FROM TODAY'S HIERARCHICAL CONTROL TO A DYNAMIC MONITORING AND DECISION SYSTEM (DYMONDS) TO SUPPORT ENERGY TRANSITION

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– Methods, Tools and Technologies

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Outline

- Revisit how is electricity service provided today, and how it can be improved by enhancing today's practice
- How is done: Today's hierarchical control and the basic limits to current practice
- New approach and why it can be successful
- What difference it will make
- Question 1: Scheduling for reliability and resiliency (AC OPF)
- Question 2: Ensuring feasible and stable end-to-end interactive service?
- What are the performance measures to demonstrate success

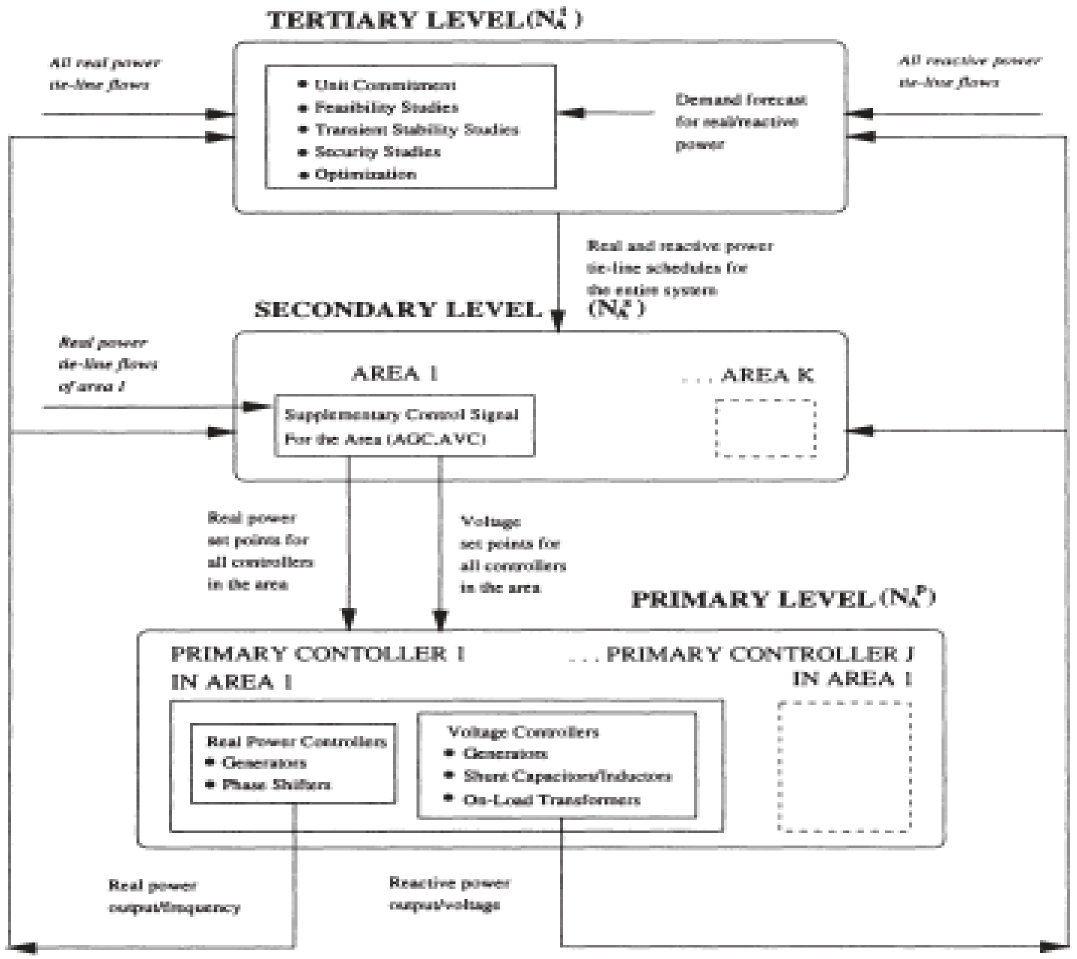
Electricity provision today*

- Top down centralized dispatch and control of large-scale power plants to:

- Task 1) supply predictable system demand;
- Task 2) Compensate predictable transmission losses;
- Task 3) Schedule generation so that there are no ``congestion" delivery grid problems;
- Task 4) Have sufficient regulation reserve to regulate frequency and voltage deviations caused by hard-to-predict slow power imbalances;
- Task 5) Have sufficient security reserve to supply predictable demand reliably even during the worst cas (N-1/N-2) outages;
- Task 6) Provide service during extreme events (N-k, k>>2) in a resilient way

*Ilić, Marija, and Francisco Galiana. "Power systems operation: old vs. new."*Power Systems Restructuring*. Springer, Boston, MA, 1998. 15-107.

