The Future of Electric Power Grid

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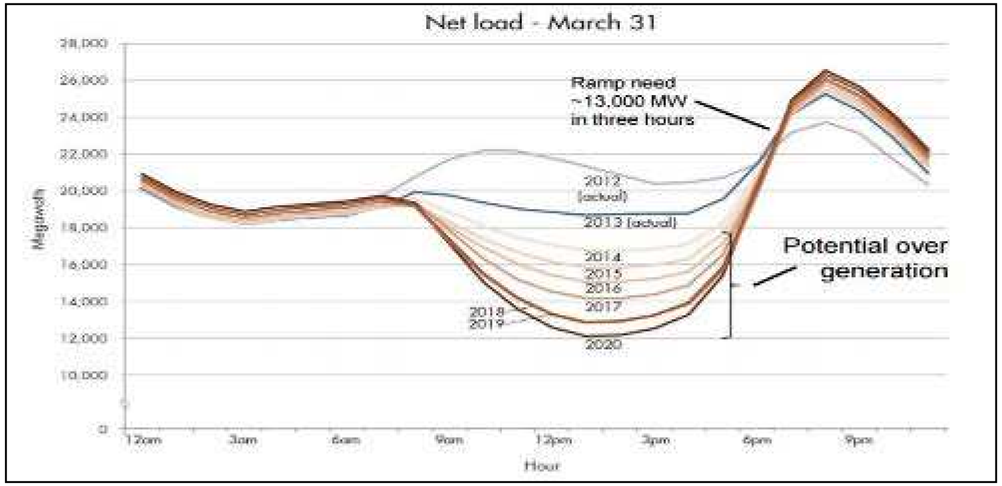
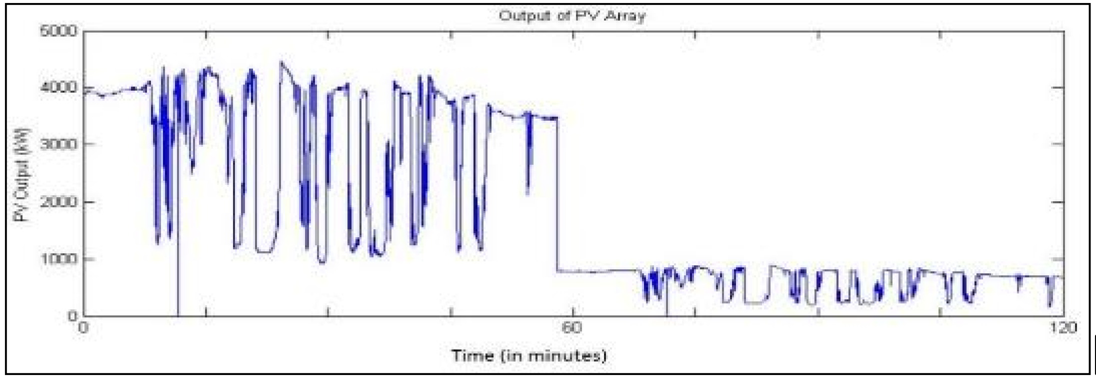
New operations and market problems



[1]



[2]

Increased ramp (flexibility) requirement due to :

(a)wind integration

(b)High solar PV penetration

❖New operating problem:

❖Balance supply-demand in near real-time in systems with renewables

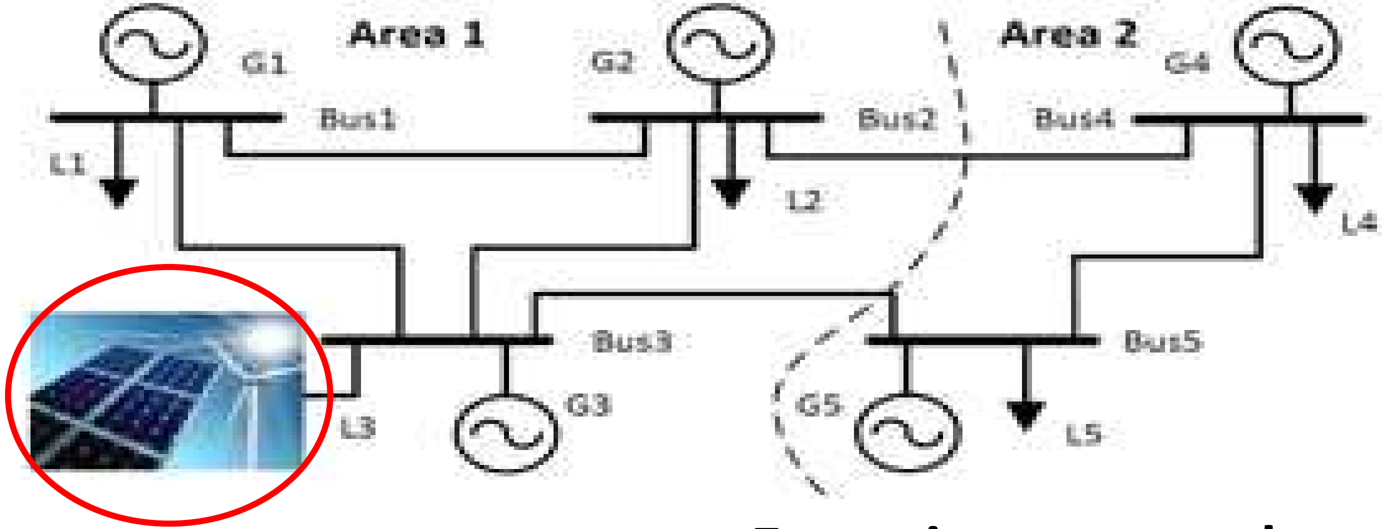
❖New market problem:

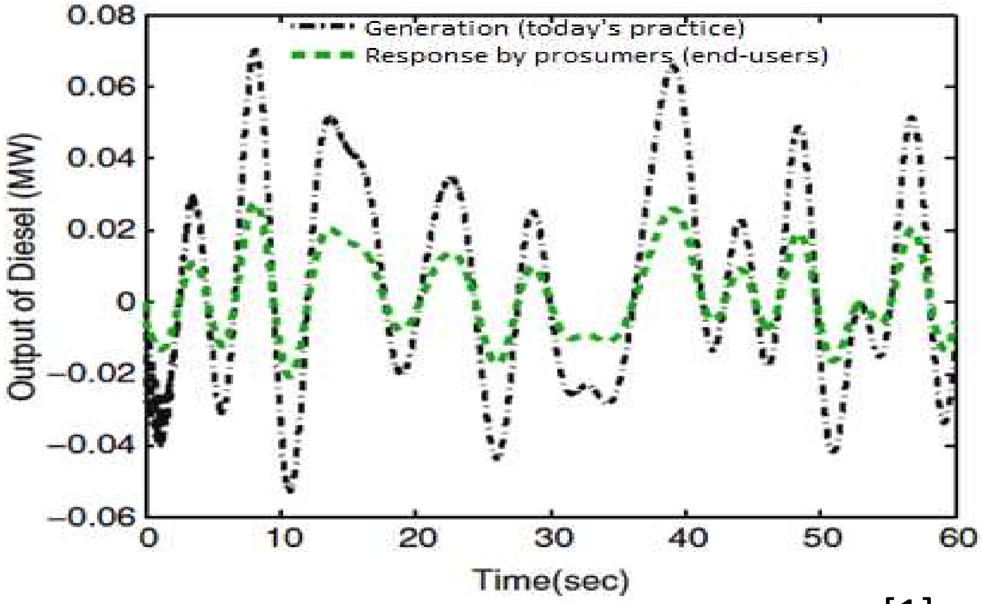
❖Provide price incentives for fast responding generation and demand

California ISO (2016) What the duck curve tells us about managing a green grid Calif. ISO, Shap. a Renewed Futur, pp.1-4

Salcedo, R.O., Nowocin, J.K., Smith, C.L., Rekha, R.P., Corbett, E.G., Limpaecher, E.R. and LaPenta, J.M. (2016) Development of a real-time Hardware-in-the-Loop power systems simulation platform to evaluate commercial microgrid controllers (No. TR-1203). Massachusetts Inst of Tech Lexington Lincoln lab.

Different ways of balancing supply-demand





[1]

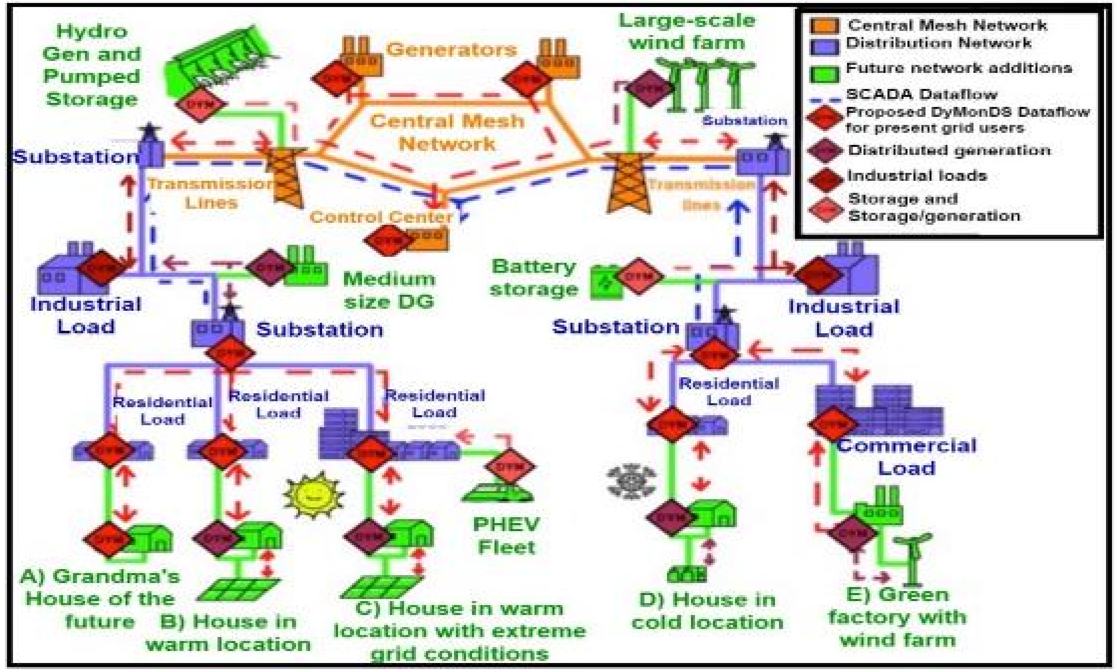
Microgrid/ Aggregate of Prosumers

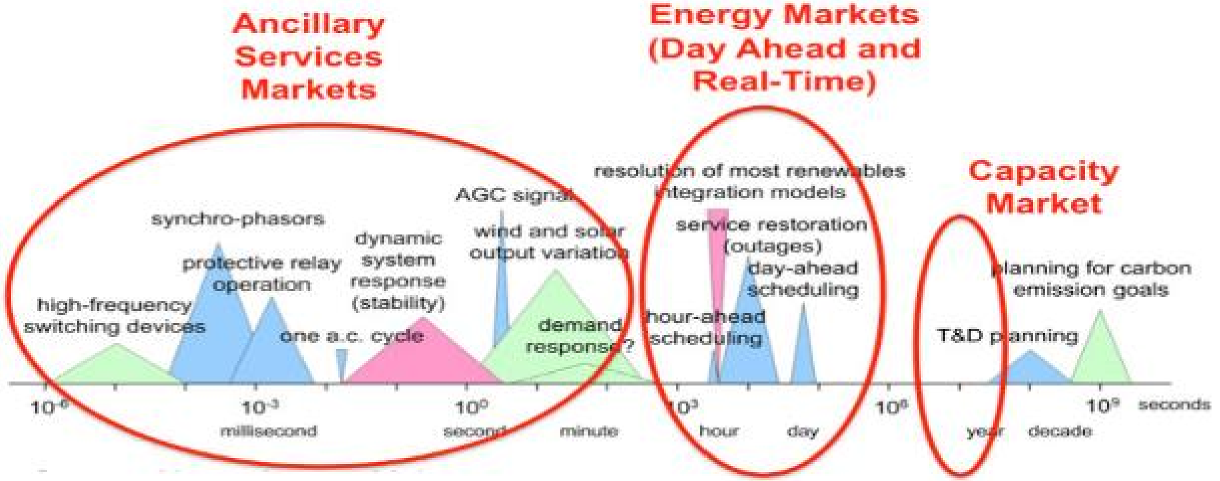
Excessive wear and tear

Much less fast generation required

Value of fast flexible end-user response

Roadblocks to prosumer integration





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

Need for next generation SCADA (architectures)

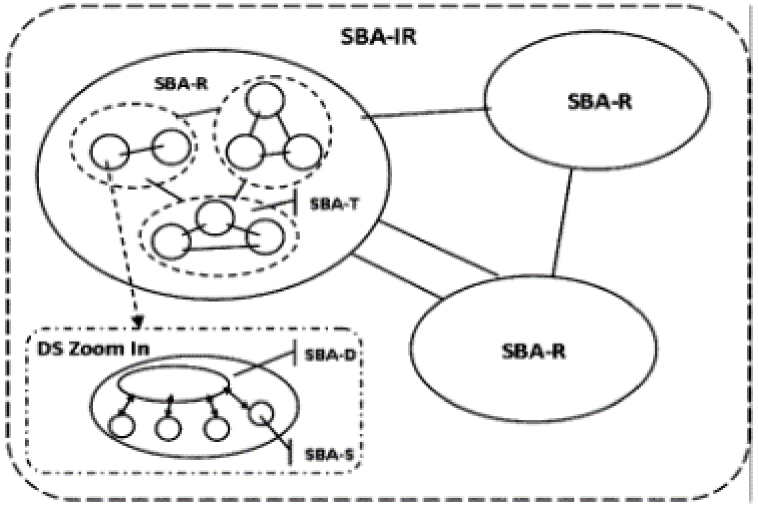
Challenges and opportunities*

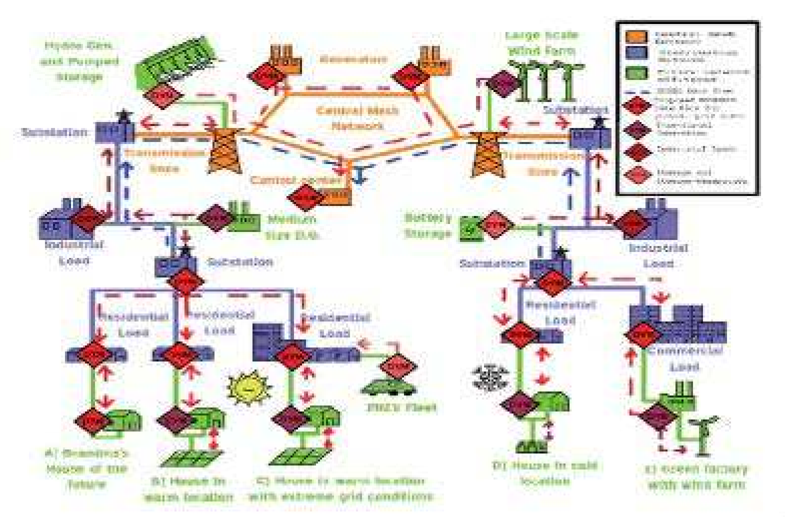
- ***Technical challenges:*** Design high tech operating technology (OT) and integrate it with information technology (IT) to enable energy services: efficient in normal operation; reliable/resilient during extreme events (disasters, cyber-attacks).
- ***Business challenges***: No legal, political nor economic incentives for investment in OT/IT for secure and reliable energy services.
- ***Technical opportunities***: Major innovation, high tech jobs.
- ***Business opportunities: a) for utilities*** *(high tech energy services business at value);* ***b) for vendors*** *(massive development and deployment of OT/IT infrastructures;* ***c) for electric energy users*** *(energy services at value).*

