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# Ten Years Later: Rethinking Principles of Smart Architectures and Data-enabled Software


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**Increasing Real-Time and Day-Ahead Market Efficiency and Enhancing Resilience through Improved Software**

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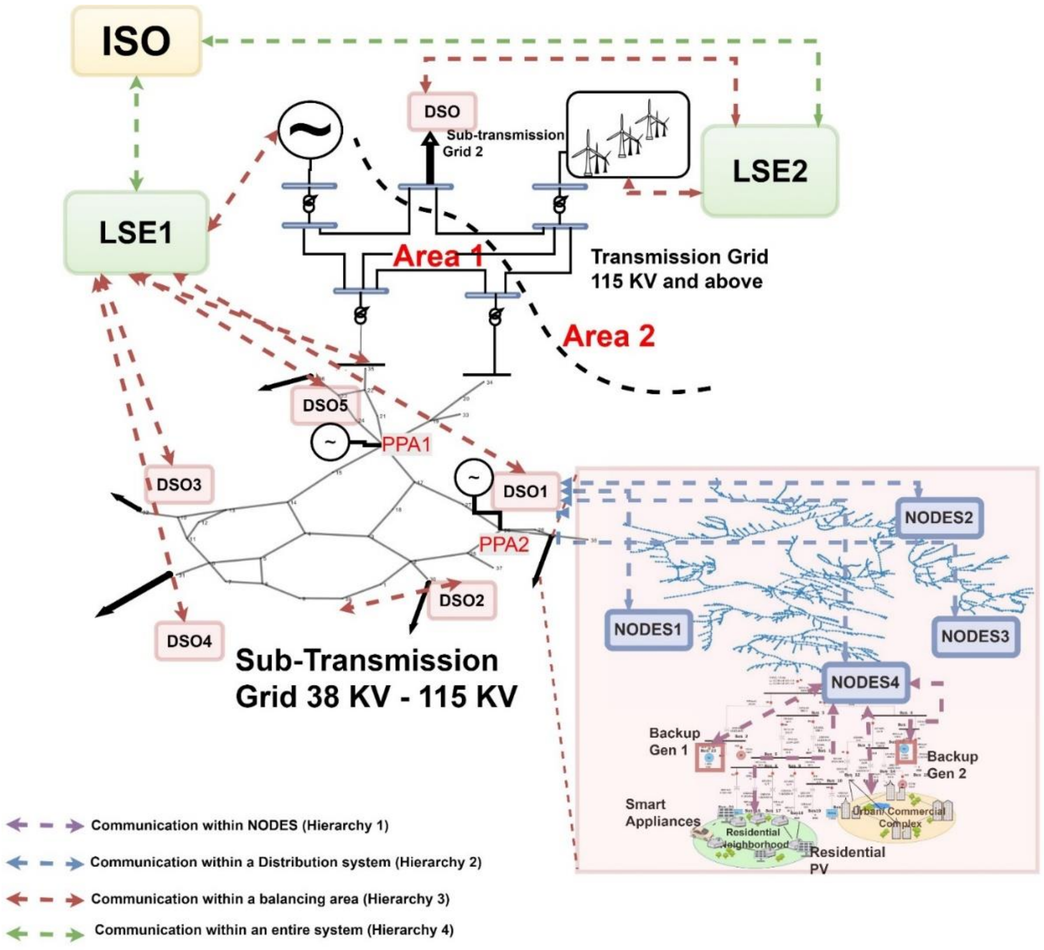
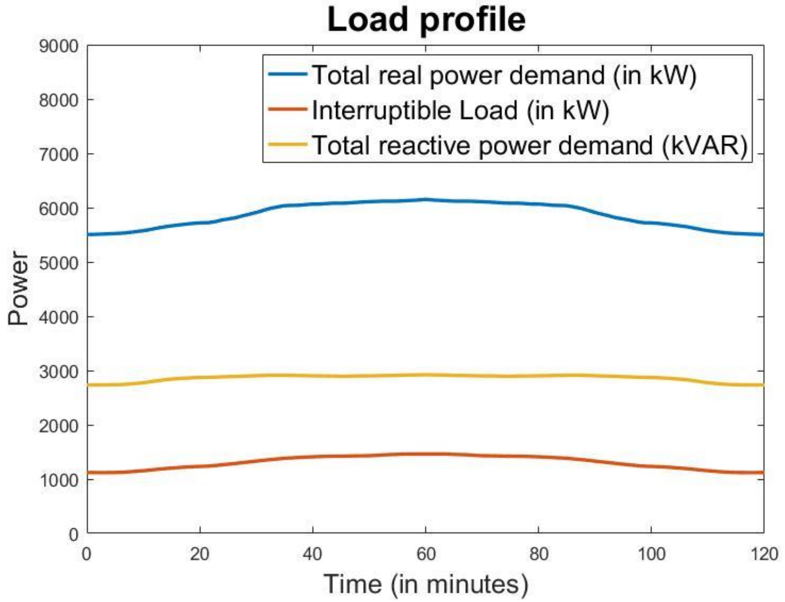
# Outline

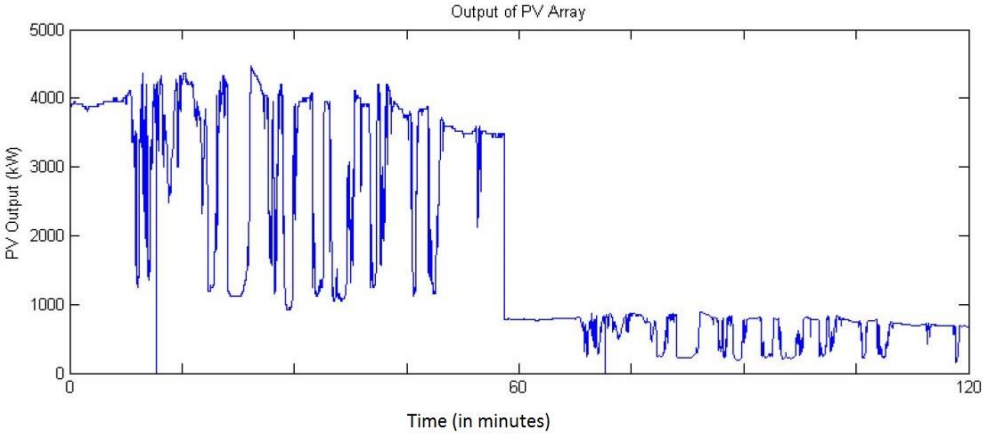
- The key role of spatial and temporal interactions
- Engineering solutions in early architectures
- Challenges and opportunities in the changing industry architectures: need for paradigm shift
- Change of paradigm; natural evolution from the early architectures
- Quantifiable notion of a ``better" architecture
- SCADA and software—enablers of performance

# Temporal and spatial interactions across stakeholders




New high frequency disturbances from renewables



# Huge hidden inefficiencies

❖ **Reliability constraints:**

- Limited use of clean resources in normal operations (large stand-by/spinning reserve)
- Impossible to ensure resilient service (Puerto Rico)

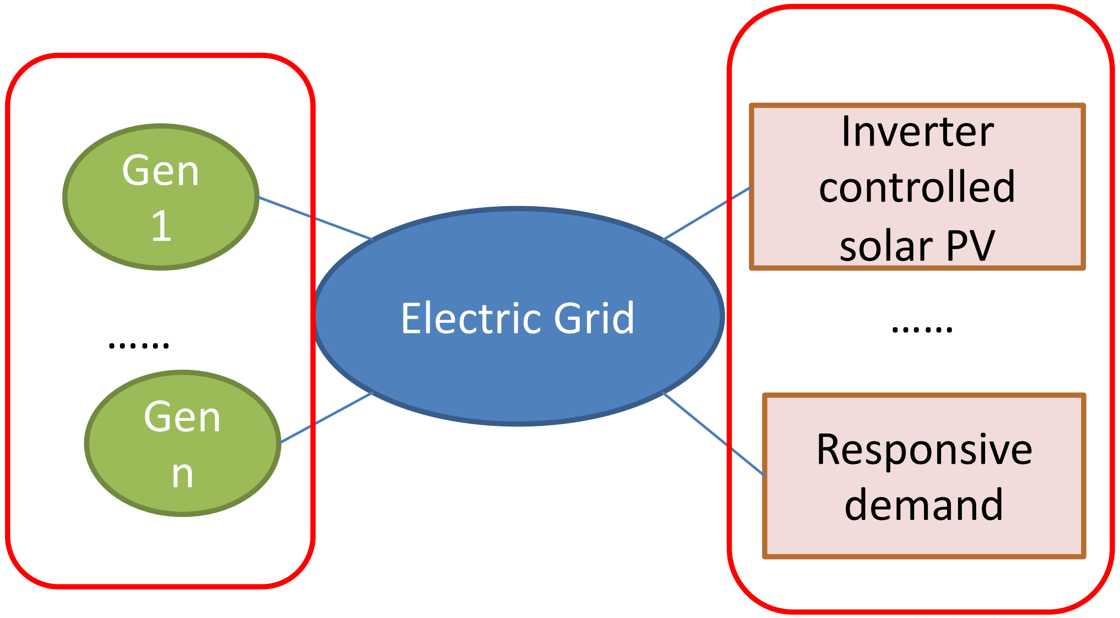
❖ **``Seams" constraints --poor spatial integration**

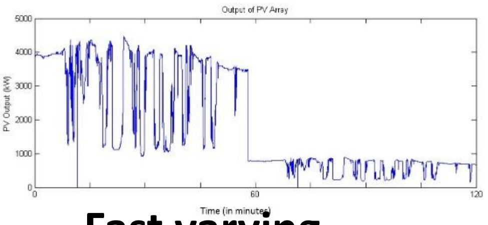
- Small isolated grids require large reserve for reliable service during equipment failures
- BPS interconnection built to share cost of reserve over large area (Eastern Interconnection)