Today's hierarchical control*

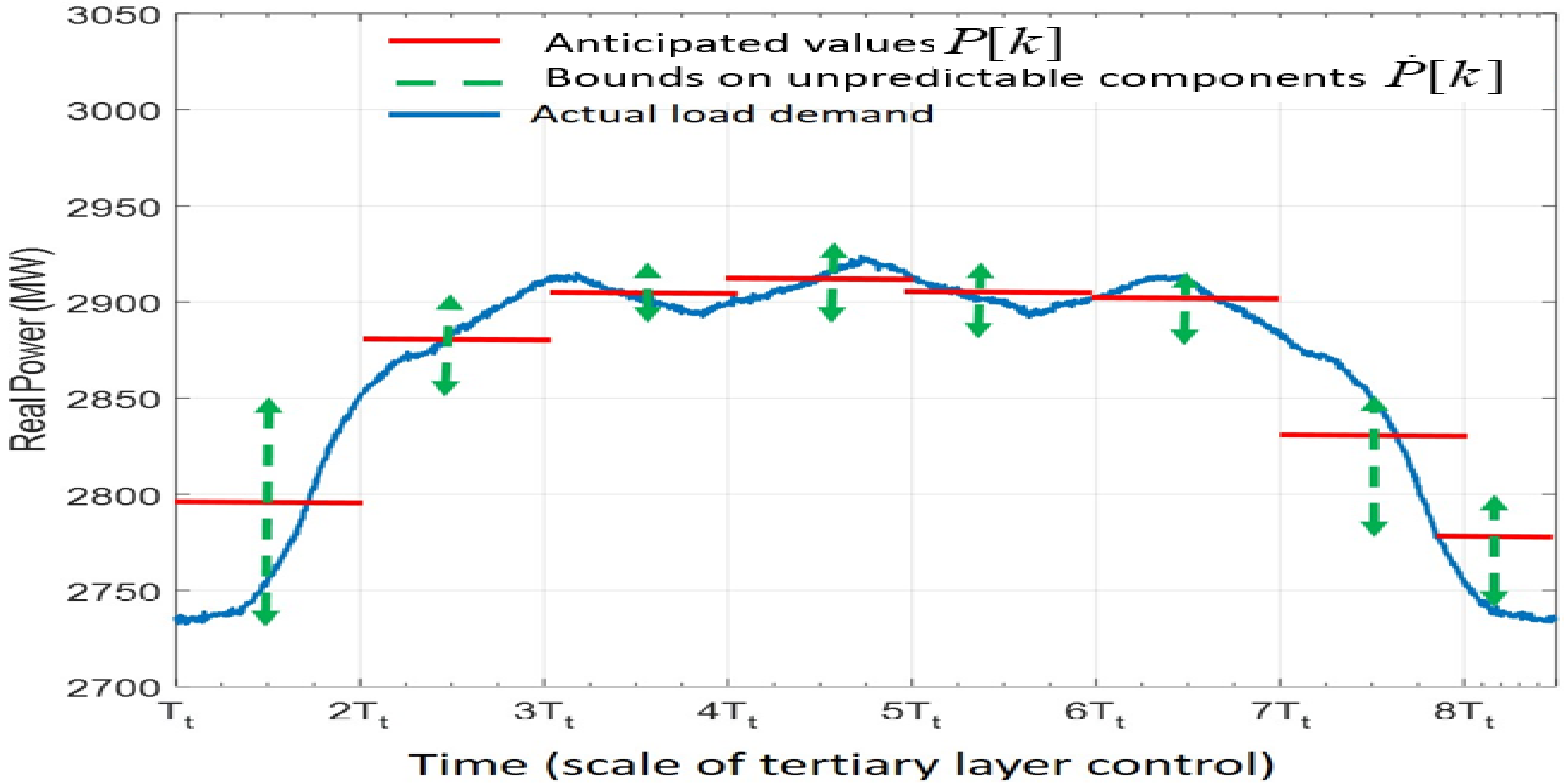


❖Implied assumptions

- P/Q decoupling
- Time scale separation
- Linearized control of generators
- Mainly Bulk Power System (>69kV)

*Ilic, M., & Liu, S. (2012). Hierarchical power systems control: its value in a changing industry. Springer Science & Business Media.

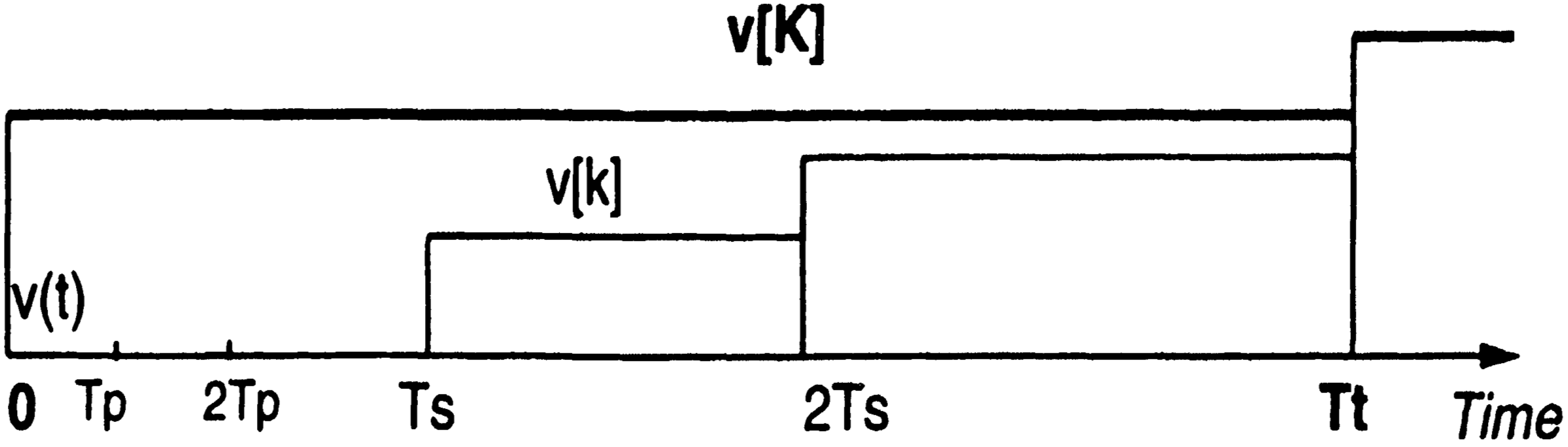
Basis for temporal hierarchies (load induced)



$$P_L = P_L(t) + P_L[k] + P_L[K] \qquad k, K = 0, 1, \cdots$$

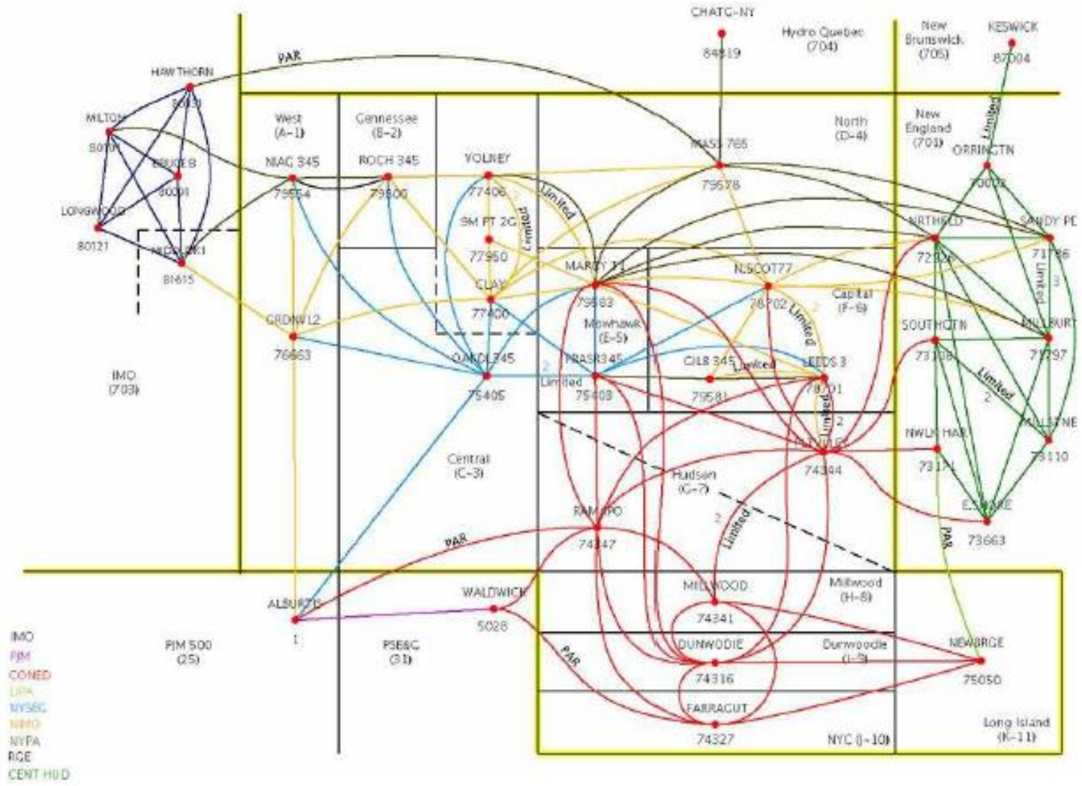
$$Q_L = Q_L(t) + Q_L[k] + Q_L[K] \qquad k, K = 0, 1, \cdots$$

Basis for hierarchical control



- PRIMARY CONTROL --- FASTEST TIME SCALE (T_p), SMALLEST MODULES (equipment)
- SECONDARY CONTROL – SLOWER TIME SCALE (T_s), MEDIUM SIZE MODULES (control areas)
- TERTIARY CONTROL– SLOWEST TIME SCALE (T_t), LARGEST MODULES (system)

