Carnegie Mellon

Electric Energy EESG Systems Group

Electrical & Computer ENGINEERING

Models and Functionality of the SGRS Simulator based on DYMONDS

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How It all started—hindsight view

- Innovation in power systems hard and slow
- Outdated assumptions in the new environment
- No simulators to emulate time evolution of complex event driven states
- Fundamental need for more user-friendly innovation/technology transfer
- General simulators (architecture, data driven) vs. power systems simulations (physics-based, specific phenomena separately)
- Missing modeling for provable control design
- Difficult to define performance objectives at different industry layers; coordination of interactions between the layers for system-wide reliability and efficiency ; tradeoff between complexity and performance
- Challenge of managing multiple performance objectives

- EESG Ilic group http://www.eesg.ece.cmu.edu/
- Dynamic Monitoring and Decision Systems (DyMonDS) framework for enabling smart SCADA; direct link with sustainability (enabler of clean, reliable and efficient integration of new resources); main role of interactive physics –based modeling for IT/cyber
- Cooperative effort with National Institute of Standards (NIST) for building Smart Grid in a Room Simulator (SGRS)
- ***Recent new unifying modeling in support of DyMonDS***

Fundamental challenge

- Modeling/operating new paradigm; education to support evolution from today's approaches
- The key role of smarts in implementing sustainable socio-ecological energy systems
- New physics-based modeling
- Emerging cyber paradigms

  --for micro-grids

  --for bulk- power grids

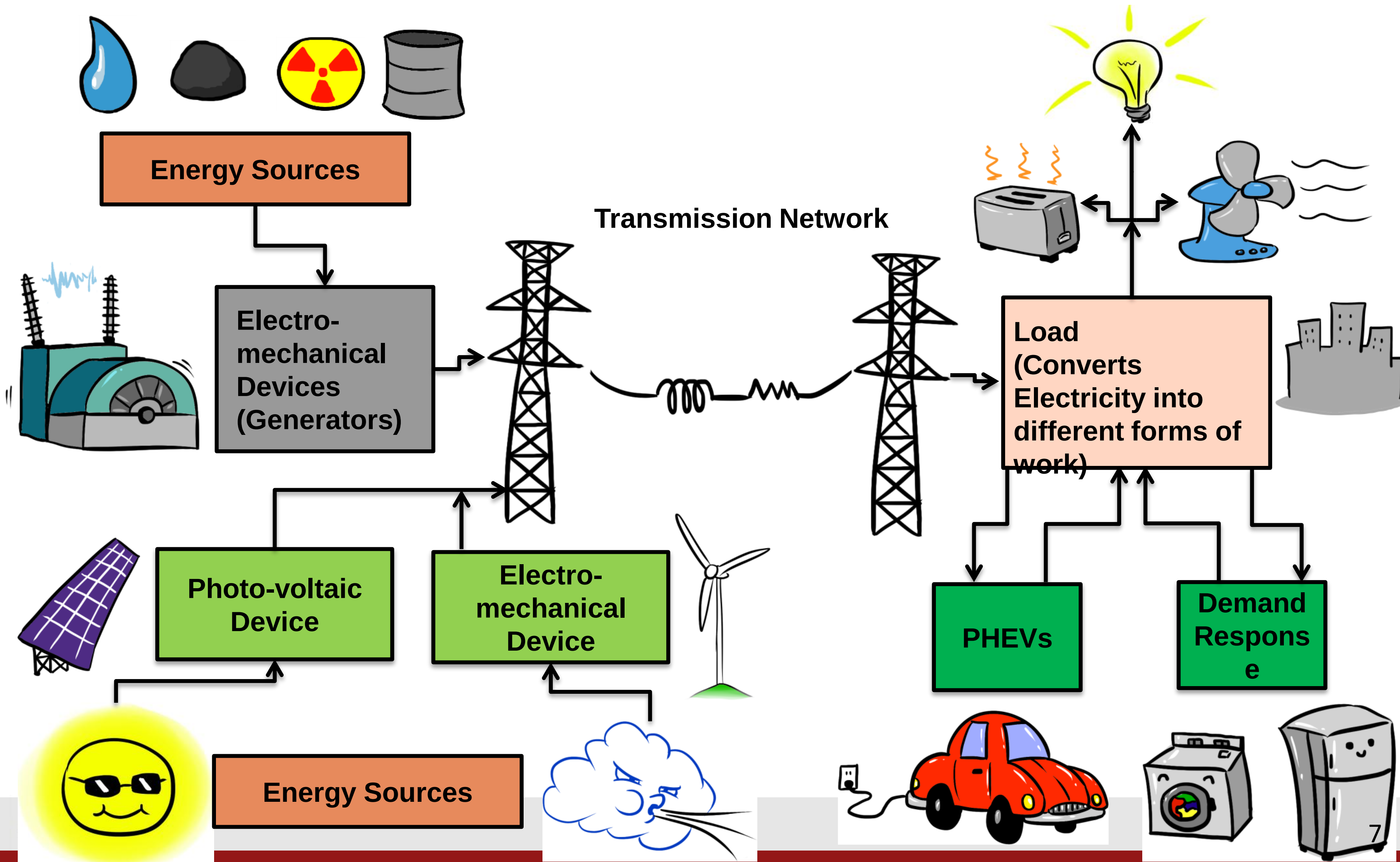
  --for hybrid power grids

  --assumptions made and their implications

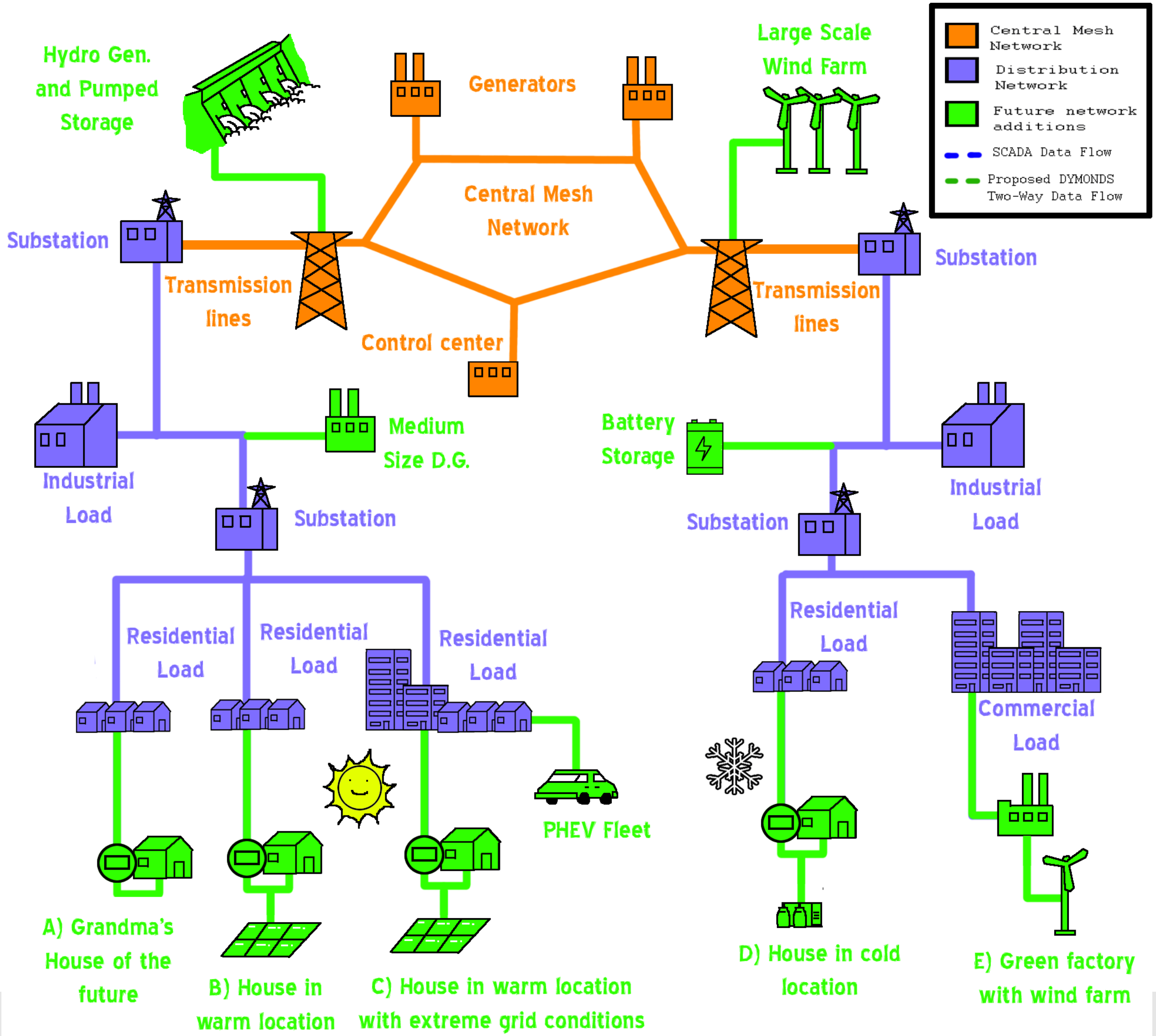
Recent pilot experiments

- Industry-government(-academia) collaborations on hardware for smart grids
- University campuses (``micro-grids”) –UCSD, IIT Chicago
- Utilities deploying AMIs, synchrophasors (PMUs)
- Lessons learned—Familiarity with new smart hardware
- The remaining challenge (protocols for systematic integration of scalable technologies at value)

