NATIONAL COUNCIL
ON ELECTRICITY POLICY

Annual Meeting 2019

Evolving Transmission, Distribution, and Customer System Coordination

Wednesday, September 11 – Thursday, September 12

Austin, Texas

Physical System & Operating Essentials

Hon. Nick Wagner, Moderator

Paul De Martini

Jeff Taft

GRID ARCHITECTURE

Grid Architecture Concepts for TDC Coordination

September 11, 2019

Pacific Northwest
NATIONAL LABORATORY

How to Build A House

What do you pick up first:

a shovel

or a pencil?

The Word "Architecture" Is Used Many Ways

- House or building layouts
- Master plans
- Organization models
  - device like an integrated circuit chip
  - company internal arrangement
- Block diagrams
- High level ("logical") design views of IT systems
- System designs or implementations
- Other abstractions like layer models

We need to be clear on what we mean by grid architecture.

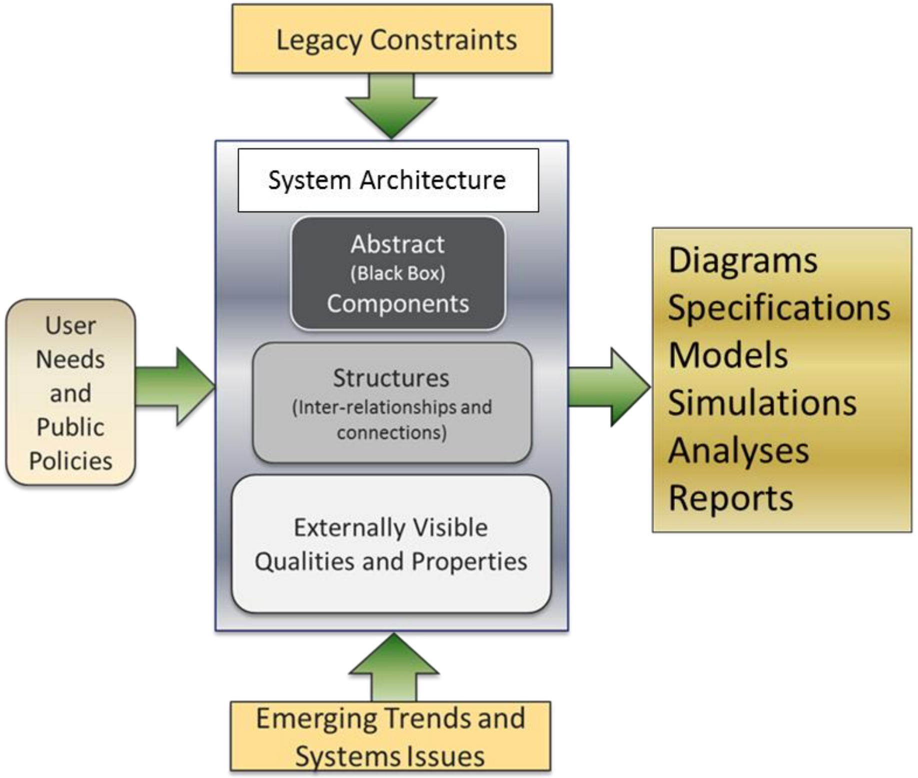
System Architecture

Architecture

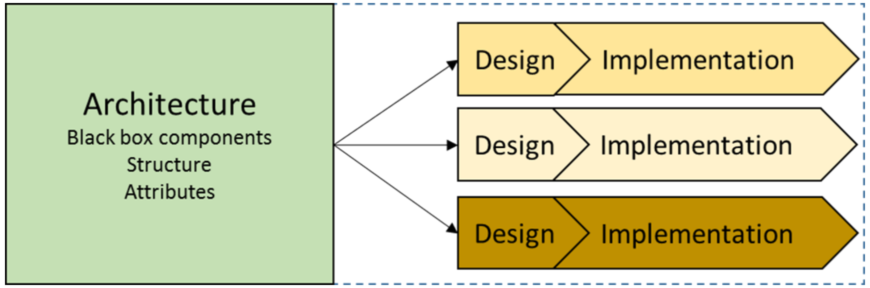
- An abstract depiction of a system, consisting of black box components, structure, and externally visible properties

Purposes:

- Identify legacy constraints
- Remove barriers and refine essential limits
- Help manage complexity (and therefore risk)
- Support early stage modernization processes
- Identify gaps in structure, technology
- Assist communication among stakeholders
- Define platforms
- Inform interfaces and interoperability

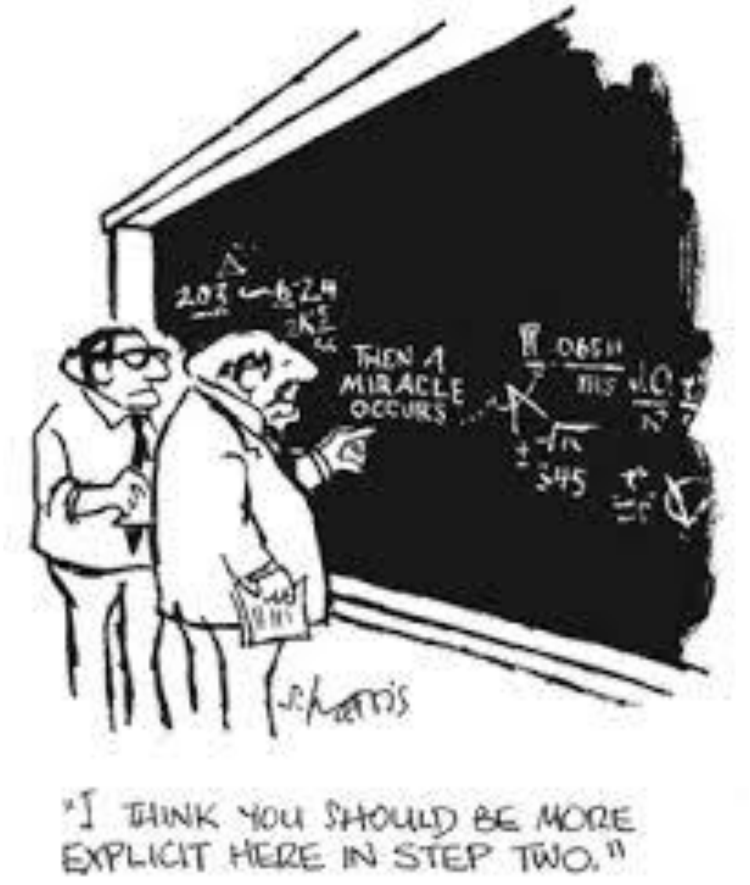


Architecture is *not* design.



Elements of System Architecture: Components

- Abstract components
  - The individual parts, viewed as “black boxes”
  - Example: storage battery
    - At this level we do not specify how the battery works
    - Care about externally visible characteristics like storage capacity, max power rating
  - But thoroughly grounded in reality
    - no “magic” boxes, miracles, or anti-gravity



Source: Sidney Harris

Elements of System Architecture: Structure

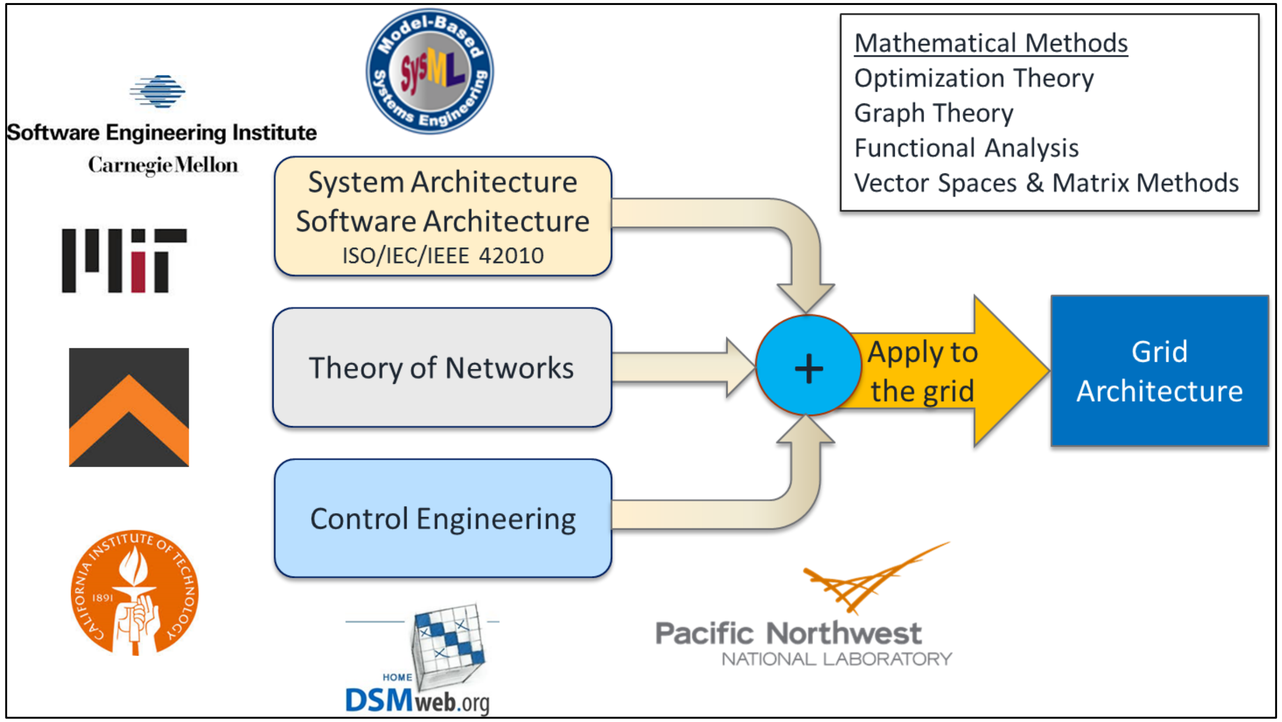
- Abstract components
  - The individual parts, viewed as “black boxes”
  - But thoroughly grounded in reality (no “magic” boxes)

- Structures
  - The overall shape of the system and how components interact
  - Any complex system has multiple structures, requiring multiple views
  - No real architecture can be represented in a single diagram

Grid Architecture is System Architecture for the Grid

Grid Architecture is the application of system architecture, network theory, and control theory to the electric power grid.

A grid architecture is the highest level description of the complete grid, and is a key tool to help understand and define the many complex interactions that exist in present and future grids.



System Complexity and Electric Grids

Low Complexity

Medium Complexity

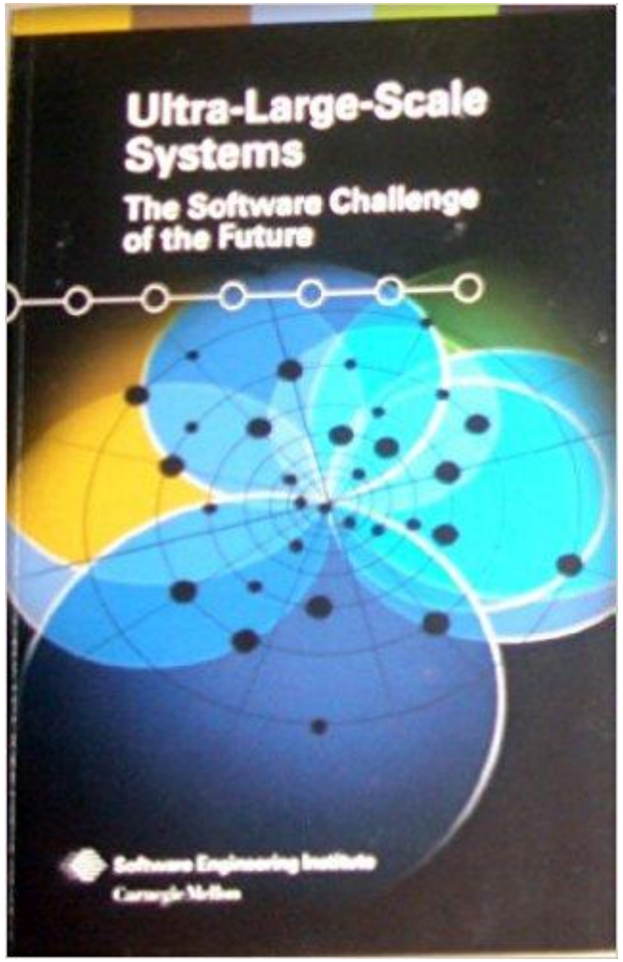
High Complexity

Power systems are off the chart…

Complexity is the hidden bear in the room when dealing with grid modernization.

