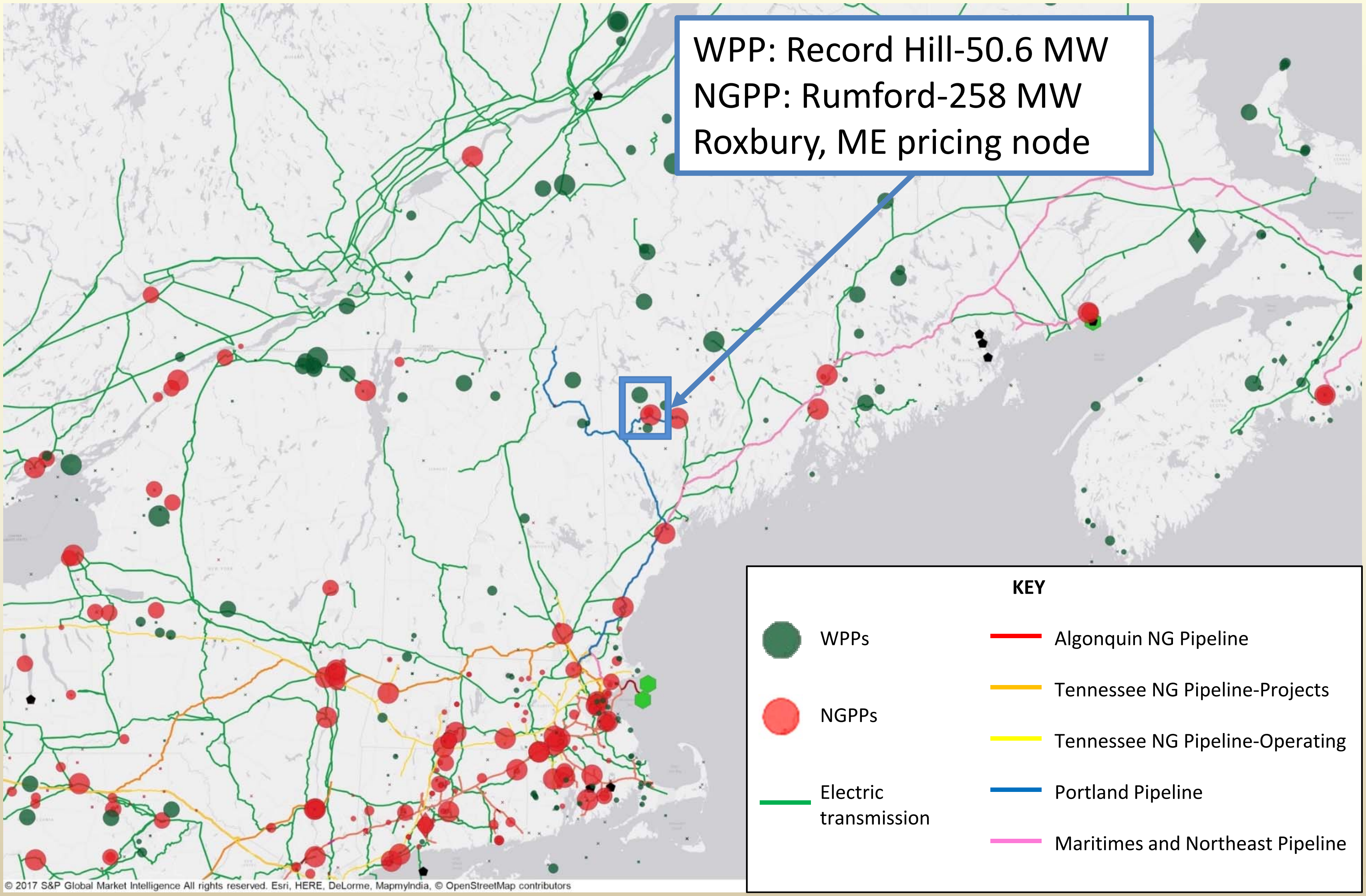
- Use of ancillary markets and peaker units to accommodate wind power socializes costs [1].
- Wind will face penalties for unmet commitments [2].