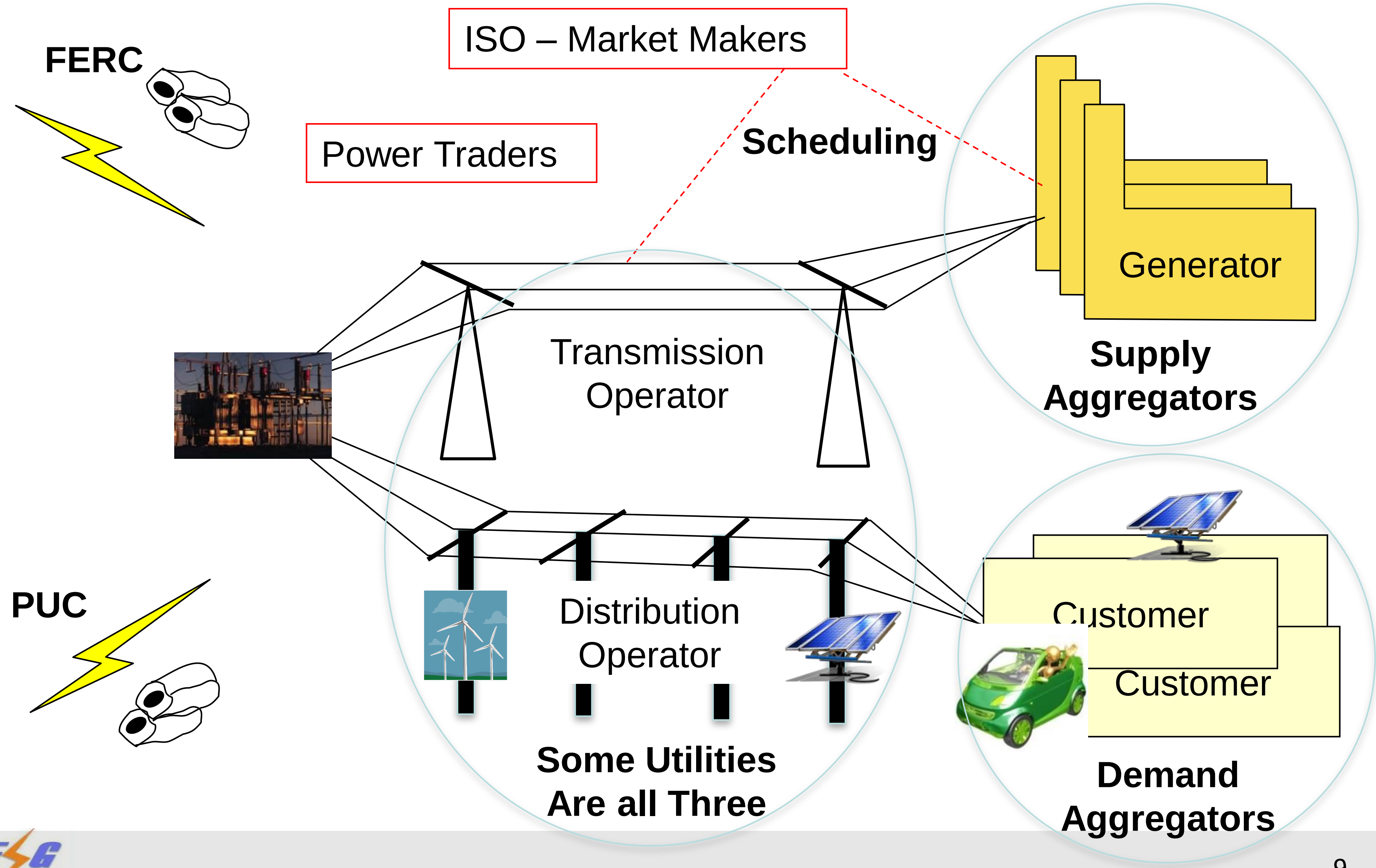
Lessons learned from pilot experiments—familiarity with new hardware (AMIs, PMUs, PHEVs, EVs, microgrids)



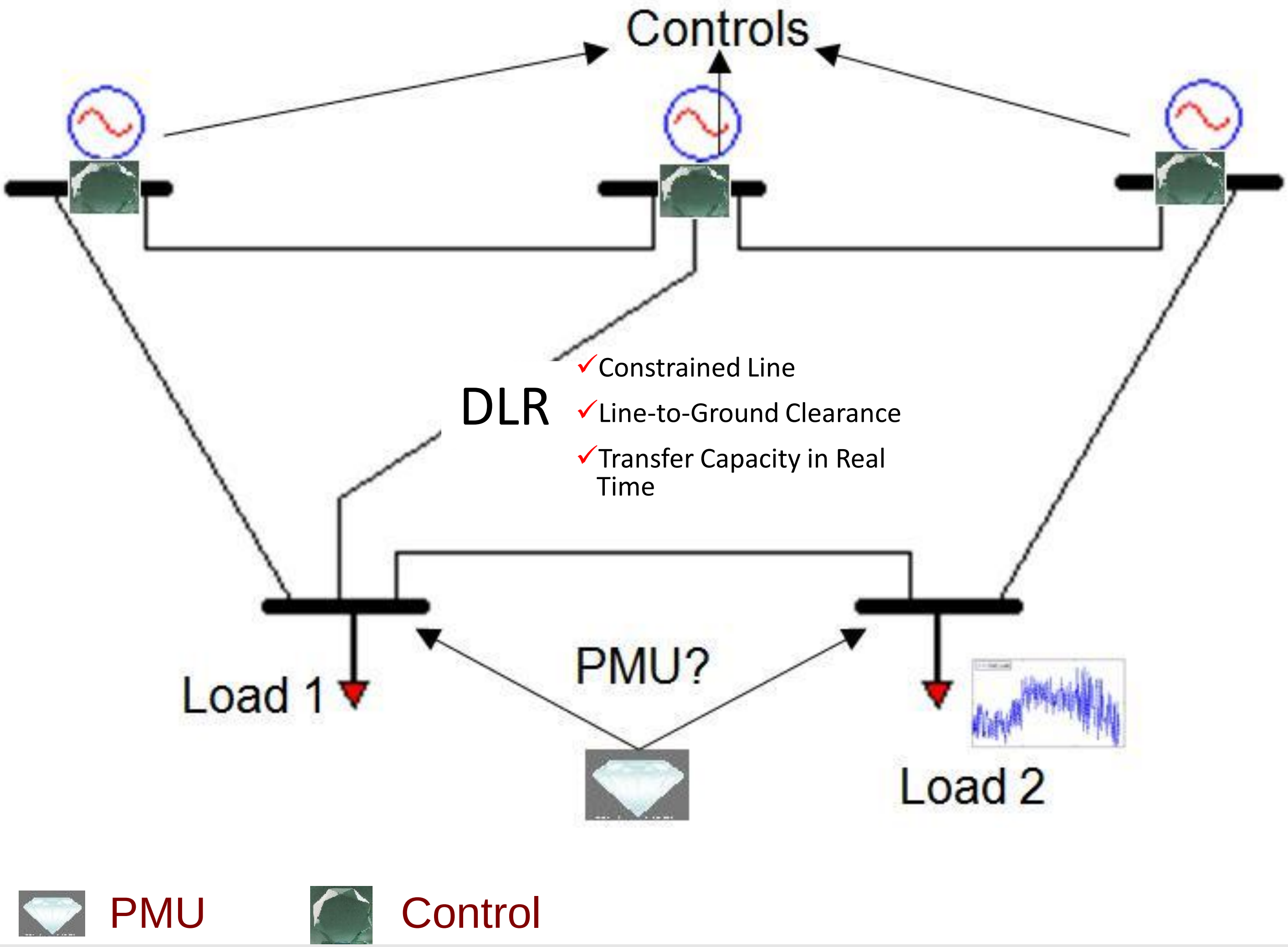
Future Smart Grid (Physical system)