Ultra-Large-Scale Systems

- Based on concepts/theory developed at Carnegie-Mellon University
- Mark Klein, Linda Northrop, et. al, Ultra-Large-Scale Systems, Software Engineering Institute, Carnegie-Mellon University, 2006
- This is a kind of system, not an architecture
- Basic presumption is that some classes of systems have levels of complexity that “push far beyond the size of today’s systems and **systems of systems** by every measure…”
- Defense systems – DoD
- US health care system
- Electric Power Grids

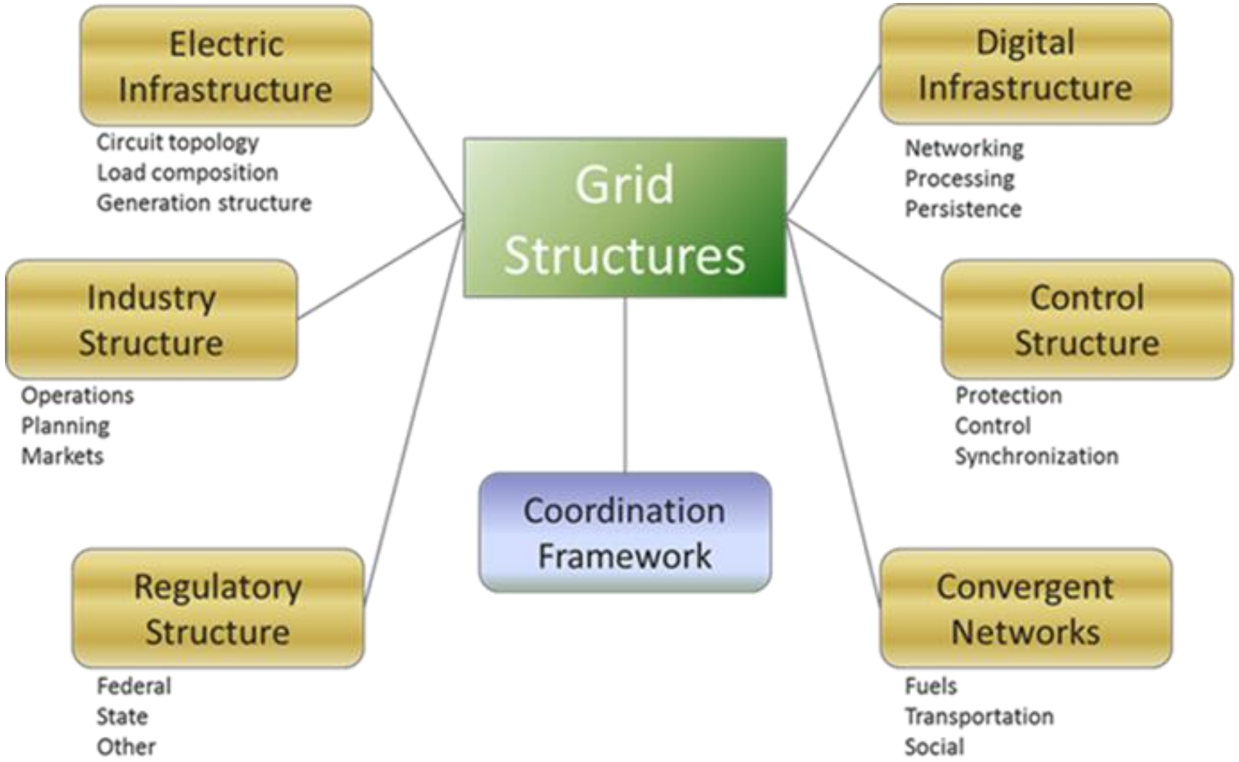


Seven Ultra Large Scale Systems Characteristics

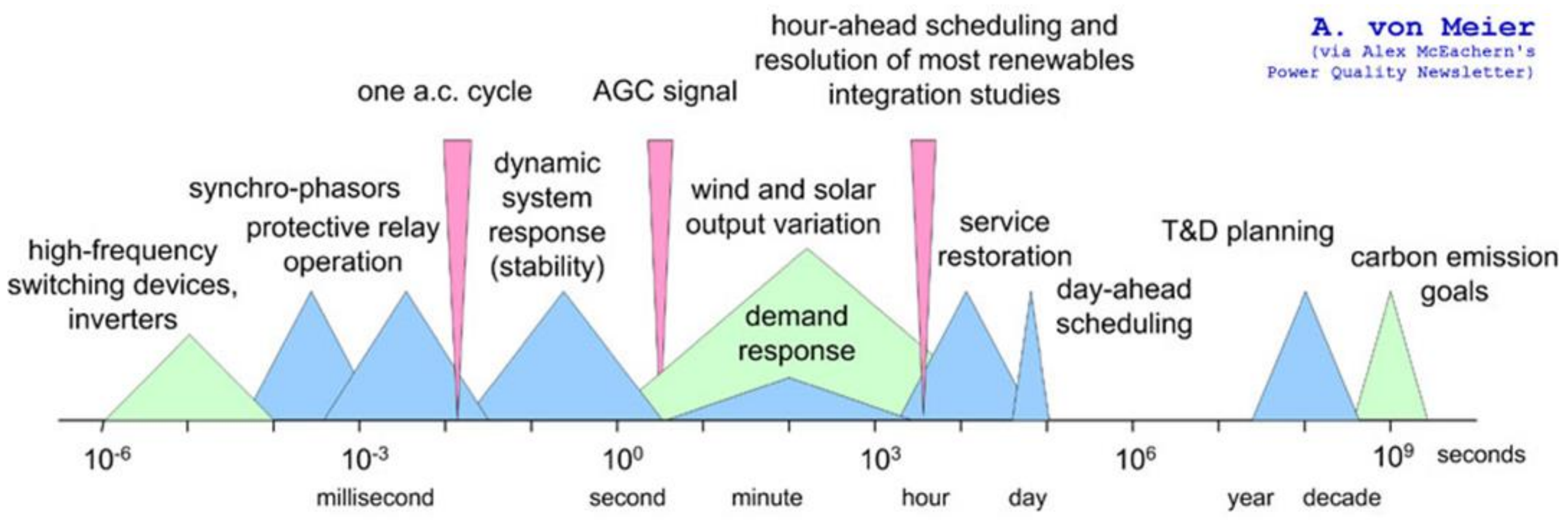
1. Inherently conflicting diverse requirements
2. Decentralized data, control, and development
3. Continuous (or at least long time scale) evolution and deployment
4. Heterogeneous, inconsistent, and changing elements
5. Wide time scales
6. Wide geographic scales
7. Normal failures

Why is the Grid Ultra-Large-Scale Complex?

- The grid is comprised of many already complex structures
- These structures are interconnected and interact in complex ways
- This results in an explosion of complexity.

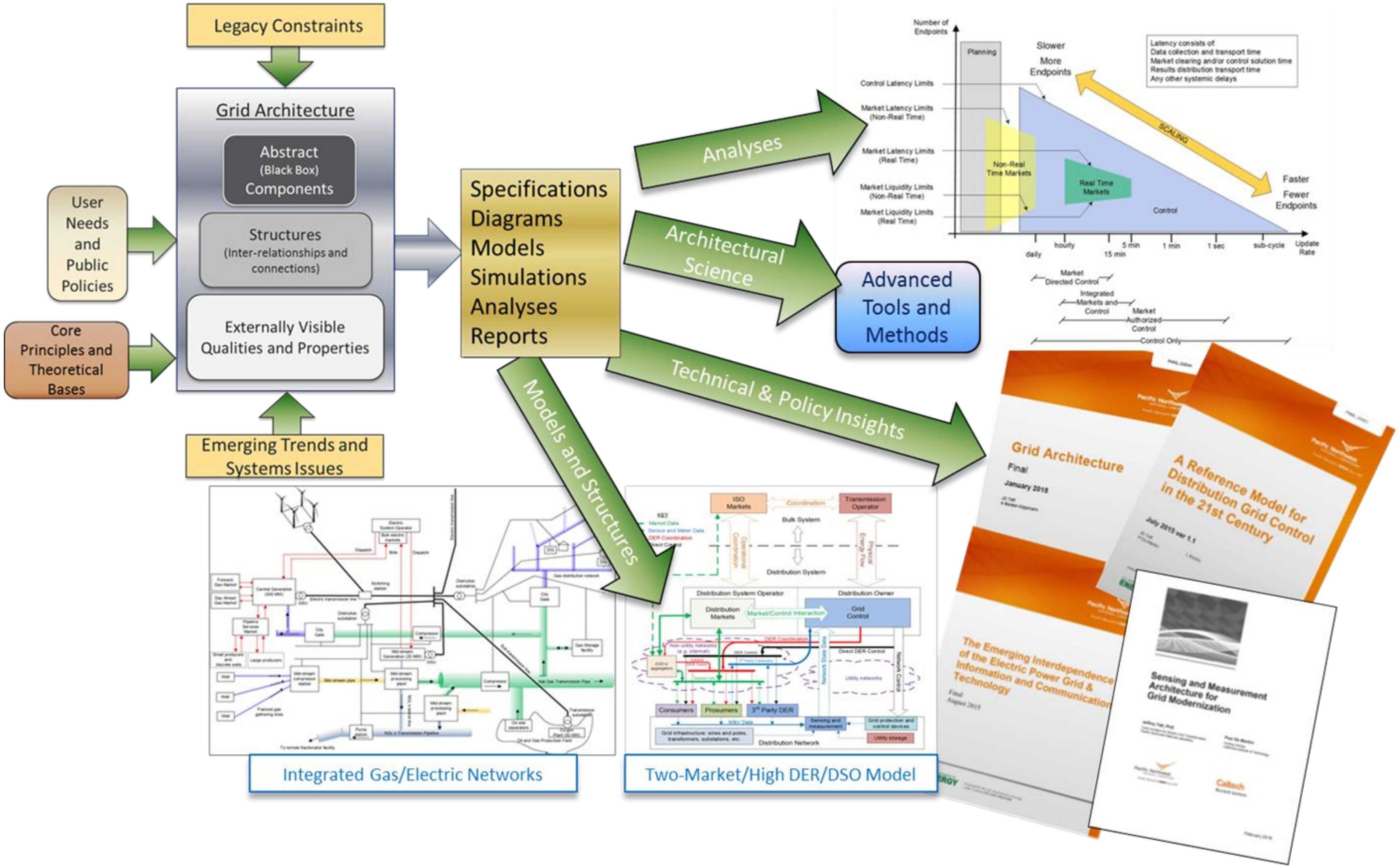


Wide Time Scales



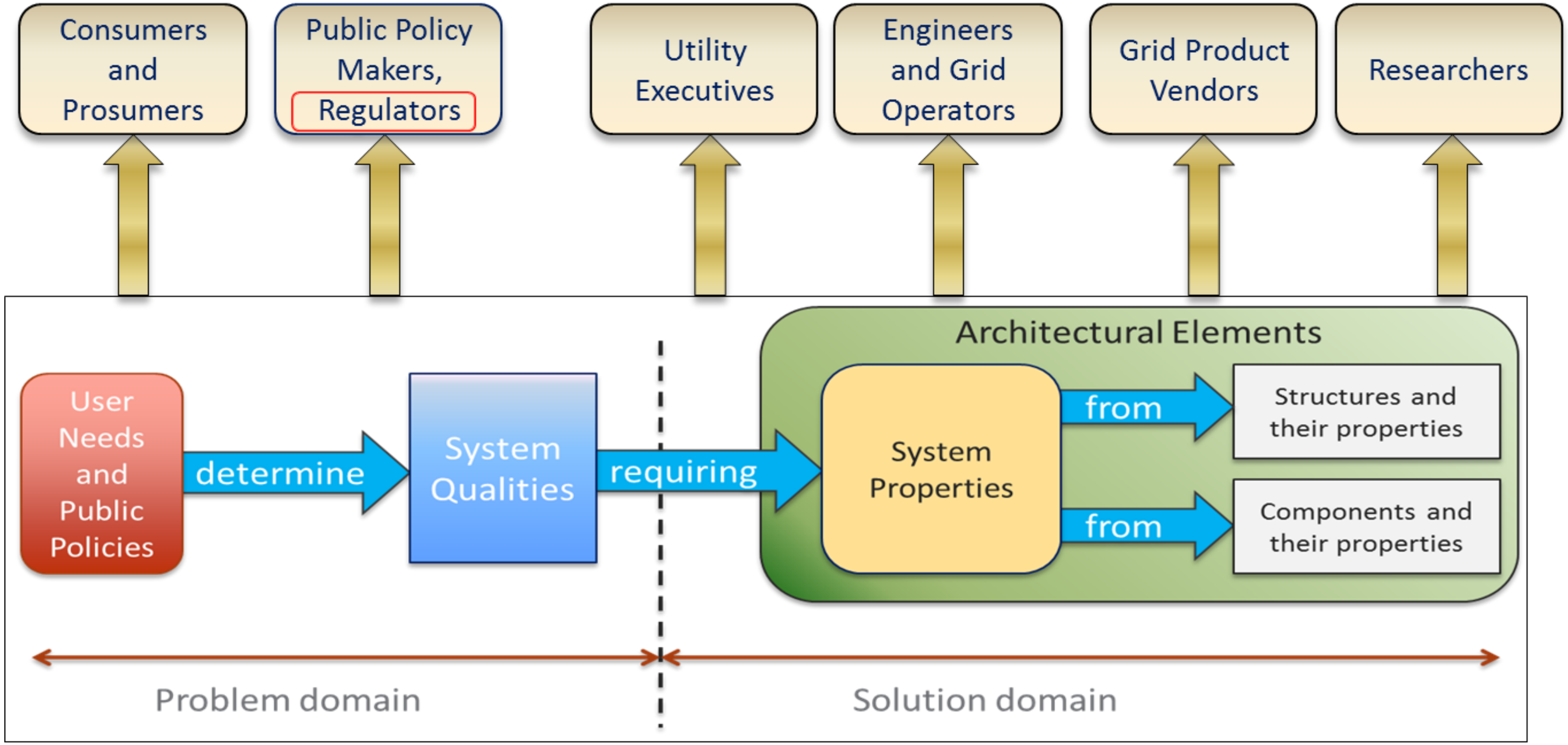
- Most control theory assumes a narrow range of relevant time scales
- Grid control must be structured for anything from milliseconds to days at least
- If planning is understood to be part of the overall control process, then the time scales extend to years
- Distribution level dynamics are shifting toward shorter time scales due to distribution level VER penetration (wind and solar PV)
- The value to be extracted from DER depends in part on temporal granularity
- DER control and coordination must be capable of handling the faster dynamics