Today’s wicked problem of energy services

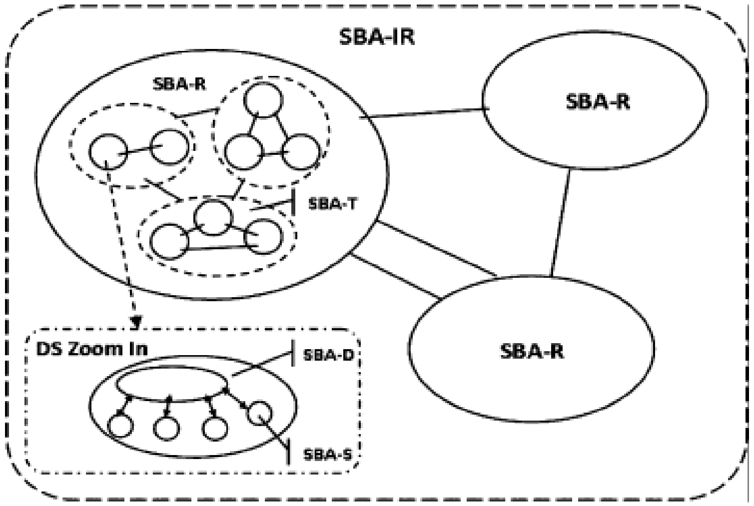


Temporal, spatial and governance complexity of the physical system

Un-aligned sub-objectives

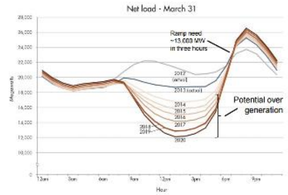
Emerging fundamental needs

- 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**

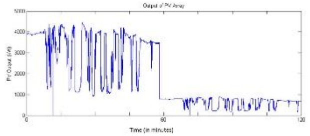


Intelligent Balancing Authorities (iBAs)

Temporal inter-twining

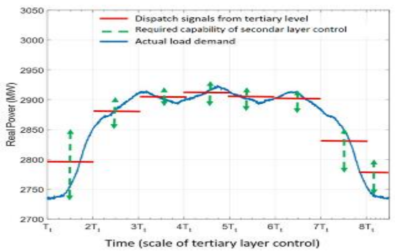


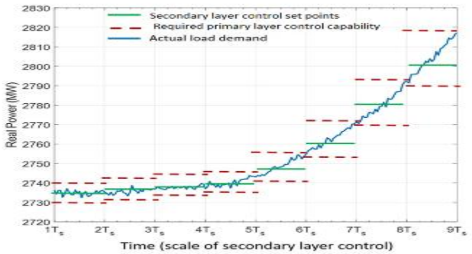
Aggregate effect of solar



Local solar

Hard to predict inputs





Nonzero mean effects

Ilic, M. D. (2010). Dynamic monitoring and decision systems for enabling sustainable energy services. *Proceedings of the IEEE*, *99*(1), 58-79.

Today's wicked problem of energy services: Basic limits

Outmoded control paradigm

- Static, deterministic
- Central EHV/HV/MV grid control;
- Large preventive reserves;
- No real time corrective actions
- No participation of MV/LV/DERs

What needs to be done

- Efficient energy service requires temporal, spatial and functional alignment of energy resources and demand
- T&D system needs to be operated to integrate the growing number of DERs, storage and intermittent resources in a flexible data-enabled way in order to manage uncertainties in an efficient manner

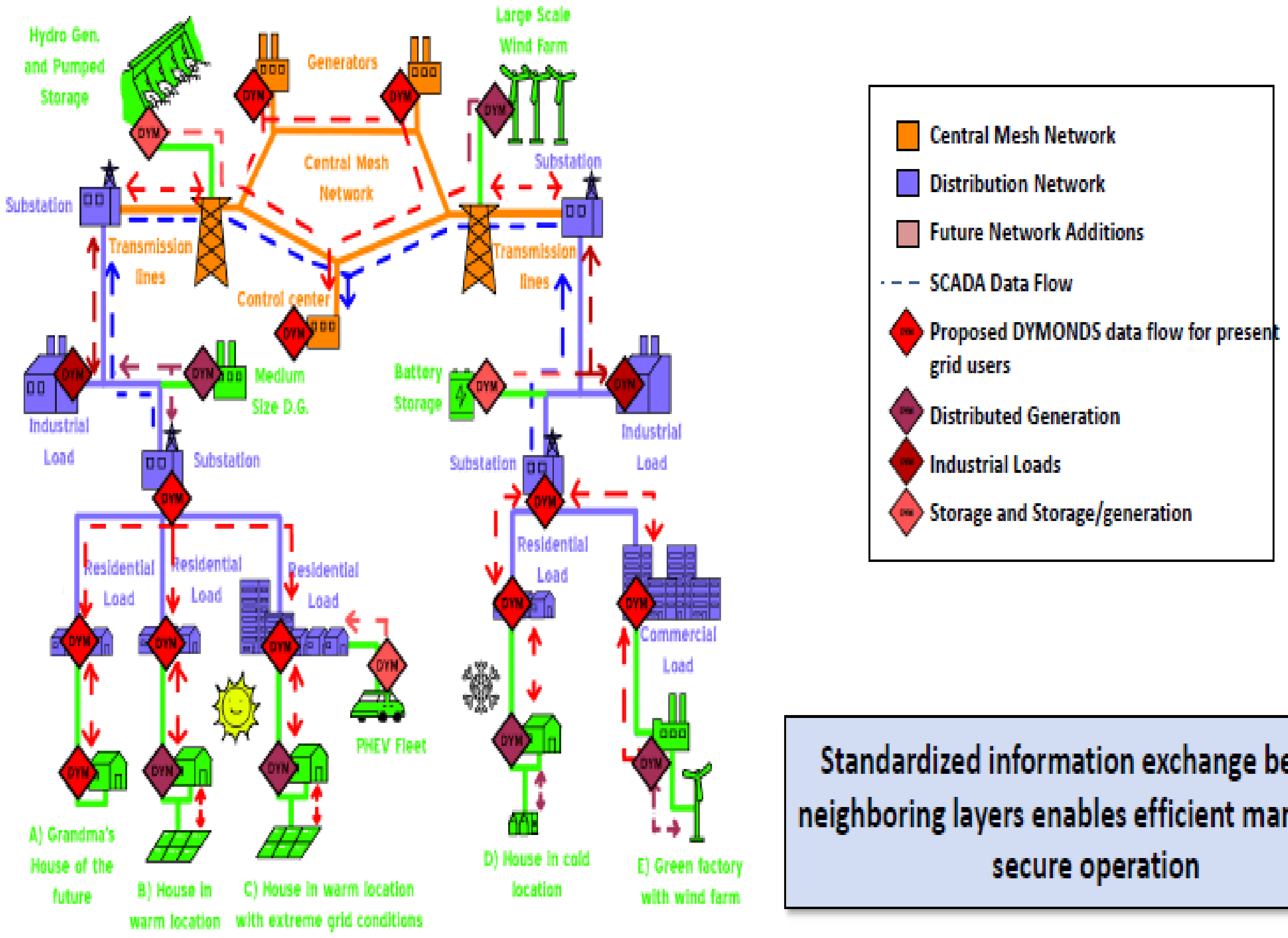
Resulting limitations

- Significant waste through excess reserves (typically 20-30% unused reserves)
- Significant waste due inefficient use of existing infrastructure (only 30% of transmission capacity currently used)
- Long distance transmission very costly, and limits resilience (e.g. California)
- Limits on proportion of renewables that can be accommodated (In Puerto Rico, system claims that 15% is max, our simulations show that xx is possible with no change in physical transmission system.)
- Lack of resilience to major storms, failures, attacks
- Lack of ability for communities, other stakeholders to "push envelope" on environmental impact, efficiency without major sacrifices in scale/pooling efficiency