Contextual complexity



Potential of Measurements, Communications and Control

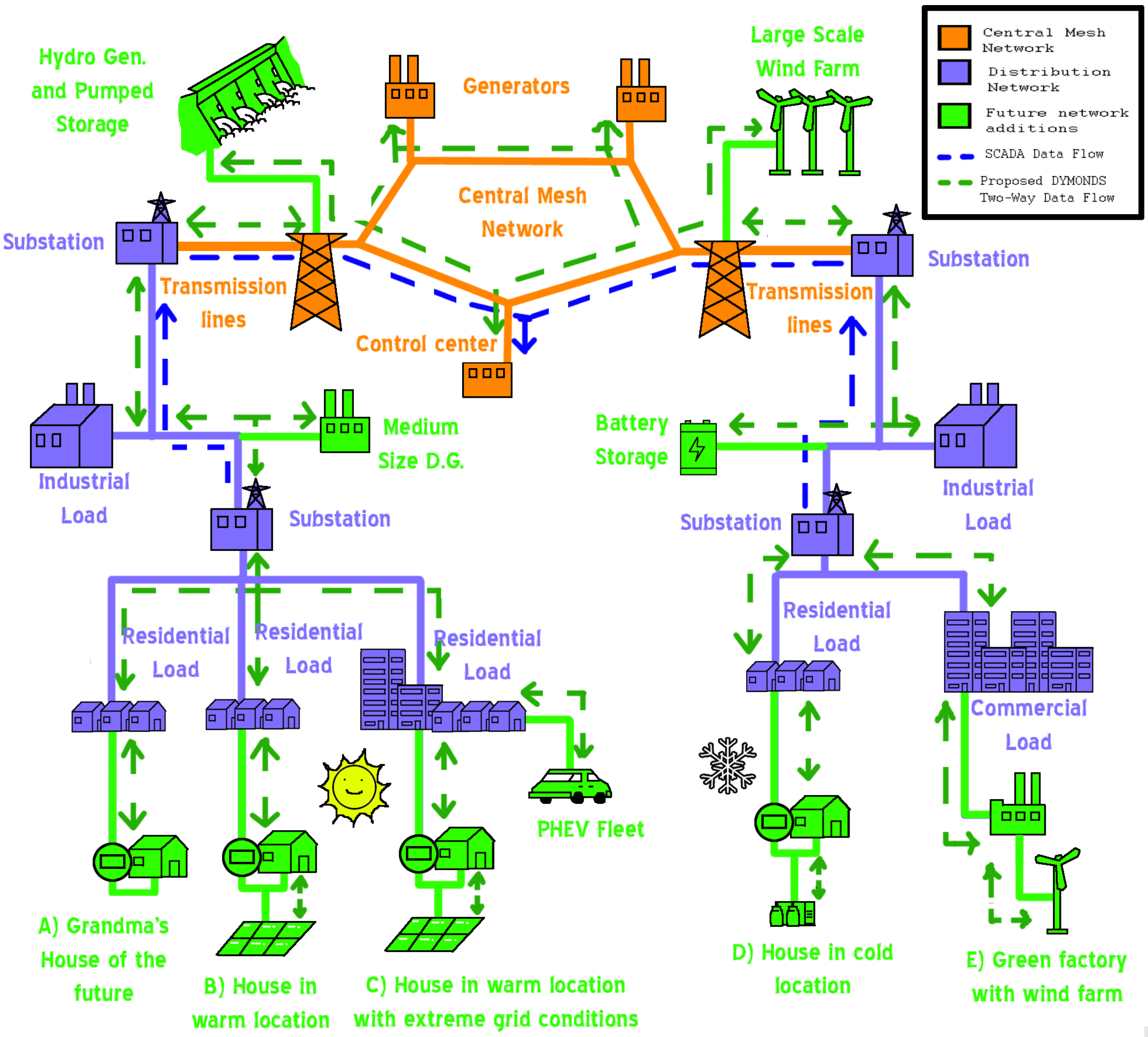


Critical: Transform SCADA

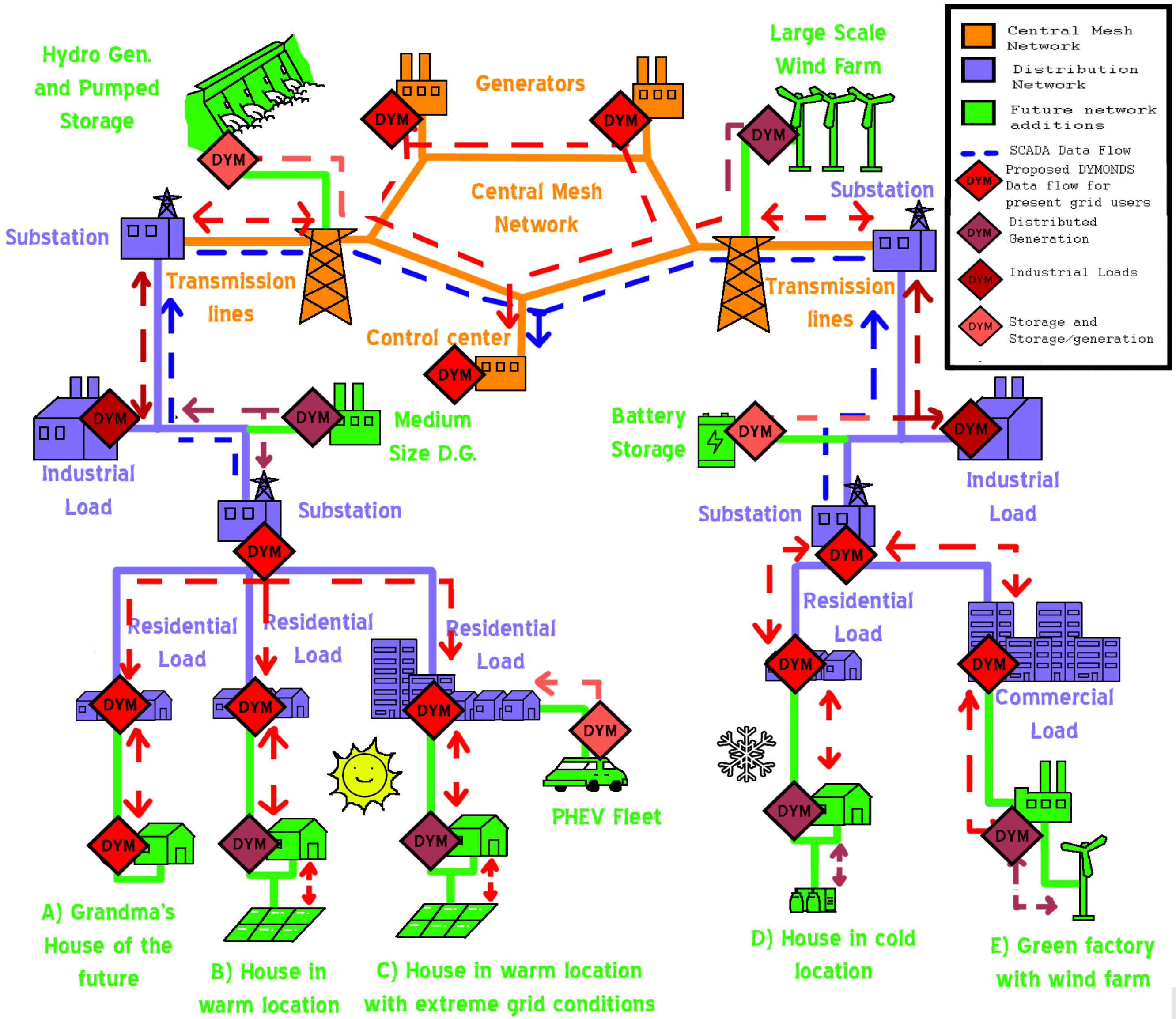
- From single top-down coordinating management to the multi-directional multi-layered interactive IT exchange.

- At CMU we call such transformed SCADA Dynamic Monitoring and Decision Systems (DYMONDS) and have worked with industry and government on: (1) new models to define what is the type and rate of key IT exchange; (2) new decision tools for self-commitment and clearing such commitments. \http:www.eesg.ece.cmu.edu.

New SCADA


Central Mesh Network
Distribution Network
Future network additions
SCADA Data Flow
Proposed DYMONDS Two-Way Data Flow
Hydro Gen. and Pumped Storage
Generators
Large Scale Wind Farm
Central Mesh Network
Substation
Transmission lines
Control center
Substation
Transmission lines
Industrial Load
Medium Size D.G.
Battery Storage
Industrial Load
Substation
Substation
Residential Load
Residential Load
Residential Load
Residential Load
Commercial Load
PHEV Fleet
A) Grandma's House of the future
B) House in warm location
C) House in warm location with extreme grid conditions
D) House in cold location
E) Green factory with wind farm

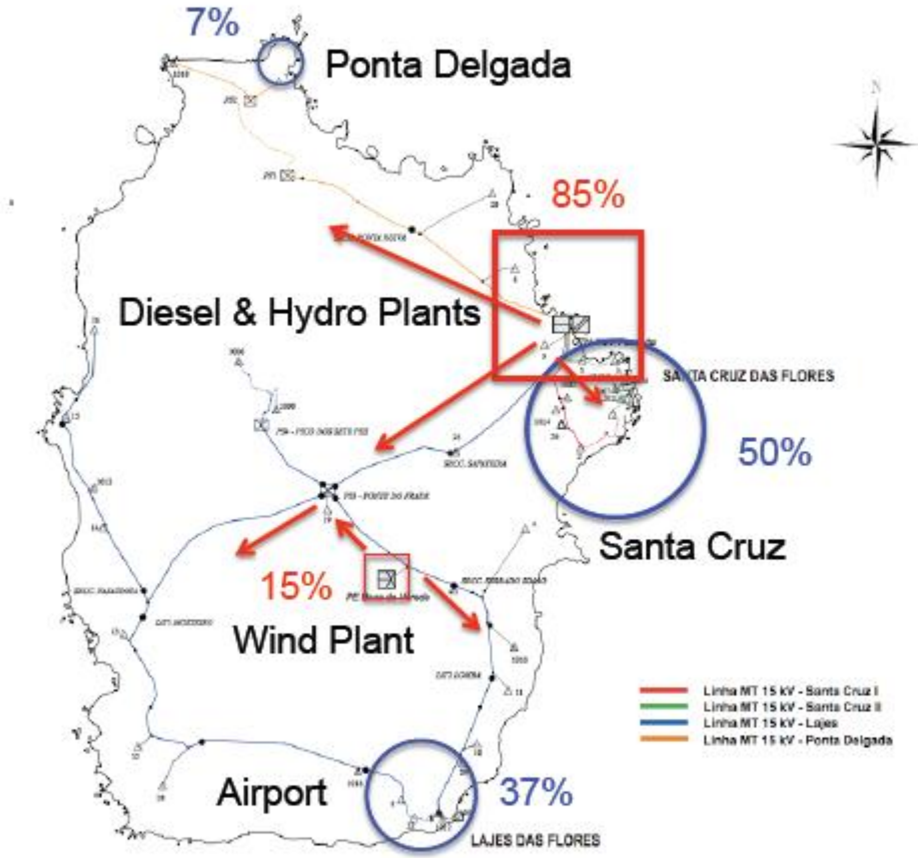
DYMONDS-enabled Physical Grid



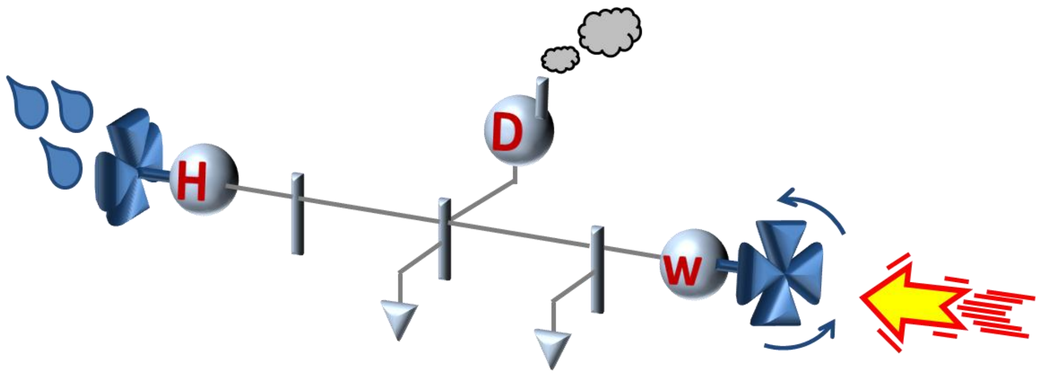
"Smart Grid" ←→ electric power grid and ICT for sustainable energy systems

Core Energy Variables	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 • Needed to align interactions

From old to new paradigm—Flores Island Power System, Portugal



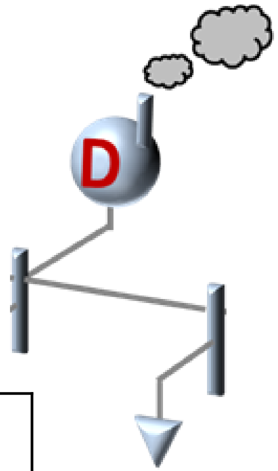
Controllable components—today's operations (very little dynamic control, sensing)



H – Hydro
D – Diesel
W – Wind

*Sketch by Milos Cvetkovic

Two Bus Equivalent of the Flores Island Power System



State	Equilibrium
$e'_q[pu]$	0.9797
$\delta[rad]$	0.0173
$\omega[pu]$	1
$v_r[pu]$	0.8527
$e_{fd}[pu]$	0.7482
$v_f[pu]$	0
$P_m[pu]$	0.01
$a[pu]$	0

Generator	Diesel
$x_d[pu]$	8.15
$x_q[pu]$	8.15
$x'_d[pu]$	0.5917
$x'_q[pu]$	0.5917
$T'_{q0}[s]$	2.35
$T'_{d0}[s]$	2.35
$J[s]$	2.26
$D[pu]$	0.005