Manage Complexity; Produce *Insight*

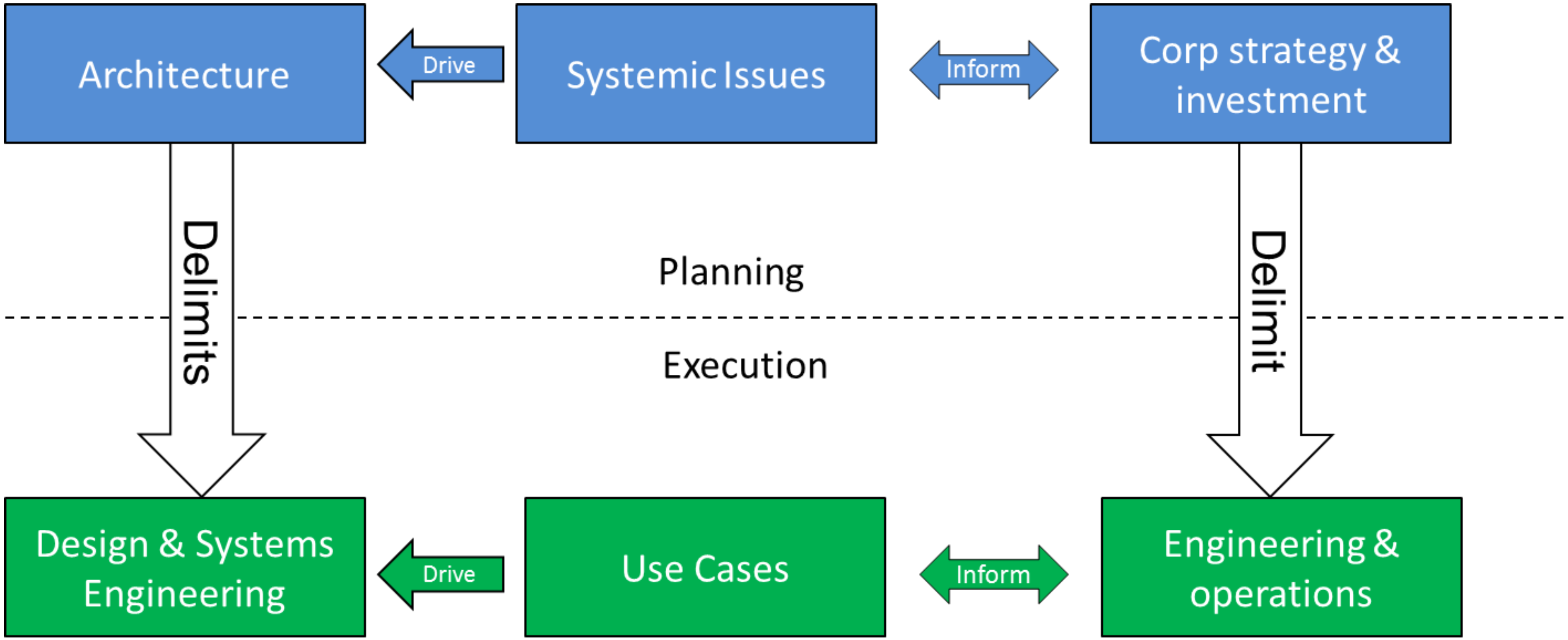


You Do Not Have to be an Architect to Use the Results of Grid Architecture

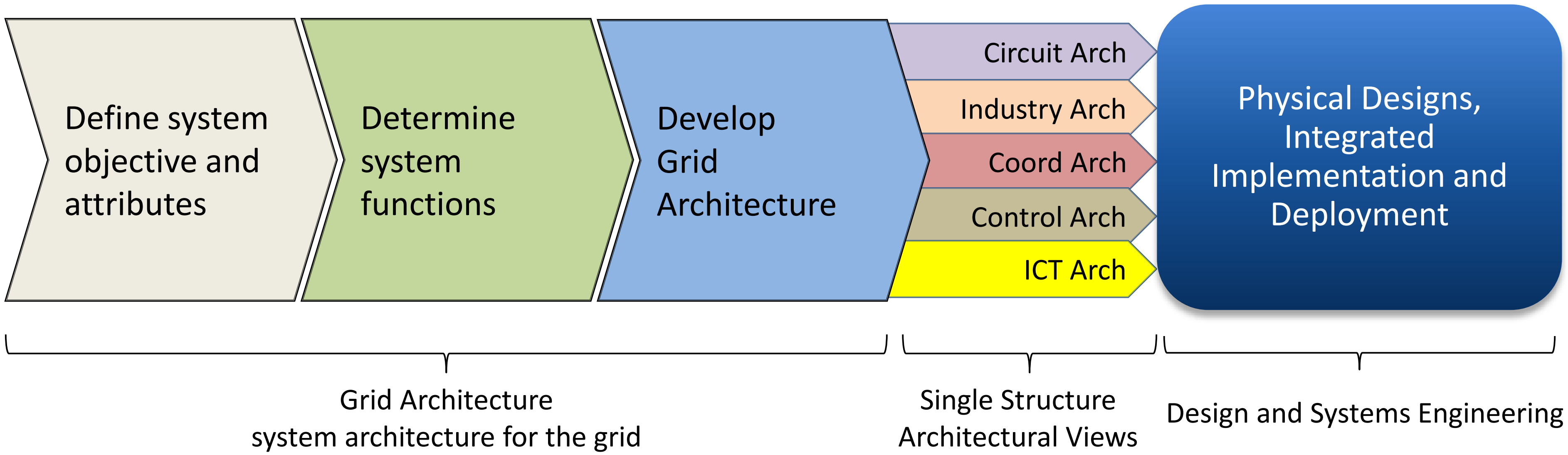
Grid Architecture supports a wide range of stakeholders, including:



Architecture and Design



Sequential Relationship of Architecture, Design, and Systems Engineering



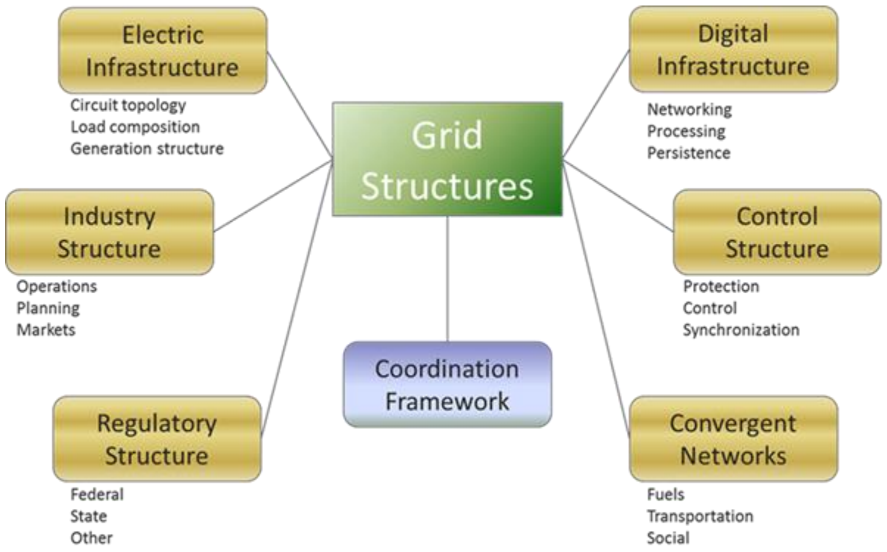
With Grid Architecture You Get…

Without Grid Architecture You Get…

Structure

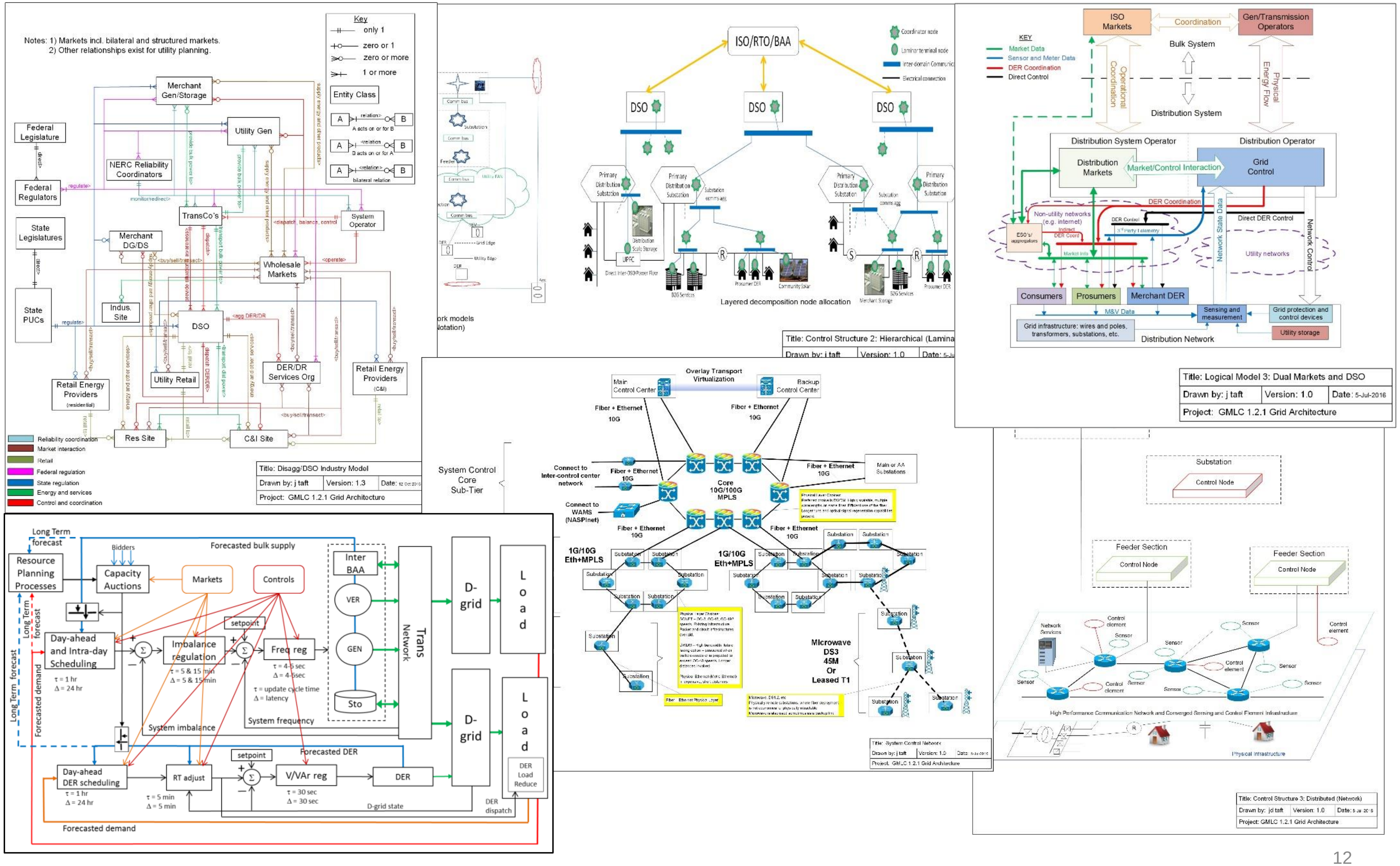
Grid Architecture Focuses on Structure

- The grid is composed of many inter-linked structures
- Because we have inherited much legacy grid structure, new capabilities and improved characteristics can require understanding of existing grid structure and potential changes to grid structure
- Determining minimal changes to relieve structural constraints is a key grid architecture problem