Solution:

- Contracts between Natural Gas and Wind Power Producers (NGPPs and WPPs) to fulfill unmet commitments.
- NGPPs benefit from exclusive energy rights to WPP shortfalls.
- WPPs benefit from reduced penalty payments enableing more aggressive bidding and increased energy market income.

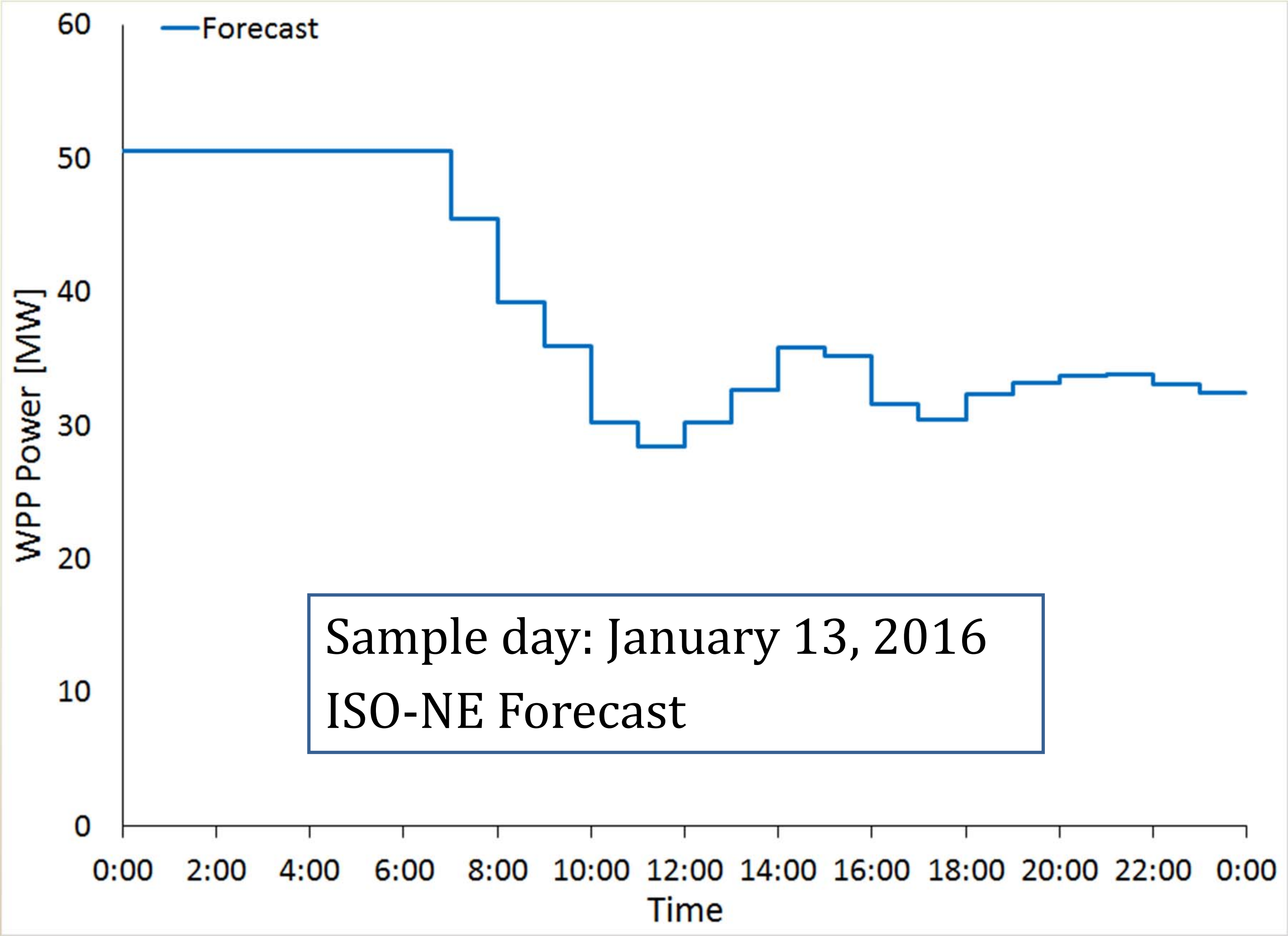
[1] Brown, P. *How does wind generation impact competitive power markets?*. Congressional Research Service, 2012.
[2] Bitar, E., et al. "Selling random wind." *2012 45th Hawaii International Conference on*. IEEE, 2012