Transmission line	From Diesel to Load bus
$R[pu]$	0.3071
$L[pu]$	0.1695

Base values

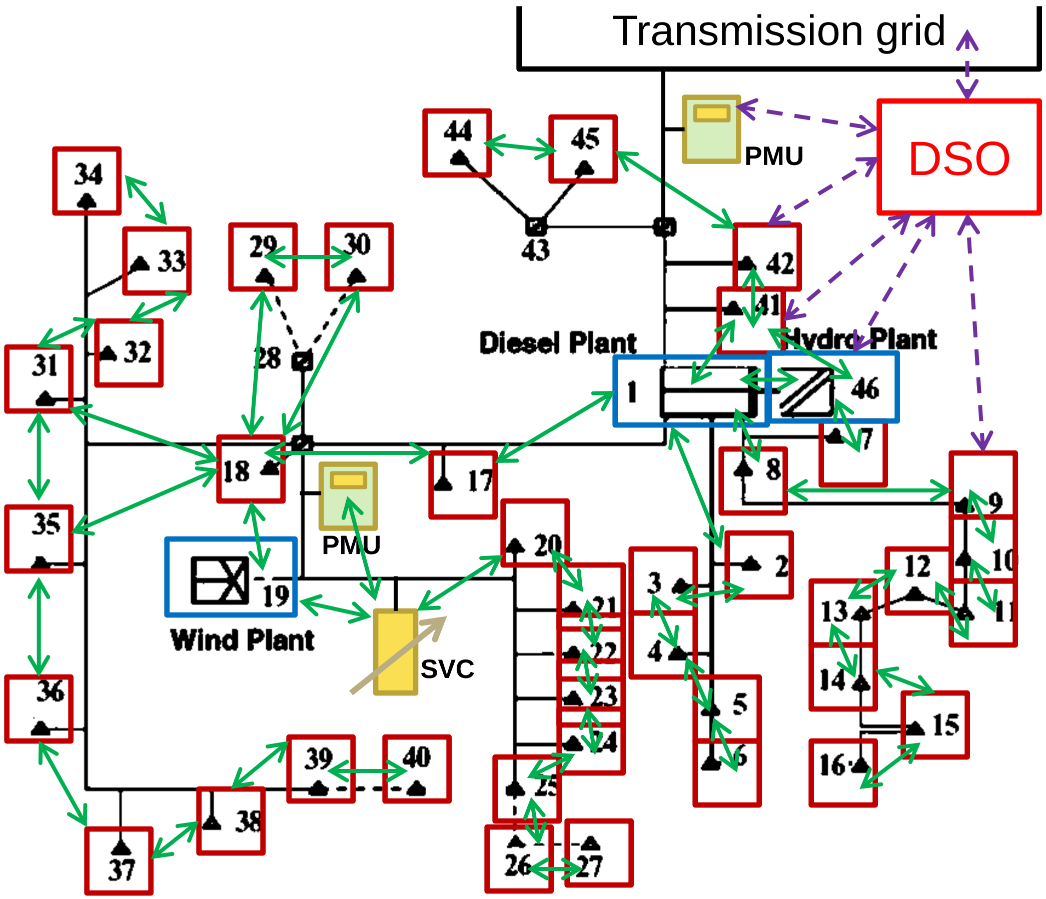
$S_b = 10MVA$
$V_b = 15KV$

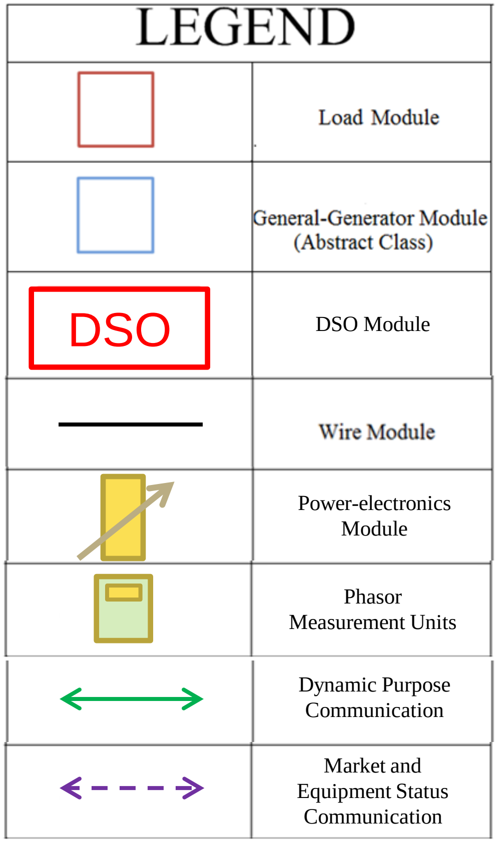
AVR	Diesel
$K_A[pu]$	400
$T_A[s]$	0.02
$K_E[pu]$	1.3
$T_E[s]$	1
$S_E[pu]$	0.1667
$K_F[pu]$	0.03
$T_F[s]$	1

Governor	Diesel
$k_t[pu]$	40
$T_g[s]$	0.6
$r[pu]$	1/0.03
$T_t[s]$	0.2

Base values $S_b = 10MVA, V_b = 0.4KV$

Information exchange in the case of Flores---new (lots of dynamic control and sensing)





Smart grid ---
multi-layered interactive dynamical system

- Requires new modelling approach
- Key departures from the conventional power systems modeling
  - system is *never* at an equilibrium
  - all components are dynamic (spatially and temporally); often actively controlled
  - 60Hz component may not be the dominant periodic signal
  - system dynamics determined by both internal (modular) actions and modular interactions
- Groups of components (module) represented in standard state space form

Comparison of today's and emerging dynamic systems

- Small system example
- Qualitatively different disturbances require different dynamic models
  - Case 1: zero mean disturbance; static load model
  - Case 2: non zero mean disturbance; load a dynamic distributed energy resource (DER)
- **Short summary of modeling assumptions for today's hierarchical control** (**Case 1**)
- Critical issues with static load modeling and its implications on system feasibility
  - Importance of Q
- Critical issues with non zero mean disturbance
  - Steady state 60 Hz and nominal voltage assumption may not hold
- **Proposed unifying dynamic modeling –Basis for DyMoNDS** (**Case 2**)
  - All components are dynamic (ODEs; discrete time models); based on systematic temporal model reduction
  - Has inherent spatial structure (multi-layered interactive models)
  - Interactive information exchange (no longer top-down only) to ensure consistent implementation of multi-layered control architecture

Case 1: zero mean disturbance & static load model

- Assumed zero-mean deviation from prediction ⇨ equilibria conditions

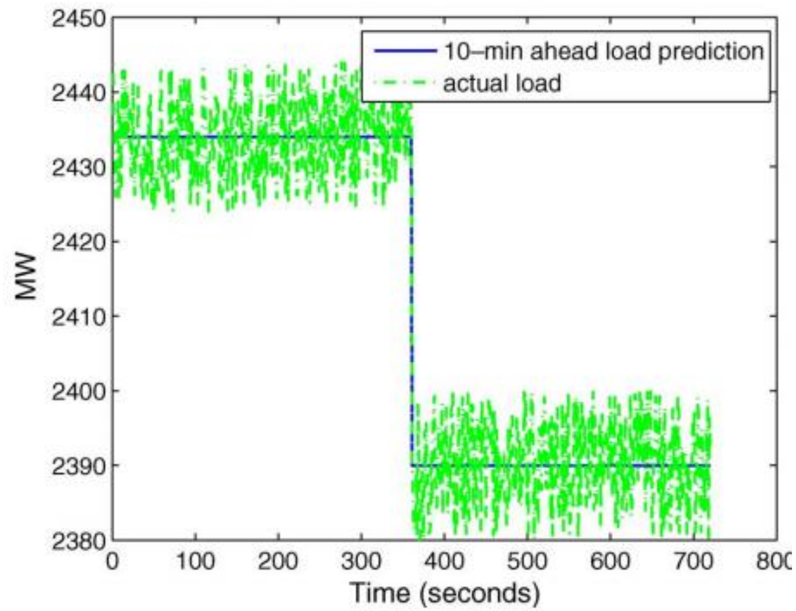


Fig. 3. ***10-min-ahead load prediction and second-by-second actual load.***

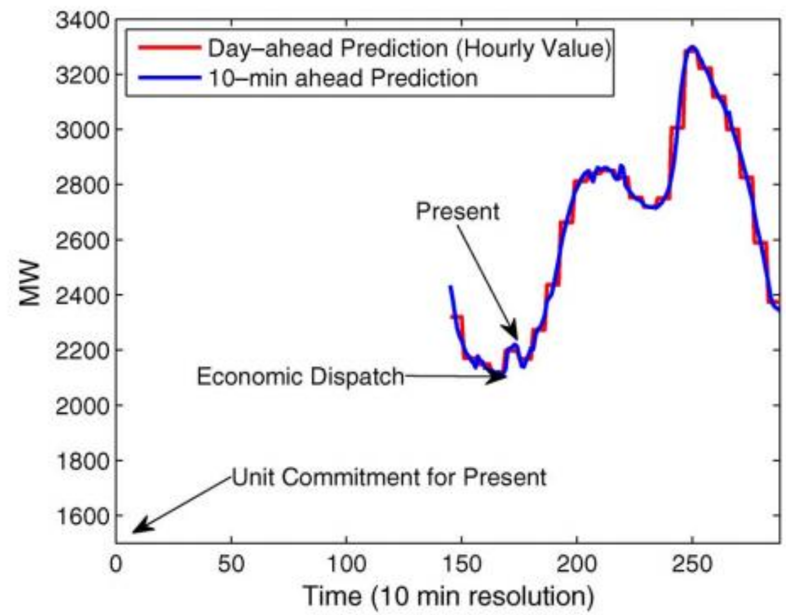


Fig. 2. ***Day-ahead and 10-min-ahead load prediction, and timing of UC and ED functions.***

$$L(t) = \hat{L}[H] + \Delta_{LH}(t)$$

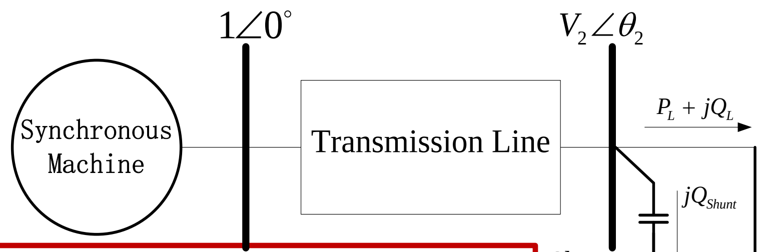
$$L(t) = \hat{L}[k] + \Delta_{Lk}(t)$$

$$\|\hat{L}[H]\| \gg \|\Delta_{LH}(t)\|$$

$$\|\Delta_{LH}(t)\| > \|\Delta_{Lk}(t)\|.$$

Xie, L., Carvalho, P. M., Ferreira, L. A., Liu, J., Krogh, B. H., Popli, N., & Ilic, M. D. (2011). Wind integration in power systems: Operational challenges and possible solutions. *Proceedings of the IEEE*, *99*(1), 214-232.

Small example of today's power system



- Modelling assumptions
  - Static load+Disturbance ($P_L + jQ_L$; $\mathrm{R_L} + \mathrm{jX_L}$)
  - NO transmission system dynamics

No dynamic interaction between components (Assumption)

  - Load disturbance much smaller than predicted load components
  - Synchronous machine is the only locally controlled dynamic component
    - Primary control cancels the effects of $\Delta_{Lk}(t)$ *(Governor / AVR stabilization)*
    - Secondary control cancels the effects of $\Delta_{LH}(t)$ (Steady state regulation)
    - Tertiary control balances $\hat{L}[H]$ and $\hat{L}[k]$ (Steady state scheduling)

Basis for hierarchical control (top down info flow)

- Equilibria (steady state model) separable from stabilization (dynamic model)
- No bottom-up information required from components to system level

X. Miao, K.D. Bachovchin, M. D. Ilic . Effect of load type and unmodeled dynamics in load on the equilibria and stability of electric power system. Submitted to CDC 2015

Effects of load modelling assumptions on system feasibility in today's operation scheduling – Constant PQ Load

- Scheduling equilibria (steady state) model is obtained assuming perfect stabilization and regulation ⇒ Power flow equations
- Feasibility results are dependent on load model used [1].