# Striking evidence of grid delivery inefficiencies

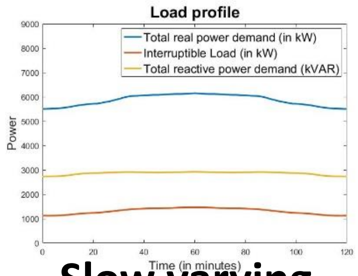
- 1GW less used from Niagara on a hot summer day by NYC than theoretically possible
- Estimated low penetration of solar in Puerto Rico grid
- Major spillage of wind power in Germany and Texas
- Inability to integrate small DERs by the US distribution companies; conservative ``hosting capacity"
- Threat of brown-outs in New England due to gas shortages/retirement of nuclear plants
- … most of these can be traced to the conservative grid proxy limits (hard temporal and spatial constraints; intra- and inter CA)

# Fundamental sources of electricity system inefficiencies




**Fast varying generation**




**Slow varying demand**

Energy conversion losses in generation and demand equipment

**Non-thermal T&D losses**

Not all power produced can be delivered due to

-- temporal mismatch in energy conversion rates

--T&D electrical maximum transfer

**T&D thermal capacity under-utilized (30%)**

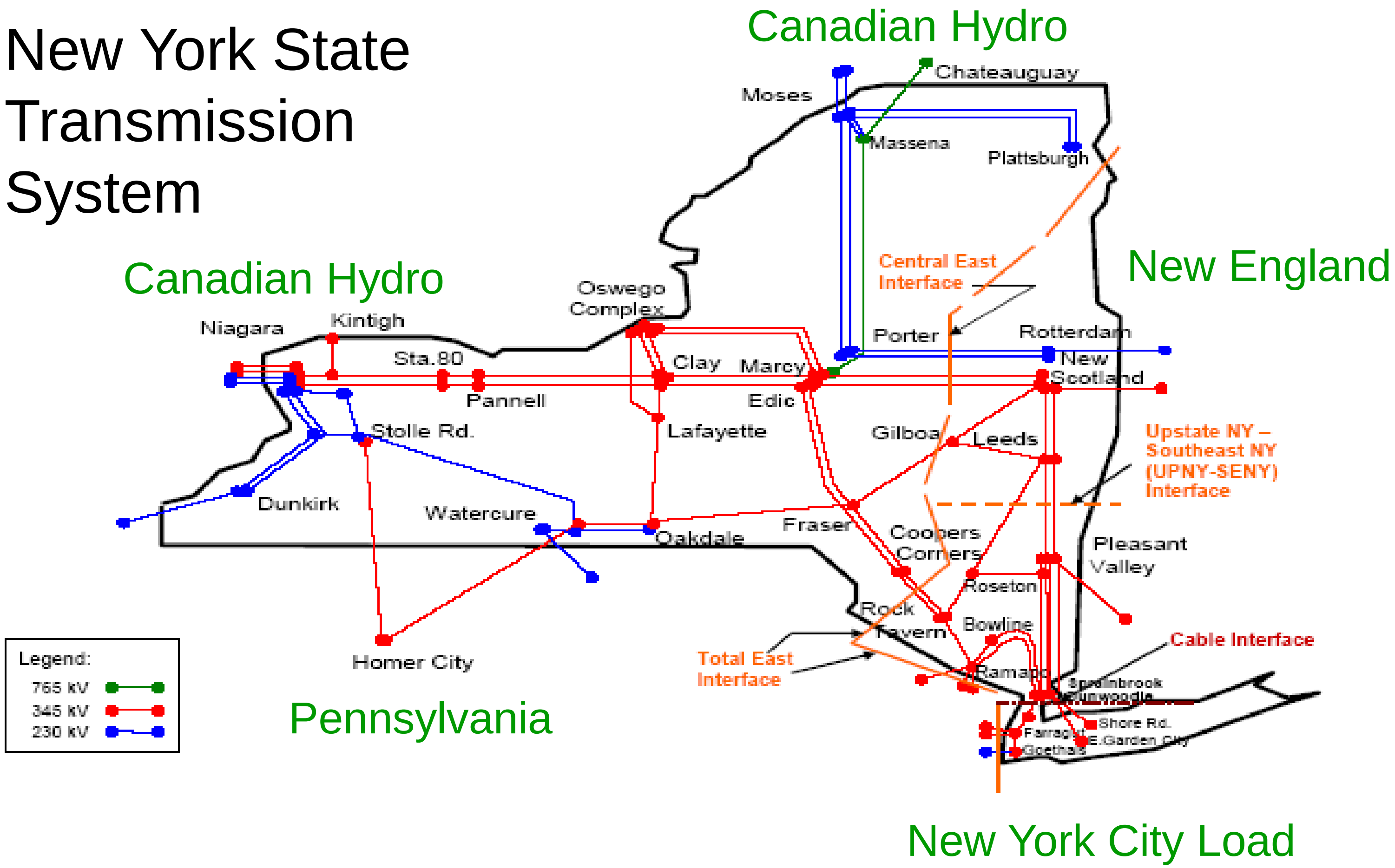
Thermal losses (2-6%) negligible compared to non thermal losses.

# How it used to work.. early architectures

- Both reliability and efficiency critically determined by the integration of temporal and spatial interactions
- Efficiency through:
  - Aggregate load predictions
  - Cooperative spatial planning and operations for reliability
  - Look ahead plant scheduling -- slow base load plants on (dirty, and clean)
- Inefficient management of uncertainties—proxy constraints
  - Contingency (the worst case approach)
  - Frequency and voltage regulation; stabilization