Ilic, Marija, Lessard Don, A distributed coordinated architecture of electrical energy systems for sustainability, EESG@MIT WP, 2021 (available at request)

Proposed new approach:End-to-end flexible interactive operating paradigm

- **Transform BAs into iBAs** In order to support interactive control and co-design today' s BAs should be sub-divided into intelligent balancing authorities (iBAs) – groups of stakeholders, both utility and third parties, with their own sub-objectives. Each iBA is responsible for electricity services to its members and must communicate its commitments in terms of intVars to participate in electricity services with others
- **Information exchange in terms of energy, power and rate of change of reactive power.** intVars with physical interpretation as a generalized ACE.
- **Next generation SCADA to support information exchange among iBAs** As the operating conditions vary, stakeholders process the shared information, and optimize their own sub-objectives, subject to own constraints and preferences; and communicate back their willingness to participate in system-wide integration

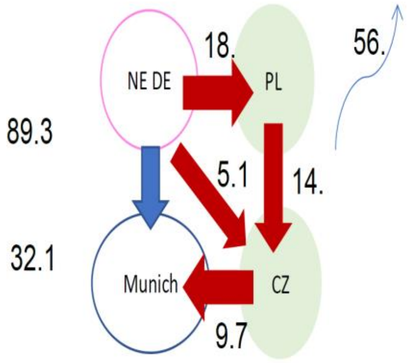


Standardized information exchange between neighboring layers enables efficient markets and secure operation

Dynamic Monitoring and Decision Systems (DyMonDS) breakthrough architecture

If adopted, it will be successful (demonstrations up to date, normal operations)

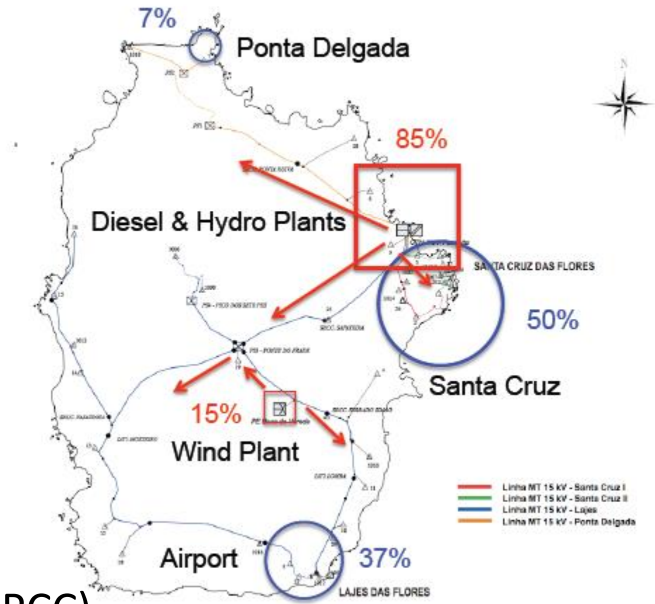
Wind power delivery from NW Germany to Bavaria