TABLE I. LOAD PROFILE & SYSTEM PARAMETER

	Small Q_L	***Medium Q_L***	***Large Q_L***
Active Power P_L (pu)	1.736	1.736	1.736
Reactive Power Q_L (pu)	0.2	1.8	7.848
Power Factor	0.99	0.69	0.2

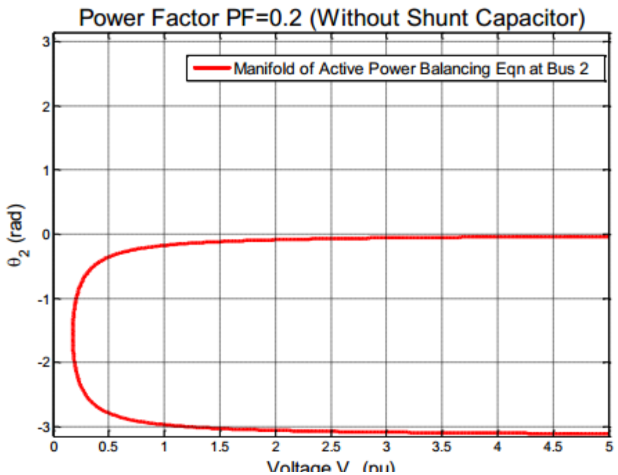
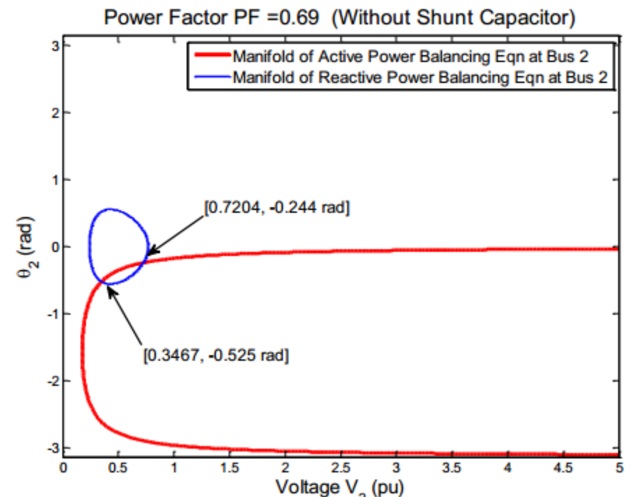


TABLE II. POSSIBLE SOLUTIONS WITH SHUNT CAPACITOR

	Small Q_L	***Medium Q_L***	***Large Q_L***
Number of Solutions	2	2	0
Solution Set I	$\begin{cases} V_2 = 0.9615 \\ \theta_2 = -0.18 \end{cases}$ *Feasible*	$\begin{cases} V_2 = 0.7204 \\ \theta_2 = -0.244 \end{cases}$ *Non-feasible*	N/A
Solution Set II	$\begin{cases} V_2 = 0.182 \\ \theta_2 = -1.27 \end{cases}$ *Non-feasible*	$\begin{cases} V_2 = 0.3467 \\ \theta_2 = -0.525 \end{cases}$ *Non-feasible*	N/A



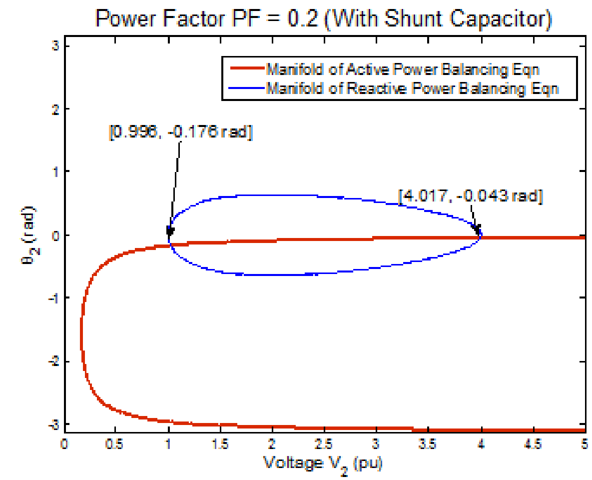
[1] X. Miao, K.D. Bachovchin, M. D. Ilic . Effect of load type and unmodeled dynamics in load on the equilibria and stability of electric power system. Submitted to CDC 2015

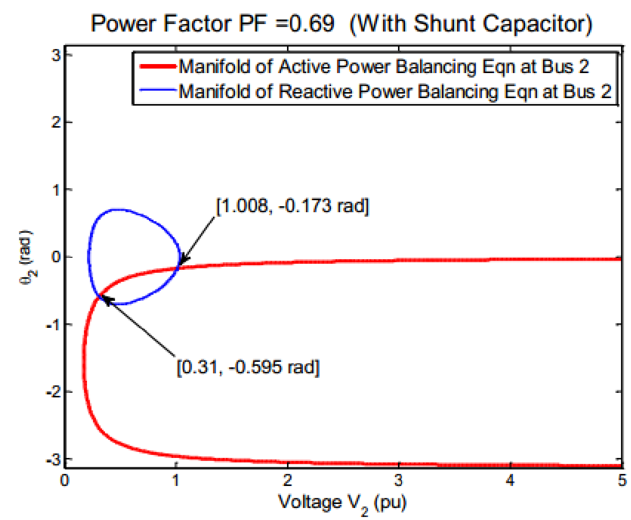
Effects of load modelling assumptions on system feasibility and stability in today's operation

- Scheduling equilibria (steady state) model is obtained assuming perfect stabilization and regulation ⇨ Power flow equations
- Feasibility results are dependent on load model used [1].

TABLE III. POSSIBLE SOLUTIONS WITH SHUNT CAPACITOR

	Medium Q_L	***Large Q_L***
Shunt Capacitor B_{sh} (pu)	2	8
Number of Solutions	2	2
Solution Set I	$\begin{cases} V_2 = 1.008 \\ \theta_2 = -0.173 \end{cases}$ *Feasible*	$\begin{cases} V_2 = 0.996 \\ \theta_2 = -0.176 \end{cases}$ *Feasible*
Solution Set II	$\begin{cases} V_2 = 0.31 \\ \theta_2 = -0.595 \end{cases}$ *Non-feasible*	$\begin{cases} V_2 = 4.017 \\ \theta_2 = -0.043 \end{cases}$ *Non-feasible*

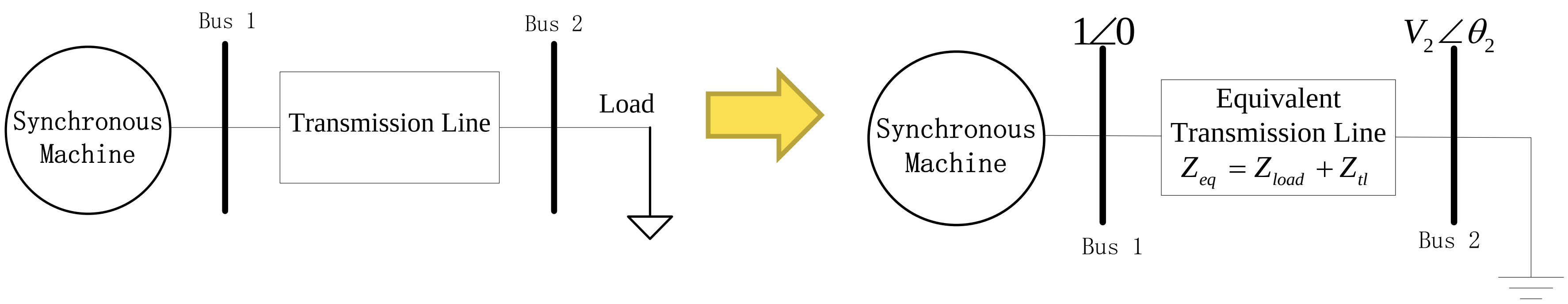




[1] X. Miao, K.D. Bachovchin, M. D. Ilic . Effect of load type and unmodeled dynamics in load on the equilibria and stability of electric power system. Submitted to CDC 2015

Effects of load modelling assumptions on system feasibility in today's operation scheduling – Constant Impedance

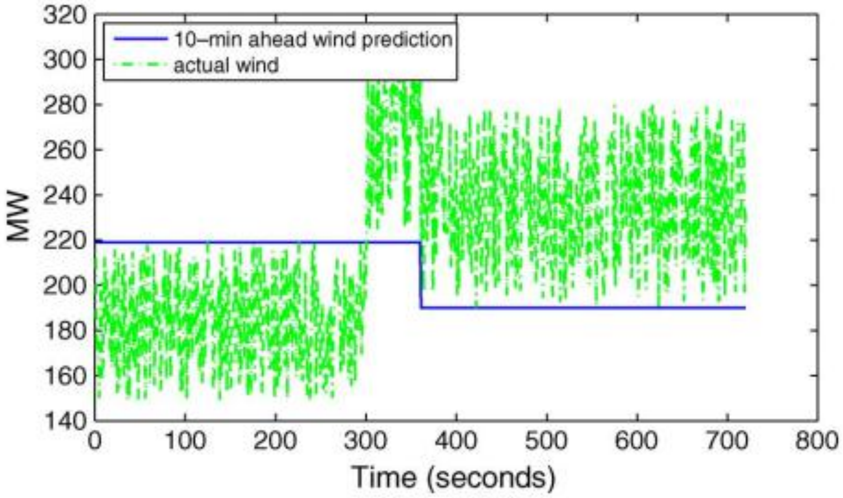
- ***Theorem [1]***: With a constant impedance load, there is always one unique solution. Conditions in terms of the line and load impedance can be found for when this solution is feasible.
- Maximum power transfer achievable when $Z_{Load} = Z_{Line}^{*}$ (capacitive load compensation) ⇒ High voltage problems
- For $V_{load} \in [0.95 - 1.05\ p.u]$, we need: $0.95|Z_{eq}| \leq |Z_{load}| \leq 1.05|Z_{eq}|$

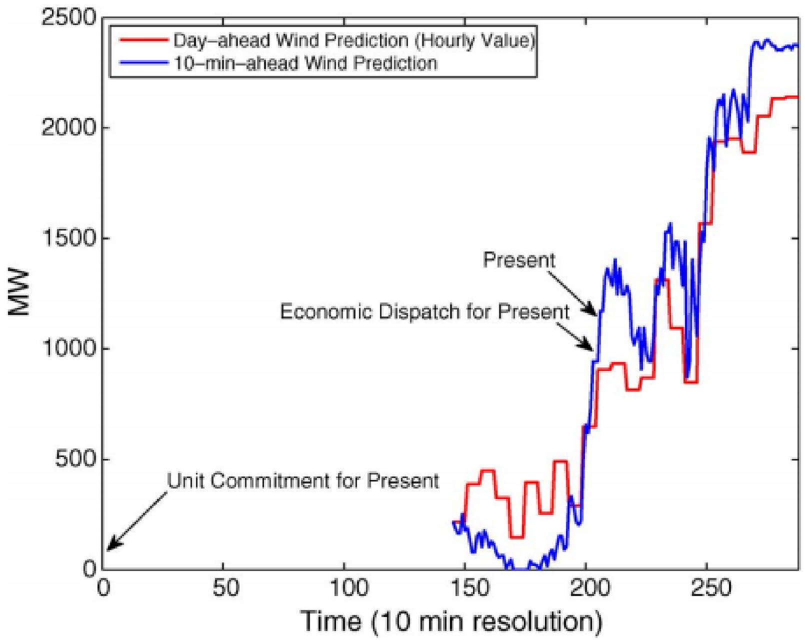


[1] X. Miao, K.D. Bachovchin, M. D. Ilic . Effect of load type and unmodeled dynamics in load on the equilibria and stability of electric power system. Submitted to CDC 2015