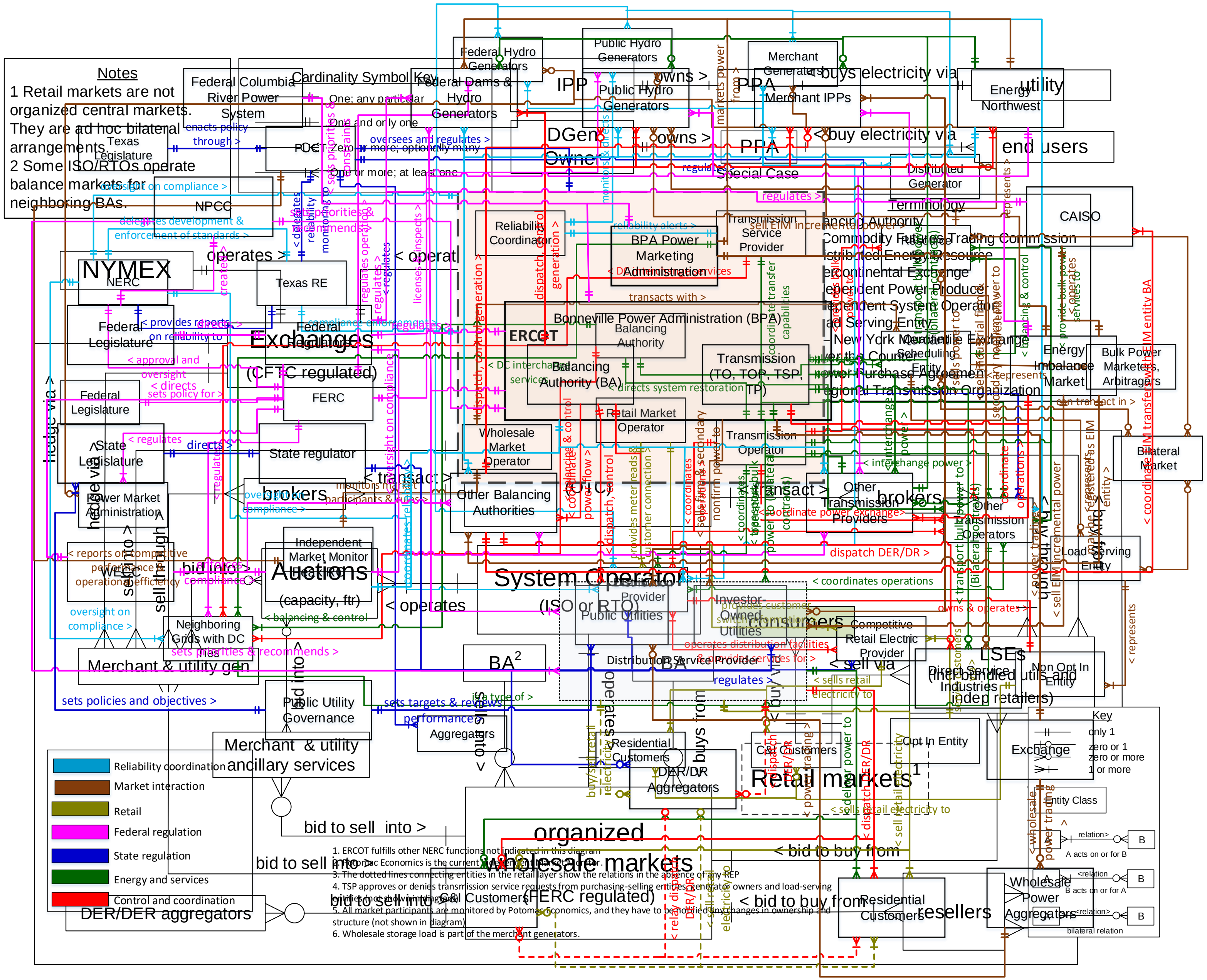


- Get the structure right and all the pieces fit into place neatly, all the downstream decisions are simplified, and investments are future-proofed
- Get the structure wrong and integration is costly and inefficient, investments are stranded, and benefits realization is limited

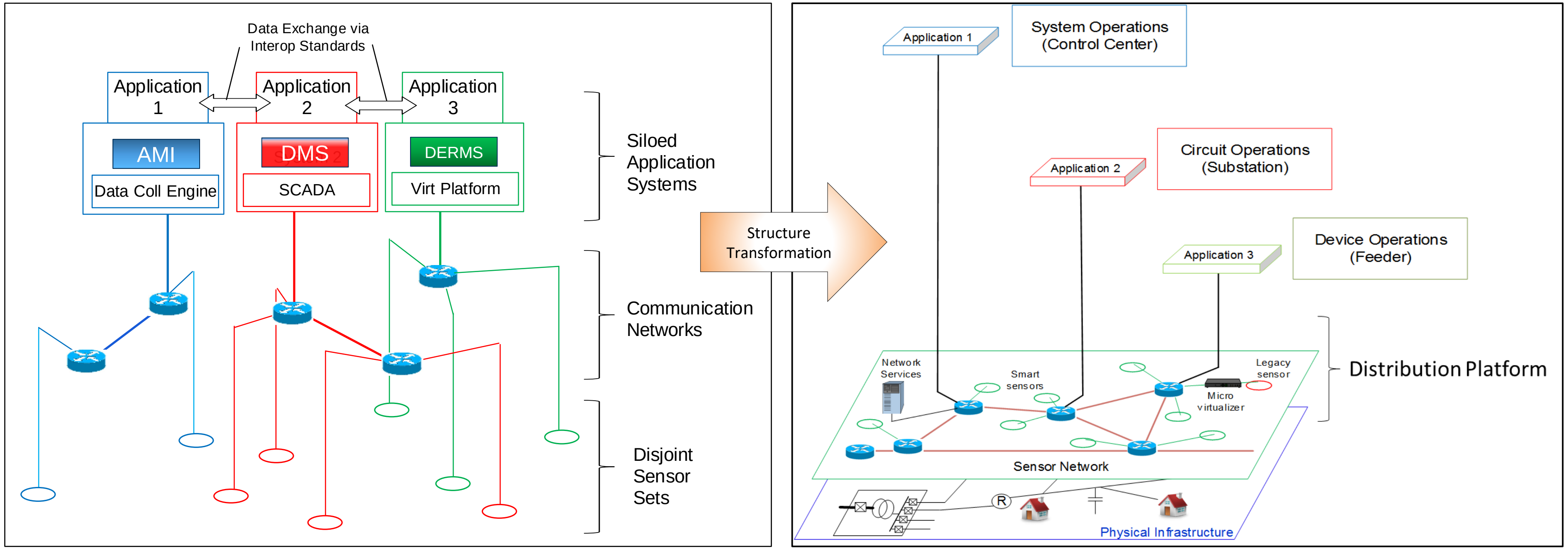
The Grid = Multiple Structures



Structural Models



Sensor-Communications Network Layers: Reduce Dependency & Brittleness



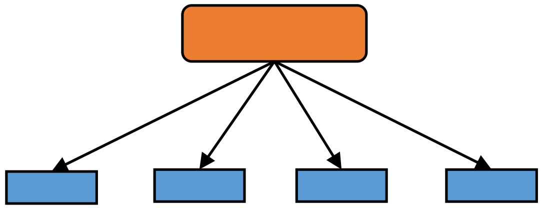
Brittle & Expensive

Resilient & Future-proofed

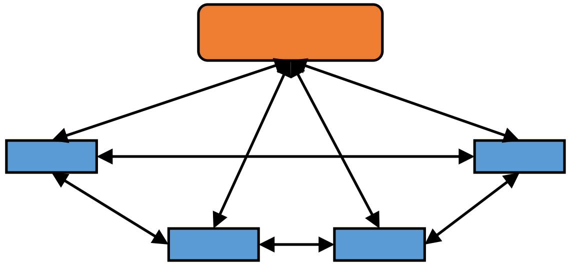
Coordination Structure

Definitions

- Decentralized System – multiple separate entities operating independently with at most some small amount of supervision



- Distributed System – decentralized system where the parts cooperate to solve a common problem



- This implies some form of peer-to-peer interaction and communication

- Coordination is the means by which a set of decentralized elements to cooperate to solve a common problem, thus becoming a *distributed system*
  - This is the essence of distributed system function

- Therefore *coordination structure* is a key aspect of distributed systems, distributed control, etc.

Definition: The Grid Coordination Problem

- Grid coordination is the systematic operational alignment of utility and non-utility assets to provide electricity delivery
- Coordination was not a well recognized issue for electric distribution until fairly recently
  - Some forms have been around a long time
    - C&I DR
    - Bulk gen in deregulated industry segments
- The motivation for the present level of interest is the rise of two things:
  - Distribution connected DG and DS
  - Flexibly controllable loads

This is an issue because many of these resources are not owned by the utility and often cannot be controlled directly.

Layered Decomposition

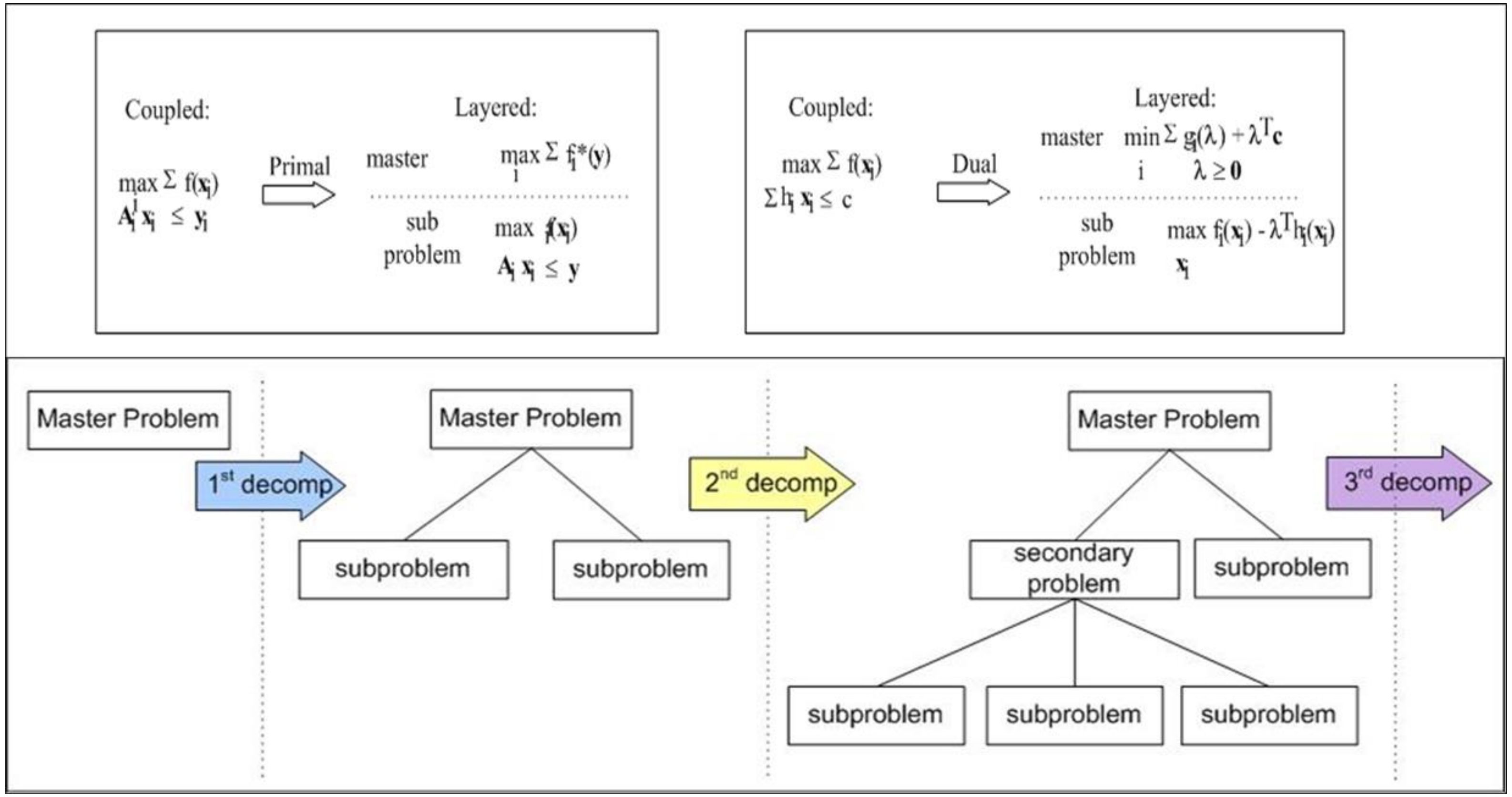
Structural Basis for System Coordination

- Want structure to be derived rigorously
- Need a distributed form with knowable properties
- Here we are not interested in a specific solution but rather a class of solutions
- We wish to extract essential *structure* by understanding the problem class