Simulation – WPP & NGPP Selection

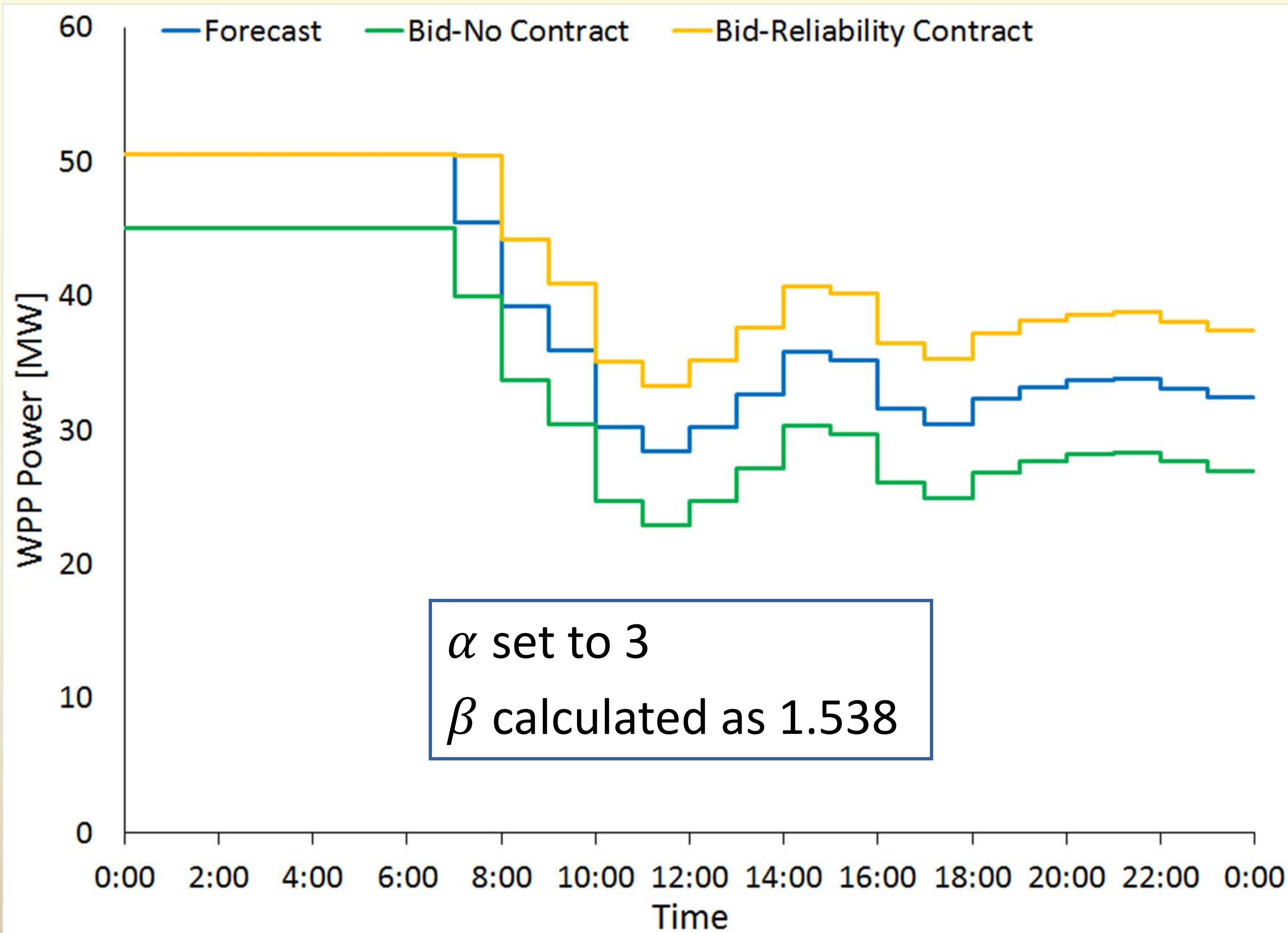


Map developed in SNL Energy-S&P Global