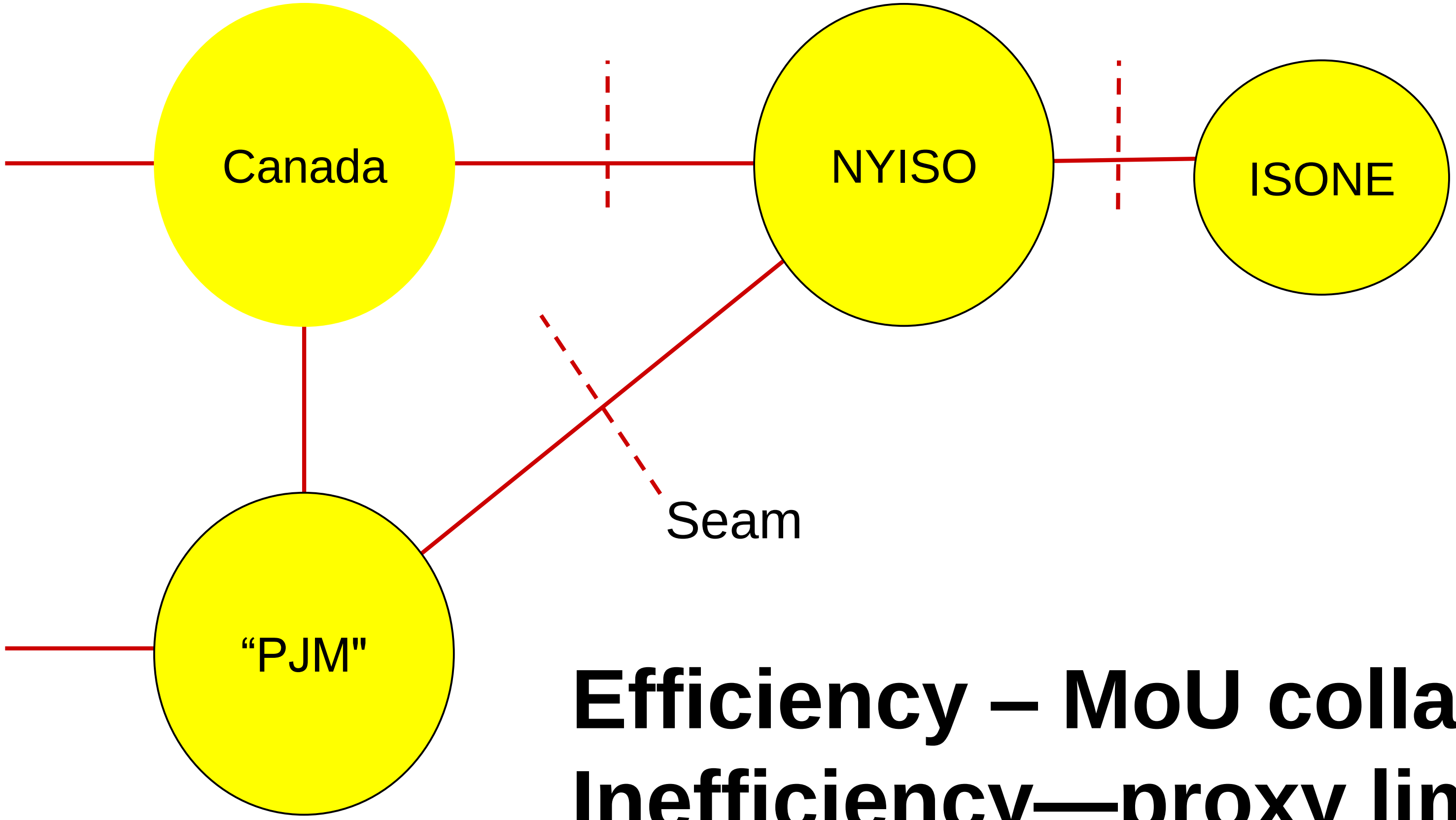
# NPCC region

New York State Transmission System



# Regional planning for reliability

4 Control Areas

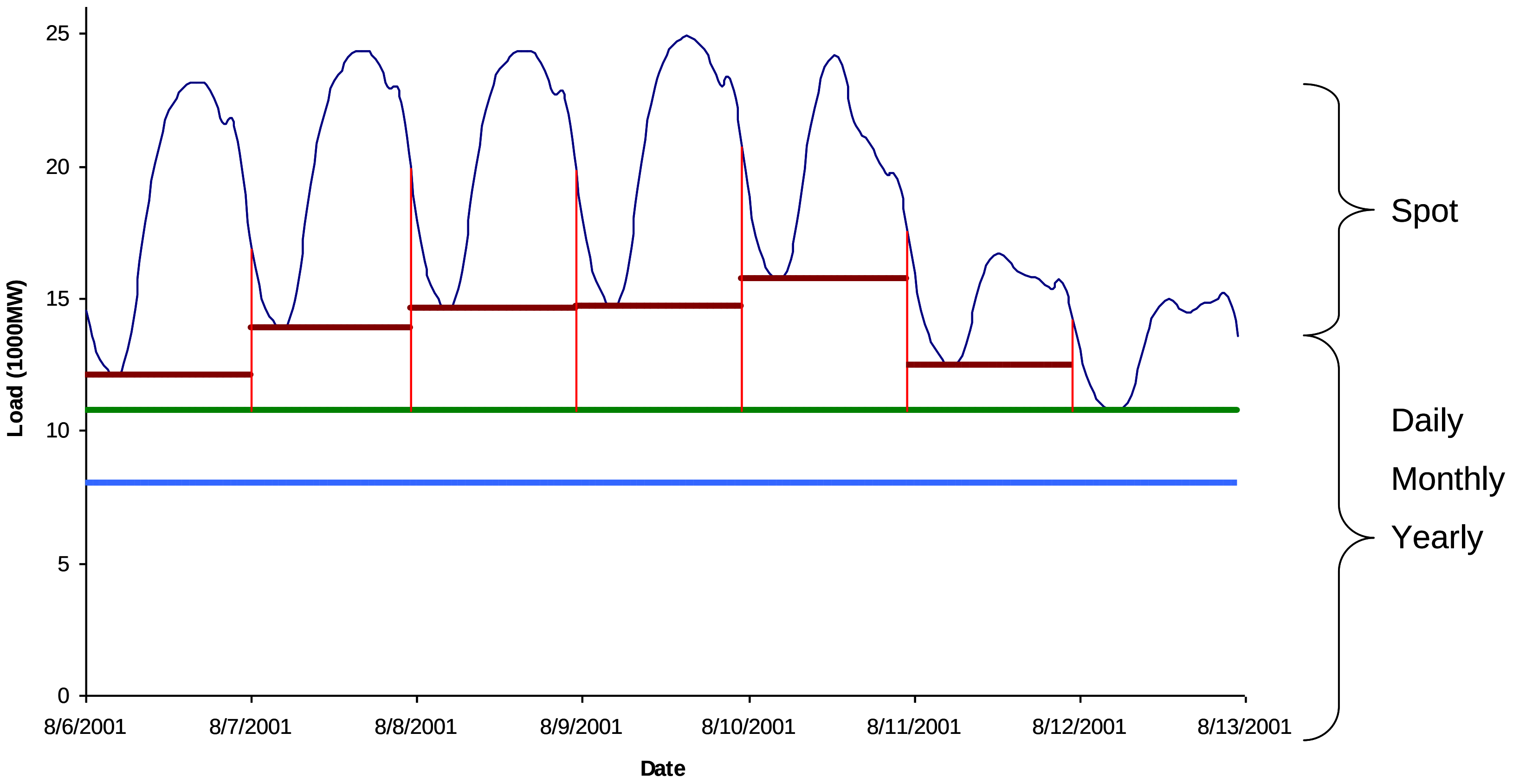



**Efficiency – MoU collaboration**
**Inefficiency—proxy limits**

# CA-level generation scheduling: UC and ED

- Unit Commitment (UC): for long-term forecasted demand, turn ON slow plants to supply base load; short-term turn OFF (decommit) slow units only if necessary; turn ON fast units given day or week ahead demand forecast
- Economic Dispatch (ED): given a mixture of energy resources, schedule the resource output of fast individual energy (modify output of slow only if/when necessary) so
  - power supply always balances forecast net demand
  - eneration cost is minimized

# Decentralized CA-level operations



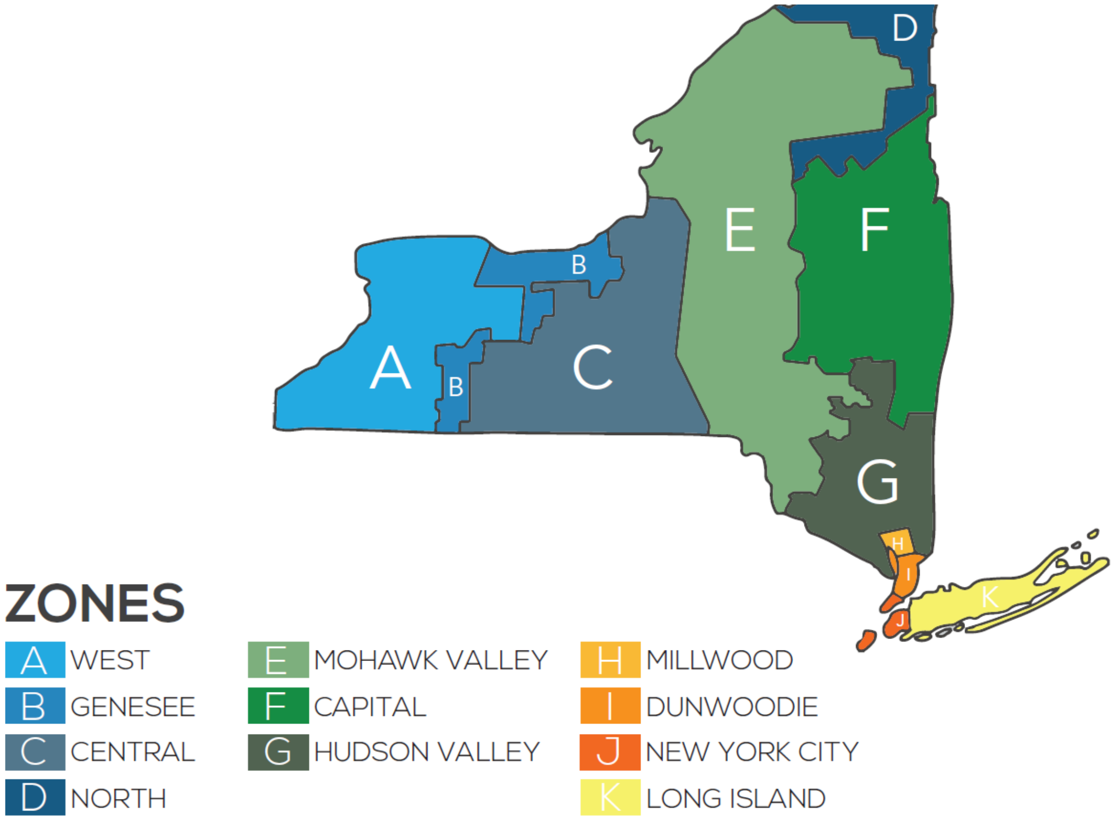

**Temporal efficiency---look ahead scheduling**

**Spatial inefficiency– uncoordinated seams**

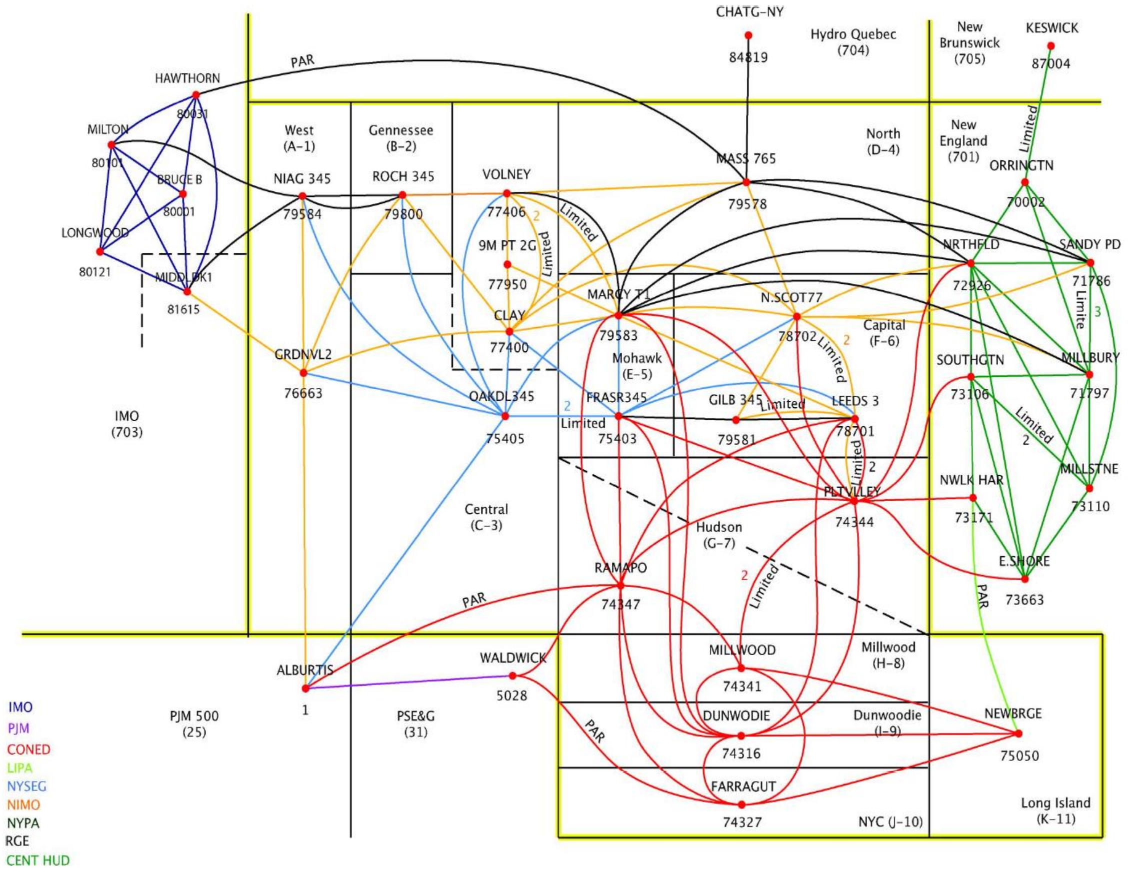
# More recent architectures

- NERC becomes NERO (mandatory reliability standards at higher granularity)
- Vertical unbundling (intra-CA seams)
- Deployment of wind/solar
- Demand response by large commercial and industrial loads
- Distributed demand response with small solar PVs, EVs, and controllable appliances
- Wholesale spot (short term) electricity markets
- Lack of long-term feed-forward demand predictions