Ilic, Marija, Toward a Unified Modeling and Control for Sustainable and Resilient Electric Energy Systems, Foundations and Trends in Electric Energy Systems,Vol. 1, No. 1 (2016) 1–14, DOI 10.1561/3100000002

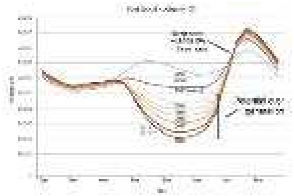
Emerging needs

- New architectures (nested, multi-layered)
- Operations and planning – data-enabled interactive decisions Multiple heterogeneous decision makers (physics, sub-objectives);
- Multiple granularity, temporal and spatial; intermittent
- Need for decision tools at different system layers and for their interactions over time and geography
- Lack of well-defined protocols for supporting this process
- Lack of provable software algorithms





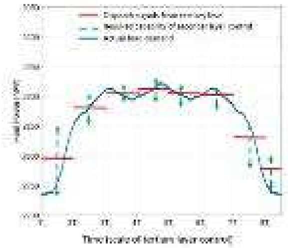
Temporal inter-twining

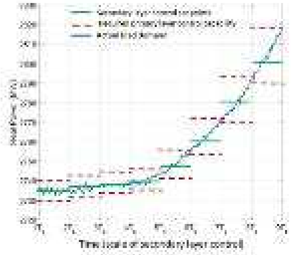


Aggregate effect of solar

Local solar

Hard to predict inputs





Nonzero mean effects

Basic questions: Managing complexity in a provable way

- Distributed algorithms with minimal coordination
- Distributed algorithms which internalize heterogeneous physics; multi-temporal decisions; uncertainties;
- Minimal coordination for near-optimal system level outcomes that accounts for static grid nonlinearities
- Many answer exist under specific assumptions and for specific grid architectures
- Specific to particular use (dispatch; grid management)
- Open question: Can one unify/manage complexity for the general case of non-linear meshed networks with many heterogeneous dynamic decision makers?

Opportunities

❖ **Pro-active use of on-line data for enhanced performance at value**

--Highly dynamic distributed complex networks with many decision makers

--Dynamic Monitoring and Decision Systems (DyMonDS) (Next generation SCADA)

❖ **Efficient supply-demand balancing and delivery in normal operation**

--From off-line worst case reserves to on-line data-enabled flexible utilization

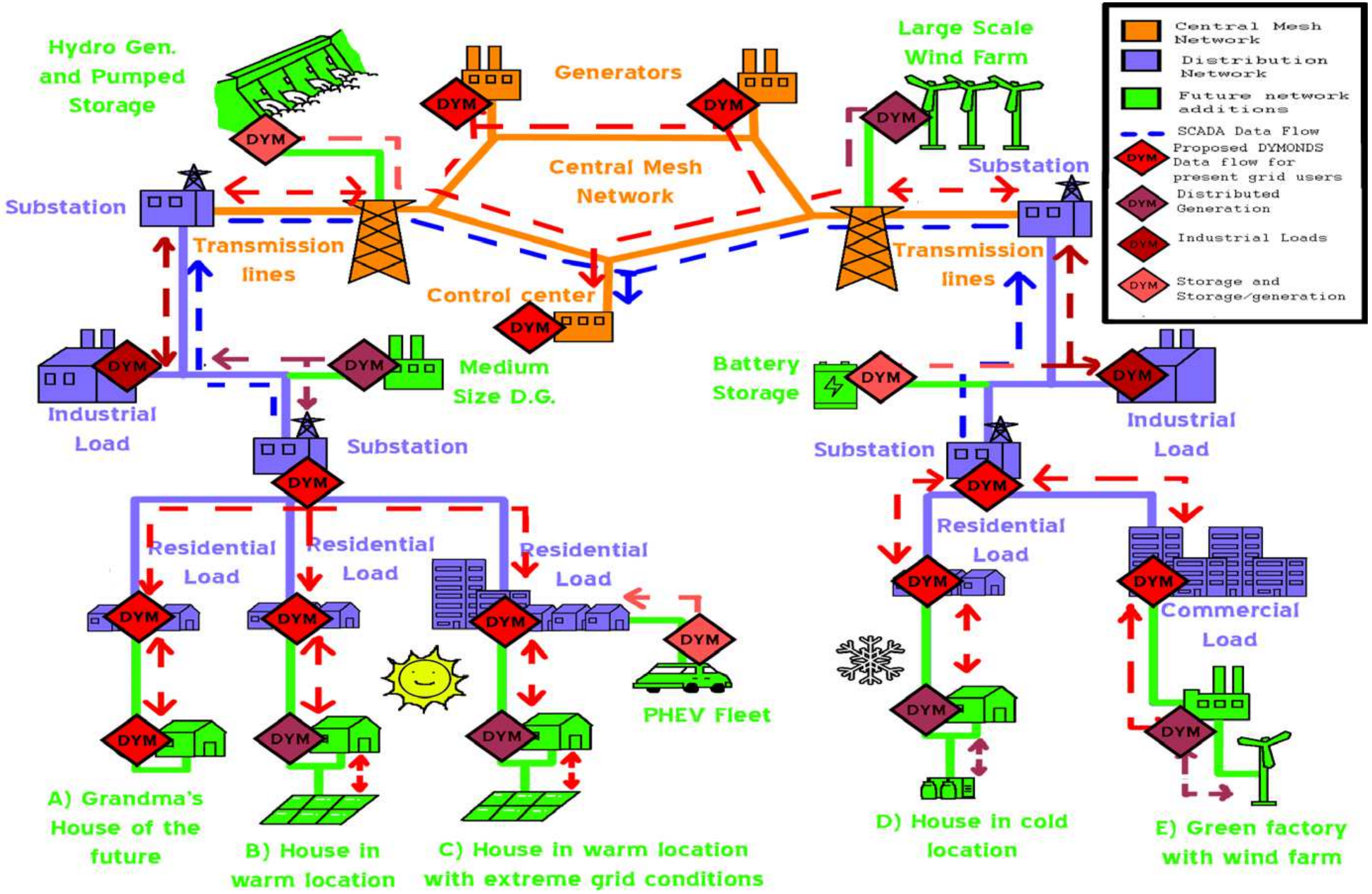
--Interactive power balancing, incl. EVs; Key role of data-enabled delivery (grid control)

❖ **Efficient management of uncertainties in extreme conditions**

--Graceful degradation of service instead of wide-spread blackouts [6]

--Resilient service during extreme events

NEXT GENERATION SCADA—
Dynamic Monitoring and Decision Systems (DyMonDS)



Challenges—It may not work!

- **Sensing, communications, control technologies mature**

- **Missing piece of the puzzle: Integration framework for aligning end users, resources and governance system**

- **Multi-layered interactive data-enabled (Internet-like) protocols**

-- Highly distributed decision makers

--Minimal coordination of interactions

- **Design and demonstration of end-to-end next generation SCADA (DyMonDS); co-design on today's BPS SCADA**

Back to basics--Overcoming complexity by systematic modeling

- Functions of distributed decision makers as well as the objectives of higher level aggregating entities can be established using a unifying modeling energy-based framework.
- An outgrowth of specifications/standards used today for AGC)
- Possible to operate the system by specifying performance in terms of ACE-like variables, now for all iBAs and over a stratum of temporal horizons.
- The technical challenge: Extension of ACE

Unifying energy-based modeling of dynamics

- ❖ Component level (module, S within the SoS)
- ❖ Interactive model of interconnected systems
- ❖ Model-based system engineering (MBSE)—

--multi-layered complexity

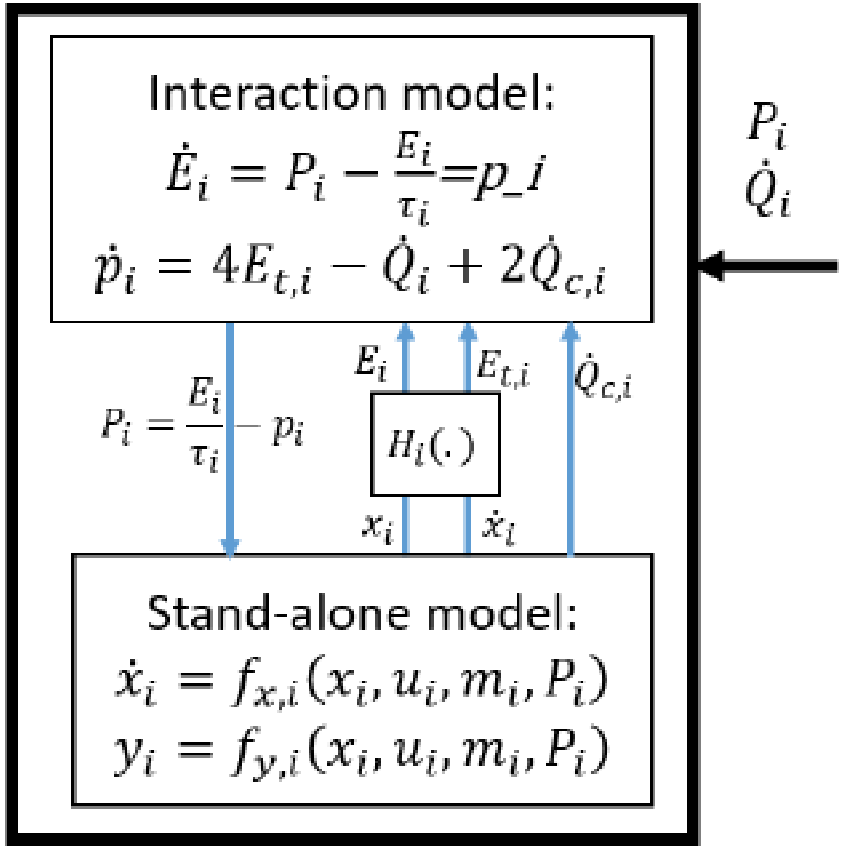
--component (modules) – designed by experts for common specifications (energy; power; rate of change of power)

--interactions subject to conservation of instantaneous power and reactive power dynamics; optimization at system level in terms of these variables

--physically intuitive models

Ilić, Marija D., and Rupamathi Jaddivada. "Multi-layered interactive energy space modeling for near-optimal electrification of terrestrial, shipboard and aircraft systems." *Annual Reviews in Control* (2018).

Component-level model in energy space*



Definitions:

Instantaneous Power: $P_i = \langle e_i | f_i \rangle \forall (e_i, f_i) \in \mathcal{E}_i \times \mathcal{F}_i$

Rate of change of Reactive Power: $\dot{Q}_i = \langle e_i | \dot{f}_i \rangle - \langle f_i | \dot{e}_i \rangle$

Stored energy: $E_i = H_i(x_i)$

Stored energy in tangent space: $E_{t,i} = H_i(\dot{x}_i)$

Dissipated energy: $D_i = B_i(x_i)$

Time constant: $\tau_i = \frac{E_i(x_i)}{D_i(x_i)}$

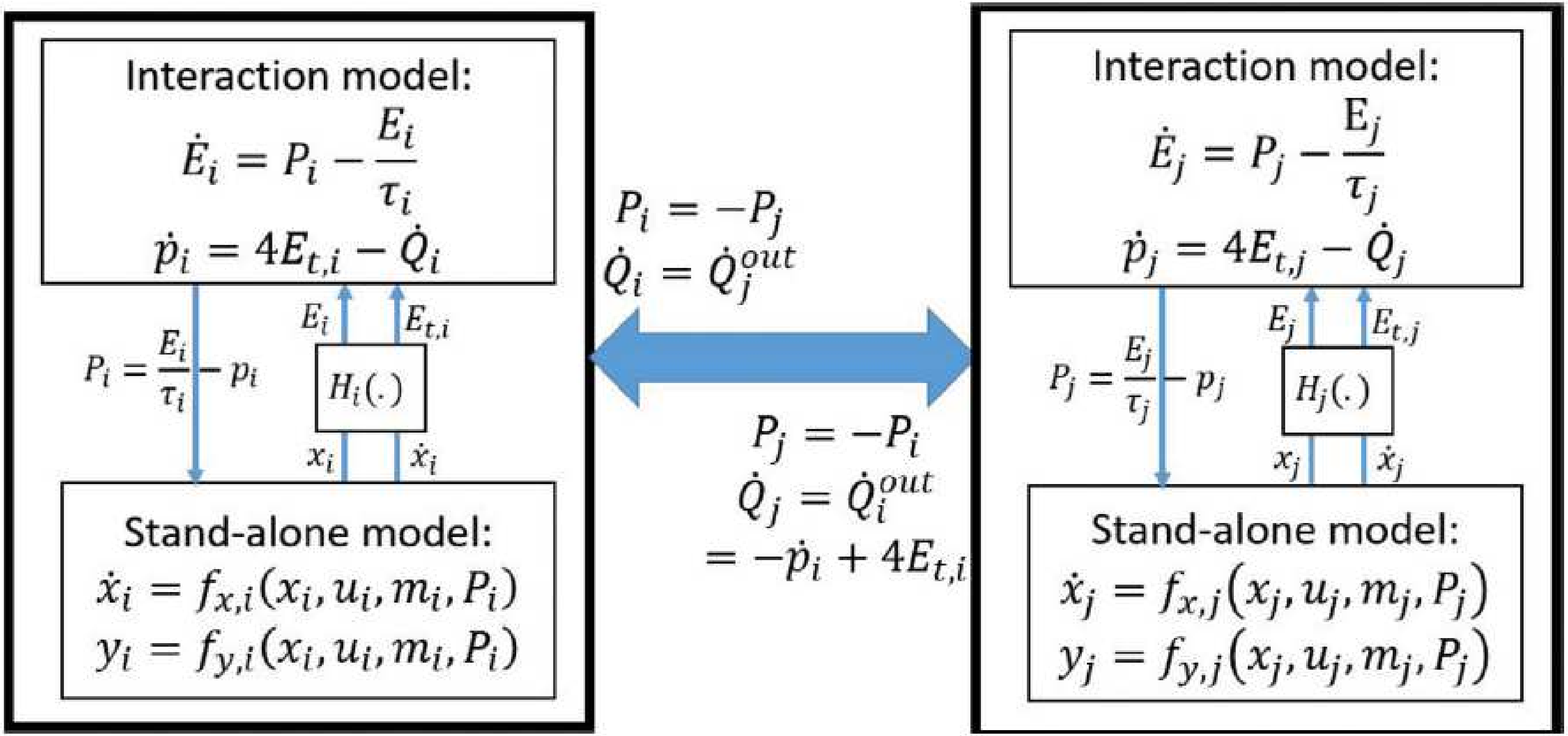
Capacitive Reactive Power prodution: $\dot{Q}_{c,i} = \langle e_{j,i} | \dot{f}_{j,i} \rangle - \langle f_{j,i} | \dot{e}_{j,i} \rangle$