Wind power disturbance – multiple time scales

- Observe the non-zero mean deviation from prediction ⇒ disequilibria conditions





$$P_{Gw}(t) = \hat{P}_{Gw}[H] + \Delta_{Gw_H}(t)$$

$$P_{Gw}(t) = \hat{P}_{Gw}[k] + \Delta_{Gw_k}(t)$$

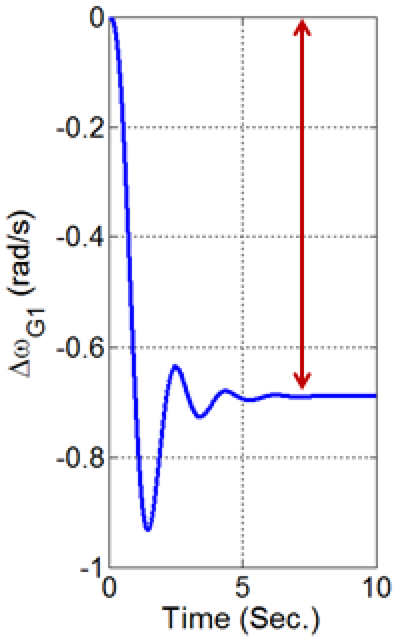
$$\|\Delta_{Gw_H}(t)| \gg \|\Delta_{Gw_k}(t)\|$$

$$\left\|\hat{P}_{Gw}[k]\right\| \gg \|\Delta_{Gw_k}(t)\|.$$

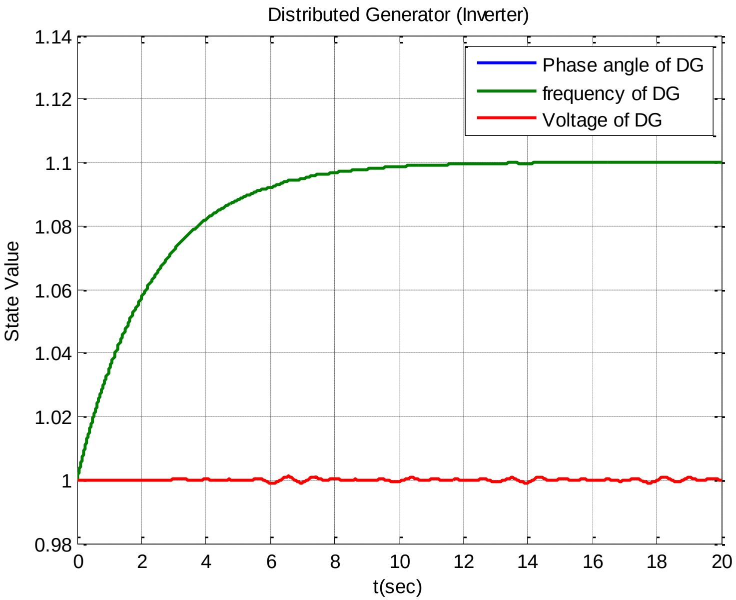
Xie, L., Carvalho, P. M., Ferreira, L. A., Liu, J., Krogh, B. H., Popli, N., & Ilic, M. D. (2011). Wind integration in power systems: Operational challenges and possible solutions. *Proceedings of the IEEE*, *99*(1), 214-232.

Fundamental effect of non-zero mean disturbance

- Synchronous machine with non zero mean disturbance in real power load
  - Structural singularity [2]



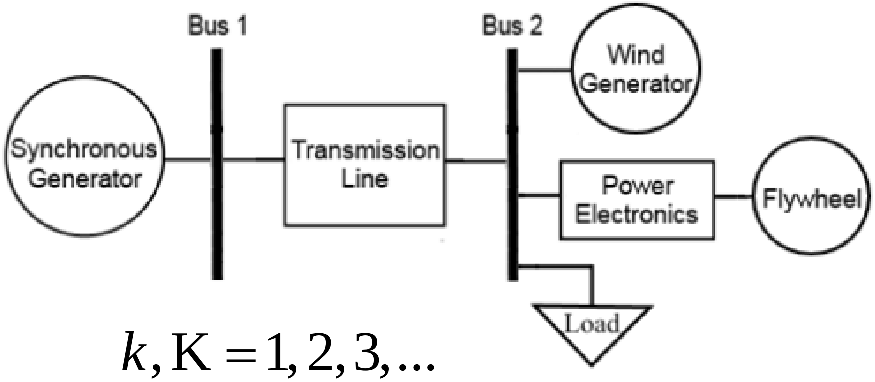
- Wind power plant with power electronics connected to constant impedance load [3]



[2]Q. Liu. Wide-Area Coordination for Frequency Control in Complex Power Systems. Ph.D. Thesis, CMU, Aug 2013.
[3] X. Miao, M. Ilic. EESG working paper, 2015

Multi-temporal dynamic model of controllable load (DER)—stand-alone module level

- DER dynamics replaces static load and is modeled as any other dynamic component with non zero exogenous disturbance



$$\dot{x}_i(t) = f_i\left(x_i(t), x_j(t), u_i(t), m_i(t)\right)$$

$$x_i(0) = x_{i0}$$

$$m_i(t) = M_i[K \cdot T_M] + M_i[k \cdot T_s] + \Delta m_i(t)$$

where $m_i(t)$ – Exogenous input

$x_i(t)$ – State variable of Module i

$x_j(t)$ – State variable of Module j, $j \in C_i$

$k, \mathrm{K} = 1, 2, 3, \ldots$

$T_M = 10\,\text{min}, 1\text{ hour}, 24\text{ hour}$

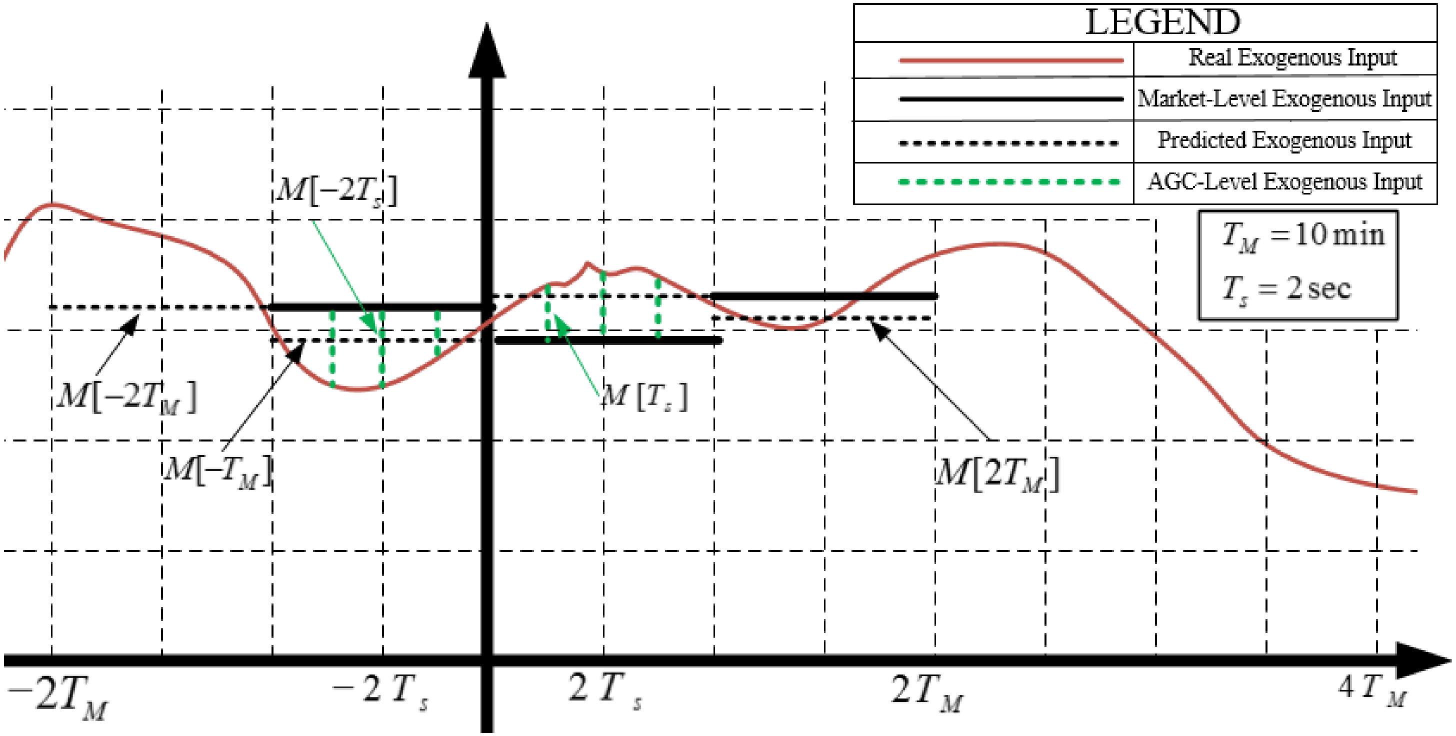
$T_s = 1 - 60\,\text{sec}$

- Responsive load (for example: Smart building) can have:

$$u_i = u_i(t) + u_i^{ref}[k \cdot T_s] + u_i^{ref}[k \cdot T_M]$$

Local AGC Market

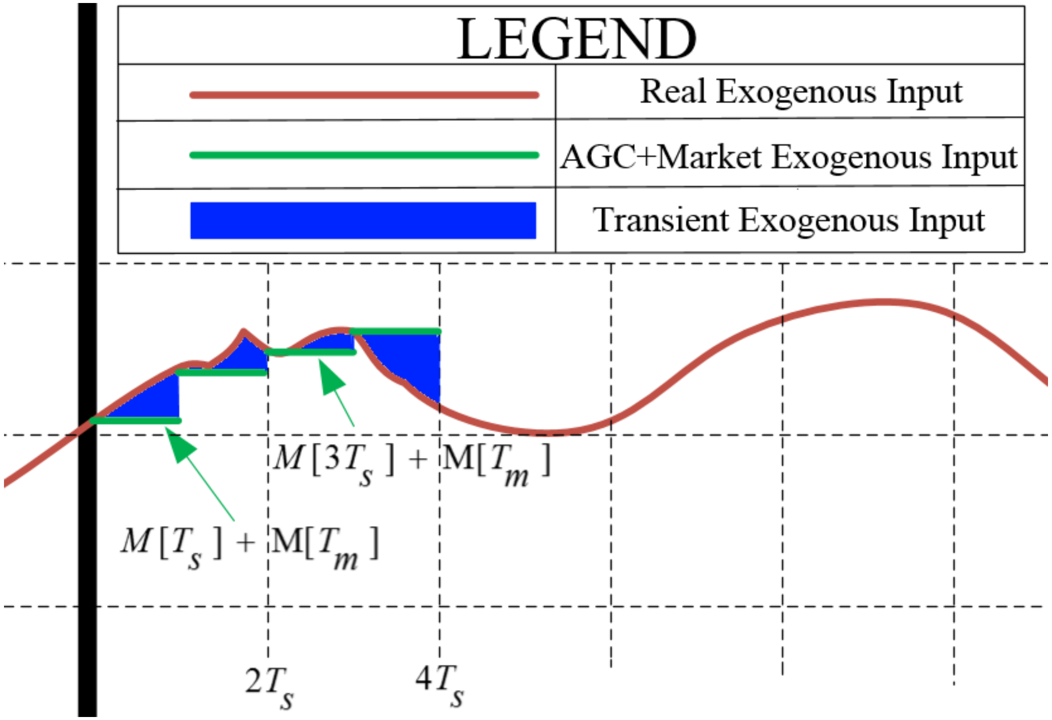
Multi-temporal exogenous input – Zoom Out



$$m_i(t) = M_i[K \cdot T_M] + M_i[k \cdot T_s] + \Delta m_i(t)$$

Real Exogenous Input | Market-Level Exogenous Input | AGC-Level Exogenous Input | Transient Exogenous Input