# NYCA—intra- CA area seams



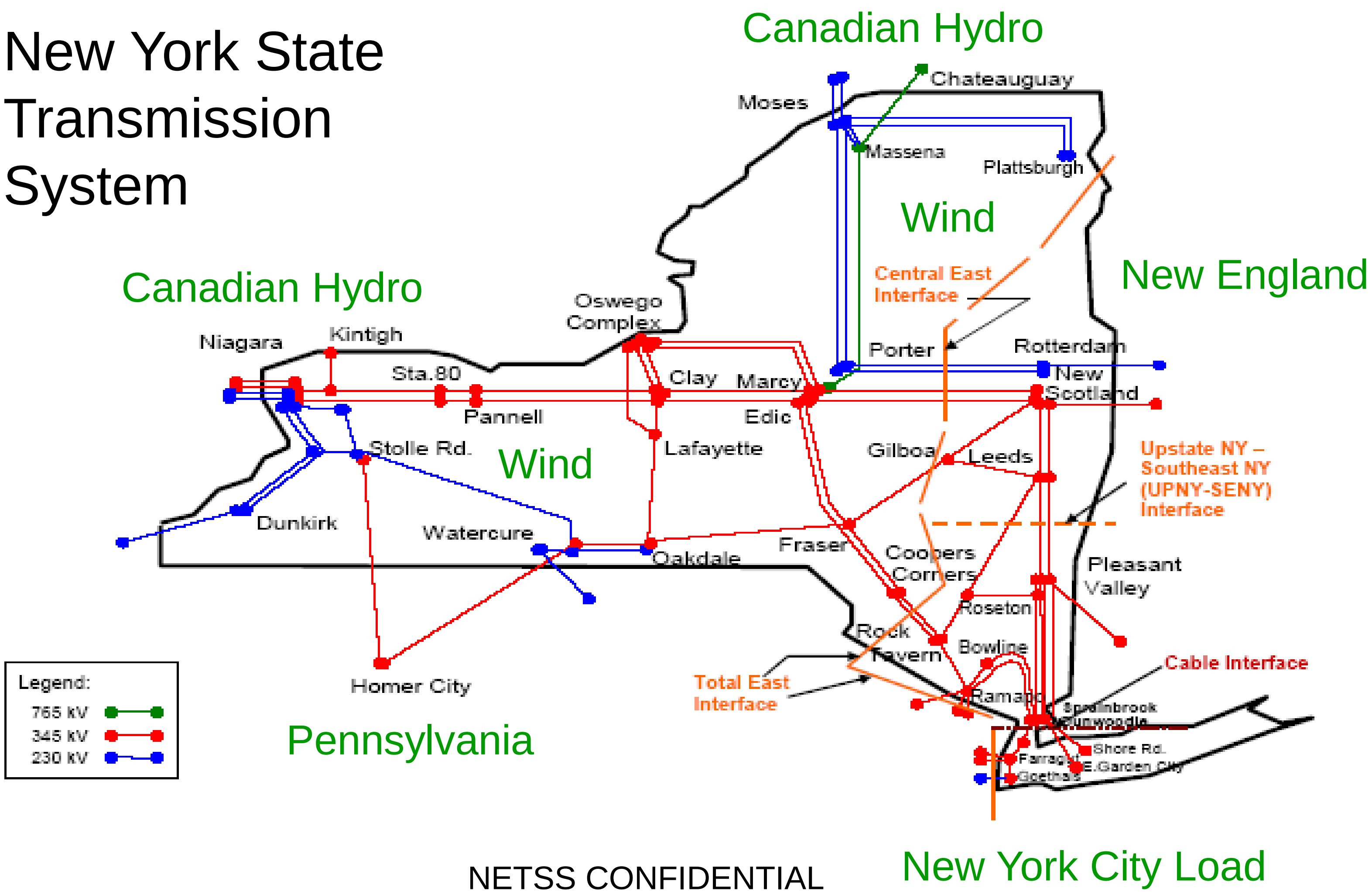

NYISO market zones




NYISO utilities

# Maximum Power Transfer Problem

New York State Transmission System



# Root-cause of on-going industry challenges

- Inconsistent (unaligned) temporal and spatial integration dictated by
- Mandatory reliability standards
- Sub-objectives of stakeholders
- SCADA design
- Planning/operations/market rules
- Software tools used by ISOs/TSOs/DSOs/DERMS/stakeholders
- DSOs/DERMS/stakeholders participation work in progress

# On-going industry efforts

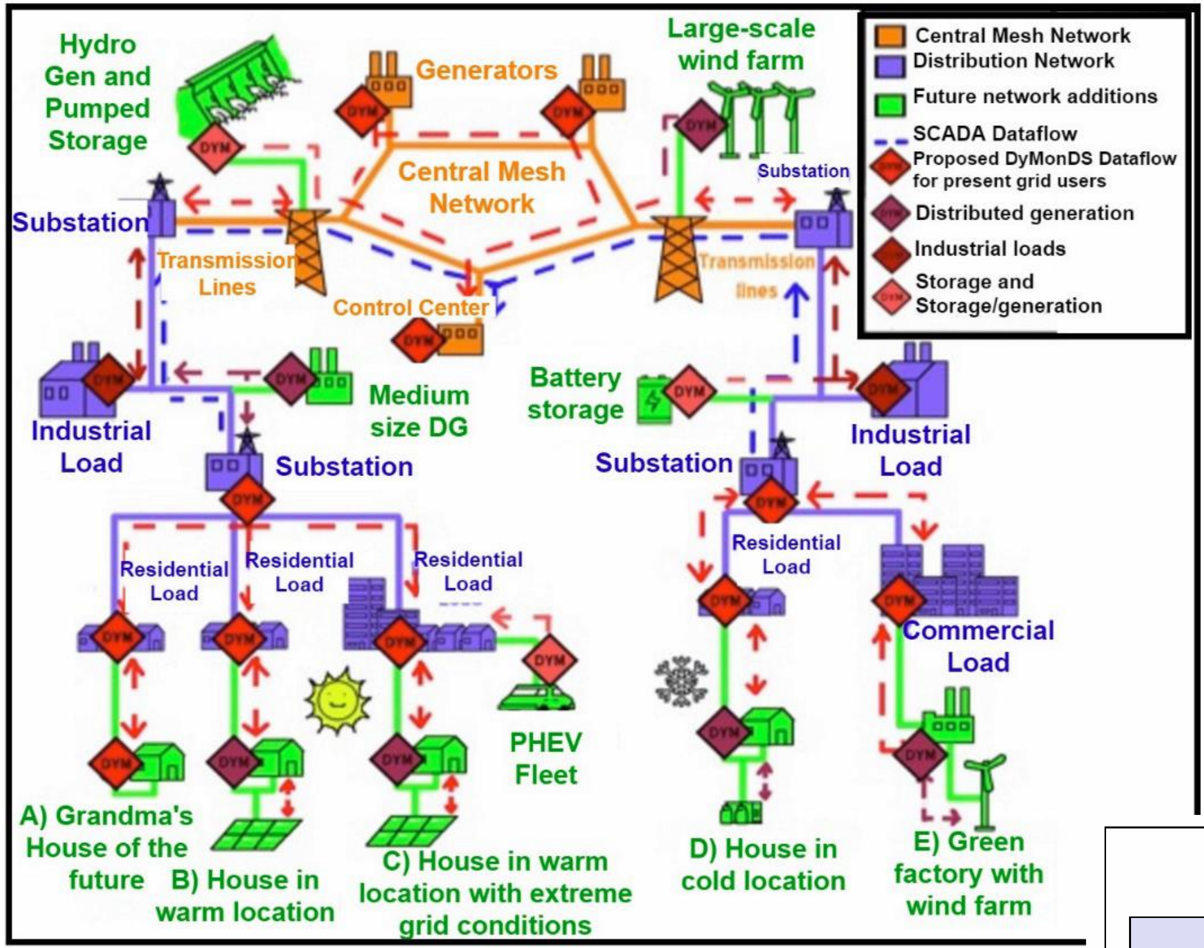
- Top down CA-level architectures
- Software for multi-temporal centralized CA-level UC and ED
- Still conservative grid proxy constraints; ``reliability related”
- No systematic solutions for integrating spatial seems (intra- and inter-CAs)
- Computational complexity challenges (FERC conferences 1-10)
- Pricing for incentivizing temporal and spatial integration?
- Probably impossible to implement to high level of granularity