$\forall e_{j,i}, f_{j,i} \subseteq \mathcal{X}_i; j \in \mathcal{C}_i$ – capacitive elements in sub-system i

$E_{t,i}$ = Rate of change of component exergy

$\dot{Q}_i - 2\dot{Q}_{c,i}$ = Rate of change of component anergy

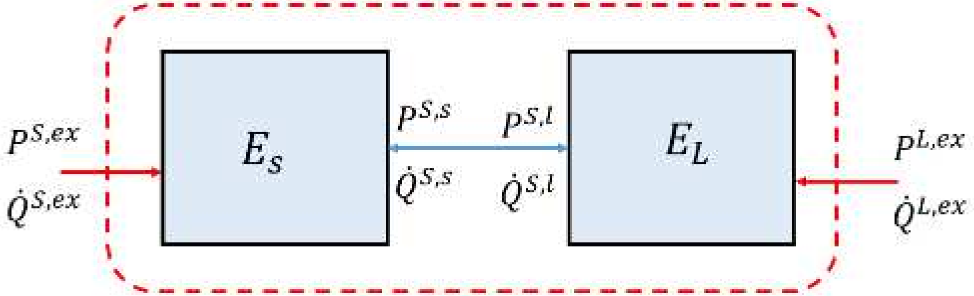
MBSE in energy space --Multi-layered interactive model



Optimization in energy space

- Optimization problems for coordinating iBAs become linear convex optimization problems in the energy space
- Optimizers (aggregators, ISOs, markets) to find the best values from the range specified by the iBAs.
- Win-win protocol
- The protocol is a win-win protocol, since all entities operate within the ranges they selected. If it is not possible to find feasible soluthese primal-dual optimization protocols in energy space can be mapped into corresponding pricing.

Centralized optimization problem formulation in energy space



$$\min_{\substack{P^{S,s}(t),P^{S,l}(t),\dot{Q}^{S,s}(t),\\ \dot{Q}^{S,l}(t),E_t^{S,s}(t),E_t^{S,l}(t)}} \int_0^t \dot{Q}^{S,s}(\tau)^2 + \dot{Q}^{S,l}(\tau)^2 d\tau$$

Constraint Set 2:
Source Interaction dynamics:

$$\dot{E}_s(t) = p_s(t) =$$
$$= P^{s,s}(t) + P^{s,ex}(t) - \frac{E_s(t)}{\tau_s}$$
$$\dot{p}_s(t) = 4E_{t,s}(t) - \dot{Q}^{s,g}(t) - \dot{Q}^{s,ex}(t)$$

$$P^{S,s}(t) = P_s(t); Q^{S,s}(t) = Q_s(t)$$
$$E_{t,s} = E_s(\dot{x}_s)$$

Constraint set 1:
Interconnection constraints:

$$P^{s,g} + P^{L,g} = 0$$
$$\dot{Q}^{s,g} + \dot{Q}^{L,g} = 0$$

Dissipativity constraint

$$\dot{P}^{s,ex} + \dot{P}^{L,ex} \leq \frac{\dot{E}_s}{\tau_s} + \frac{\dot{E}_L}{\tau_L}$$

Real and Reactive Power Limits

$$P^{g,min} \leq P^{S,g} \leq P^{g,max}$$
$$P^{l,min} \leq P^{S,l} \leq P^{l,max}$$
$$\dot{Q}^{g,min} \leq \dot{Q}^{S,g} \leq \dot{Q}^{g,max}$$
$$\dot{Q}^{l,min} \leq \dot{Q}^{S,l} \leq \dot{Q}^{l,max}$$

Constraint Set 3:
Load Interaction dynamics:

$$\dot{E}_l(t) = p_l(t) =$$
$$= P^{s,l}(t) + P^{l,ex}(t) - \frac{E_l(t)}{\tau_l}$$
$$\dot{p}_l(t) = 4E_t^l(t) - \dot{Q}^{s,l}(t) - \dot{Q}^{L,ex}(t)$$

$$P^{S,l}(t) = P_l(t); Q^{S,l}(t) = Q_l(t)$$
$$E_{t,l} = E_l(\dot{x}_l)$$

Constraint set 4:
Source Stand-alone Component dynamics:

$$\dot{x}_s(t) = f_{x,s}(x_s(t), u_s(t), P_s(t))$$
$$y_s(t) = f_{y,s}(x_s(t), u_s(t), P_s(t), \dot{Q}_s(t))$$
$$u_s^{min} \leq u_s(t) \leq u_s^{max}$$
$$y_s^{min} \leq y_s(t) \leq y_s^{max}$$

Constraint set 5:
Load Stand-alone Component dynamics:

$$\dot{x}_l = f_{x,l}(x_l, u_l, P_l)$$
$$y_l = f_{y,l}(x_l, u_l, P_l, \dot{Q}_l)$$
$$u_l^{min} \leq u_l \leq u_l^{max}$$
$$y_l^{min} \leq y_l \leq y_l^{max}$$

$$\forall t \in [0, \infty)$$

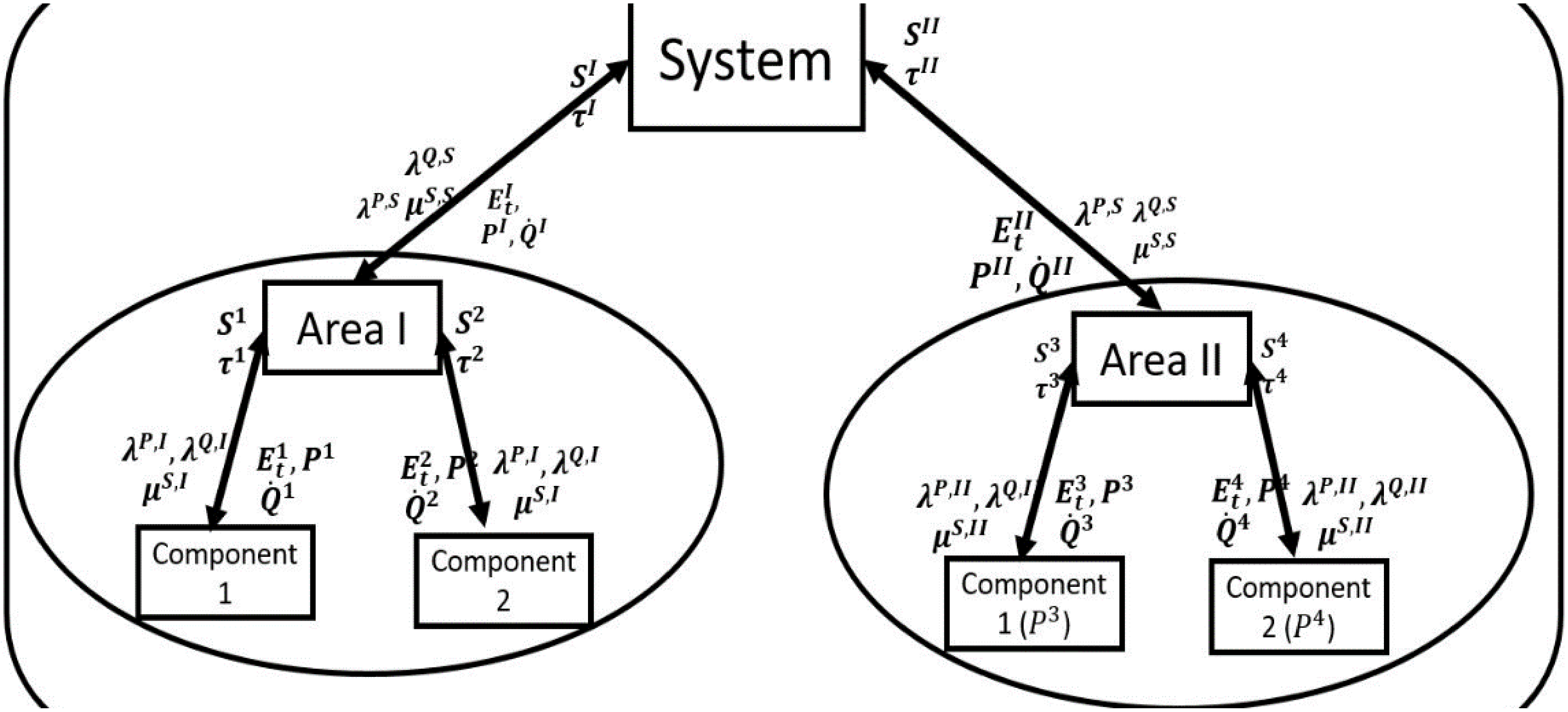
Dynamic Monitoring and Decision Systems (DyMonDS)-- ALIGNING ARCHITECTURE AND OPERATING PARADIGM

Multi-layered modular interactive modeling, simulation and cyber design framework.

In terrestrial power systems this means having smarts embedded in very complex loads, wires, storage, power plants, and having minimal coordination of energy/power/rate of change of power dynamics monitored/control at the interfaces of layers.

- **Azores Islands project** (long-term cost effective, near-zero emission systems) –Springer book

Aligning physics and dollars (markets)



ECE/CS PROBLEM:
Embedded IoT/ML/AI computer platforms?