Multi-temporal exogenous input – Zoom In



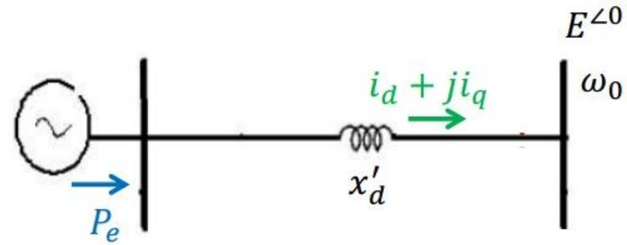
$$\underbrace{m_i(t)}_{\text{Real Exogenous Input}} = \underbrace{M_i[K \cdot T_M]}_{\text{Market-Level Exogenous Input}} + \underbrace{M_i[k \cdot T_s]}_{\text{AGC-Level Exogenous Input}} + \underbrace{\Delta m_i(t)}_{\text{Transient Exogenous Input}}$$

Generalized multi-temporal family of interacting models – module level

Electromagnetic (EM) phenomena	Electro-mechanical (EMEch) phenomena	Quasi-stationary (QS) regulation	QS short-term	QS long(er)-term
Time-varying phasors (EM)	Time-varying phasors (EMech)	$P[kT_s], Q[kT_s]$, $V[kT_s]$ driven by $M[kT_s]$; controlled by $u[kT_s]$	$P[KT_t], Q[KT_t]$, $V[KT_t]$ driven by $M[KT_t]$ and controlled by $u[KT_t]$	New equipment/topology driven by long-term predictions

Multi-layered interactive models for interconnected system (unifying transformed state space)

- Standard state space of interconnected system



$$\dot{\bar{\bar{X}}}_A = f_A\left(\bar{\bar{X}}_A, \mathrm{Z}_A, \mathrm{P}_A, u_A\right)$$

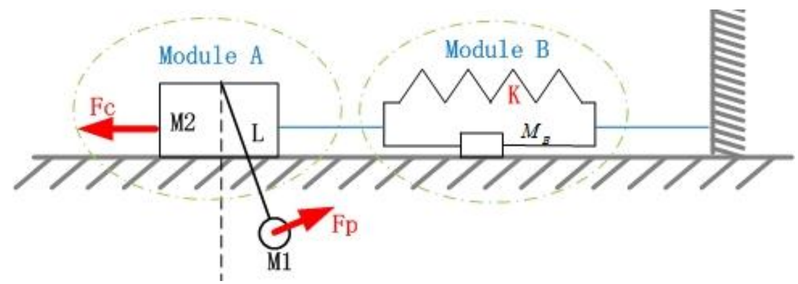
Interaction level model for coordination

$$\dot{\mathrm{Z}}_A = f_{ZA}\left(\bar{\bar{\mathrm{X}}}_A, \mathrm{Z}_A, \mathrm{P}_B\right)$$

$$\dot{\mathrm{P}}_A = f_{PA}\left(\bar{\bar{X}}_A, P_A, \dot{P}_B\right)$$

$$\dot{\mathrm{Z}}_B = f_{ZB}\left(\mathrm{Z}_B, \mathrm{P}_A, u_B\right)$$

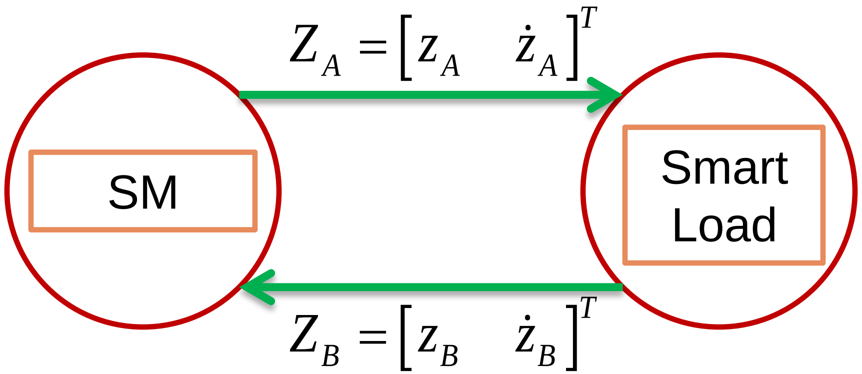
$$\dot{\mathrm{P}}_B = f_{PB}\left(P_B, \dot{P}_A\right)$$



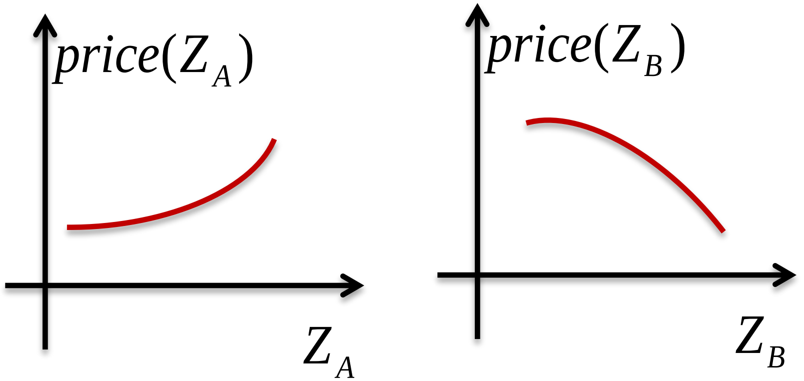
- Less assumption and communication are needed;
- System dynamics are separated into multi-layer system: internal layer and interaction layer;
- Based on above frame work, different control strategy can be used and designed: competitive or cooperative control

Required information exchange for interconnected system

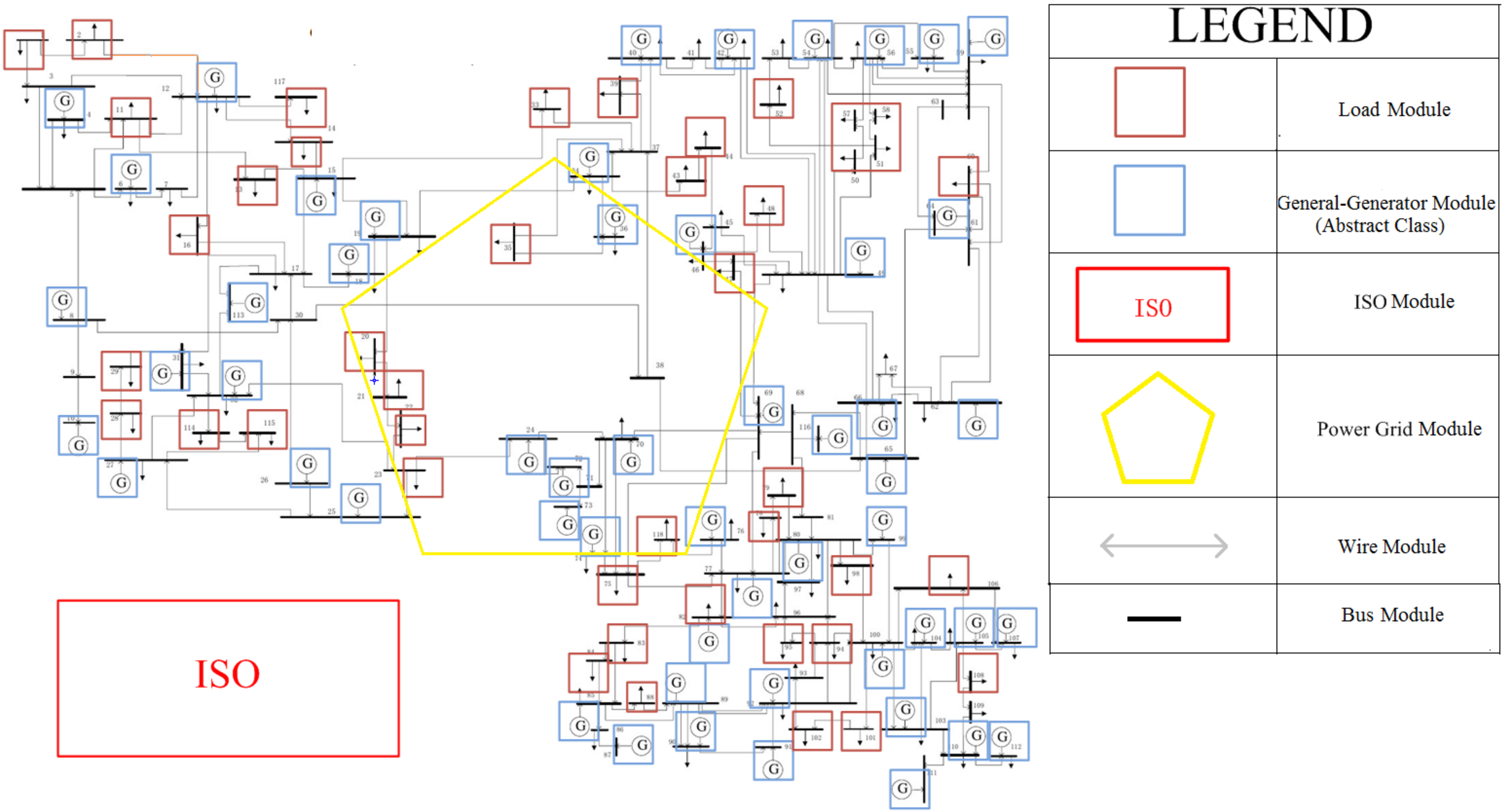
- To ensure reliability (stability, feasibility)
  - Must be exchanged interactively. They represents the total incremental energy & its rate of change; In steady state, decoupled assumption will be ***P & Q***
  - Ranges (convex function) instead of points exchanged (DyMonDS)