Mathematical Basis from Optimization Theory → Laminar Coordination Framework

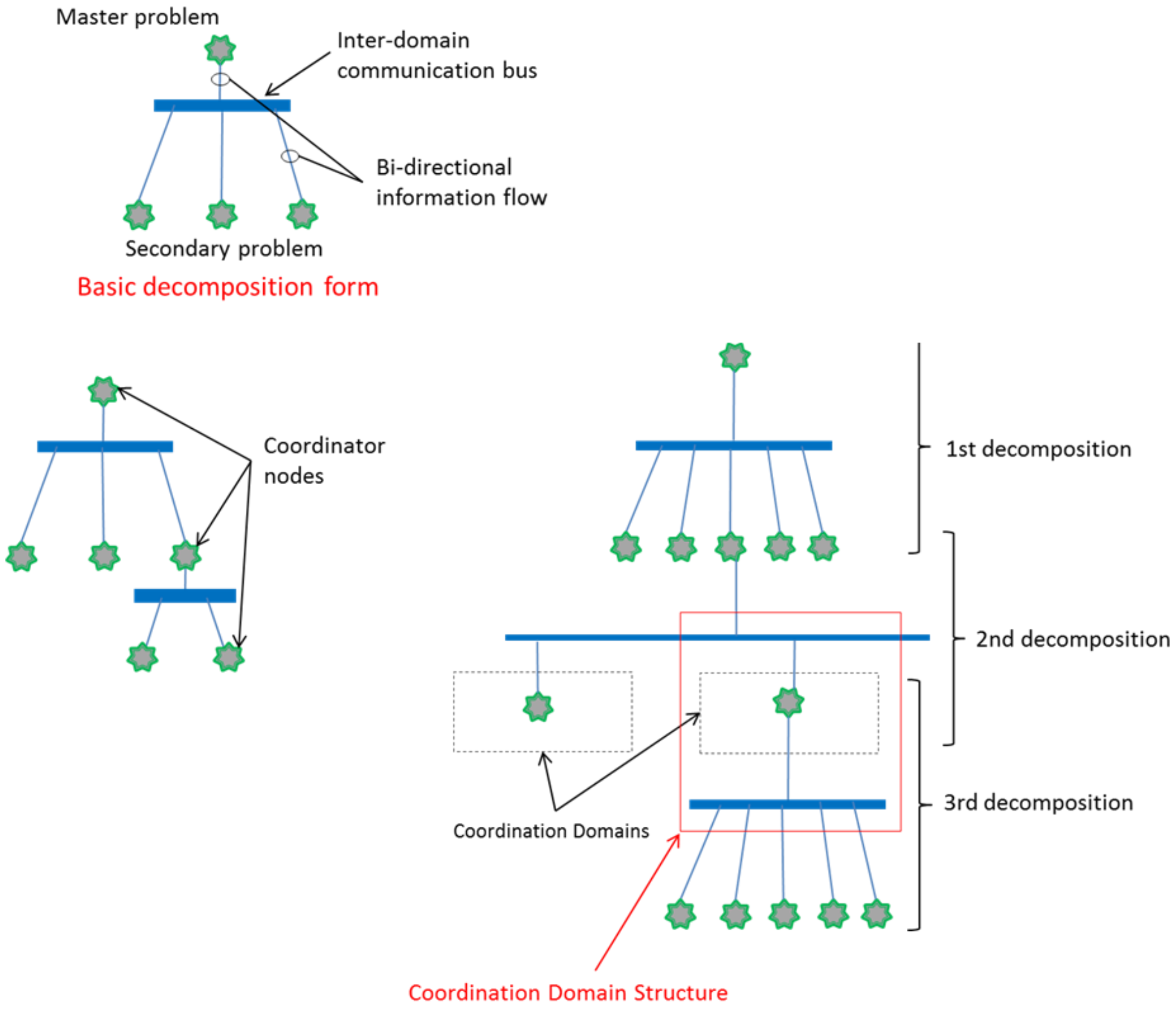
Network Utility Maximization via Layering for Optimization Decomposition

- Well-known in optimization theory for solving problems with highly coupled constraints
- We will use the math to *induce* a coordination structure



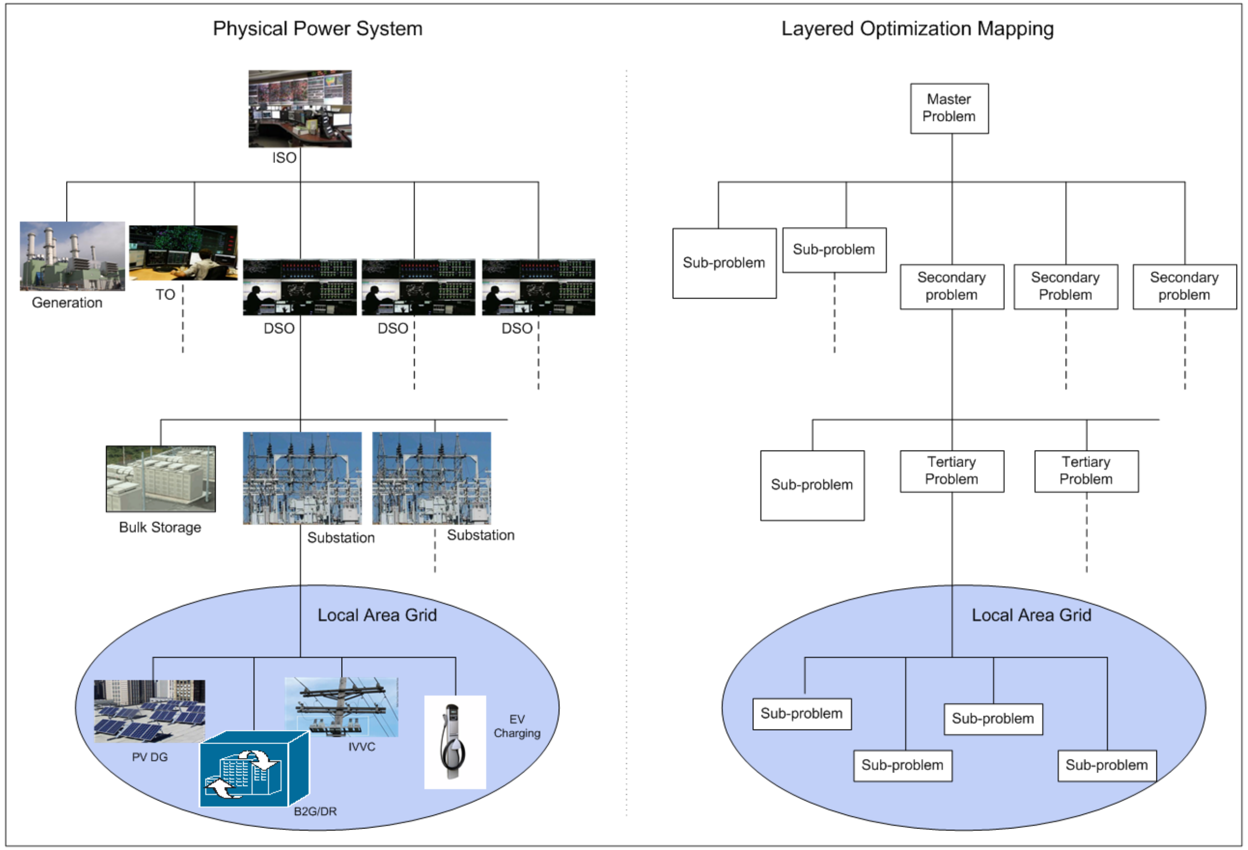
Essential Laminar Coordination Structure

- Multi-layer structure
- “Vertical” chain of coordination nodes: scalable message flow
- Core repeating building block: coordination domain



Mapping to the Grid

- Decomposition can be applied to as many levels as needed
- Boundary deference
- Multi-level constraint fusion

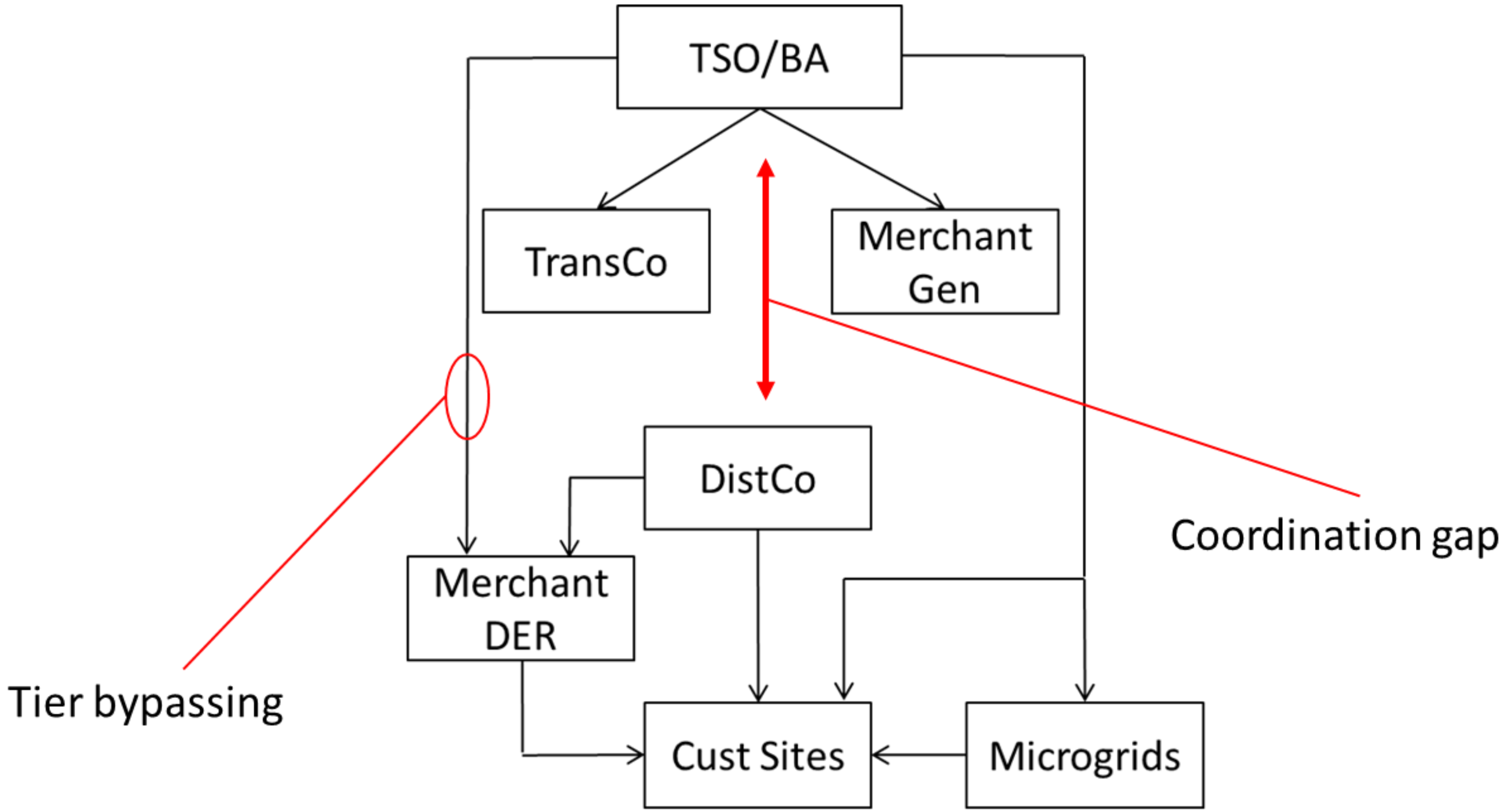


This Approach Leads to General Principles

- Multi-layer form
- Local selfish optimization inside global coordination
- Allows mixed coordination signal models:
  - Allocations (control)
  - Prices (market-like methods)
- Scalable inter-layer interaction
- Proportional buildability