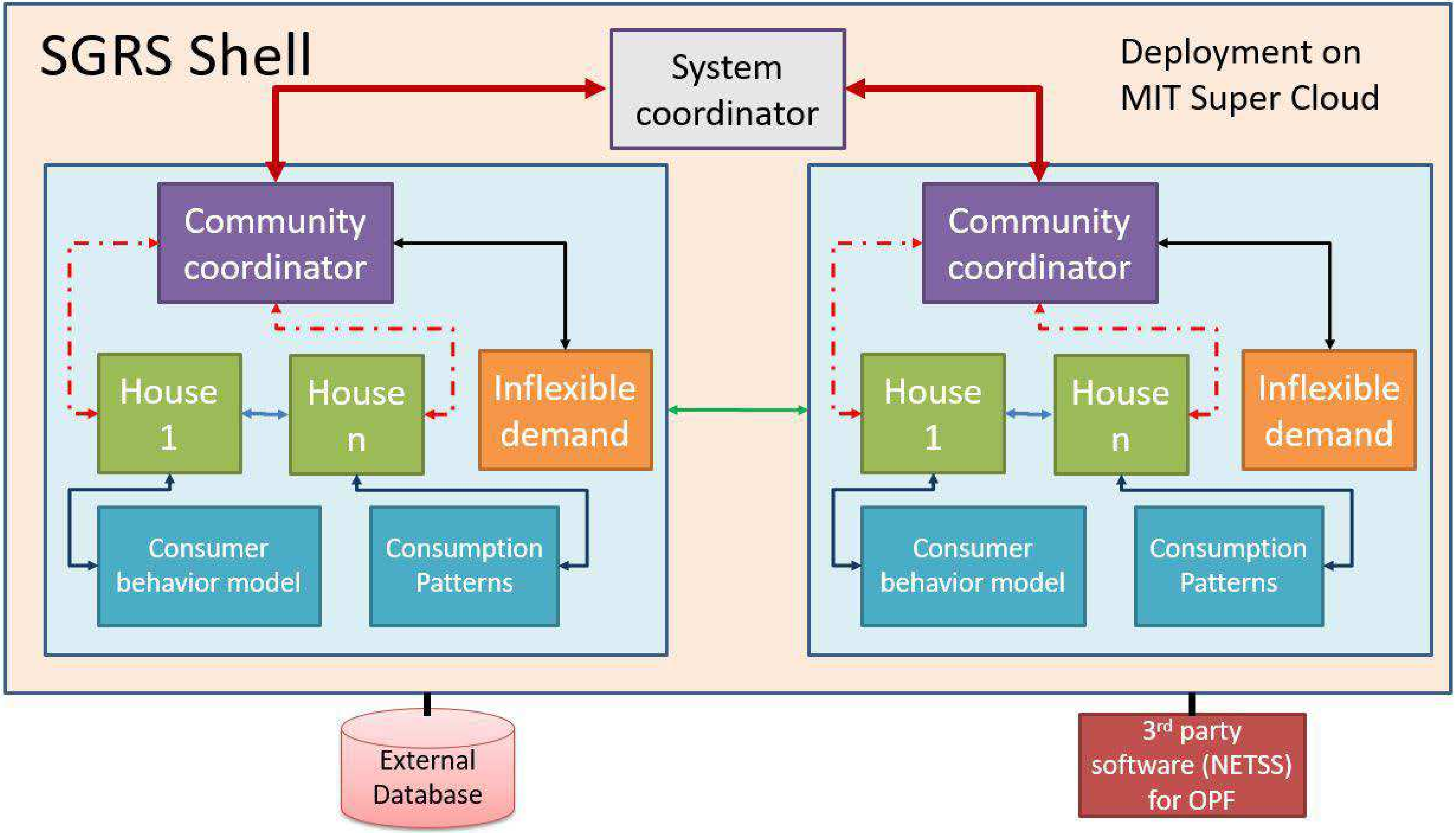


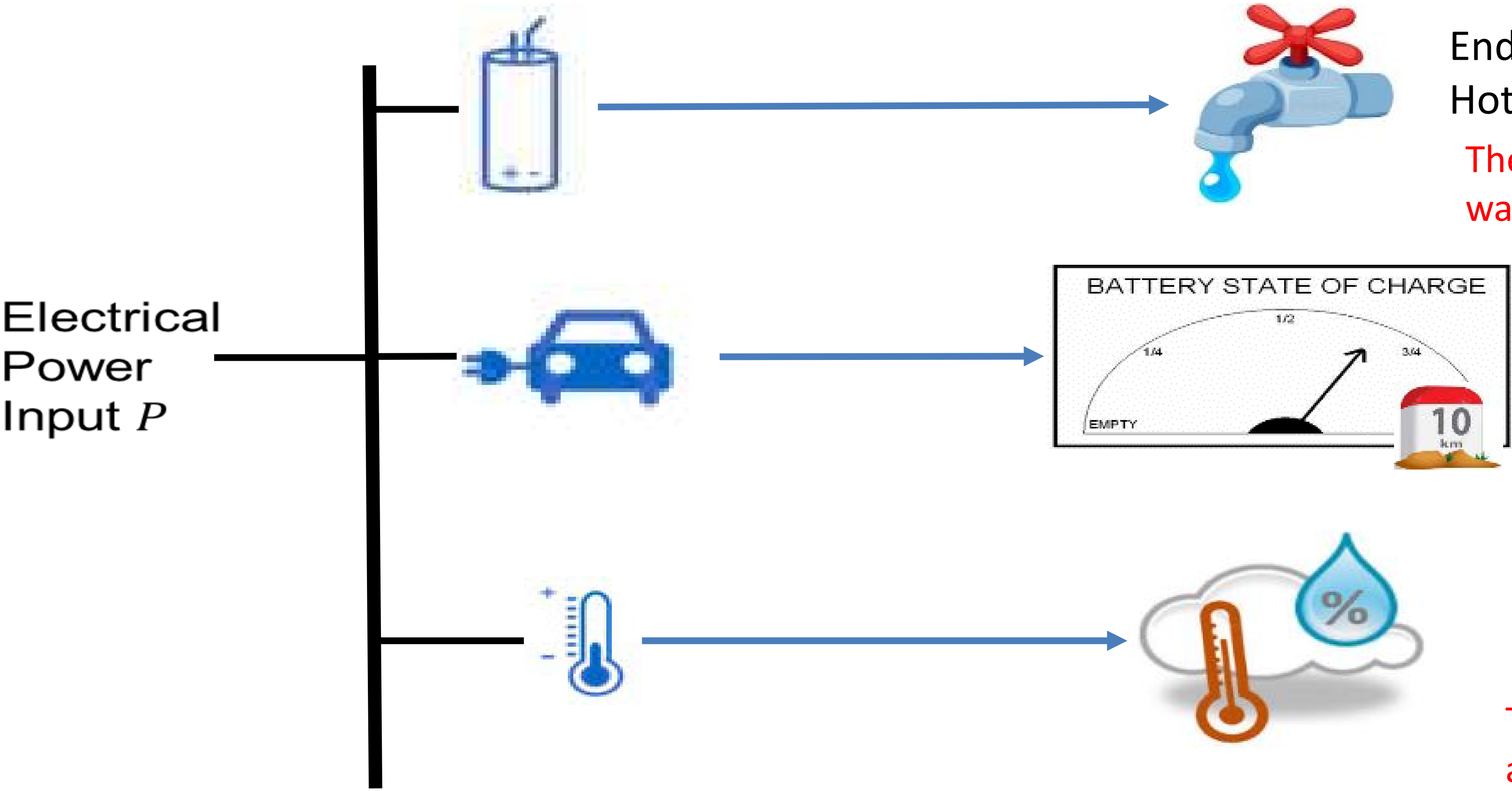
Illustration:ITenabled approach to prosumer participation

- Common energy-based modeling of heterogeneous prosumers

Understood by engineers and economists !

- Unified specifications
  - For operations: $(E, P, \dot{P})_{T_\alpha}$ triplet for operation
  - For markets: Bids for each of the triplet $\lambda(E, P, \dot{P})_{T_\alpha}$
- Modeling and control for implementing prosumer specifications
- Signals for markets and operations aligned!

Technology for implementing prosumer bids



End requirement:
Hot water flow

Thermal/ stored energy in water

End requirement:
SOC sufficient for the ride

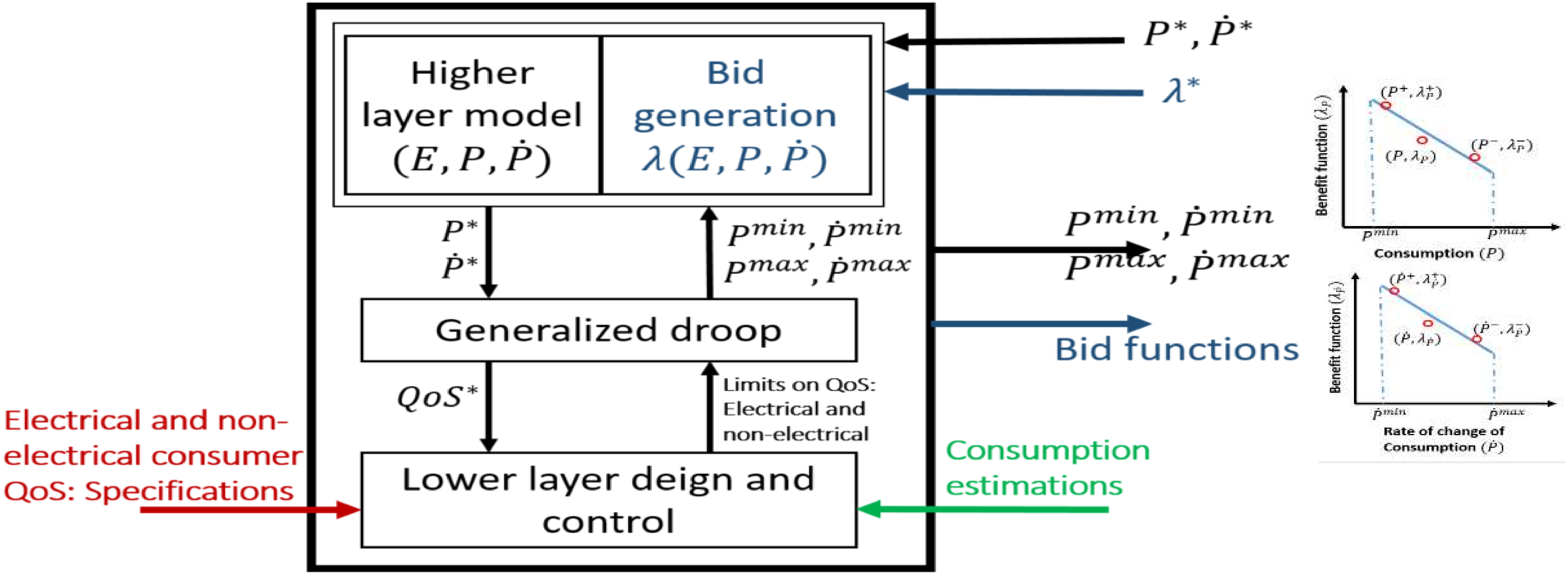
Chemical/ Electrical energy

End requirement:
Hot/cold air

Thermal/ stored energy in air

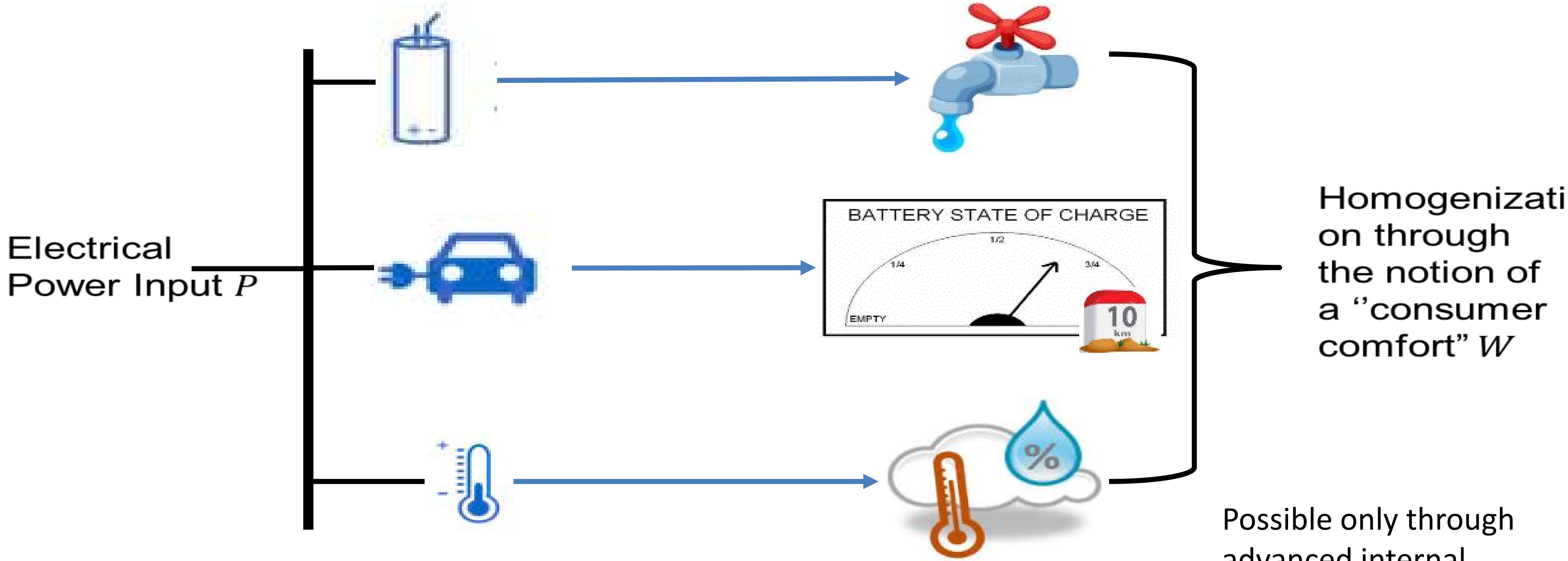
Different energy domain makes modeling for assuring provable grid side performance while satisfying end-use requirements a difficult task!

Energy-based interactive multi-layered modeling approach



[3] Ilić, M.D. and Jaddivada, R., 2018. Multi-layered interactive energy space modeling for near-optimal electrification of terrestrial, shipboard and aircraft systems. Annual Reviews in Control.

Generalized droops for defining device-level energy flows

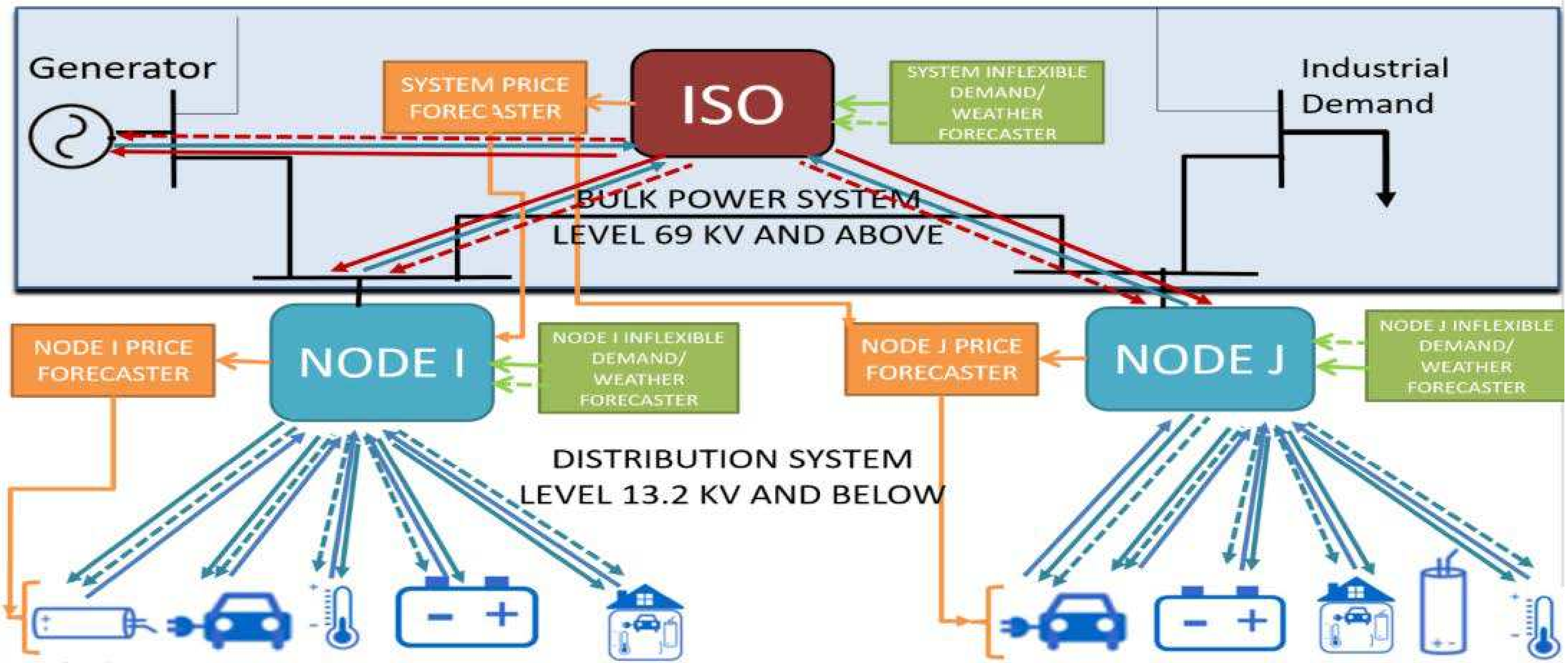


$$P[k+1] - P[k] = \sigma(W[k+1] - W[k])$$

Possible only through advanced internal controllers

Popli, N. , Jaddivada, R., O'Sullivan, F., and Ilić, M.D., 2018. Harnessing Flexibilities of Heterogeneous Generation and Controllable Demand Technologies in System Operation, (To be Submitted to IEEE Transaction on Power Systems)

System level Multi-temporal and Multi-spatial Information Exchange Architecture



Inputs to Coordinators

- Energy & Reserve Cap. Price forecasts
- Inflexible demand forecast
- Energy & Reserve Cap. bids
- Fast deviations of Inflexible demand

Outputs of Coordinators

- Energy & Reserve Cap. Dispatch Within SYSTEM
- Energy & Reserve Cap. Dispatch Within NODE
- Regulation reserve dispatch Within SYSTEM
- Regulation reserve dispatch Within NODE