Market Intelligence

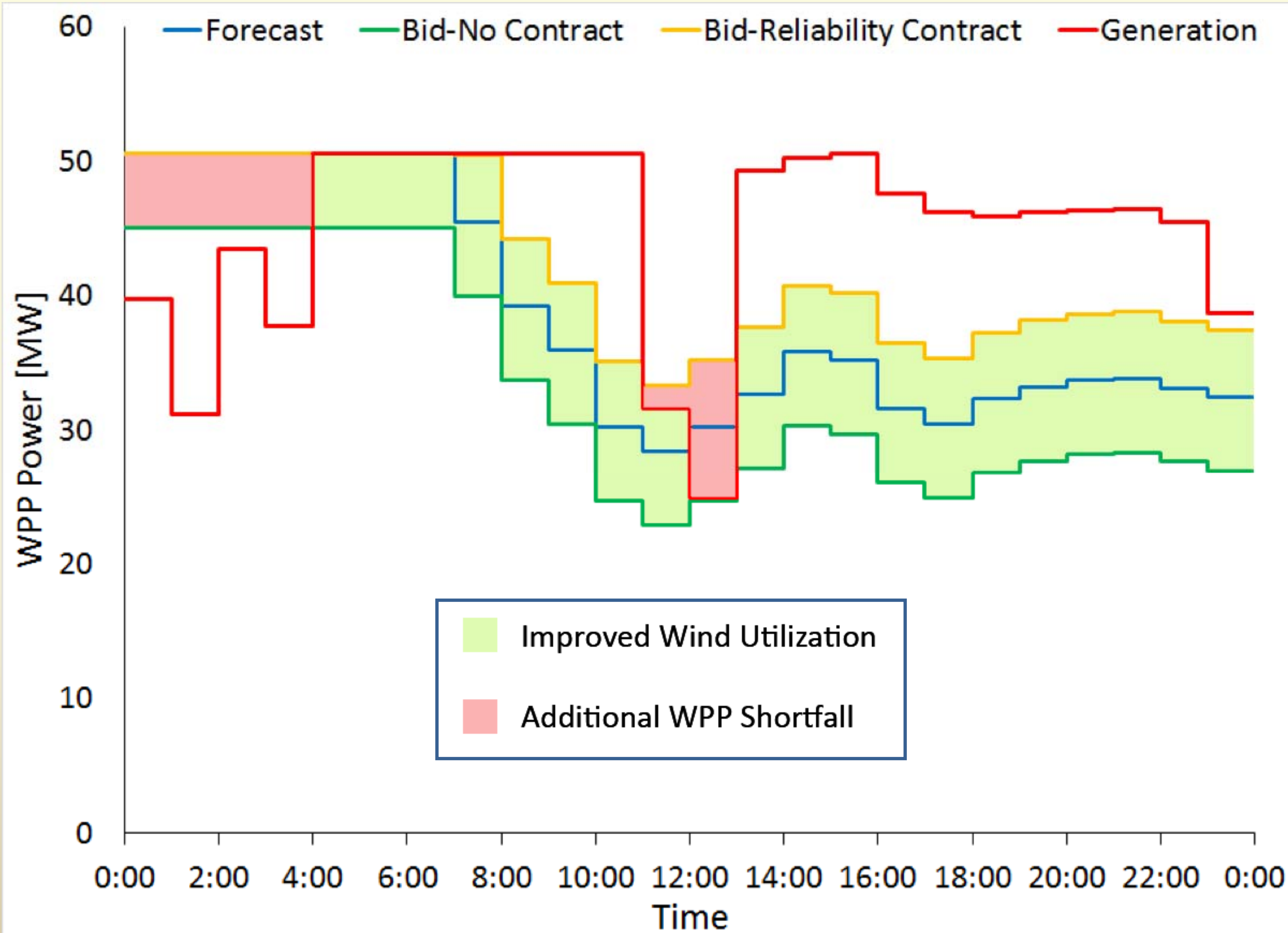
Simulation – WPP Next Day Generation Forecast