# Paradigm shift—from hard proxy constraints to interactive distributed decision making

- Both seams and inter-temporal dependencies should be managed at value and reliably
- Carefully defined derivatives must be supported by software for bidding and market clearing; sufficient to define a triplet (E_T; P; dQ/dT)– natural extension of today's ACE
- Voltage and frequency regulation results of power balancing in this space; not derivatives
- Data-enabled distributed risk management for reliability and resliliency

| Single optimization subject to constraints | Reconciling tradeoffs |
|---|---|
| Schedule supply to meet given demand | Schedule supply to meet demand (both supply and demand have costs assigned) |
| Provide electricity at a predefined tariff | Provide electricity at QoS determined by the customers willingness to pay |
| Produce energy subject to a predefined $CO_2$ constraint | Produce amount of energy determined by the willingness to pay for $CO_2$ effects |
| Schedule supply and demand subject to transmission congestion | Schedule supply, demand and transmission capacity (supply, demand and transmission costs assigned) |
| Build storage to balance supply and demand | Build storage according to customers willingness to pay for being connected to a stable grid |
| Build specific type of primary energy source to meet long-term customer needs | Build specific type of energy source for well-defined long-term customer needs, including their willingness to pay for long-term service, and its attributes |
| Build new transmission lines for forecast demand | Build new transmission lines to serve customers according to their ex ante (longer-term) contracts for service |

# New end-to-end SCADA; data-enabled protocols




- POTENTIAL BENEFITS
- ❖ Less hardware: wires, storage, generation
- ❖ 100% clean Azores islands, long-term reduced bills
- ❖ Significantly reduced wind spillage (Germany)
- ❖ Increased hosting capacity for DERs (solar, demand)
- ❖ Gradual degradation of service during extreme events
- ❖ Reliable and efficient during normal conditions
- ❖ Overall –much more sustainable electricity service of a Social Ecological Energy System

Major R&D effort needed to fix missing signals/incentives

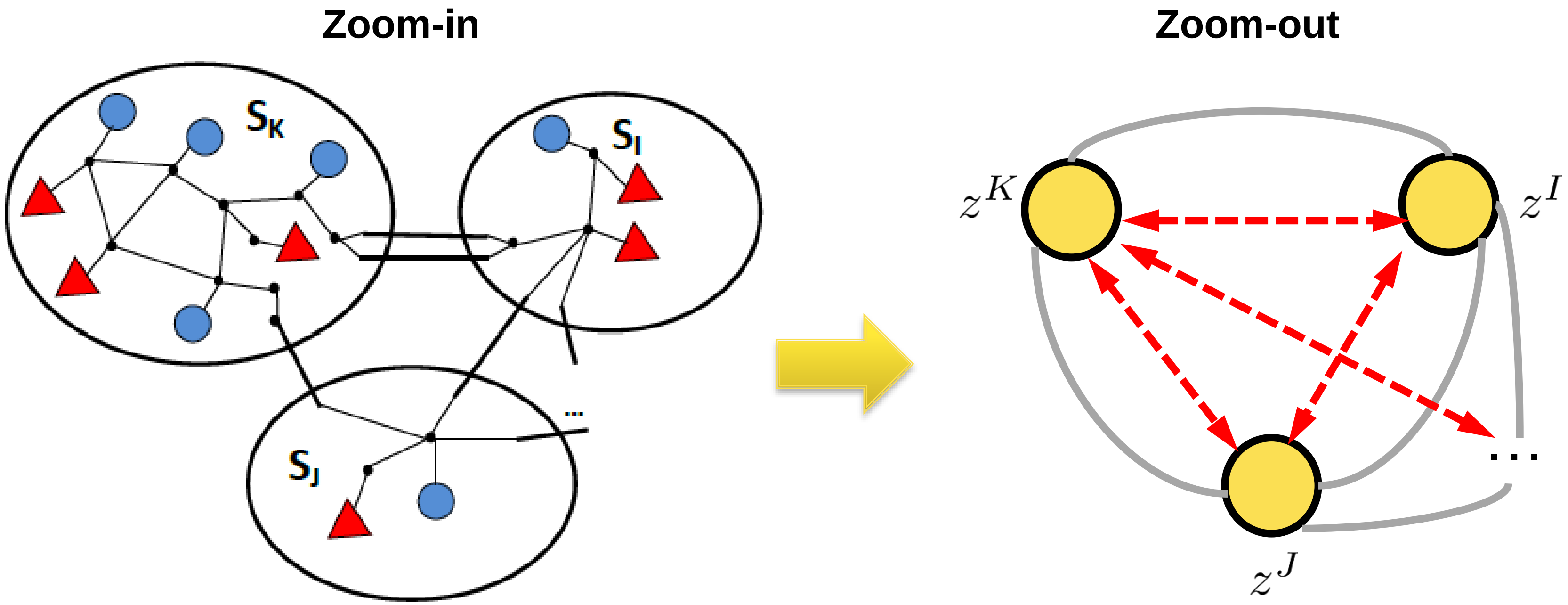
Missing spatial and temporal signals in

**Operations:**
Power and rate of change of power

**Markets**:
Prices at consumer locations for power and its rate of change and rate of change of power

# Spatial and temporal integration—Dynamic Monitoring and Decision Systems (DyMonDS)

- Multi-layered distributed decision making with minimal coordination



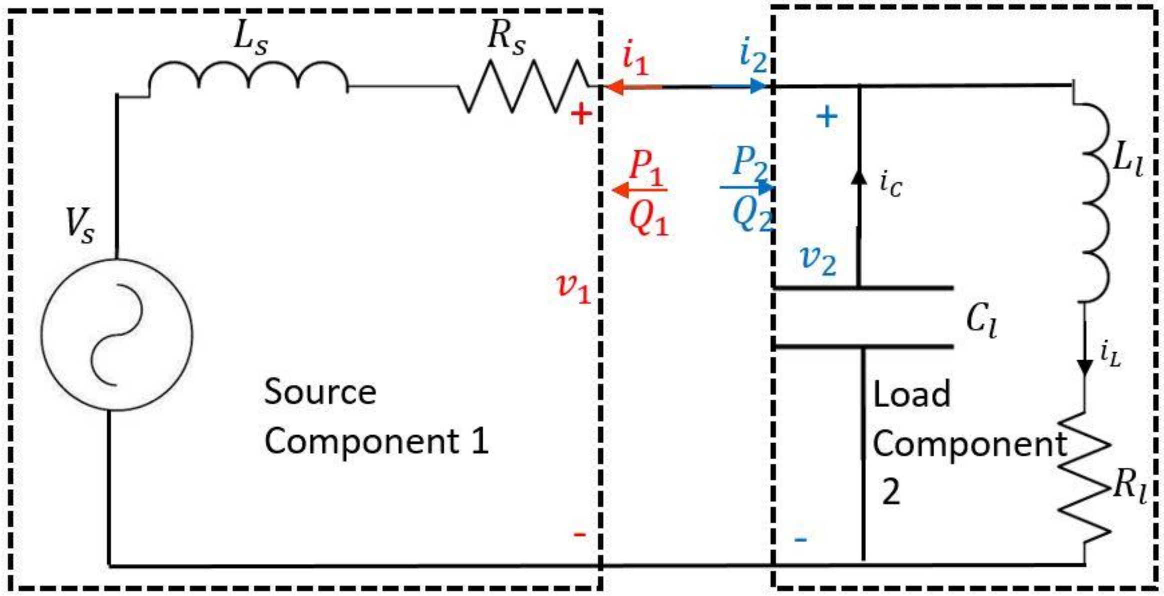
# Quantifiable measures of ``improving”

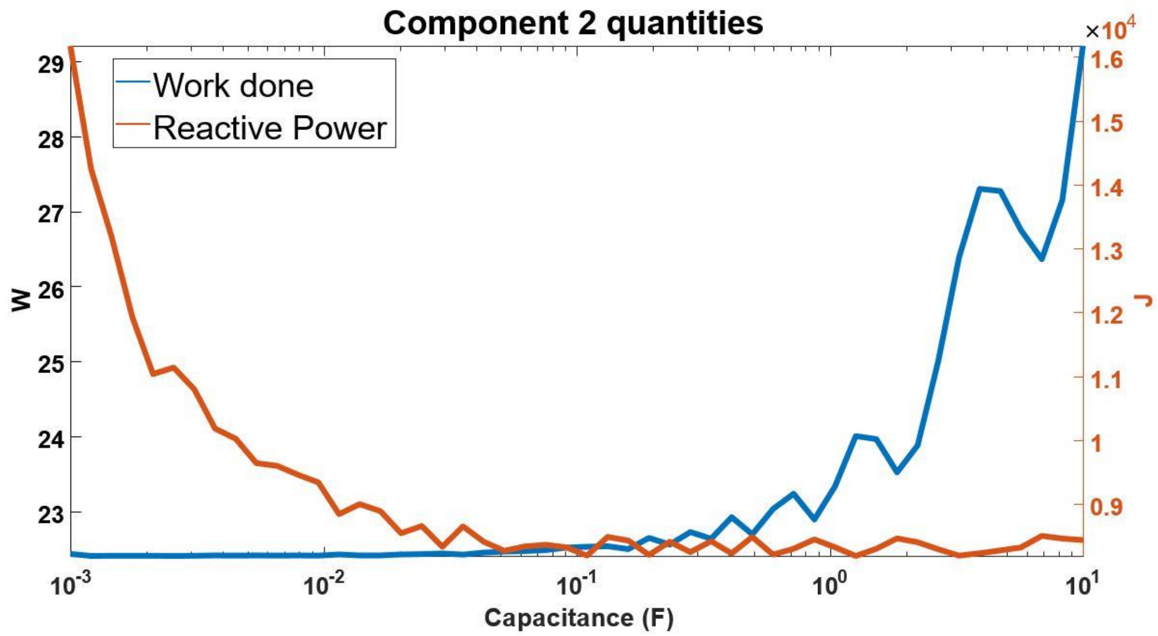
- Component level—measured in terms of potential to do real work and create less waste (hardware; smarts—power electronics control; automation; predictions; learning)
- System level--- end-to-end SCADA ``better” only if supported by the right IT signals which align technical, economic, regulatory protocols
  - Triplet of (E_T,P,dQ/dT) technical signal
  - Triplet of bids for the same technical product (derivatives)
  - Regulation of protocols to align technical and economic signals
- INTERACTIVE FRAMEWORK BASED ON PROTOCOLS