Information exchange within and across prosumers – Approach 1

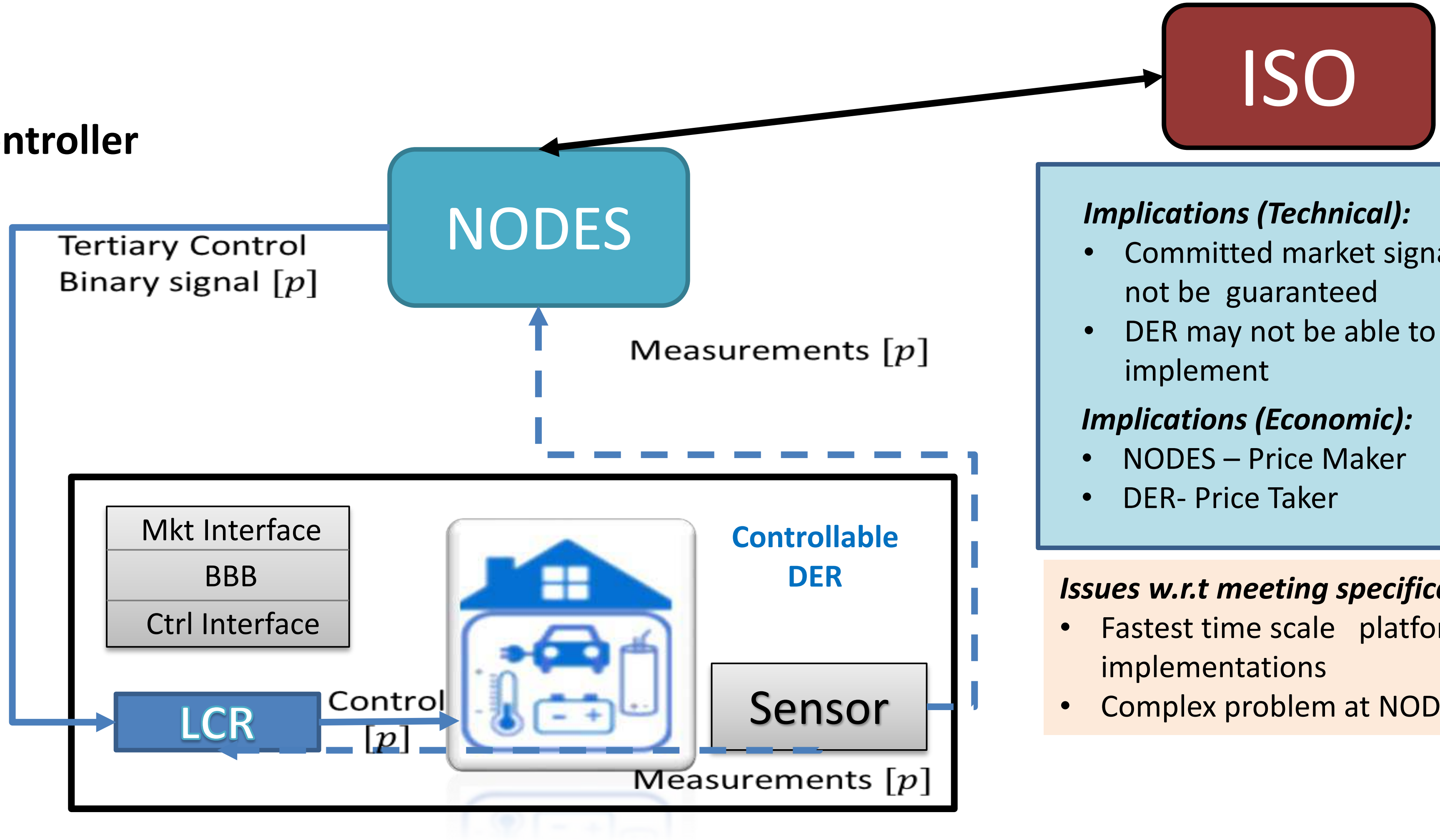
NODES as a Master Controller

Complex optimization solved through ***MINLP*** or queuing theory based

Simplifications:

- Relaxation
- Empirical DER models and approximations

Most Common Approach



Implications (Technical):

- Committed market signals may not be guaranteed
- DER may not be able to implement

Implications (Economic):

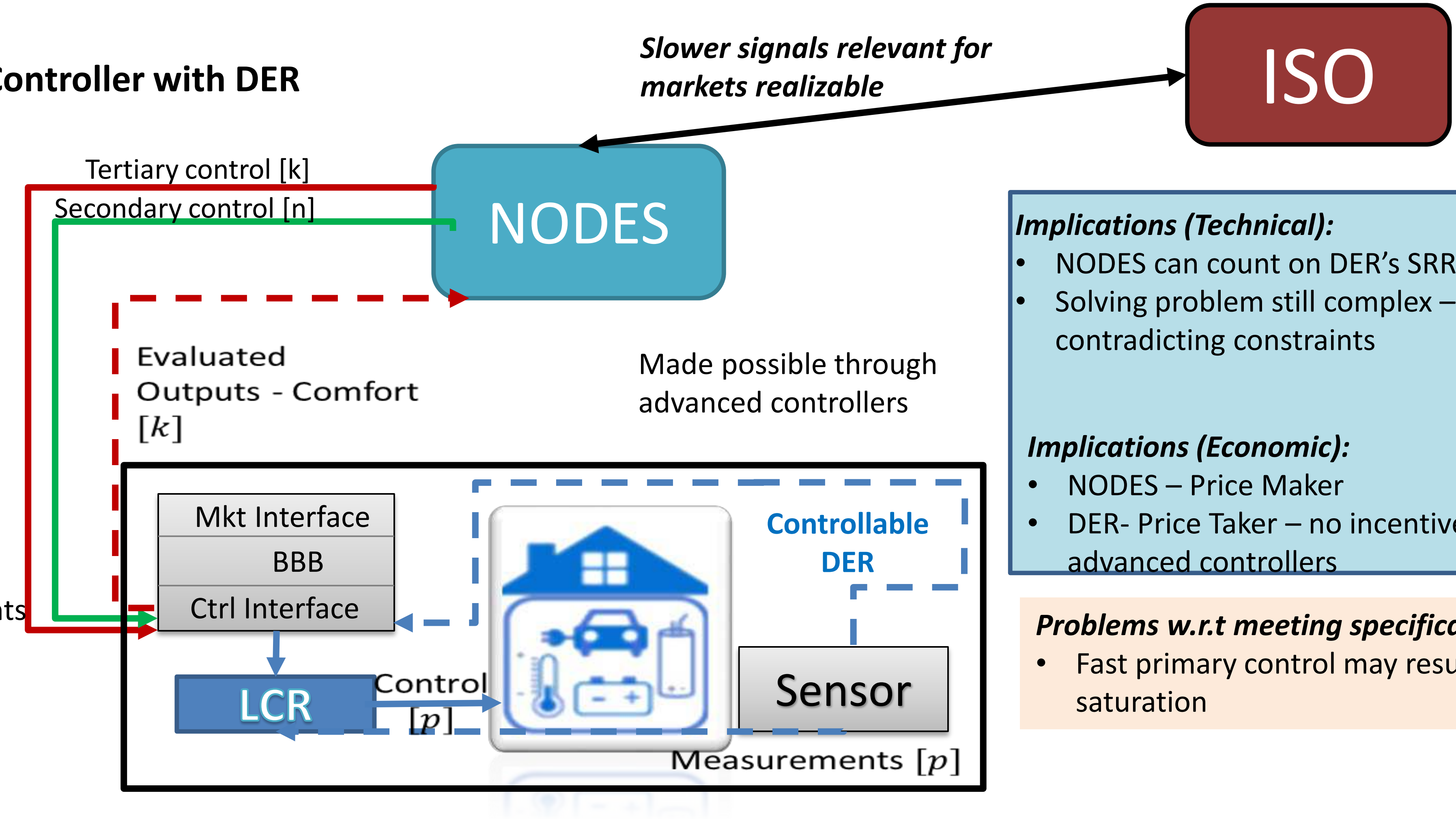
- NODES – Price Maker
- DER- Price Taker

Issues w.r.t meeting specifications:

- Fastest time scale platform implementations
- Complex problem at NODES

Information exchange within and across prosumers – Approach 2

NODES as a master Controller with DER physics internalized



Fast sensor measurements utilized to compensate non-linearities

Implications (Technical):

- NODES can count on DER's SRR provision
- Solving problem still complex – contradicting constraints

Implications (Economic):

- NODES – Price Maker
- DER- Price Taker – no incentive for advanced controllers

Problems w.r.t meeting specifications:

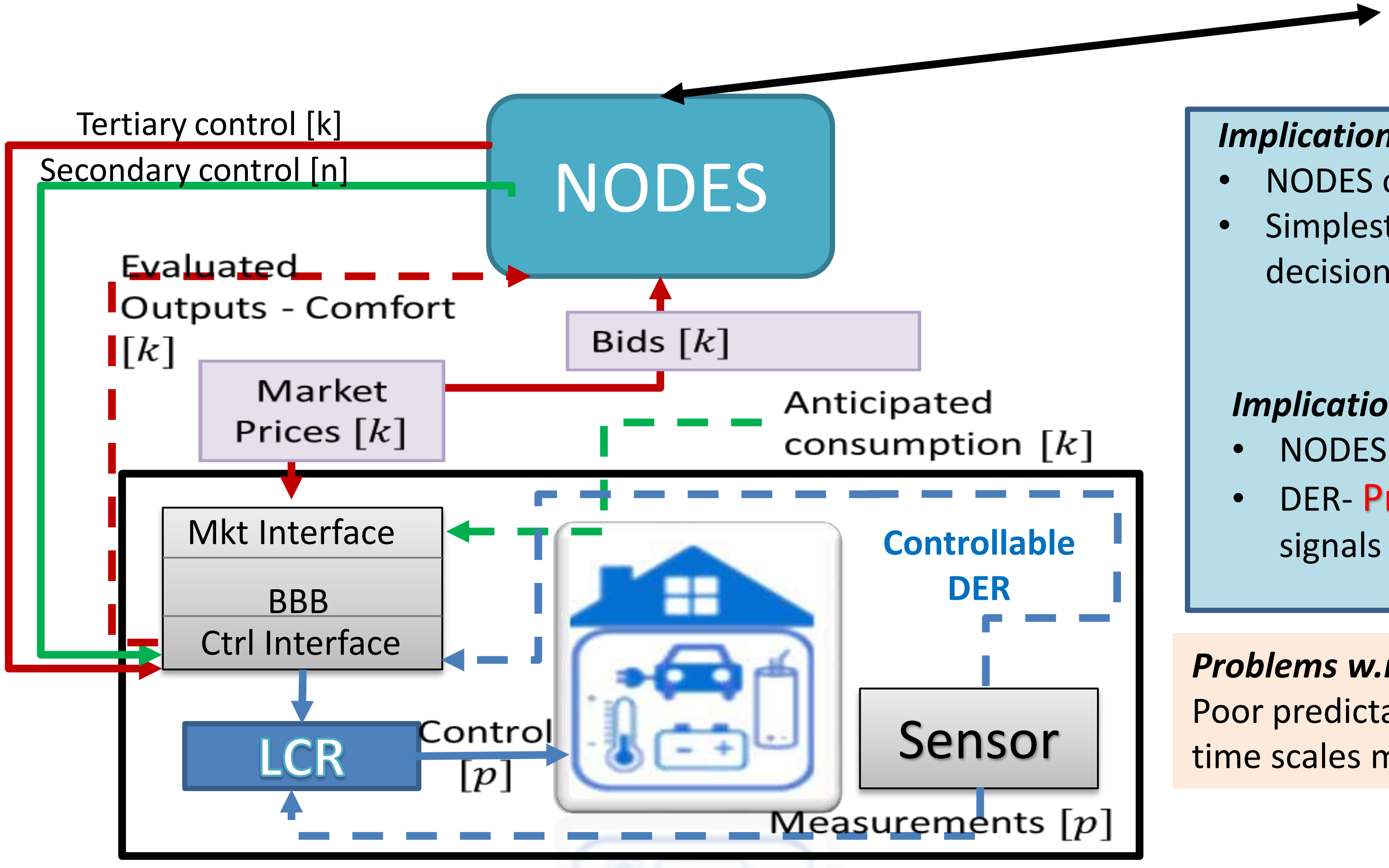
- Fast primary control may result in saturation

Information exchange within and across prosumers – Approach 3

DyMonDS-
NODES and DER distributed decision makers

Market Interface of BBB now is involved in DER decision making

Slower signals relevant for markets realizable

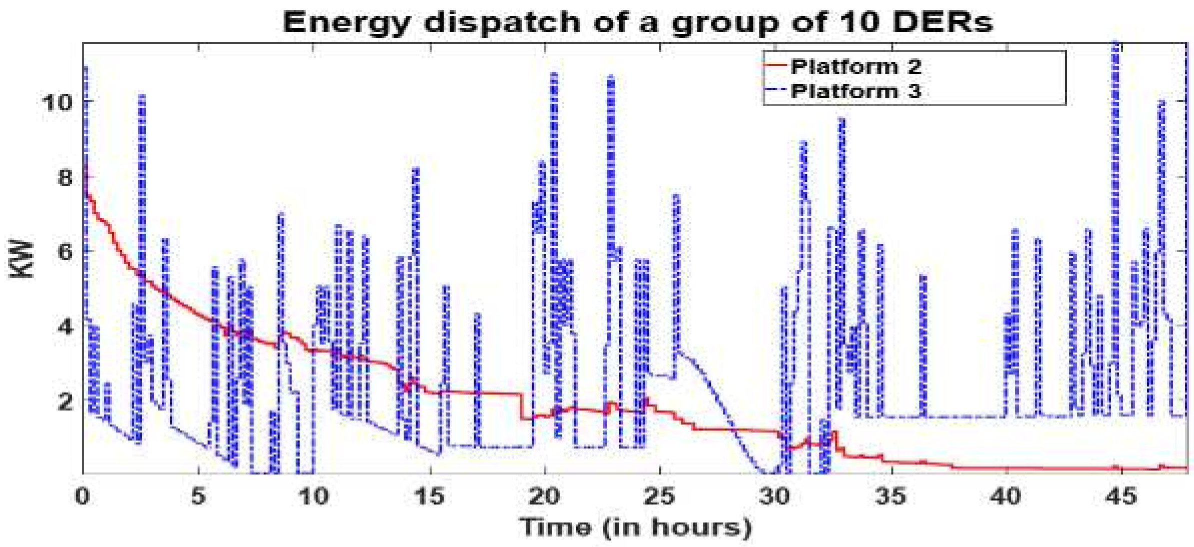


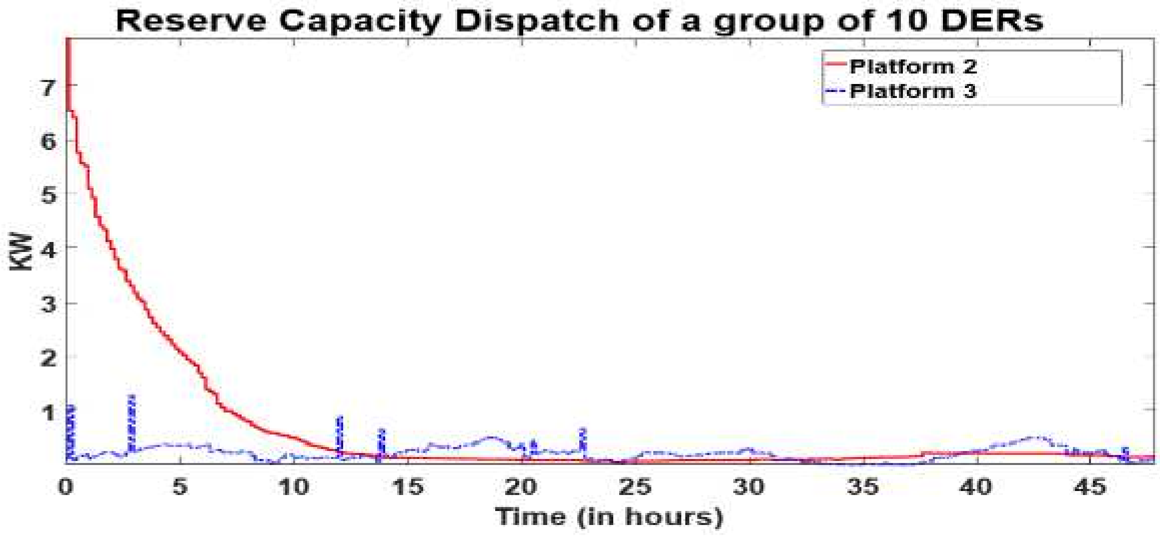
Implications (Technical):
- NODES can rely on DER's SRR provision
- Simplest problem posing at NODES due to decision making embedded in DER