Simulation – WPP Bidding Sample



Simulation – Improved Renewable Utilization



WPP generation developed with NREL-System Advisory Model

Simulation – Reliability Contract Yearly Cash Flows

Contract Between WPP and NGPP	NO		YES	
Power Plant	WPP	NGPP	WPP	NGPP
Day-Ahead Energy Market Income	$ 2,223,008	$ 19,699,267	$ 4,253,378	$ 19,699,267
Contract Payment	$ -	$ -	*-$ 2,484,849*	$ 2,484,849
Day-Ahead Penalties	-$ 1,520,554	$ -	$ -	-$ 238,007
Fuel Cost	$ -	-$ 7,690,365	$ -	-$ 8,671,295
Variable O&M Cost	$ -	-$ 1,446,424	$ -	-$ 1,646,660
Fixed O&M Cost	-$ 534,633	-$ 9,368,111	-$ 534,633	-$ 9,368,111
Profit	$ 167,820	$ 1,194,367	$ 1,233,895	$ 2,260,042

α set to 3
β calculated as 1.538

Renewable utilization increase from 66% to 78%

Yearly profits increase by $1.07 million for each party

(C): TRANSACTIVE CONTROL OF ELECTRIC RAIL SYSTEMS

Smart Railway Grid Optimization

Opportunity:

- RESGs are adopting communication and automation technologies that could allow them to respond to pricing signals or follow optimized trajectories
- Bidirectional power flow from trainsets is enabled by regenerative breaking
- Operators operate conservatively (15% margins in US schedules, 7% in Europe [1])

Objectives:

1. Optimize trajectory with pricing structure that varies in space and time (depart from work minimization) – Spring 2018
2. Develop transactive control methodology for rail system which maximizes joint electric-transit social welfare – Fall 2018 through Spring 2019

[1] Transit Matters. "Regional Rail for Metropolitan Boston." Boston, MA. URL: http://transitmatters.org/regional-rail-doc

Problem Formulation

For rail routes R that span space S in time T, we pose the cost minimization problem:

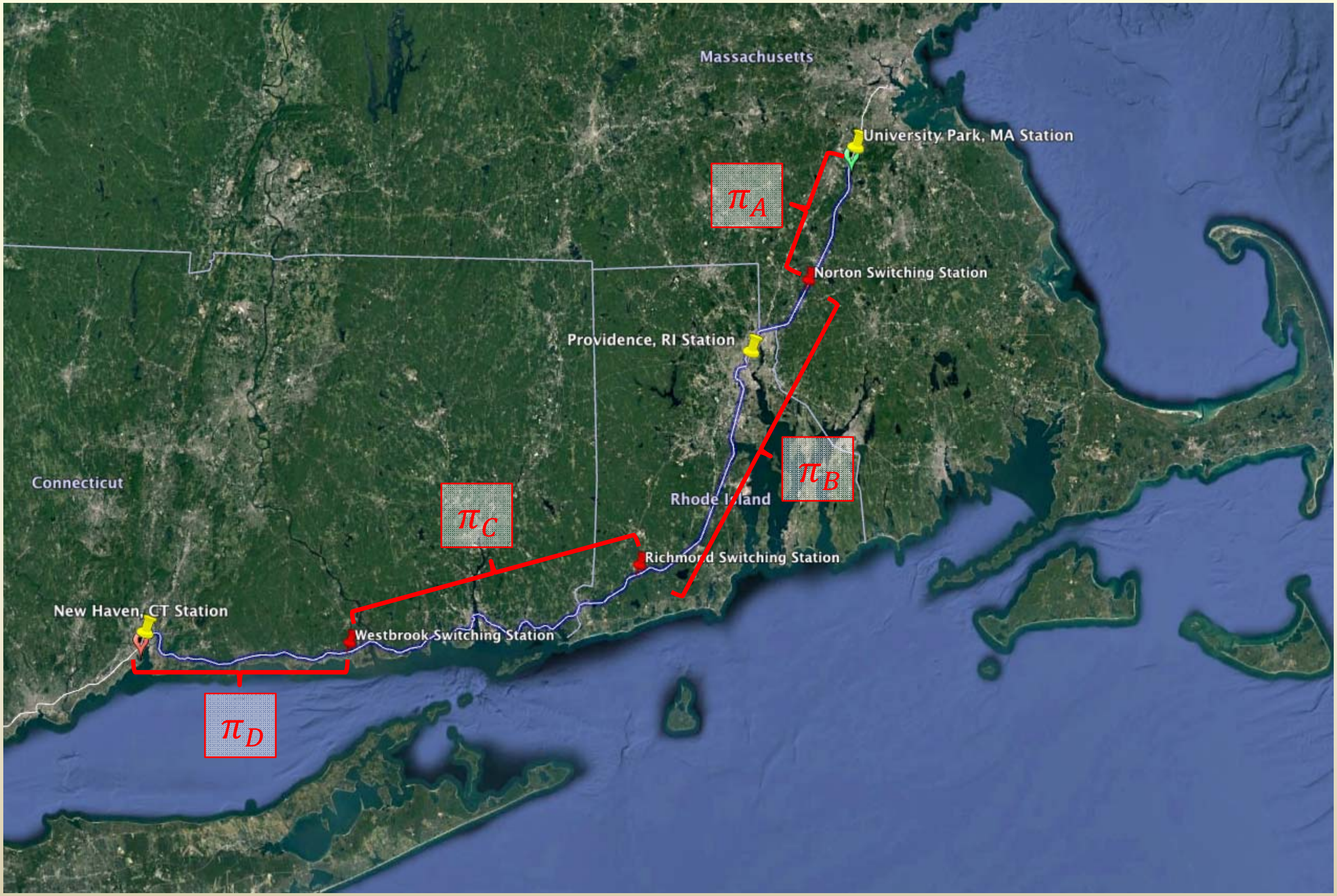
$$min \sum_R \sum_T \sum_S P(r,t,s) * \pi(r,t,s)$$