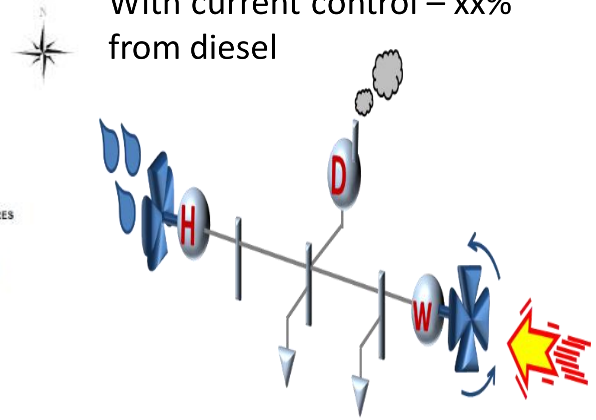


With current grid control
89.3 GW generated
32.1 GW delivered

With DyMonDS
30 GW generated
23 GW delivered

100% green Azores Islands, Portugal

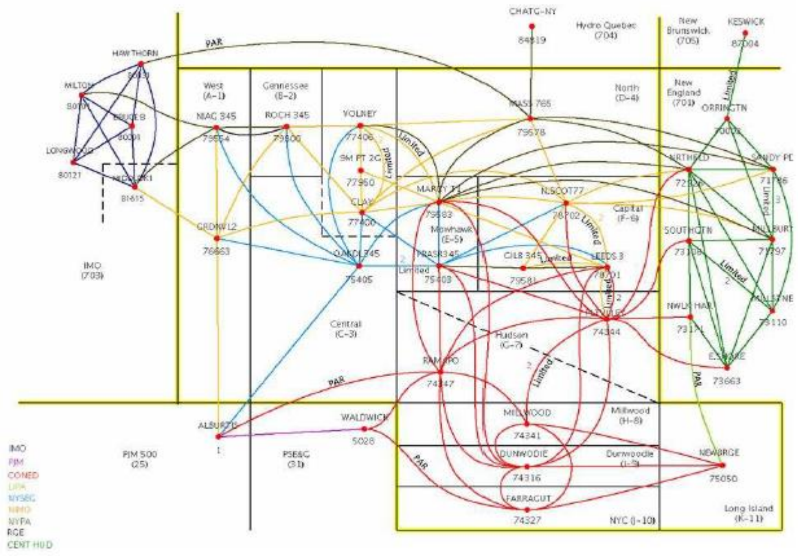




With current control – xx% from diesel

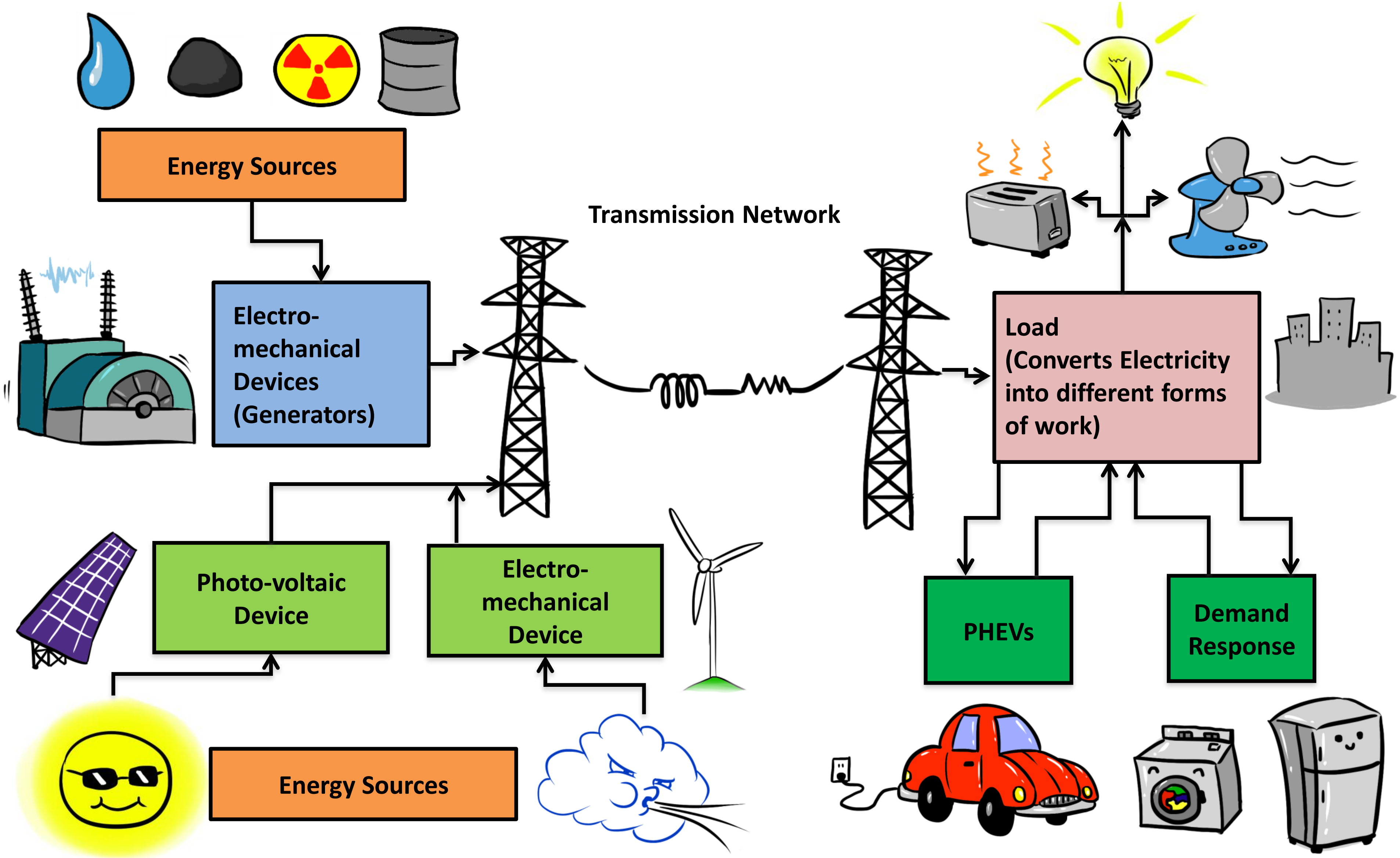
With DyMonDS
No diesel
Wind and hydro only

Complex electric energy system in the Northeast (NPCC)



Limits on moving power "around" area
Lack of resilience to climate, cyber, operator/equipment
Failure to engage "campuses" as iBAs
No integration across systems (electricity, nuclear, gas, hydrogen?)

Likely impact: Integration of diverse technologies at value



Likely impact: Making the most out of the naturally available resources without depleting them ? THE PROBLEM WE SHOULD SOLVE

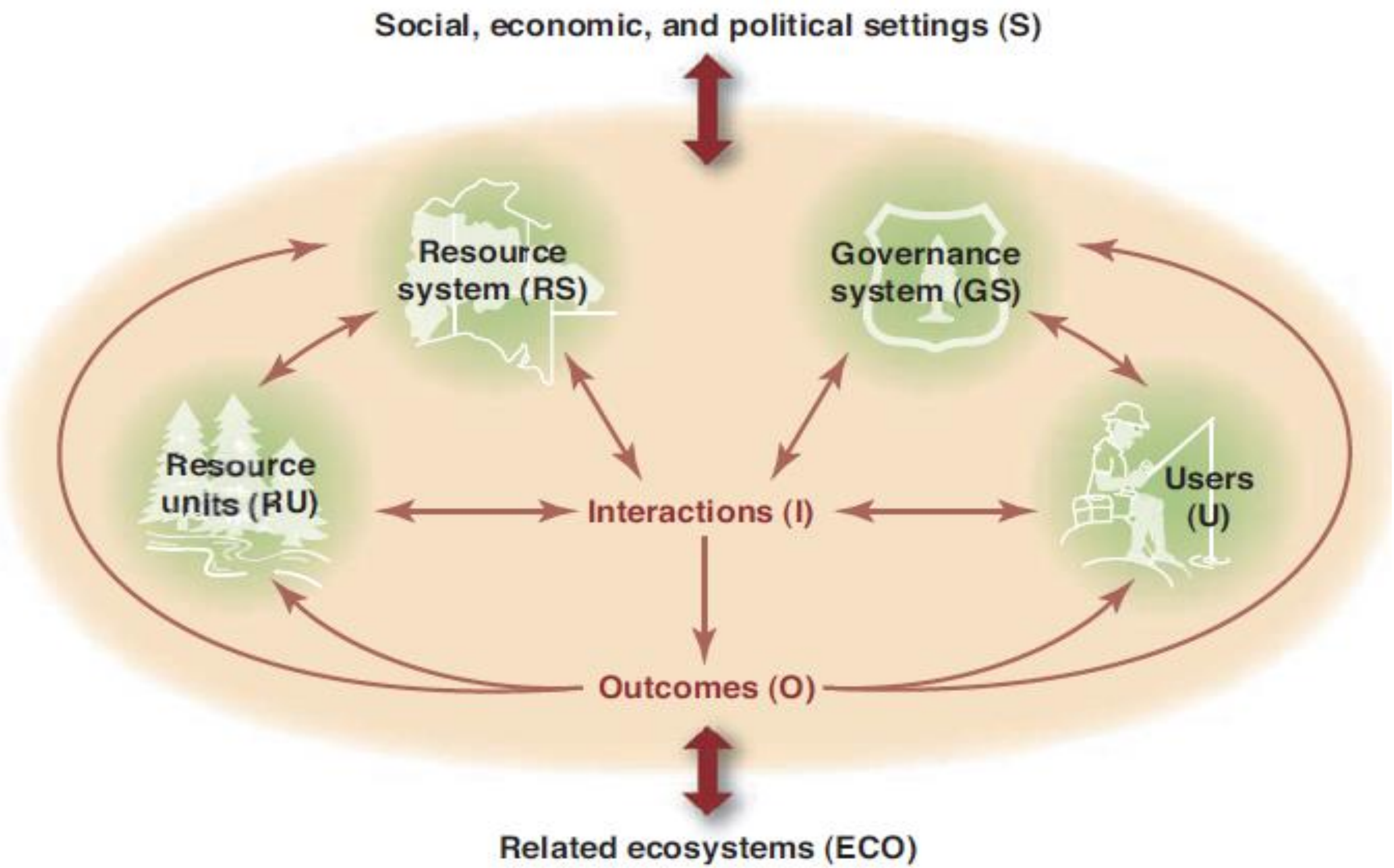
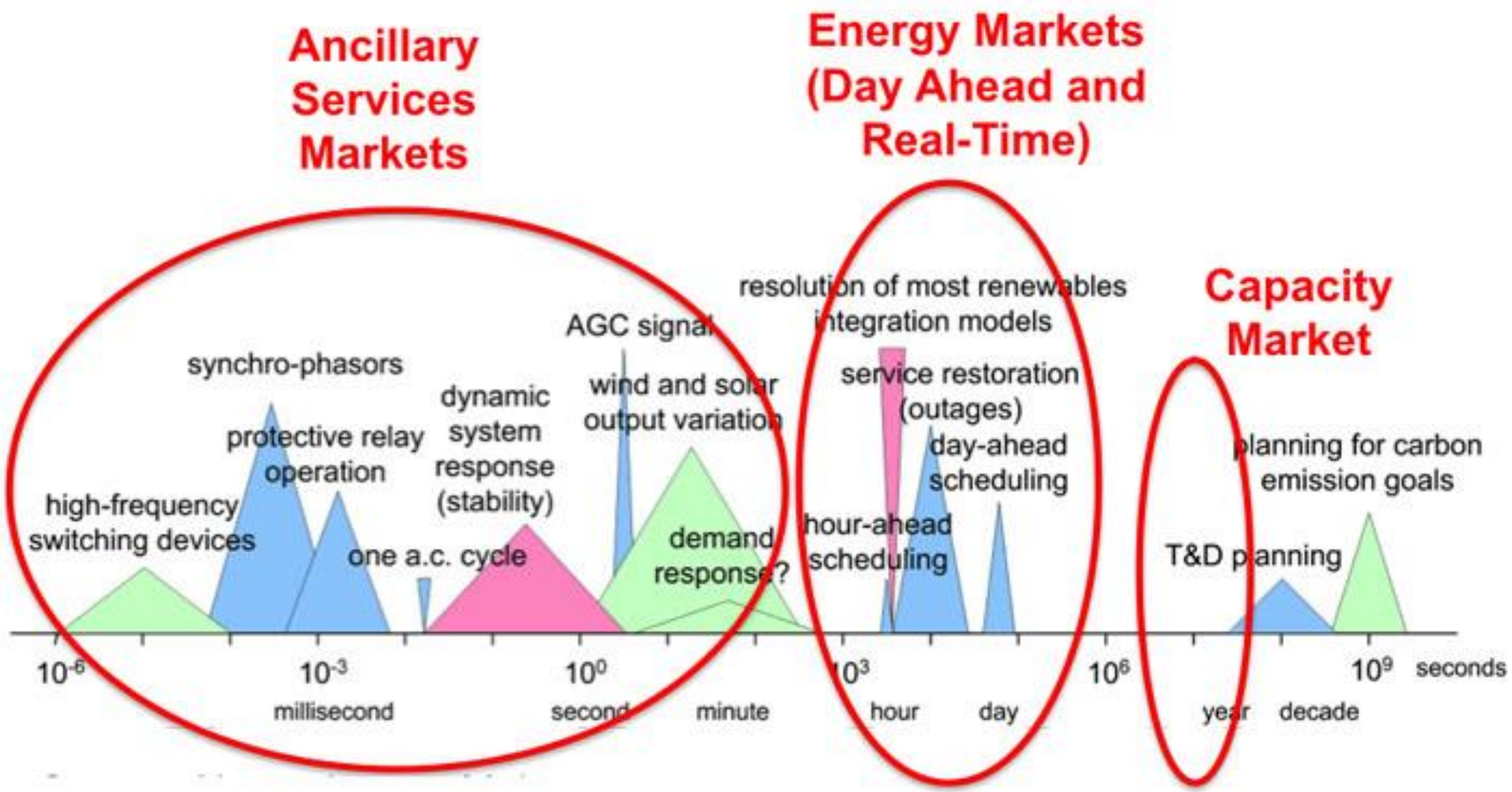