# Proposed principles for new SCADA

- First principle– generalize today's AGC standards on Balancing Authorities (BAs) in terms of area control error (ACE) into standards/protocols for intelligent Balancing Authorities (iBAs). New common variables characterizing input-output interactions between iBAs. These extensions set protocols for storage; inverter controlled PVs; demand DERs; conventional generators; and T&D.
- Second principle—an ``optimal" SEES should evolve through managing in a feedforward/feedback spatial and temporal interactions
- Third principle design/control of components and their interactions according to constructal law (Bejan)

# Reactive power characterizing inefficiency



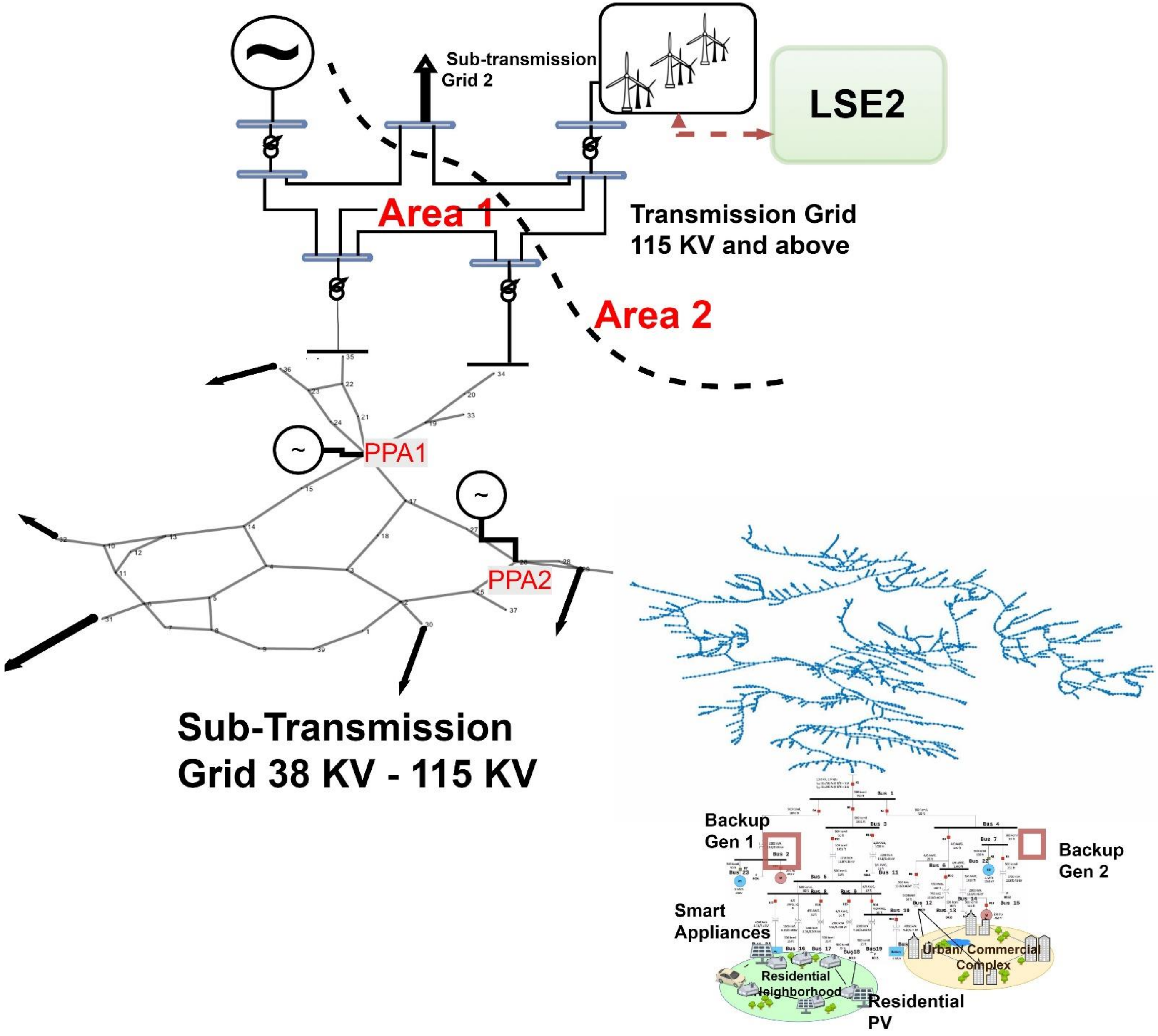




The higher the instantaneous reactive power is, the lower is the efficiency of the component

# MAJOR NEED FOR NEXT GENERATION SOFTWARE

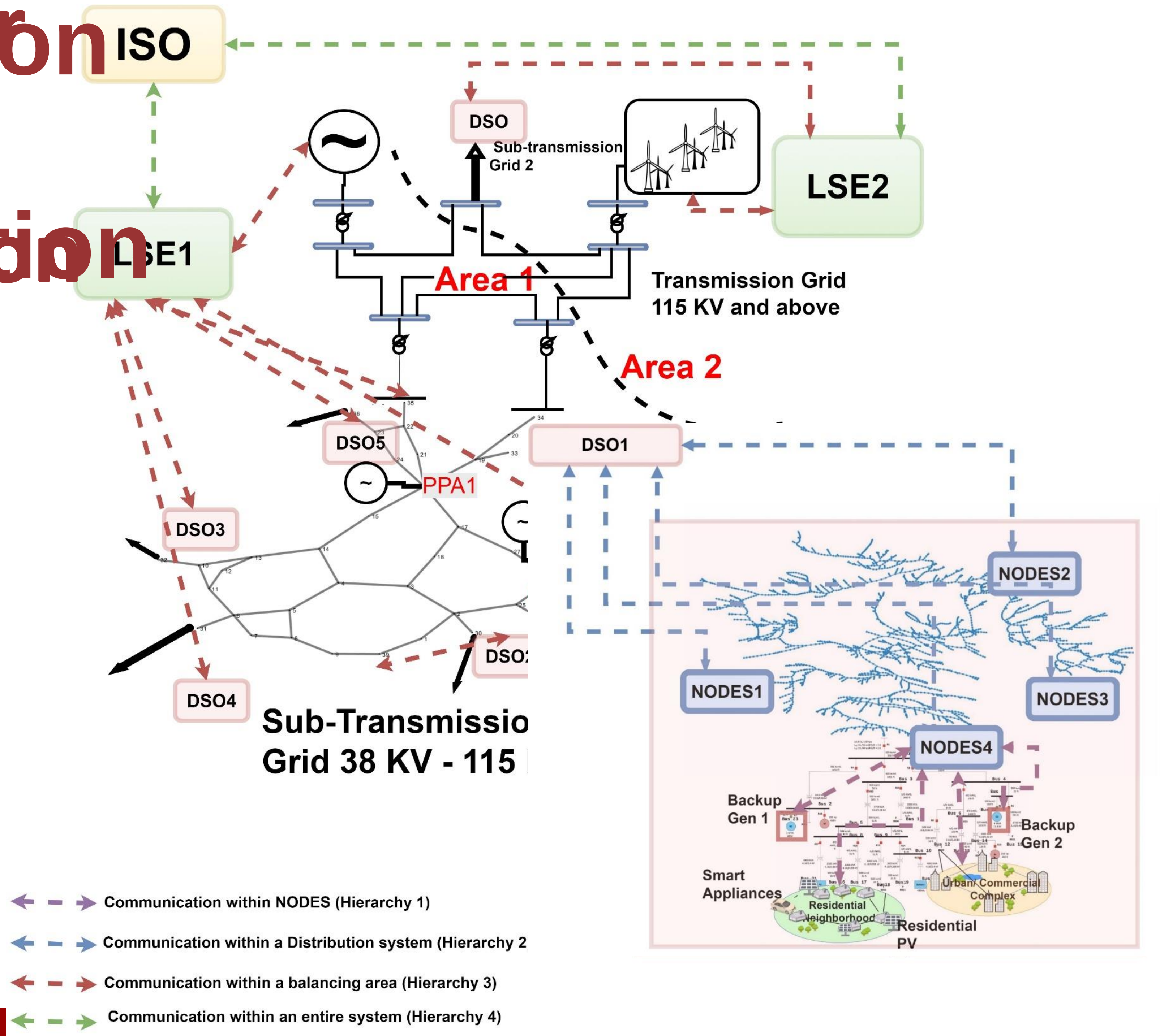
- COMPLEXITY EMBEDDED IN THE LOWER LAYERS FOR ENABLING ``BETTER” SPECIFICATIONS (E_T,P,dQ/dT) – automation, smarts, ML, predictions; storage/EV integration
- AGGREGATION OVER TIME AND STAKEHOLDERS MANAGING INTERACTIONS THROUGH MINIMAL COORDINATION
- AMPLE EVIDENCE OF ENHANCED RELIABILITY, EFFICIENCY AND RESILIENCY