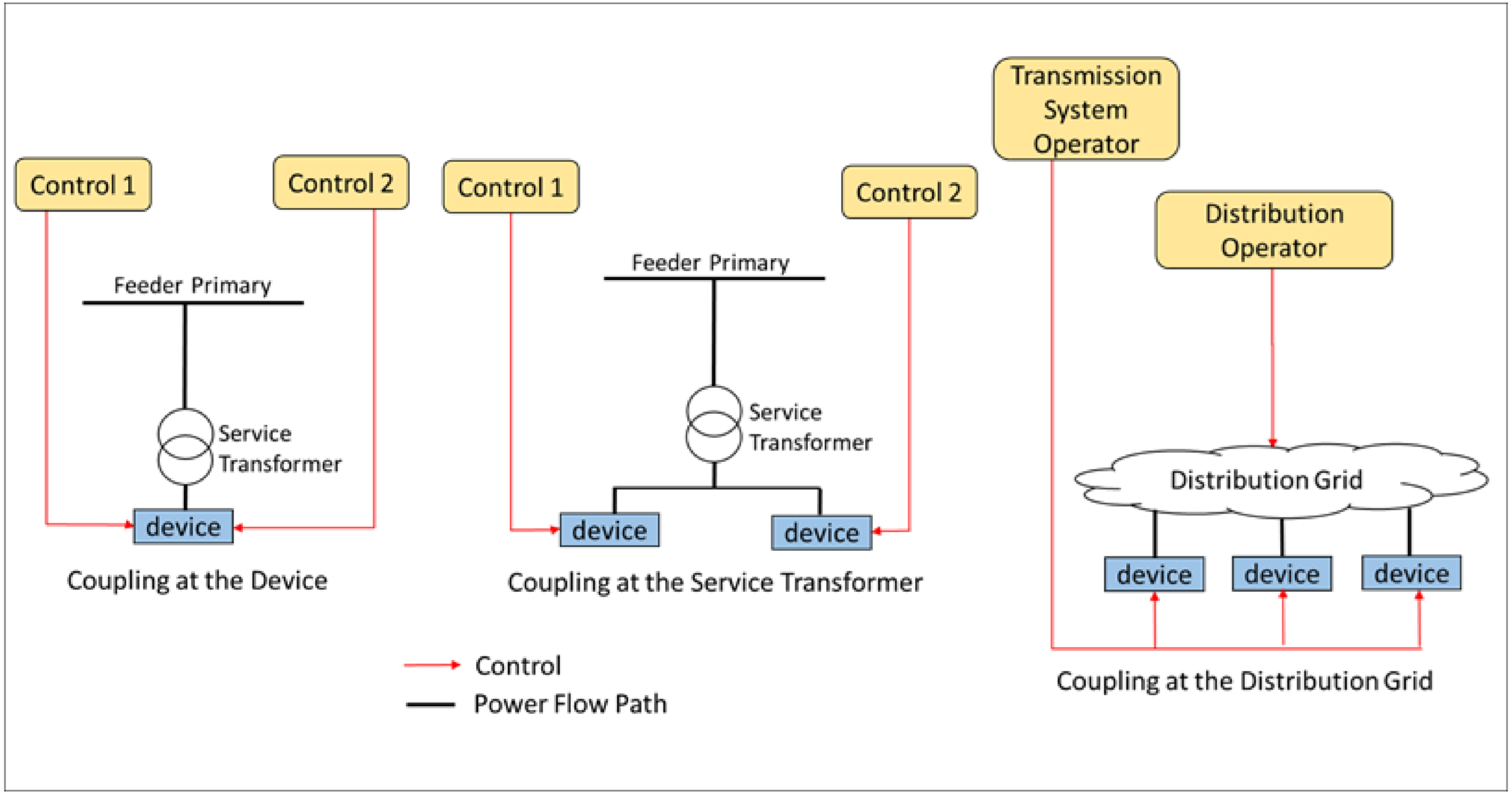
Structural Problems to Avoid-1

- Tier Bypassing
- Coordination Gapping

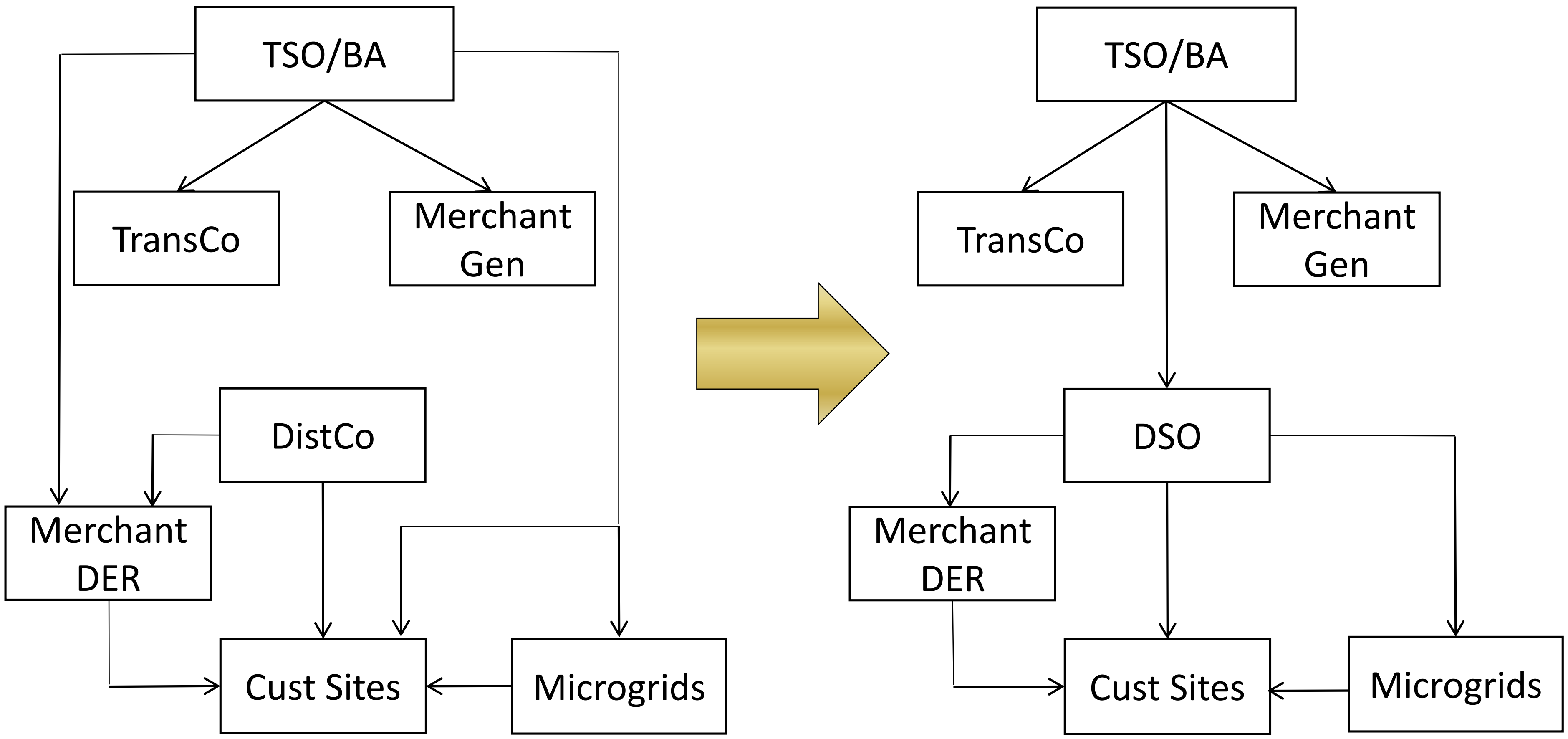


Structural Problems to Avoid-2

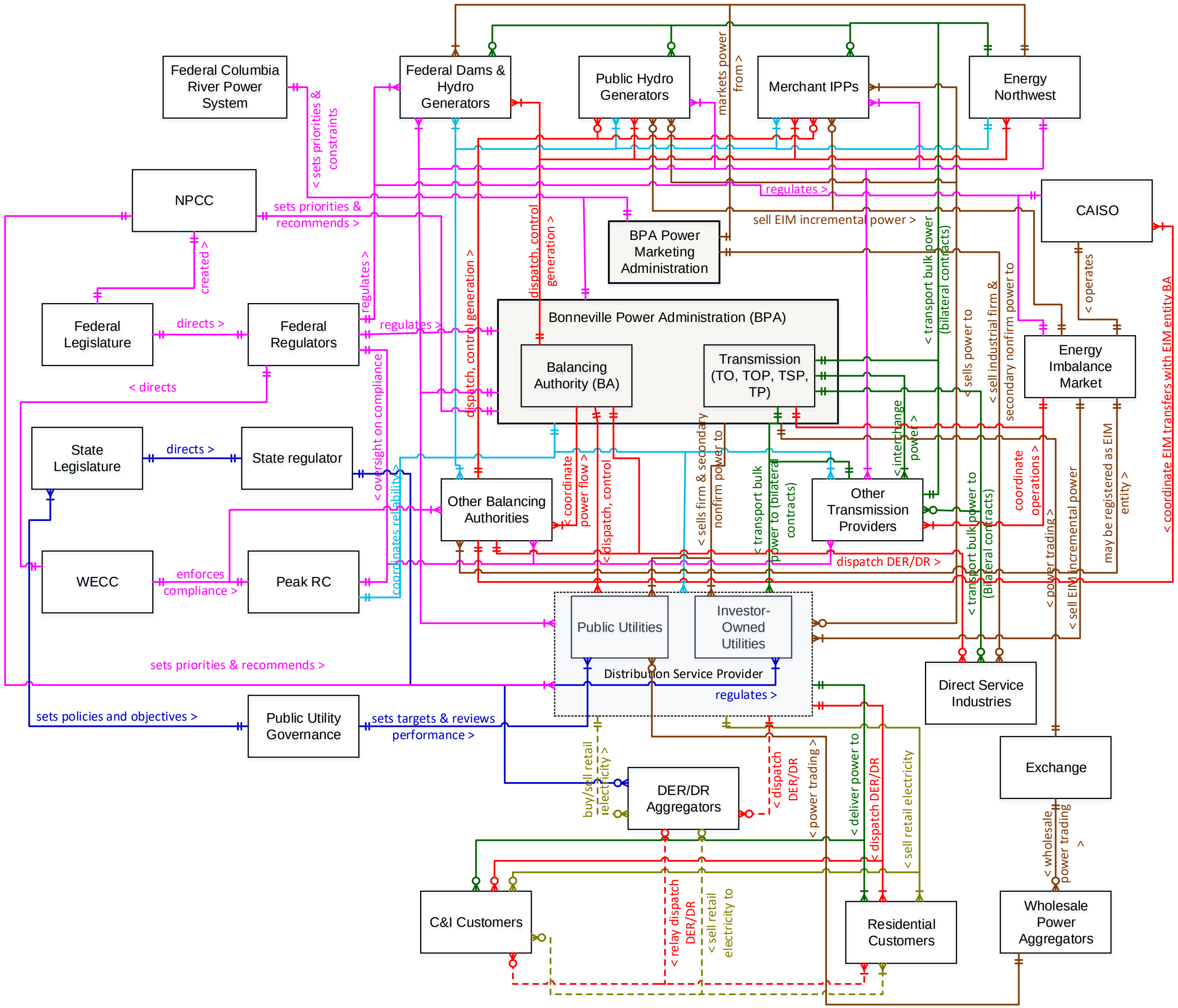
- Hidden Coupling



Adjusting Coordination Structure

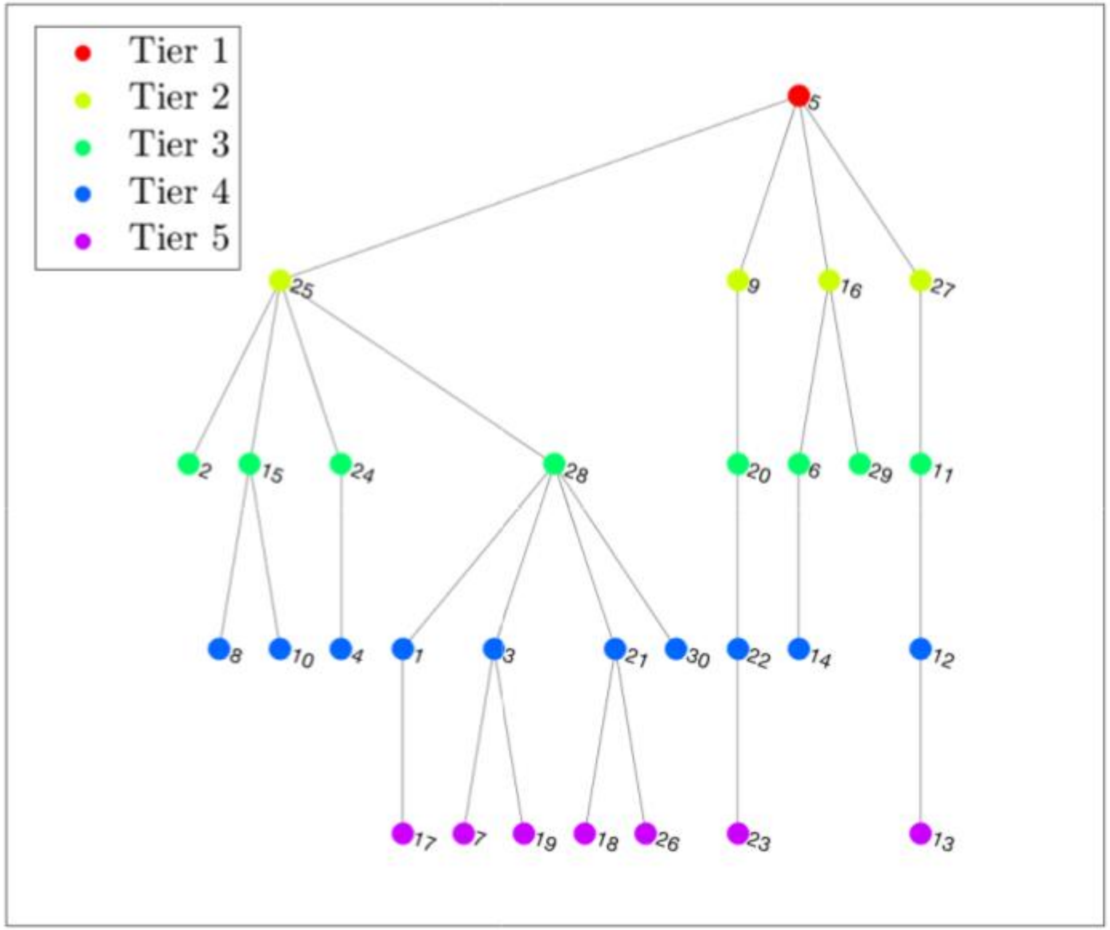


Not So Simple in Real Situations

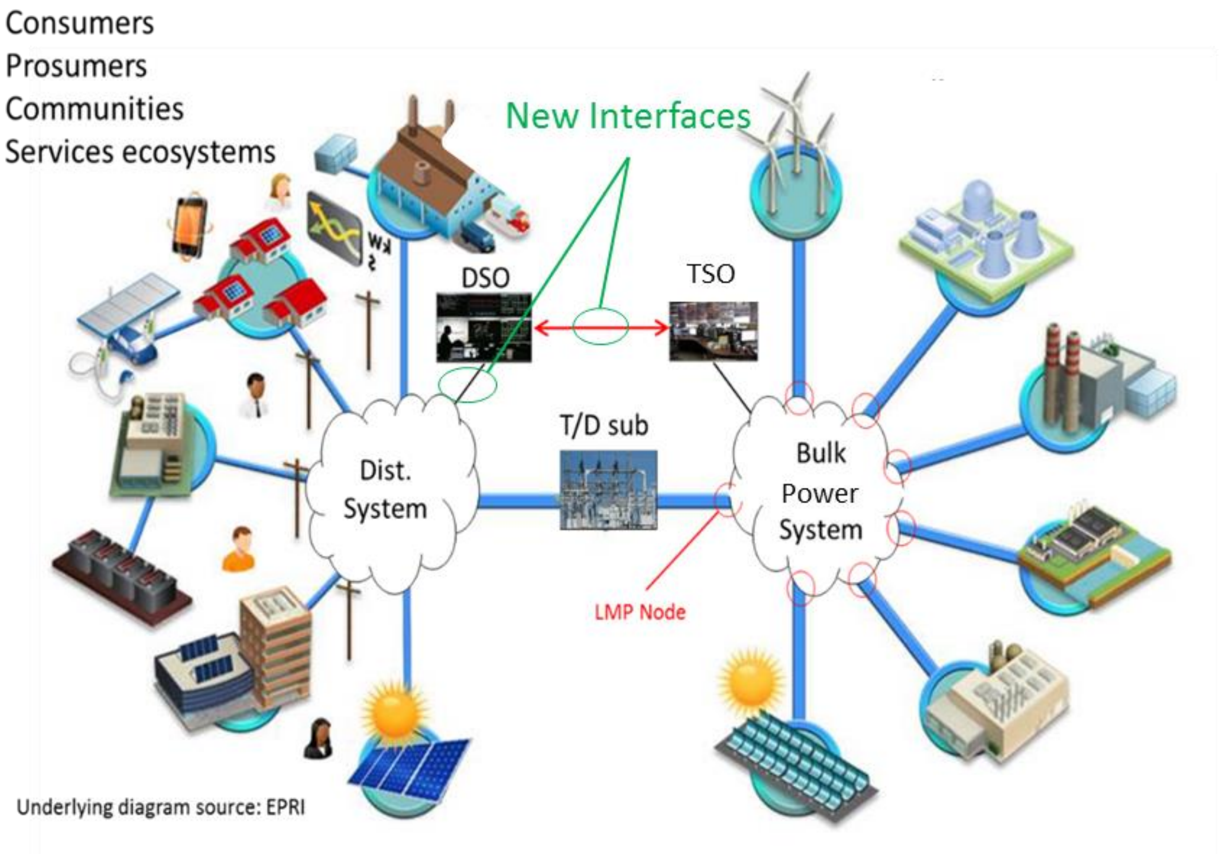


Idealized vs. Real

- Idealized architectures can look elegant and be intellectually pleasing
- Those are almost always not real
- Real architectures have to take into account lots of factors and can become messy
- We use GA methods to manage the messiness



Grid Architecture Informs the TDC Coordination Problem in Useful Ways



- Roles and Responsibilities
- Grid observability
- Distributed control
- Coordination structure

- Scalability, granularity
- Functional flexibility
- Distribution platforms
- Cyber security

GRID ARCHITECTURE

TDC Coordination

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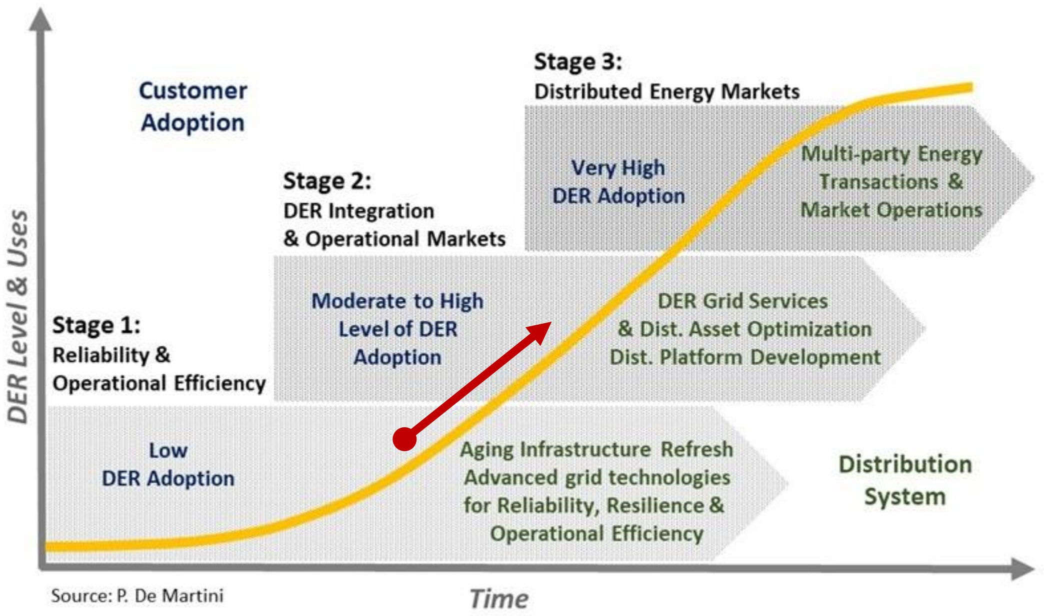
Industry Evolution: Changing Role of DER

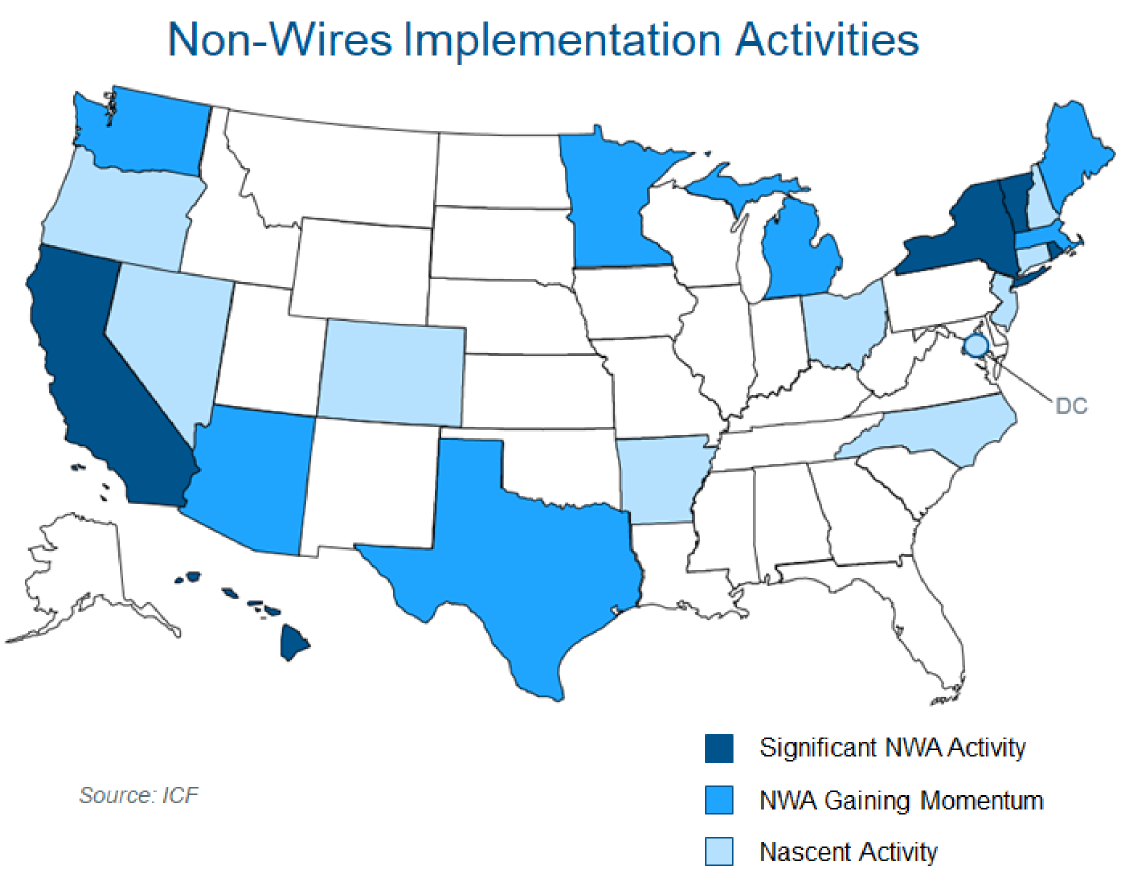


Stage 2: Operational Markets

A. Use of DER as load modifying resource for both Distribution non-wires alternatives (NWA) and Bulk Power capacity and ancillary services
B. Participation of DER export energy (discrete/aggregated ahead of the meter and aggregated behind the meter) in bulk power markets