Work minimization benchmark with fixed π

s.t.

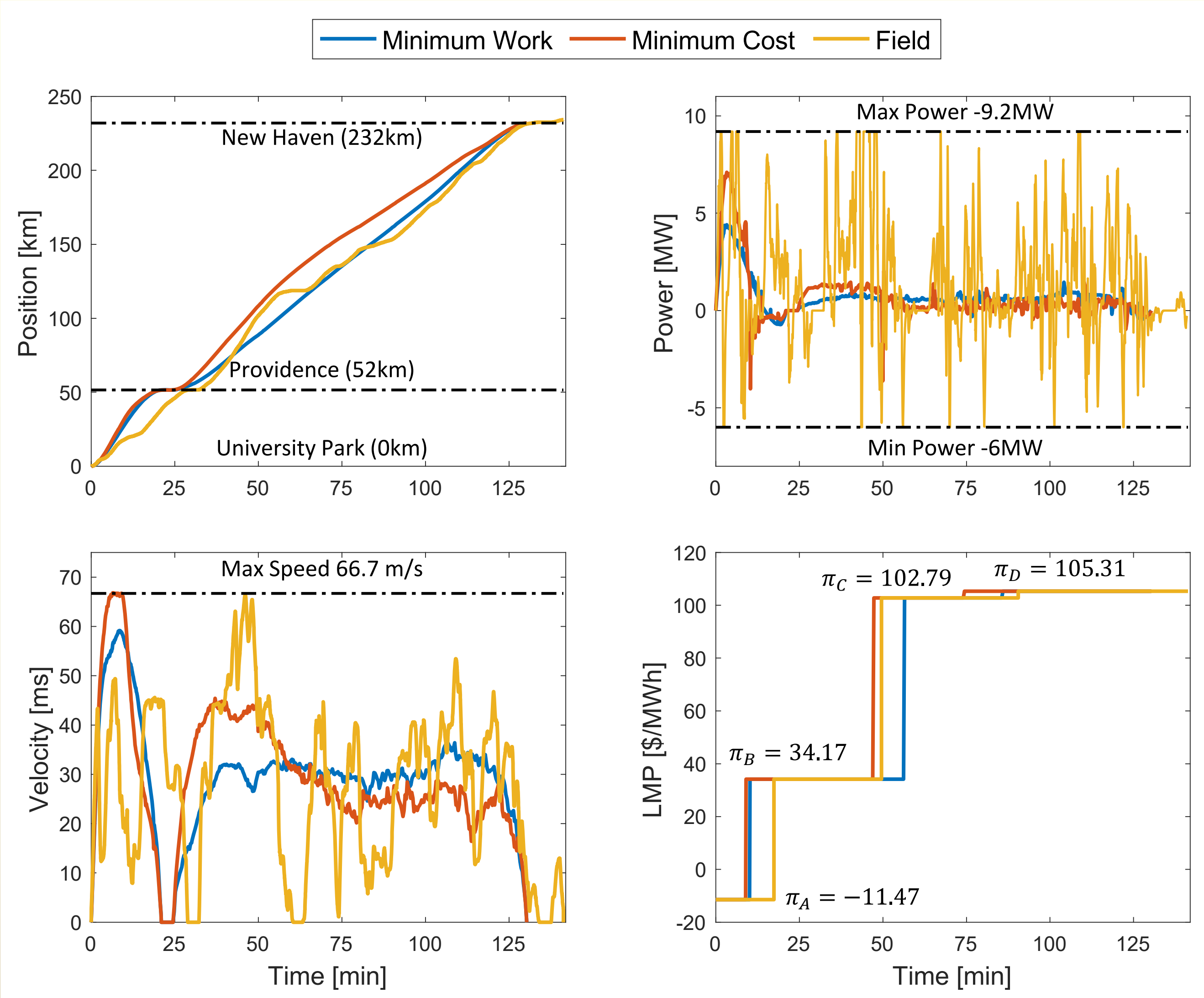
1. $t_{stop,r,i} \geq t_{stop,r,i,min}$
2. $t_{stop,r,i} \leq t_{stop,r,i,max}$
3. $P(r,t,v) \geq P_{min}$
4. $P(r,t,v) \leq P_{max}$
5. $v(r,t) \geq 0$
6. $v(r,t) \leq v_{max}$
7. $a(r,t) \geq a_{min}$
8. $a(r,t) \leq a_{max}$
9. $F_T(r,t) \geq F_{T,min}(v)$
10. $F_T(r,t) \leq F_{T,max}(v)$