# Bulk Power system



# Bulk Power system coordination

# Distribution system coordination

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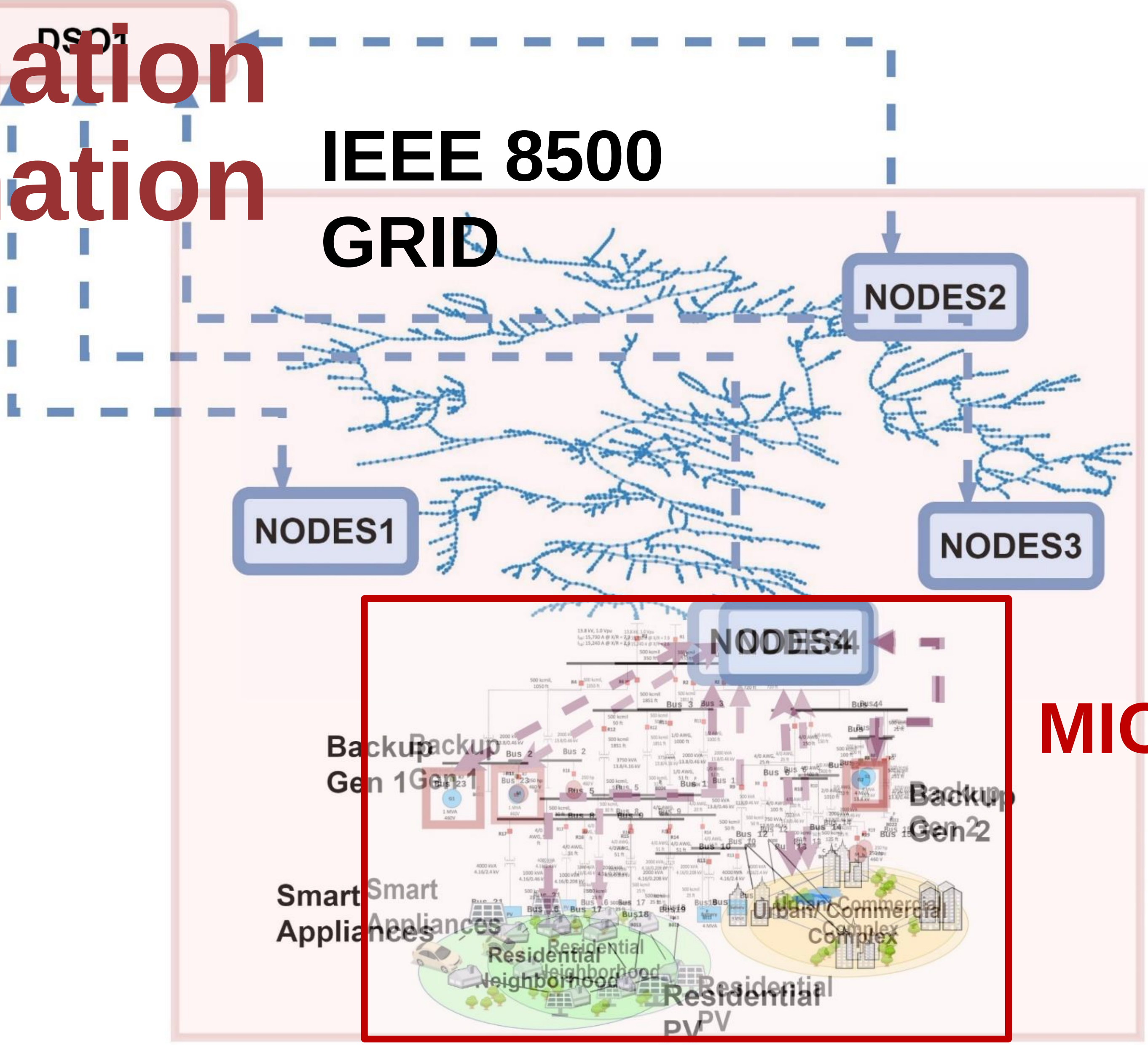
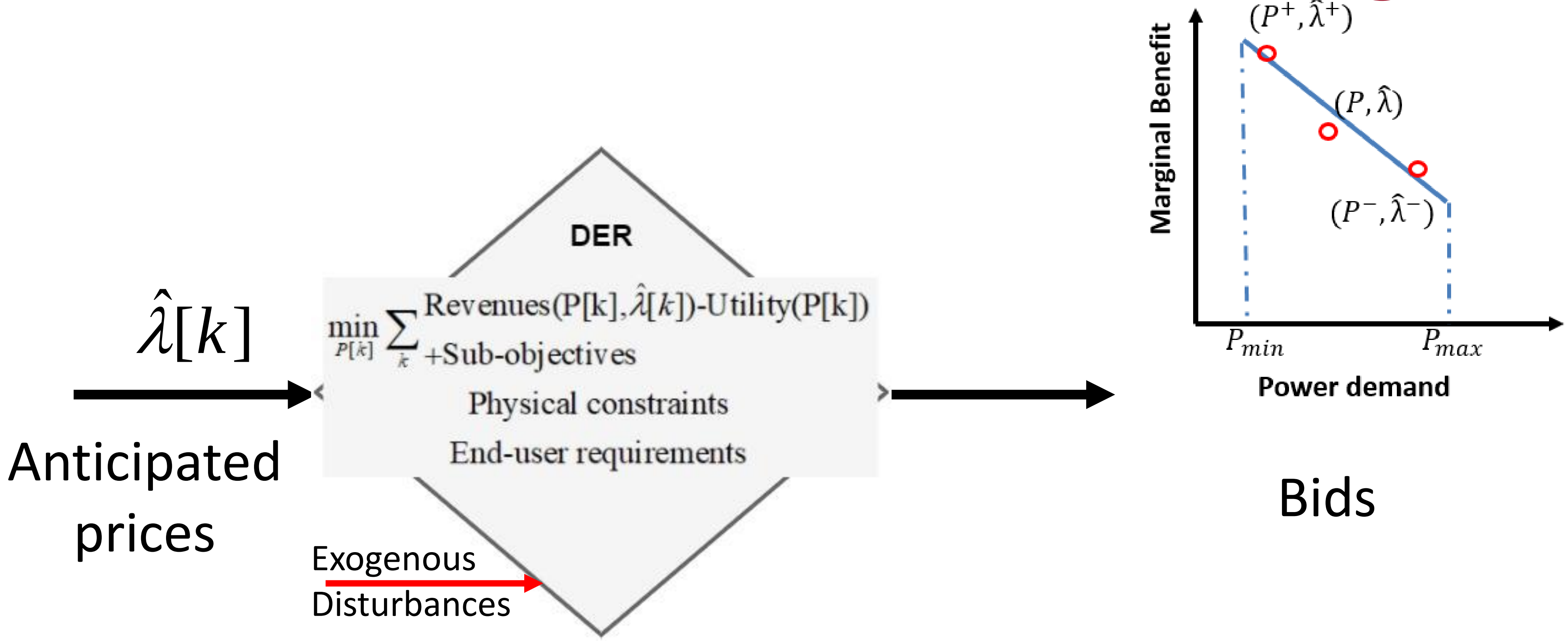
# Distribution system coordination