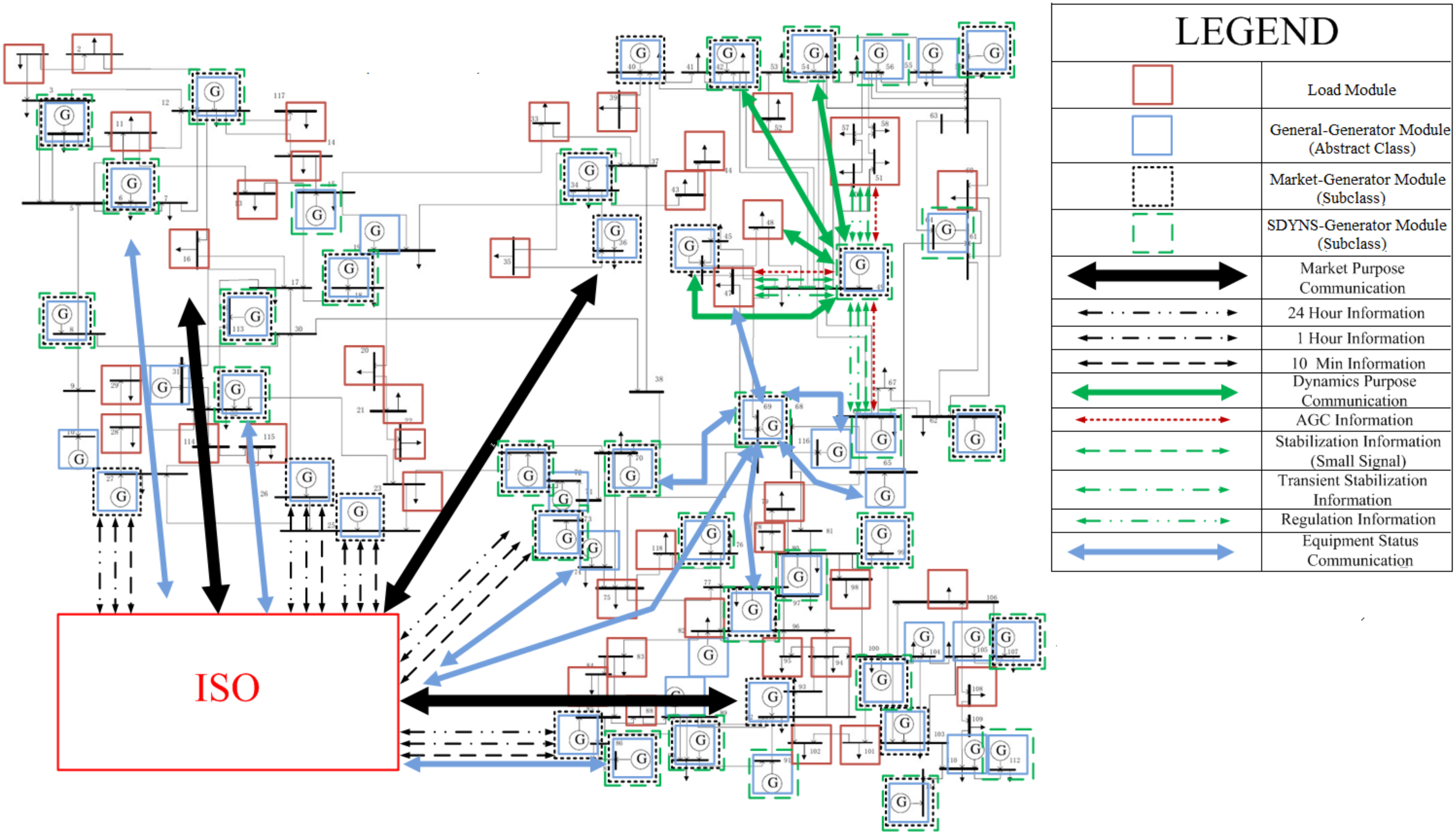
- For distributed interactive optimization
  - System-level optimization is the problem of "clearing" the distributed bids according to system cost performance [P, Q info processing requires AC OPF instead of DC OPF]



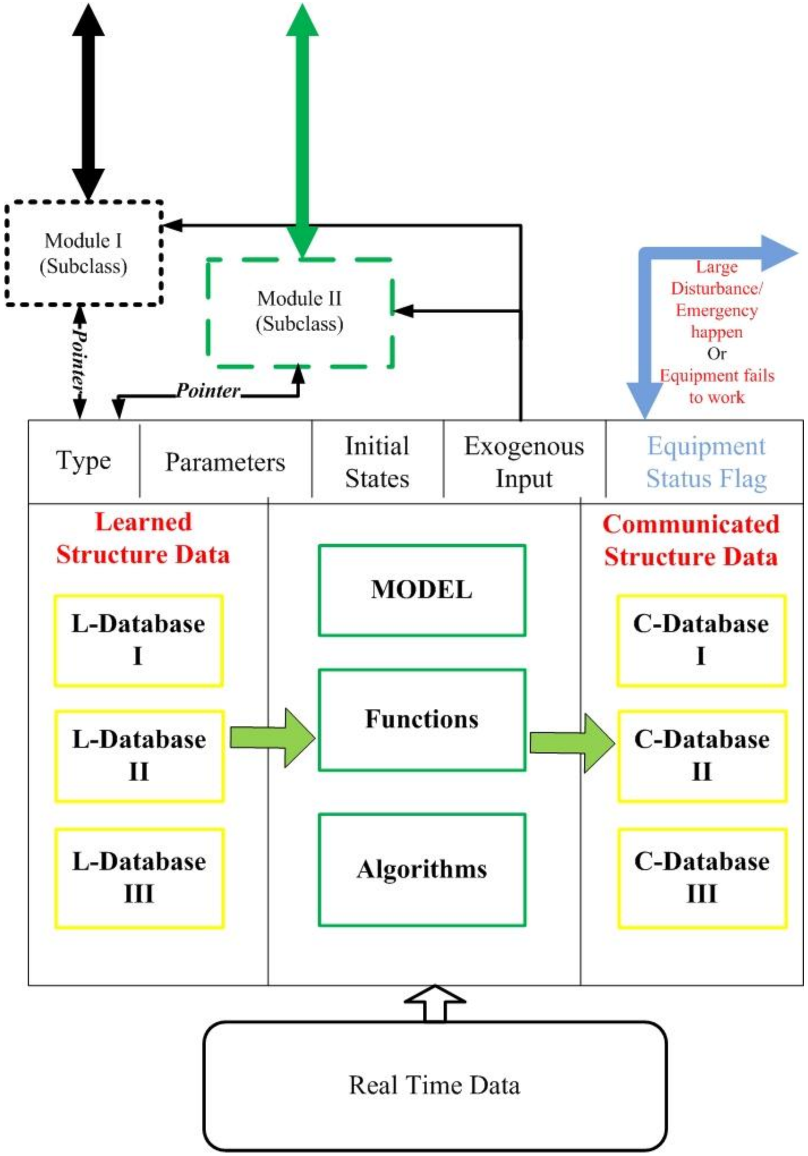
Basis for DyMonDS SGRS



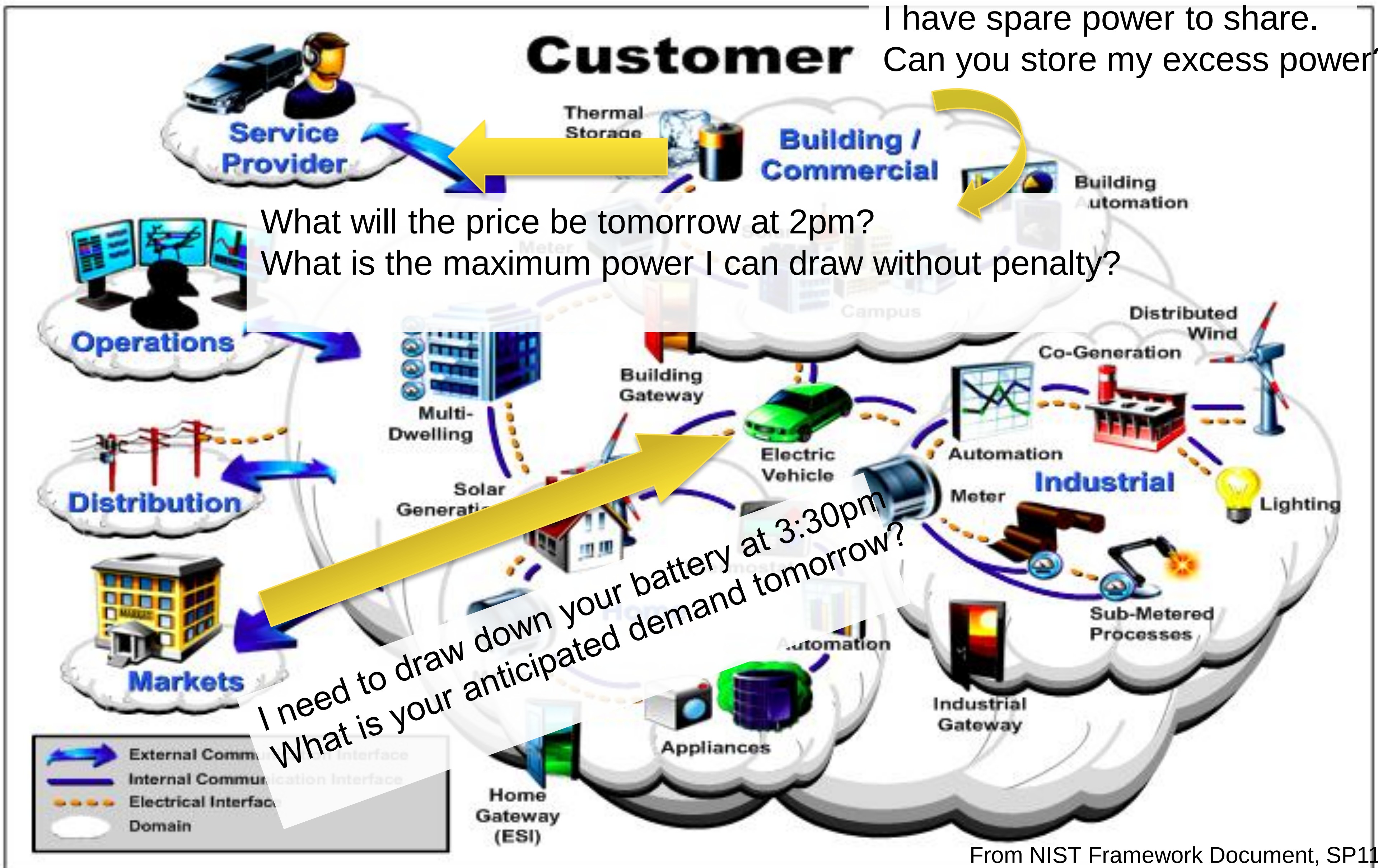
Information Exchange Between Modules



General Module Structure



Integration of Smart Consumers (DER)



Concluding remarks

- Physics-based modeling of electric power systems with non-zero mean disturbances
- Multi-layered dynamic models with explicit interaction variables relevant for coordinating levels
- Basis for consistent interactive communication within the multi-layered architecture
- Examples of problems with non-interactive information exchange (potentially unstable markets)
- Examples of enhanced AGC (E-AGC) for consistent frequency stabilization and regulation in response to non-zero mean disturbances
- Examples of fast power electronically switched cooperative control
- General communication protocols for DyMonDS Smart Grid in a Room Simulator (SGRS) based on these models
- The basis for general purpose scalable SGRS to emulate system response in the emerging power systems
- The challenge for user is to change their centralized method to DyMonDS based form

Thank you & Questions