Implications (Economic):
- NODES – Price Maker
- DER- Price Maker – Explicit economic signals for advanced controllers

Problems w.r.t meeting specifications:
Poor predictability of consumptions over faster time scales may cause saturation

Comparison of approaches 2 and 3





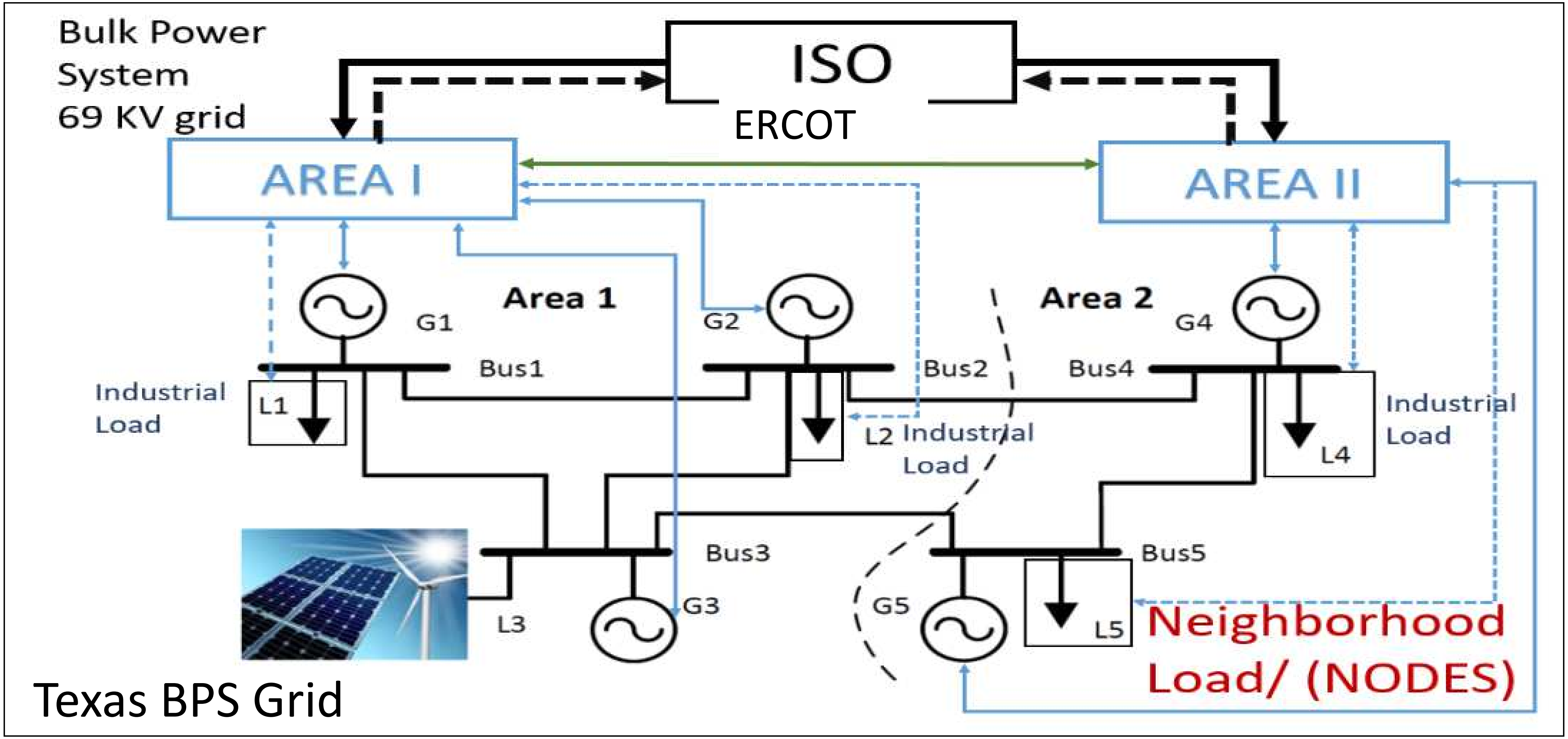
More granular decision making at prosumer level in approach 3 results in possibly larger reserve capacity dispatch and more flexibility in energy adjustment schedules of DERs

Different Implementation Platforms

Approach	Economic	Technical
1	Price Taker	Not realizable
2	Price Taker	Claiming/ not claiming feasibility
3	Price Maker	Claiming feasibility

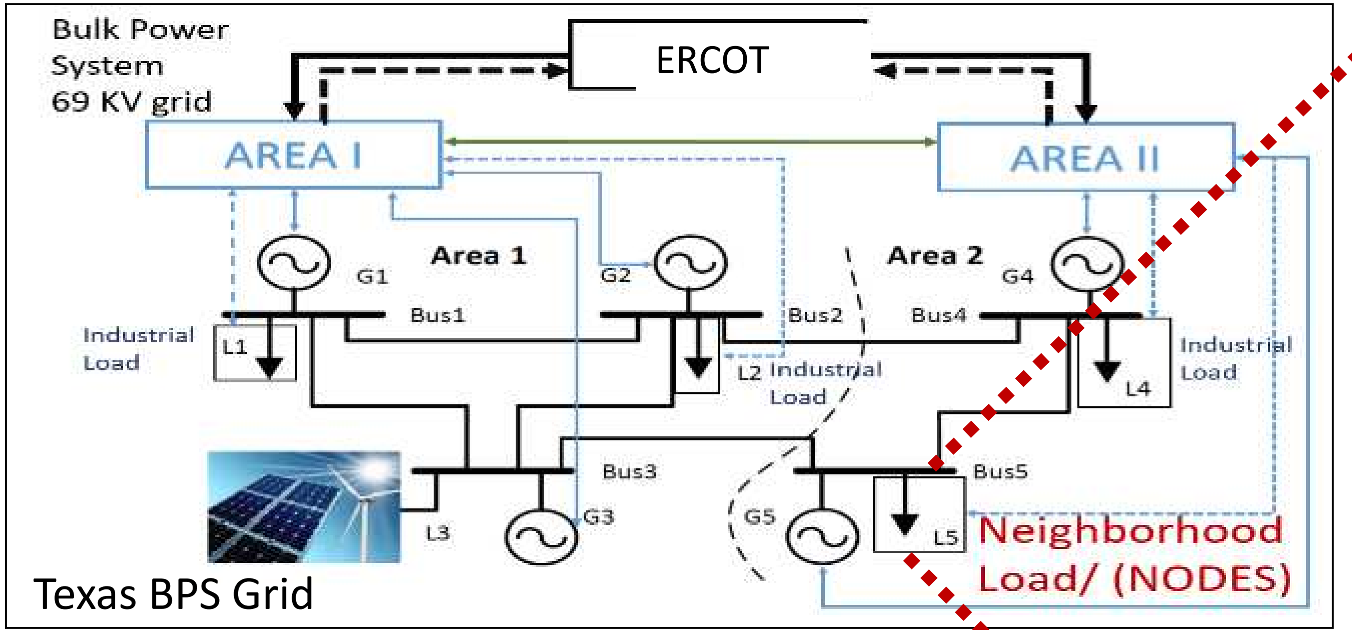
- DER-specific knowledge and its decisions are critical
- Internalizing fast dynamics at component level is important
- DERs' opting out explicitly at value in ***Approach 3 (Inelastic load)***
- **DyMonDS-based Scalable Electric Power System Simulator (SEPSS) – MIT general cloud platform**

Case Study – Test System

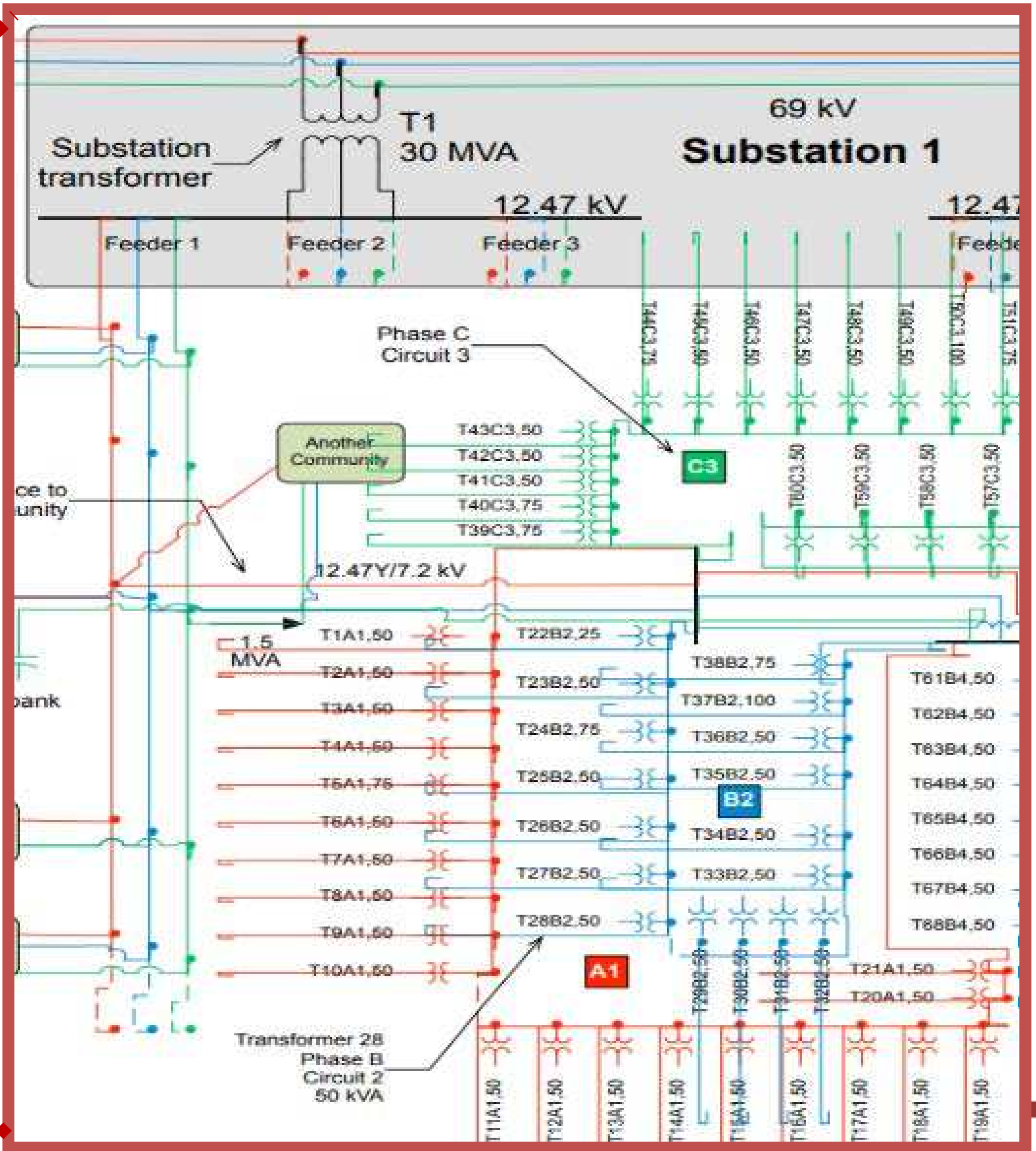


Objective: Enable price-induced participation of DERs in provision of regulation reserves