Fig. 1. The core subsystems in a framework for analyzing social-ecological systems.

Ostrom, Elinor. "A general framework for analyzing sustainability of social-ecological systems." *Science* 325, no. 5939 (2009): 419-422.

Ilic, M., Korpås, M., & Jaddivada, R. (2020). Interactive Protocols for Distributed Energy Resource Management Systems (DERMS). *IET Generation, Transmission & Distribution*.

Toward implementable **markets**---flexibility at value?



Von Meier, A., (2006) Electric power systems: a conceptual introduction. John Wiley & Sons. PJM Interconnection LLC (2017) Demand Response Strategy Tech. rep.

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**

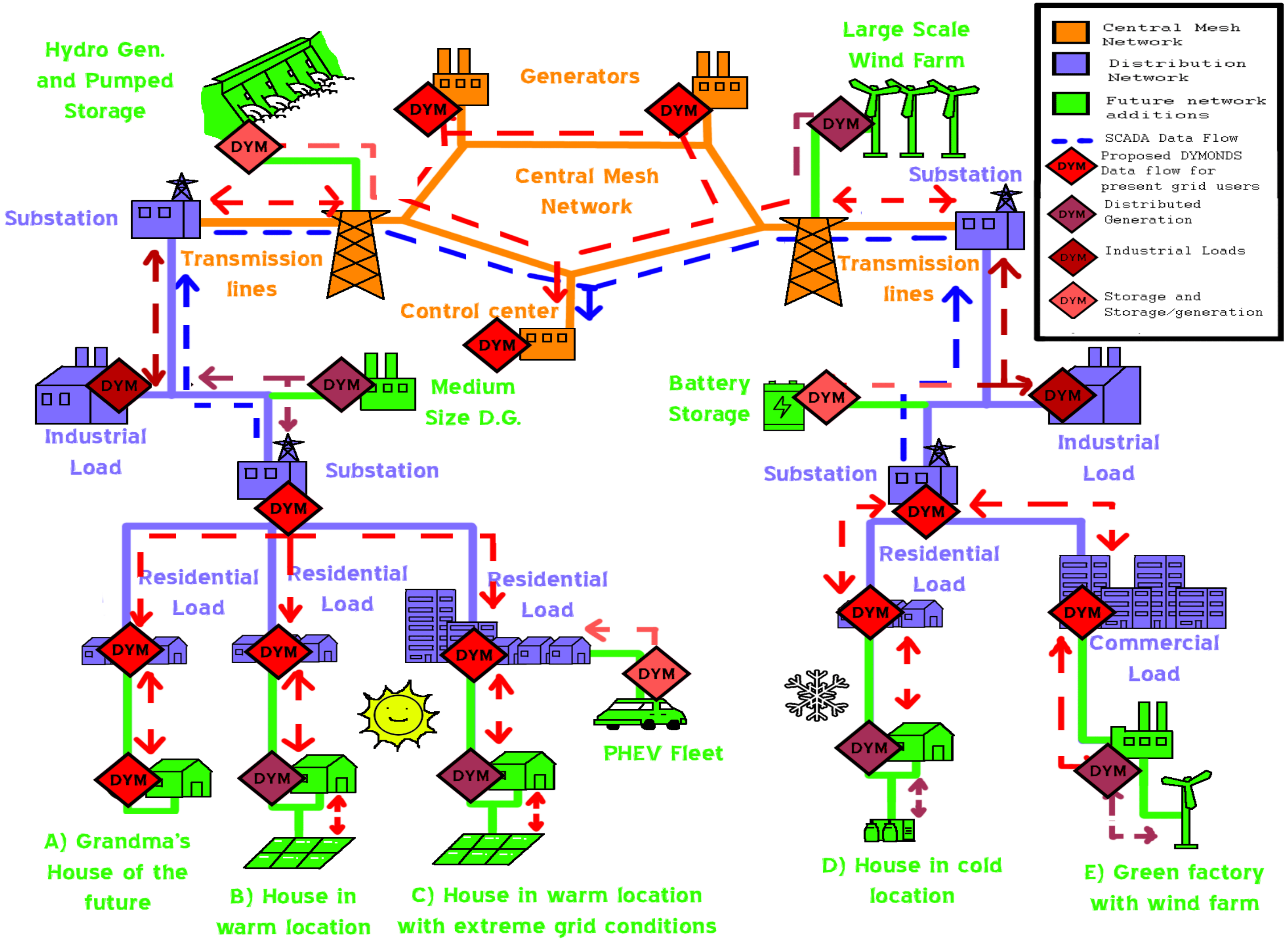
-- Highly distributed decision makers

--Minimal coordination of interactions

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

Ilic, M, A roadmap for technology deployment and its utilization at value for the changing electric energy industry, MIT EESG WP2020-2, April 2020.