Non-Wires Alternatives Today

- Still in largely pilot phase
- Momentum is building
- Growing numbers of utilities are working on NWA projects
- Propelled by regulatory mandates, internal utility decisions, and public/stakeholder input
- Integrated Distribution Planning learnings are being generated



Integrated System Operations Evolution

A spectrum of possible designs can be envisioned in terms of the complementary roles of DSO and TSO at the T-D interface.

Total TSO:
TSO optimizes the entire power system into the distribution system, including dispatch coordination of all DER services and schedules

DSO responsible for reliable distribution network operations & providing distribution network visibility to TSO

Customer/Aggregator coordinates with TSO – no operational interface with DSO

Hybrid DSO:
TSO optimizes the bulk power system – including dispatch of all wholesale DER services – but has no visibility into the distribution system

DSO optimizes the distribution system – including dispatch of all distribution DER services & coordinates with TSO on all DER dispatch

Customer/Aggregator coordinates with both TSO and DSO

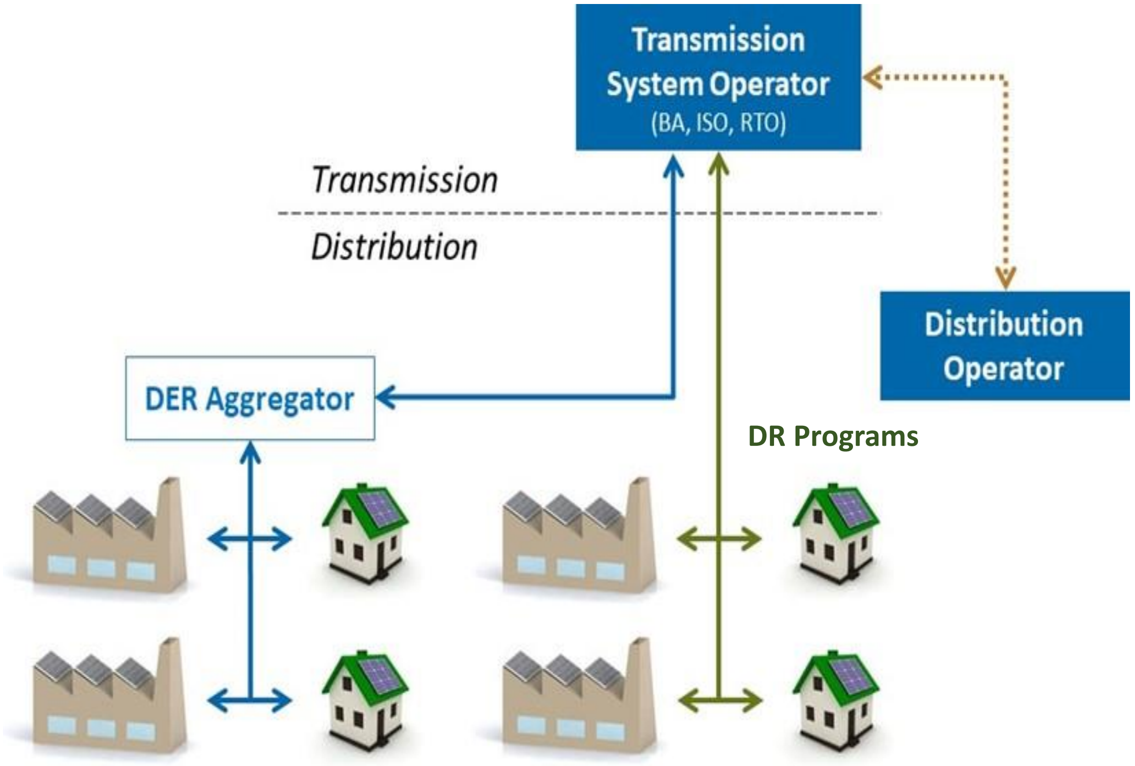
Total DSO:
TSO optimizes the bulk power system. TSO sees a single aggregate or “virtual” resource at each T-D Interface managed by DSO

DSO responsible for physical coordination & aggregation of all DER services into single resource at T-D Interface & wholesale market