Case Study – Test System

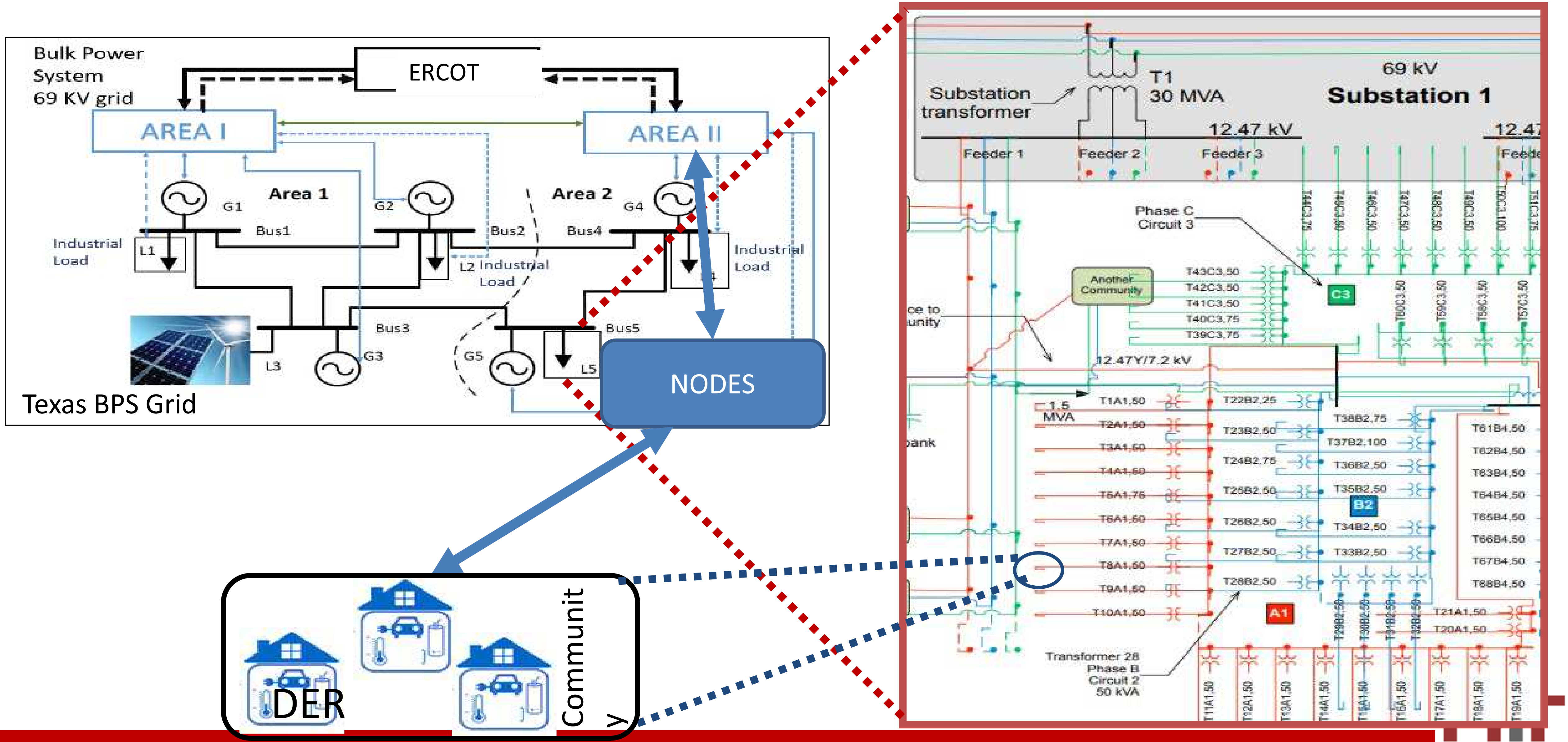


Texas BPS Grid

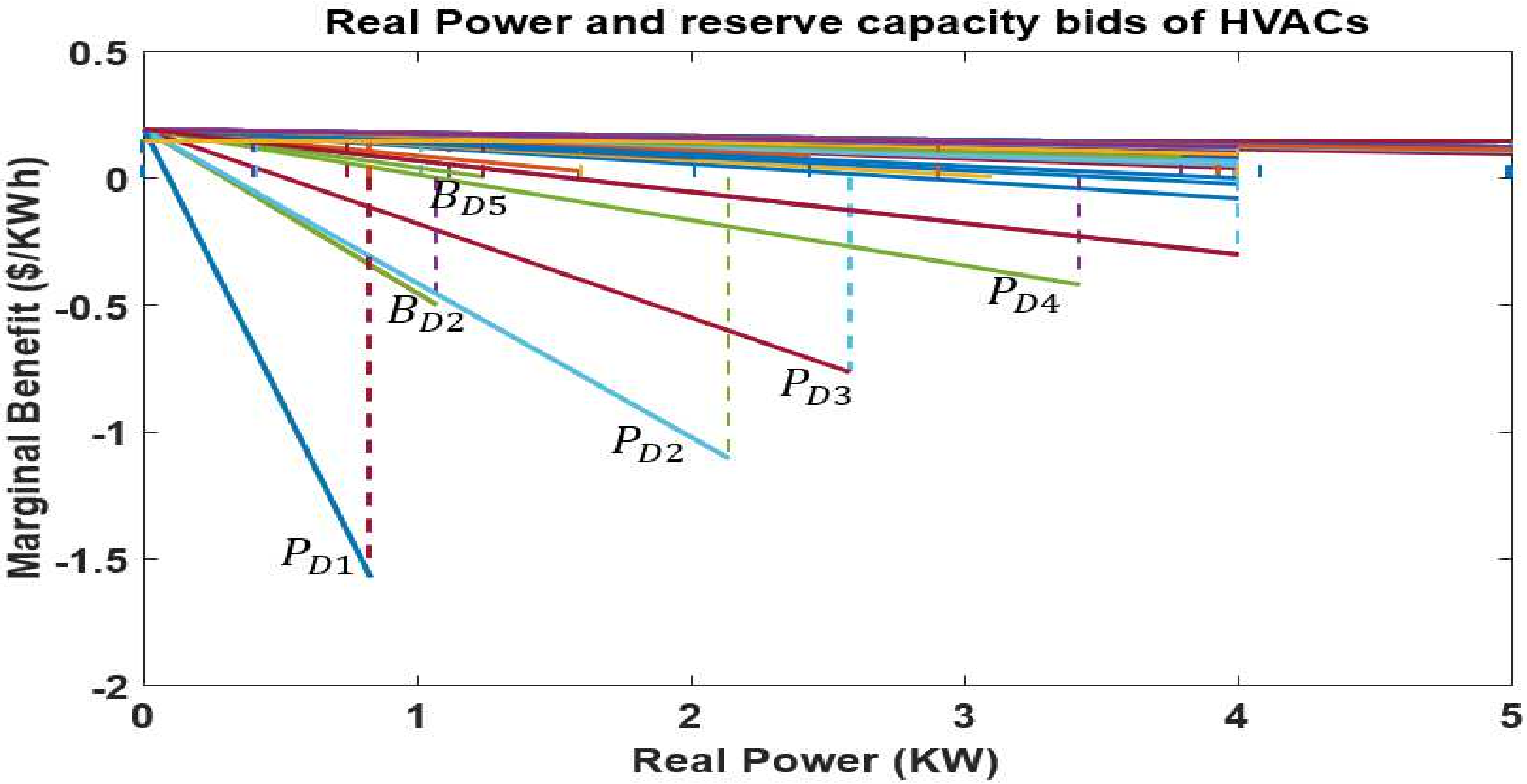


Mueller Community of Pecan Street

Results – simulation of market clearing with approach 3 using Pecan street data

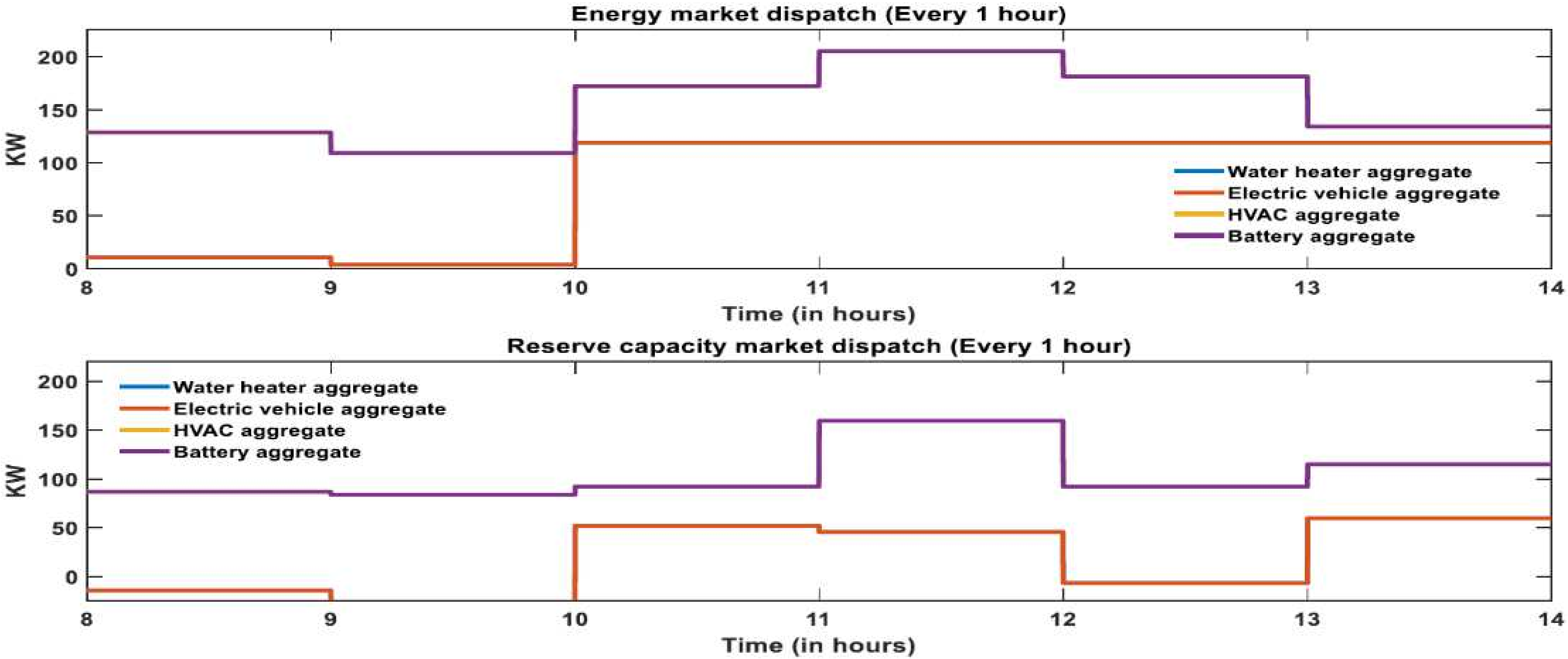


Results – Example of time-varying bids of HVAC

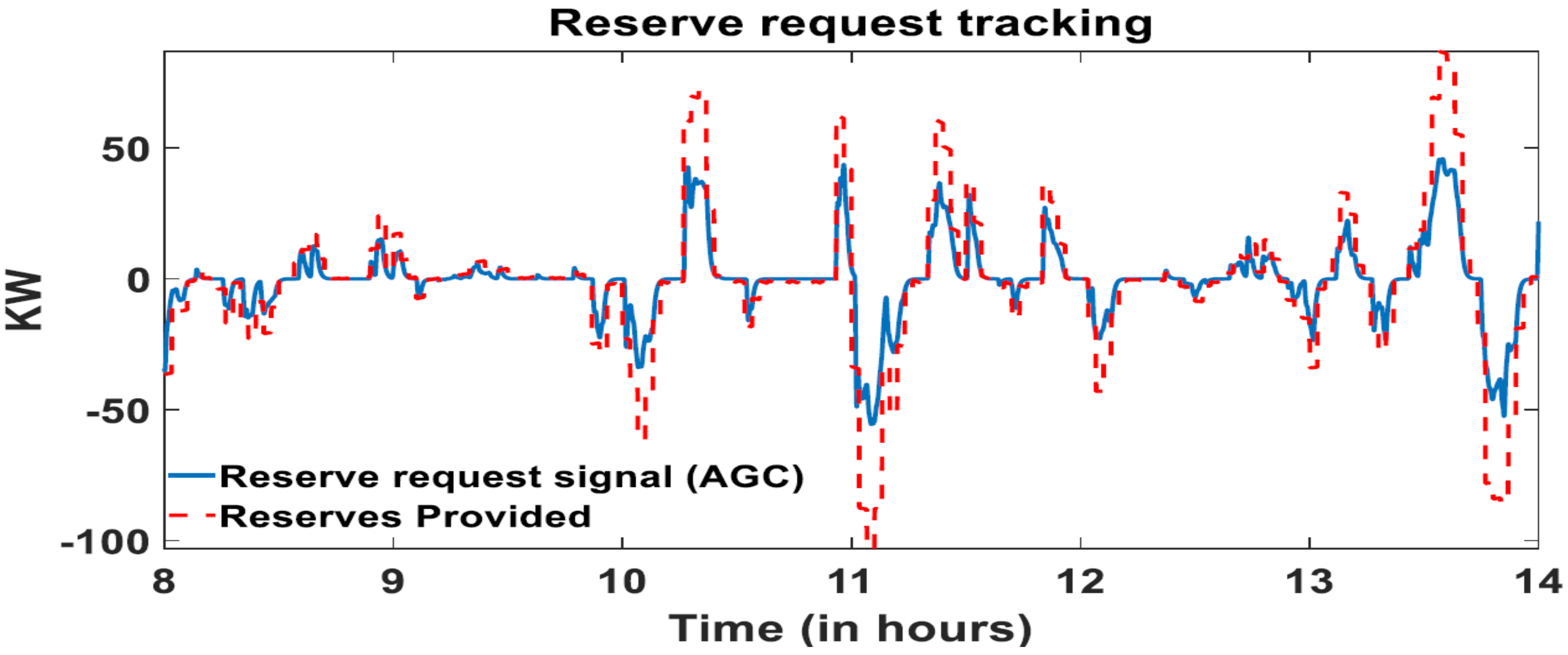


Street, P., 2015. Dataport: the world's largest energy data resource. *Pecan Street Inc*.