Amtrak North East Corridor Railway – 60 Hz Electrification



Graphic developed using Google Earth Pro

Results – Schedule With Largest Pricing Differentials



Cost reduction of 62% from field under minimum work. Cost minimization provides an extra 18% reduction.

Reduction in total work of 58% under minimum work. Cost minimization only provides a 56% reduction.

Simulation on schedule with largest absolute pricing differentials of 2016

Tuesday, August 9, 2016 3pm – AMTRAK Acela Express 2171

A Cyber-enabled Smart Grid

Summary

- **Bulk Energy and Transmission**
  - Dynamic Market Mechanisms for Real-time Markets
- **Natural Gas and Electricity Infrastructures**
  - Gas Prices and Gas Bid-volatility
  - Joint partnership between Wind and Natural Gas producers
- **Transportation and Electricity Infrastructures**
  - Electric Rail Network & Transactive Control
- **Road Ahead**
  - Distributed Optimization and Control
  - Framework for Retail Markets
  - A combined study of market-design and control spanning multiple time-scales needs to be carried out.

Recent Journal Publications

1. "Vision for Smart Grid Control: 2030 and Beyond," (Eds. M. Amin, A.M. Annaswamy, C. DeMarco, and T. Samad), IEEE Standards Publication, June 2013.
2. A. Kiani, A.M. Annaswamy, T. Samad, "**A Hierarchical Transactive Control Architecture for Renewables Integration in Smart Grids: Analytical modeling and stability,**" *IEEE Transactions on Smart Grid*, Special Issue on Control Theory and Technology, 5(4):2054–2065, July 2014.
3. A. Kiani, A.M. Annaswamy. "**A Dynamic Mechanism for Wholesale Energy Market: Stability and Robustness**", *IEEE Transactions on Smart Grid*, 5(6):2877-2888, November 2014.
4. A. Kiani, A. M. Annaswamy. "**Equilibrium in Wholesale Energy Markets: Perturbation Analysis in the Presence of Renewables**", *IEEE Transactions on Smart Grid*, 5(1):177–187, Jan 2014.
5. J. Hansen, J. Knudsen, A. M. Annaswamy. "**A Dynamic Market Mechanism for Integration of Renewables and Demand Response,**" *IEEE Transactions on Control Systems Technology*, vol. 24, No. 3, 2016.
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