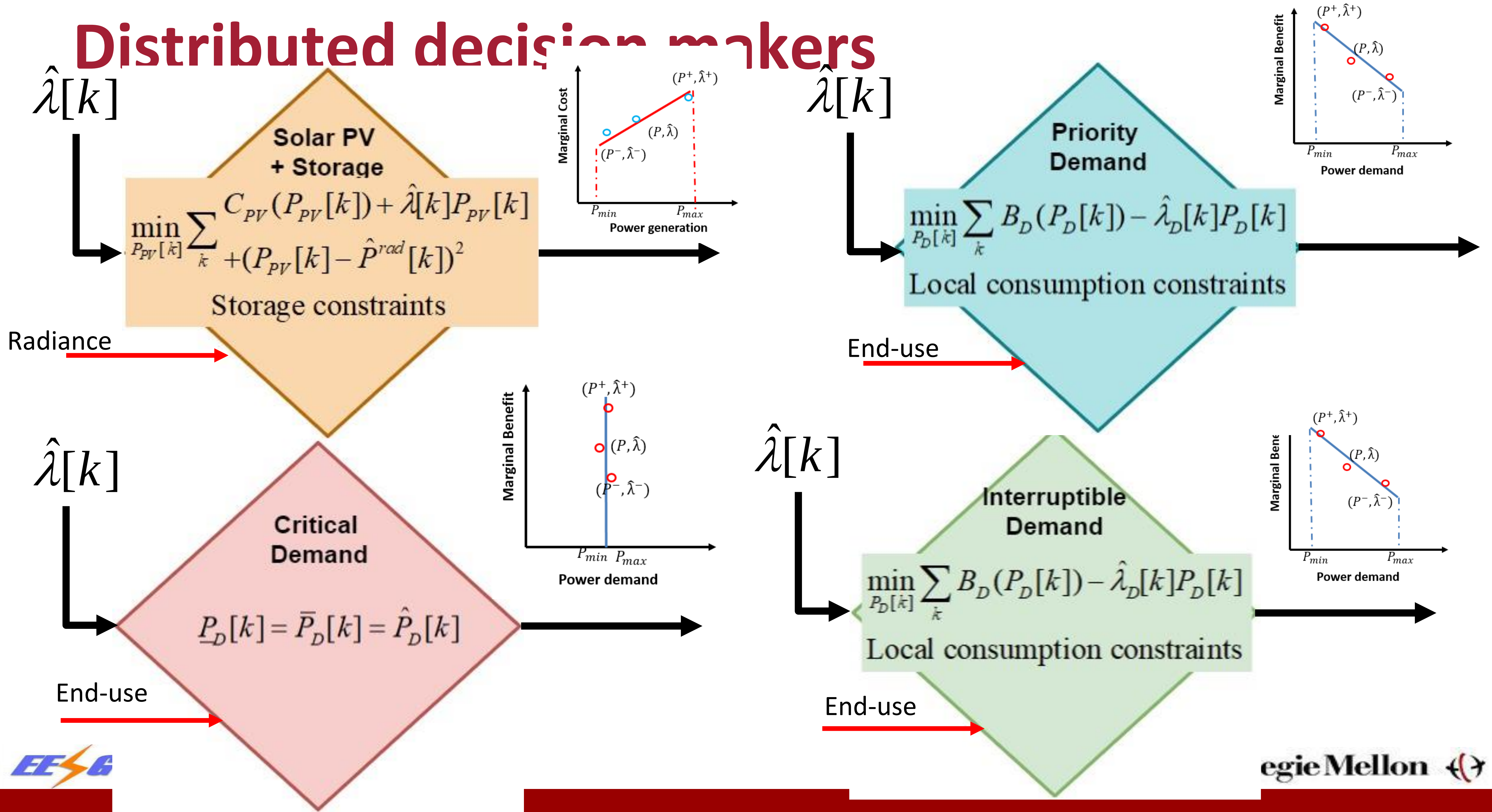
Microgrid coordination



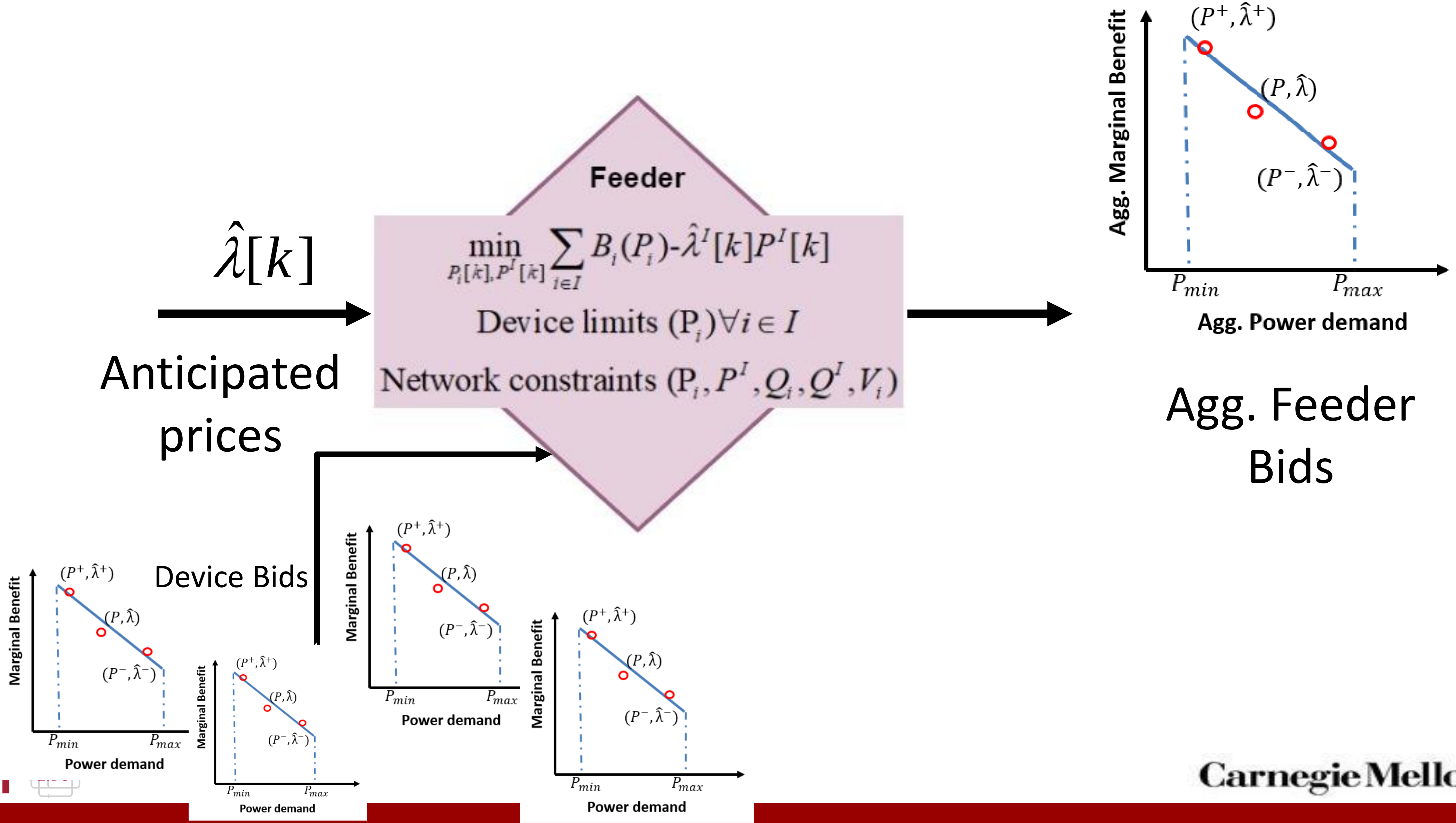
# General distributed agent decision making

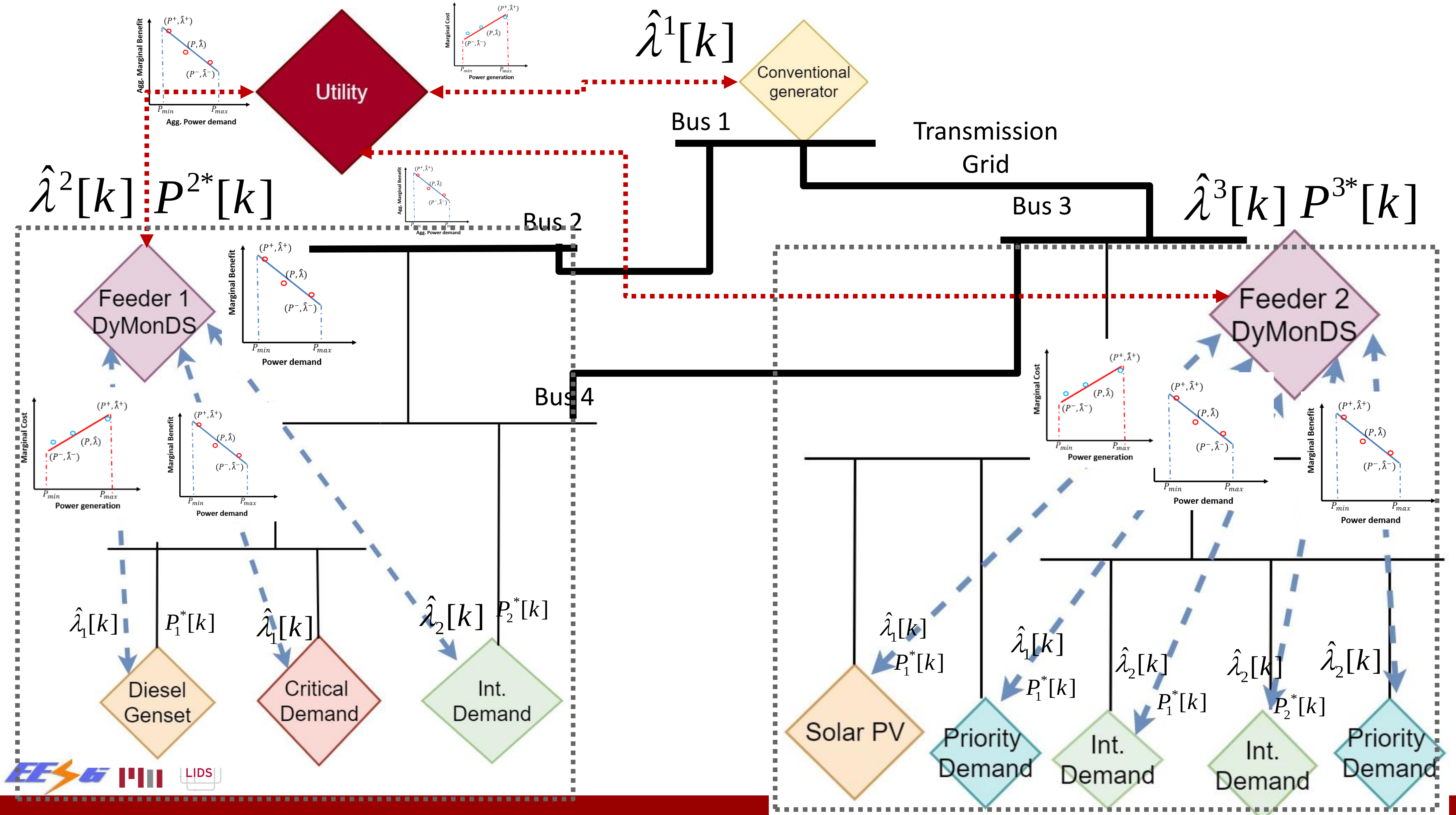


# Distributed decision makers



# Feeder-level decision making





Utility
Conventional generator
$\hat{\lambda}^1[k]$
Bus 1
Transmission Grid
Bus 2
Bus 3
Bus 4
$\hat{\lambda}^2[k]$ $P^{2*}[k]$
$\hat{\lambda}^3[k]$ $P^{3*}[k]$
Feeder 1 DyMonDS
Feeder 2 DyMonDS
Agg. Marginal Benefit
Agg. Power demand
Marginal Cost
Power generation
Marginal Benefit
Power demand
$(P^+,\hat{\lambda}^+)$
$(P,\hat{\lambda})$
$(P^-,\hat{\lambda}^-)$
$P_{min}$
$P_{max}$
$\hat{\lambda}_1[k]$
$P_1^*[k]$
$\hat{\lambda}_2[k]$
$P_2^*[k]$
Diesel Genset
Critical Demand
Int. Demand
Solar PV
Priority Demand
Int. Demand
Int. Demand
Priority Demand
LIDS

# Next Generation SCADA

- Supports two (multi)-level decision making in the changing electric energy industry; it lends itself to non-convex dual optimization solutions to spatial and temporal integration
- Natural alignment of economic incentives, efficient scheduling and end user choice
- Can be used for establishing standards protocols and giving the right incentives
- Next step– distributed management of uncertainty
- Lower layer specifications must be defined in terms of common technology-agnostic variables

# Next steps: Can begin to quantify and innovate at value

- Large scale technologies vs. large number of small scale technologies
- Distributed choice vs. coordination
- Efficiency vs reliability/resiliency
- Best practices vs.  Innovative solutions
- Predictable vs. intermittent
- Component level vs. balancing authorities vs system level standardization
- Storage vs. smarts
- Security vs. open access systems
- Climate vs. cost