DyMonDS: Basis for simple protocols that work*



*Ilić, M. D. (2010). Dynamic monitoring and decision systems for enabling sustainable energy services. Proceedings of the IEEE, 99(1), 58-79.
Ilic, Marija D. "Toward a unified modeling and control for sustainable and resilient electric energy systems." Foundations and Trends in Electric Energy Systems 1.1-2 (2016): 1-141.

System enhancements needed—hidden traps

- ***A (microgrid controller*): should have adaptive performance metrics and optimize over all controllable equipment *(not the case today)***
- ***B (secondary control-droops): modeling often hard to justify (droops only valid under certain conditions)***
- ***C (primary control)***: A combination of primary and secondary control should guarantee that commands given by microgrid controller are implementable (stable and feasible). *Huge issue—hard to control power/rate of change of power while maintaining voltage within the operating limits!*
- *Note: Control co-design key to improved performance*

Question 1: Resilient and reliable scheduling

From voltage constrained decision making (DCOPF + AC power flow) to coupled AC Optimal Power Flow

- Given an existing system, how to operate new power plants without experiencing power delivery problems.
- Given an existing system, how much new, renewable, generation to build and at which locations.
- Assess the effect of different pricing rules for integrating renewable resources on long- and short-term economic efficiency and the ability to recover capital investment cost.

ACOPF is the key software for co-optimizing power generation and voltage setting

Why is DCOPF insufficient?
With increased renewable penetration, it no longer is possible to dispatch real power with DCOPF well enough without optimizing the voltage settings

Voltage ``congestion” management using AC OPF

- The need to have ***ACOPF-based scheduling*** instead of ***AC power flow-based analyses*** tools
- Adjustments are supposed to work for both “normal” and “abnormal” conditions. (Task 5,Task 6) can also be enhanced significantly by using AC OPF*
- ACOPF-based mitigation for non-time-critical abnormal conditions is very similar to the one with normal conditions
- ***Major assumption:*** sufficient automation is in place to ensure stable system over operating ranges

**Ilic, Marija, Carvalho, Pedro, Lessard, Donald, `` Minimal Coordination of Dynamic Reserves for Flexible Operations at Value: The Case of Azores Islands”, IEEE PES GM 2021, Paper forum.*

From analysis to optimization: Features of AC-XOPF

- Having the ability to find a solution within specified network and hardware constraints
- Having the ability to optimize with respect to all available decision variables, such as real power generation, demand, and T&D voltage-controllable equipment
- Providing as part of its output optimization sensitivities
- Providing support of effective resource management according to several optimization objectives
- ***Providing as part of its output LMPs***, which are sensitivities of the performance objective with respect to power injection change at each node in the network

$$\mathrm{LMP}_i = \frac{\delta J}{\delta P_i}$$

AC-XOPF is capable of adaptively switching between using different performance metrics. This is essential for reconciling reliability and efficiency on-line when system conditions and topology change significantly over time

Question 2:Enabling feasible and stable control?

❖Interactive model of interconnected systems

--multi-layered complexity

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

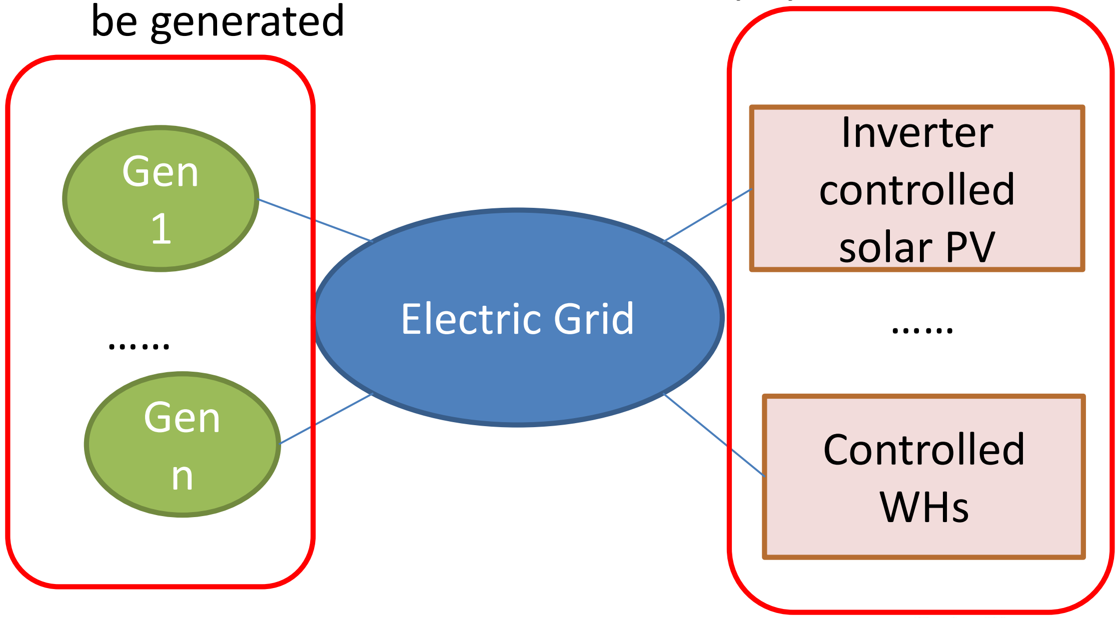
--interactions subject to conservation of instantaneous power and reactive power dynamics; optimization at system level in terms of these variables

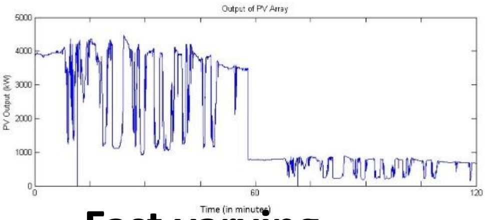
--physically intuitive models

Basic ideas underlying the energy-based dynamical models

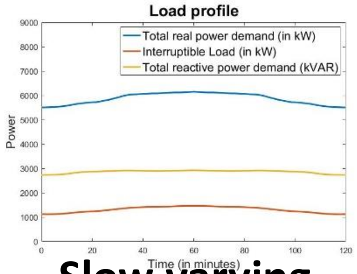
Inertia used as a proxy to rates at which energy can be generated

Synthetic inertia used instead – non-physical





Fast varying generation



Slow varying demand

Heterogeneous end-end energy conversion processes modeling is becoming critical - inertia (or synthetic inertia) – based approximated system analysis no longer are valid

Basis for energy as a state variable

Power conservation laws always hold at the interfaces of components and/or sub-systems.