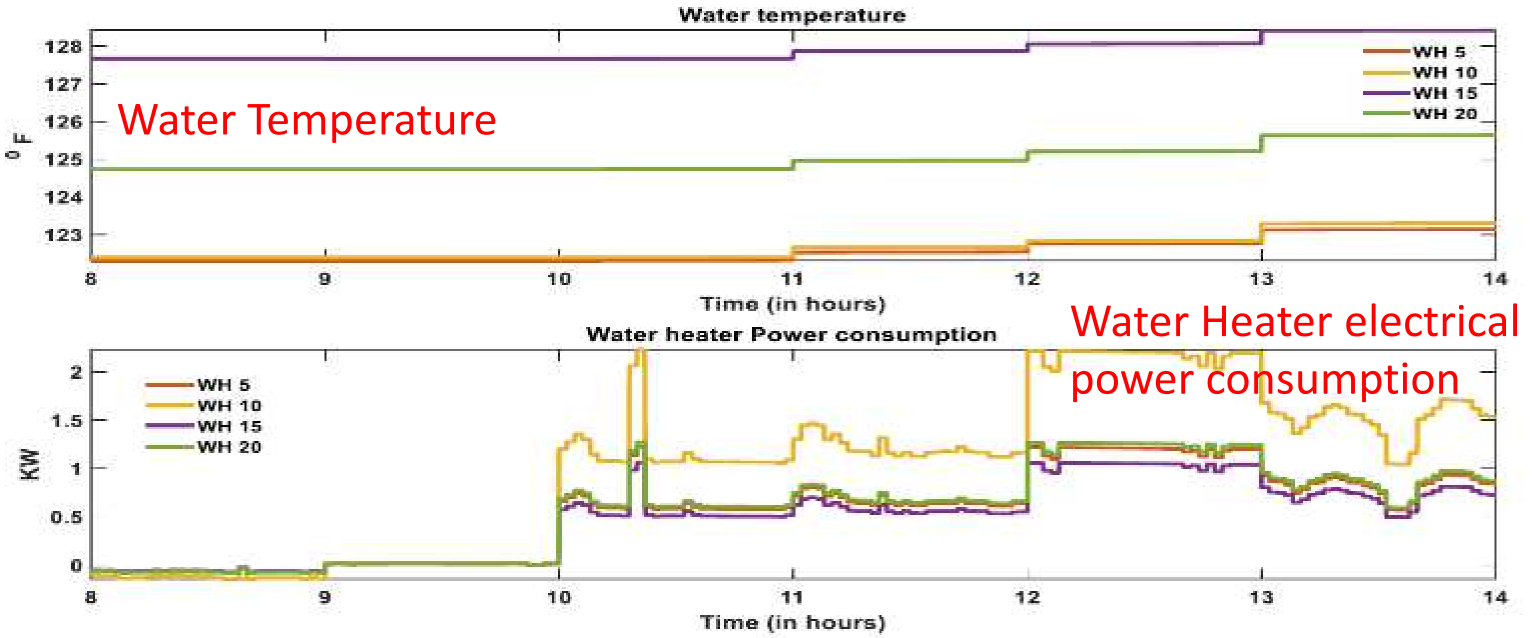
Results – Dispatch quantities every hour

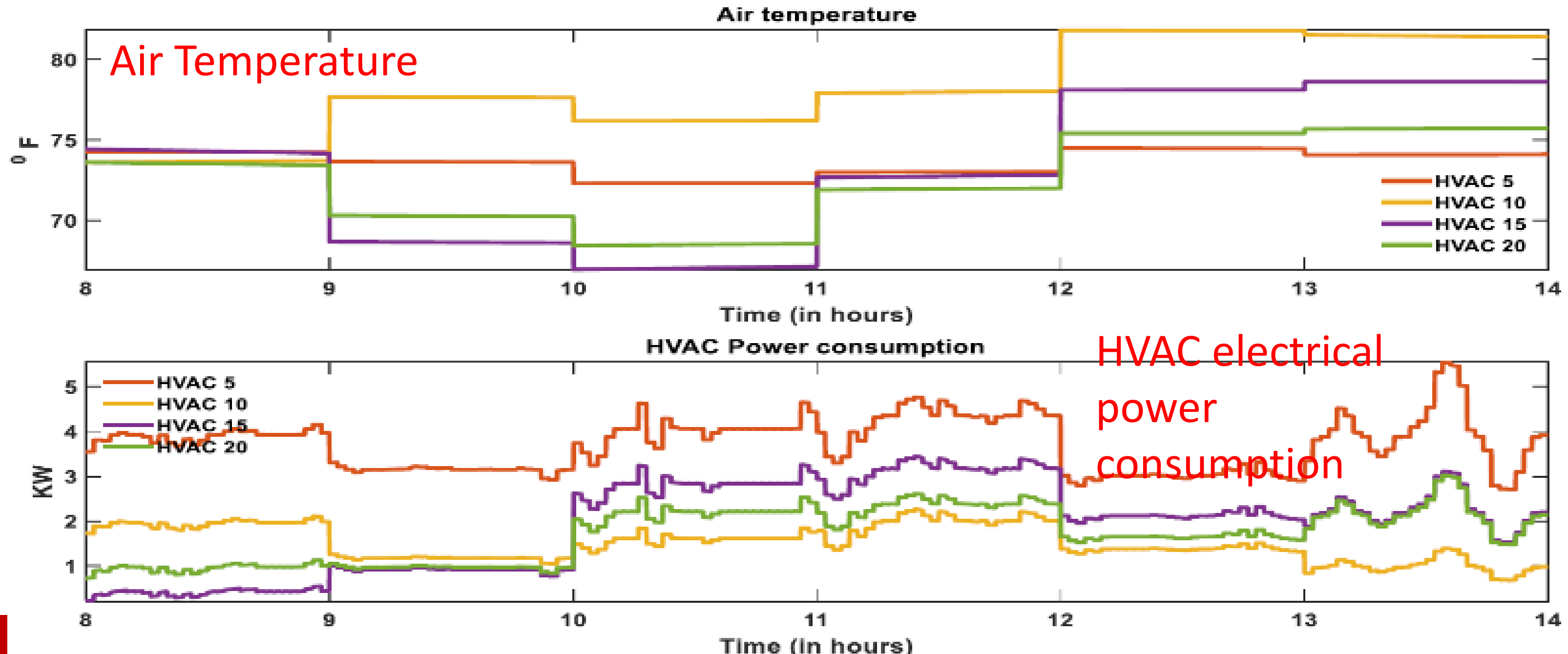


Results – Reserve dispatch quantities every 2 minutes



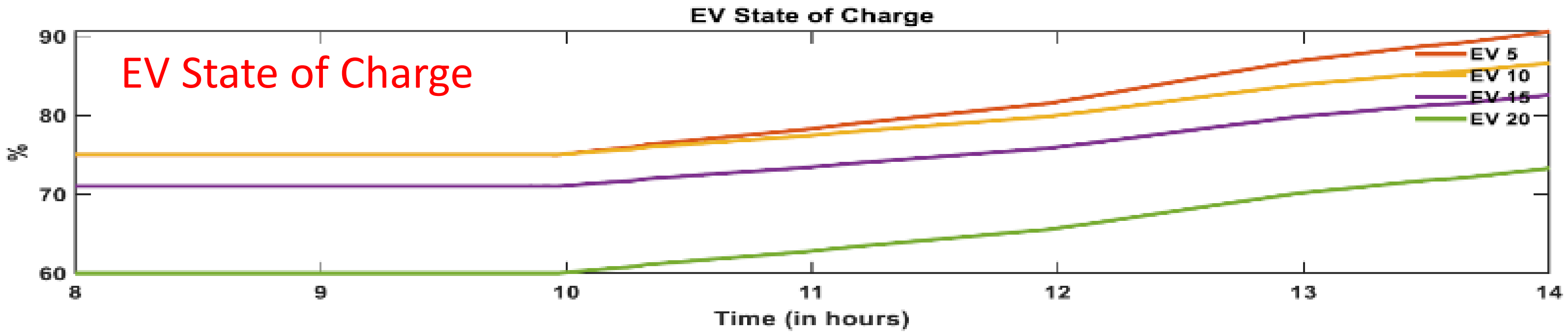
Results – Individual WH and HVAC consumption

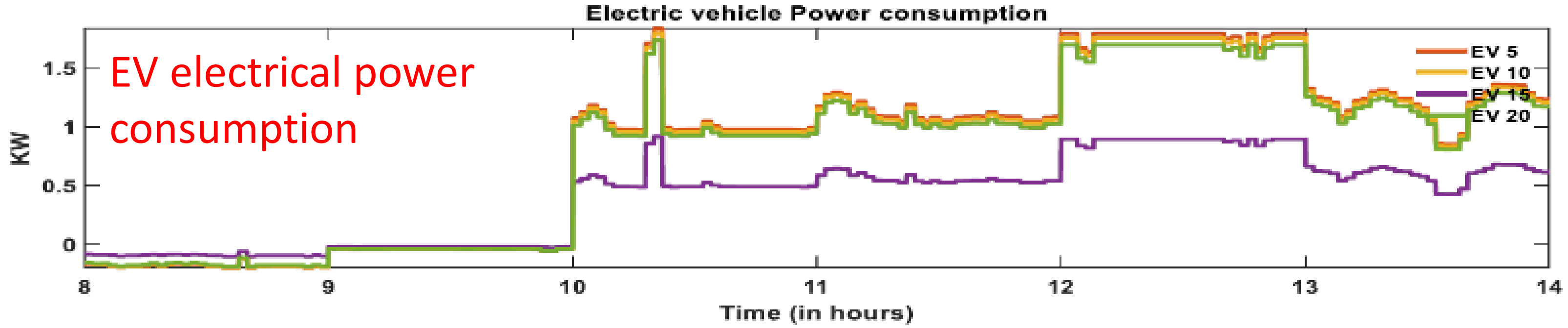


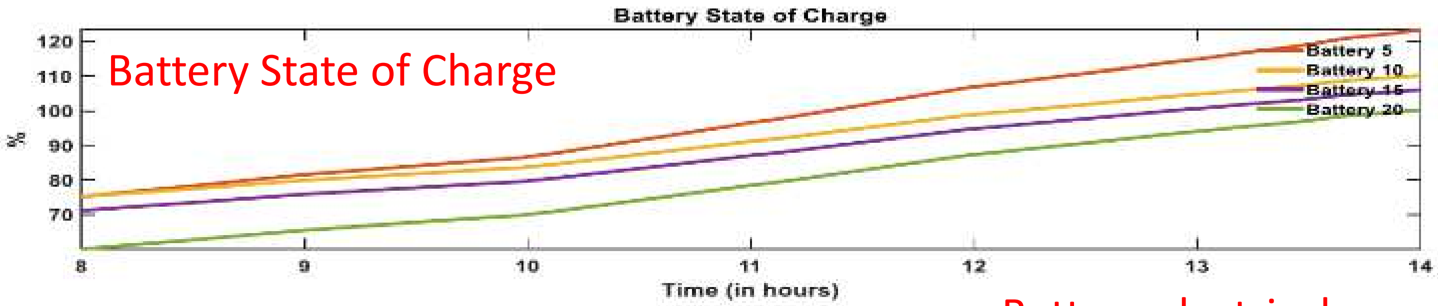


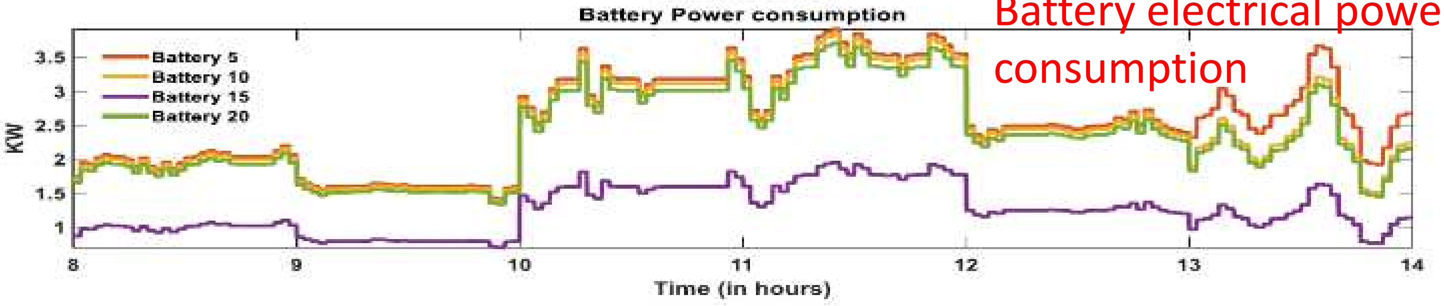
No comfort/ capacity violations

Results – Individual EV and battery consumption









No comfort/ capacity violations

Findings using MIT SEPSS

- Depending on the available communication infrastructure, the extent of prosumer participation can vary significantly
- Specifications through real power and rate of change of real power committed are such that comfort violations do not occur
- Above factors coupled with advanced primary control embedded in devices ensures implementable bids
- . Transparent price signals facilitated by temporal and spatial lifting

Way ahead

- **Huge opportunities for innovation at value**

- **Utilities –enablers of differentiated QoS and differentiated reliability**

- investments in smart switching to enable delivery at value

- **Challenges and opportunities for /industry university work**

-- Embedding intelligence into different layers (iBAs) with well-defined protocols

-- Plug-and-play protocols with minimal coordination

-- Distributed robust software development and integration with existing utility software

--Scalable electric power system simulators (SEPSS) essential (version 1 available)

Next steps

- IT-enabled engineering for complex socio-ecological systems (SES); toward autonomous systems
- The main barriers– hard to adopt (very different than hardware development; or solutions for small confined systems); hard to understand value of cooperation/interaction
- Key role :Scalable well-structured simulators with visualization

--Demonstrate solutions for aligning markets, technical solutions and cyber-security (multi-layered, interactive)

--Complex energy systems; autonomous microgrids (ships, hybrid aircrafts, terrestrial); markets

--Low hanging fruits (PR study; blackouts in US; Azores)

References

[1] Ilić, M.D. and Jaddivada, R., 2018. Multi-layered interactive energy space modeling for near-optimal electrification of terrestrial, shipboard and aircraft systems. *Annual Reviews in Control*.

[2] Ilic, M.D. and Jaddivada, R., 2018, December. Fundamental Modeling and Conditions for Realizable and Efficient Energy Systems. In *2018 IEEE Conference on Decision and Control (CDC)* (pp. 5694-5701). IEEE.

[3] Ilic, M.D. and Jaddivada, R., 2019. New Energy Space Modeling for Optimization and Control in Electric Energy Systems. In Modeling and Optimization: Theory and Applications Springer, Cham *(To Appear)*.

[4] Ilic, M. and Jaddivada, R., Exergy/energy dynamics-based integrative modeling and control for difficult hybrid aircraft missions, Utility patent Application No. 62/730,203, Filed on 9/12/2018

[5] Ilic, M., Jaddivada, R., Miao, X., & Popli, N. (2019). Toward Multi-Layered MPC for Complex Electric Energy Systems. In *Handbook of Model Predictive Control* (pp. 625-663). Birkhäuser, Cham.

[6] M.D. Ilic, R. Jaddivada, "Enabling Prosumer-Centric Transactive Energy Management (TEM)", EESG Working Paper No. R-WP-12-2018, July 2018 *(also USAEE 2018 Presentation at Washington, September 2018)*

[7] M.D. Ilic, R. Jaddivada, "Toward Operationally-Feasible and Efficient Integration of Distributed Energy Resources (DERs)", EESG Working Paper No. R-WP-11-2018 , April 2018 *(also in NIST TE challenge Phase 2, Special Final Report 2019)*

[8]M. Ilic, R. Jaddivada, X.Miao, ``Scalable Electric Power System Simulator (SEPSS)", Proc. of the ISGTEurope, 2018.

[9] M. Ilic, R.Jaddivada, X.Miao, ``Rapid Automated Assessment of Microgrid Performance Software System (RAMPS), Proc. of the ISGTEurope, 2018.