Basis for real power as an interface variable

Not all power produced can be delivered fundamentally due to mismatch in rates at which energy conversion processes of connected components take place – non thermal losses ought to be captured.

Basis for reactive power as an interface variable

Basic modeling, simulations and control principles

- 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 components.
- Second principle—an ``optimal'' social ecological energy system (SEES) should evolve through the feedforward/feedback interactions

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)

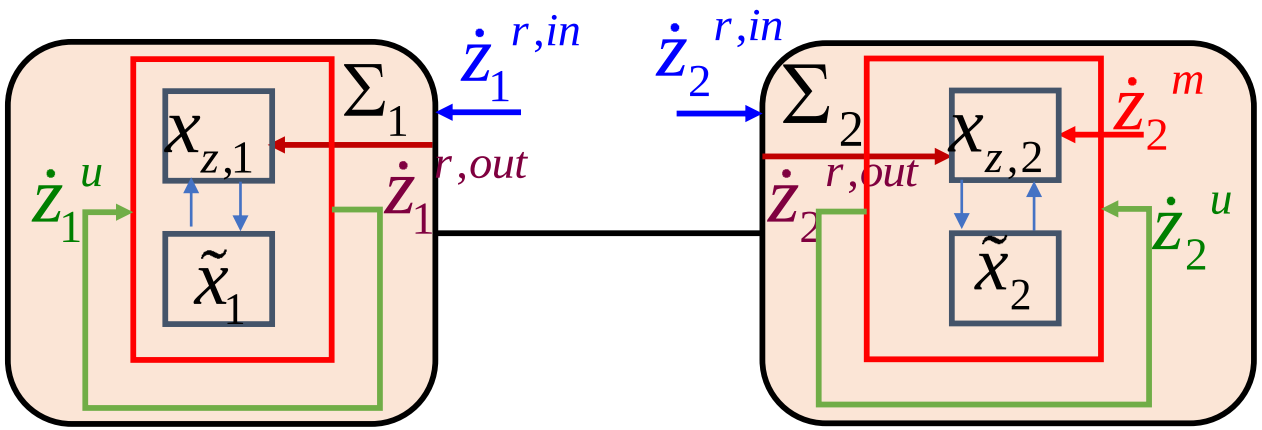
--interactions subject to conservation of instantaneous power and reactive power dynamics; optimization at system level in terms of these variables

--physically intuitive models

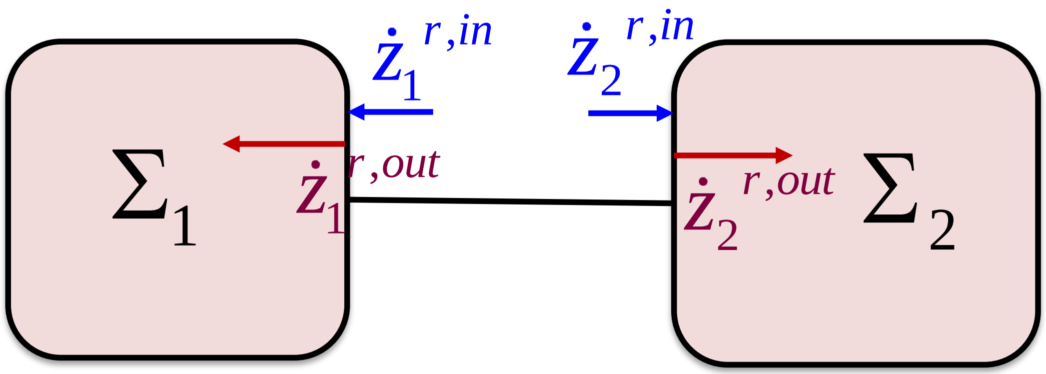
Ilić, Marija D., and Rupamathi Jaddivada. "Multi-layered interactive energy space modeling for near-optimal electrification of terrestrial, shipboard and aircraft systems." *Annual Reviews in Control* (2018).

Representation of interactions within and across components

Zoomed-in representation:



Zoomed-out representation:



Jaddivada, ER., Ilic, M, A feasible and stable distributed interactive control design in energy state space, Proceedings of the IEEE Conference on Decision and Control (CDC), December 2021.

Unifying properties of interaction variables

Property 1: [Ilic,Liu]
Interaction variables are function of local variable alone

$$z_i^{r,out} = \begin{bmatrix} \int_0^t P_i^{r,out} dt \\ Q_i^{r,out} \end{bmatrix} = \begin{bmatrix} E_i + \int_0^t \frac{E_i}{\tau_i} dt \\ \int_0^t 4E_{t,i} dt - p_i \end{bmatrix} = f(x, \dot{x})$$

Property 2: [Ilic,Liu]
Interaction variable of a component i is a variable $z_i^{r,out}$ that satisfies

$$z_i^{r,out}(t) = constant$$

when all interconnections among subsystems are removed and the system is free of disturbances

$$\dot{z}_i^{r,out} = L_z^{-1} \dot{z}_i^{r,in} = 0$$

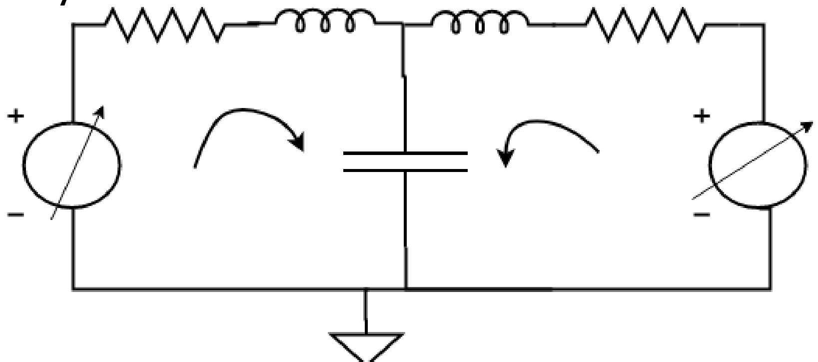
No linearization!
No decoupling!
The same definition

Property 3: (State of art in power systems)
Dynamics of reactive power can be neglected when voltage is not changing

Generalized reactive power:

$$\dot{Q}_i^{r,in} = v_i \frac{di_i}{dt} - \cancel{\frac{dv_i}{dt}} i_i = \dot{P}_i^{r,in}$$

Property 4: (Circulating currents)
Circulating currents are indicative of non-zero reactive power dynamics



Closing thoughts

❖ Necessary attributes (industry wish list) for operating and controlling future electric energy systems

- Availability* (supply-demand; new ways of doing it)
- Flexibility* (key role of control; must be provable, otherwise it does not work)
- Visibility, transparency* (data-enabled information exchange about functionalities)
- Simplicity** (modular, easy to deploy, utilize)

*Ken Mc Intyre, panelist DoE Transmission Innovation Summit, May 19,2021
**Greg Zweigle, SEL. panelist DoE Transmission Innovation Summit, May 19,2021

Looking forward

- Much room for innovation at value
- Digitalization for decarbonization; distributed interactive platforms; digital twins; ML/AI;
- Control implementation in complex nonlinear dynamical systems.
- Technology-agnostic principles for modeling, simulations and control
- Next generation software & control for changing industry

THANK YOU