Customer/Aggregator coordinates with DSO – no operational interface with TSO

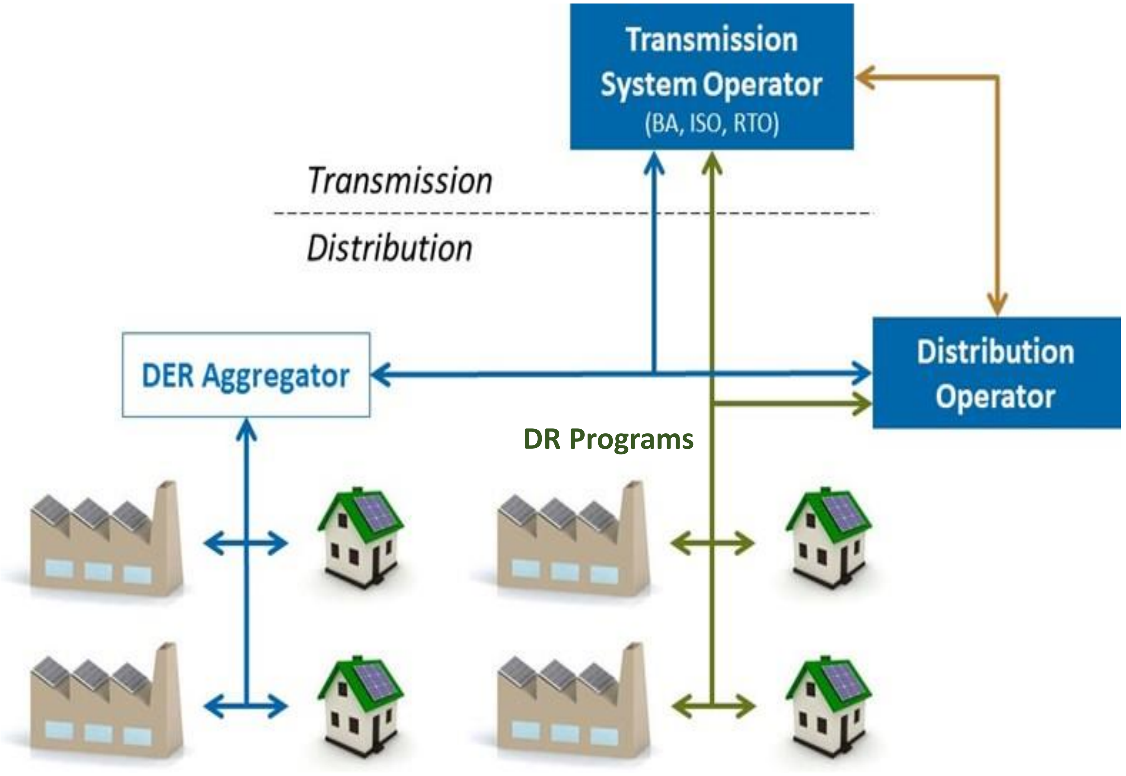
Total TSO Conceptual Reference Model

Centralized control of all DER resources across T&D – Requires TSO to also dispatch distribution NWAs and coordinate distribution operations



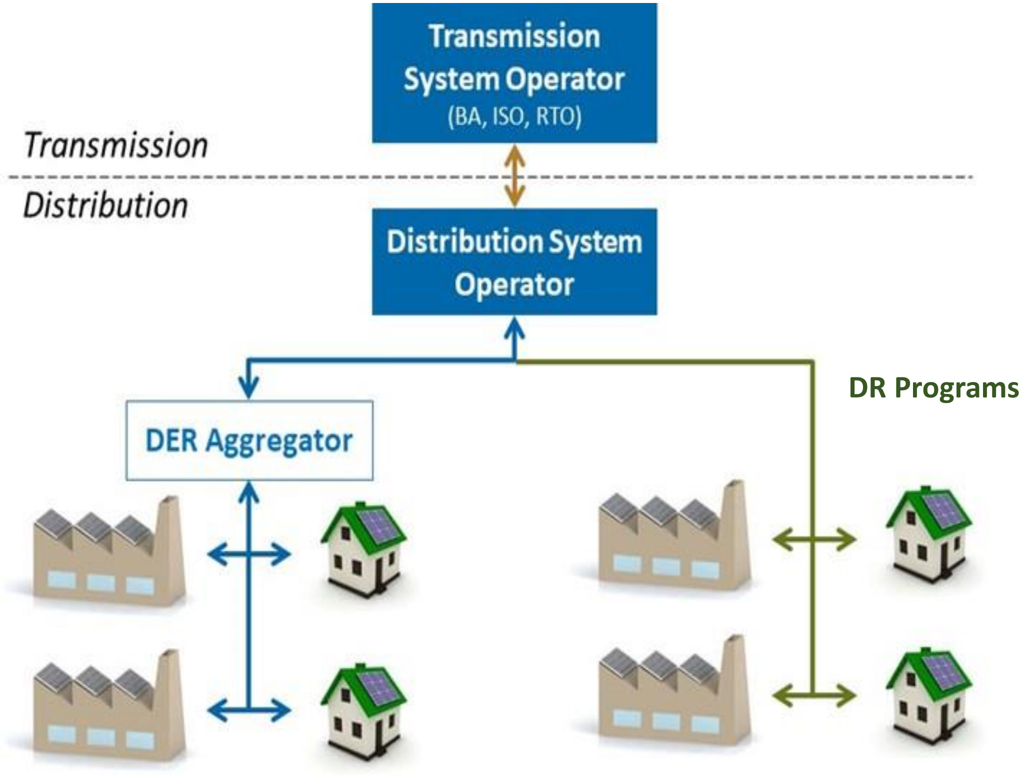
Hybrid DSO Conceptual Reference Model

Shared responsibility for use of DER for Wholesale markets and Distribution NWAs as well as coordination of grid operations



Total DSO Conceptual Reference Model

Fully Layered Approach – DSO provides the single operational interface between DER and Wholesale Market Operator



Thank You

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Physical System & Operating Essentials

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Coordination Principles

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GRID ARCHITECTURE

Application of Grid Architecture for TDC Coordination

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Architectual Considerations

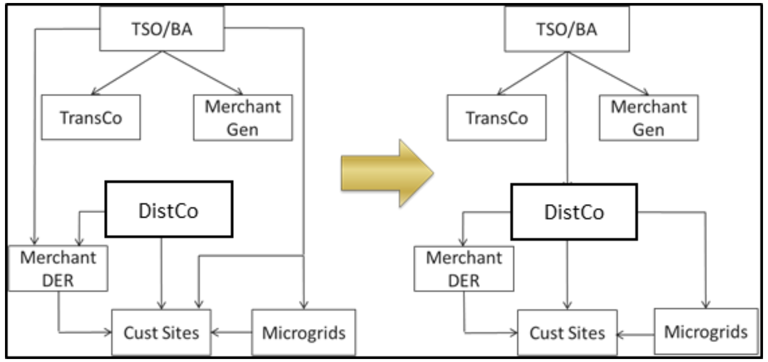
(for TSO-DSO Coordination)

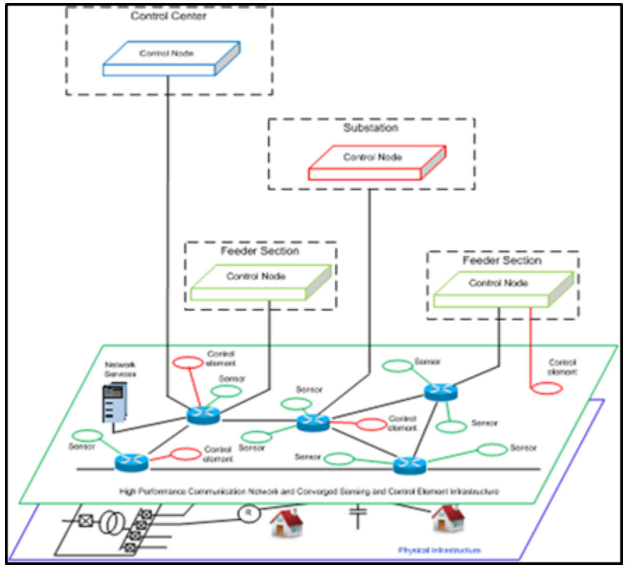
Considerations	Description
Observability	Function related to operational visibility of the distribution network and integrated DER. Observability needs of DSO and TSO depend on how the coordination framework is specified.
Scalability	Ability of system's processes and technology design to work well for very large quantities of DER resources. Coordination architecture can enhance or detract from this desired capability.
Cyber security vulnerability	Reduce cyber vulnerability through architectural structure. Structure can expose grid systems to more or less vulnerability depending on data flow structure, which depends on coordination framework.
Layered Optimization	Large-scale optimization problems are decomposed into multiple sub-problems at discrete layers of the electric system within a coordinated structure.
Tier bypassing	Creation of information flow or instruction/dispatch/control paths that skip around a tier of the power system hierarchy, thus opening the possibility for creating operational problems. To be avoided.
Hidden coupling	Two or more controls with partial views of grid state operating separately according to individual goals and constraints; such as simultaneous, but conflicting signals DER from Customer, DSO and TSO. To be avoided.
Latency cascading	Creation of potentially excessive latencies in information flows due to the cascading of systems and organizations through which the data must flow serially. To be minimized.

Source: J. Taft, Pacific Northwest National Laboratory

Some Key Architectural Issues

- Role Assignments
    - Responsibility/role matching
    - Feedback loops
        - Information flows and latencies
    - Competing or conflicting objectives
        - Local selfish optimization vs. global coordination
- Assignments cannot just be arbitrary
    - Based on solid architectural principles
    - Explain why, not just what

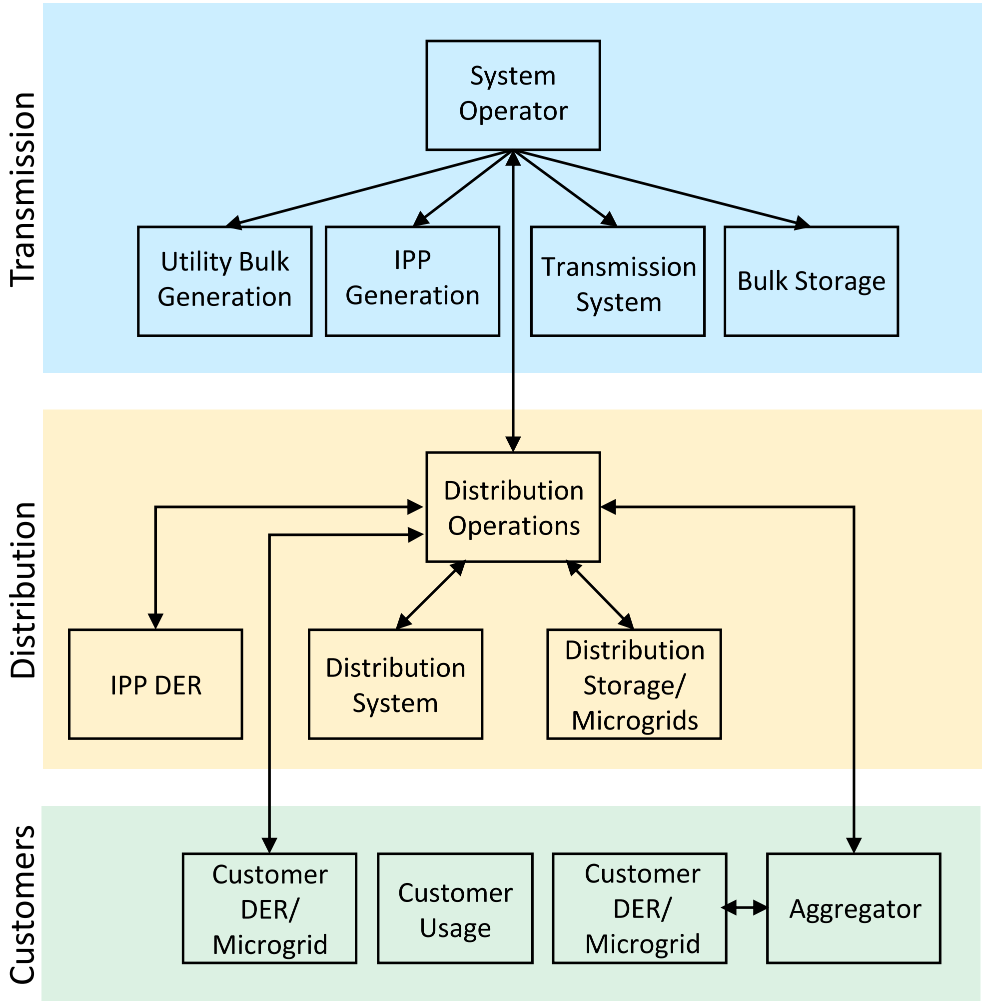




Source: J. Taft, PNNL

Coordination Framework Skeleton Diagram

- Derives from Complex Industry Structure Diagram
- Focuses on key issues to address (e.g., architectural principles)
- Indicates flow of coordination
- Use layered decomposition model (i.e. Laminar Framework) as basis for the diagrams and analysis



Source: J. Taft & P. De Martini

UK Coordination Models
Current & Future Models Under Discussion

- UK Open Networks initiative evaluating alternative TSO-DSO Coordination Models
- 5 Future Models have been identified and under evaluation
  http://www.energynetworks.org/electricity/futures/open-networks-project/

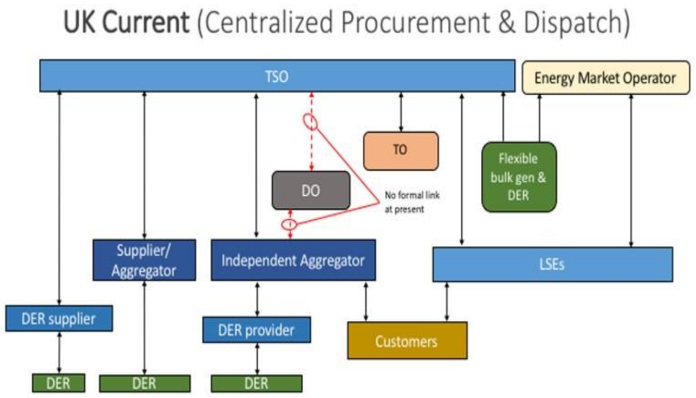
Example Grid Architectural Analysis:

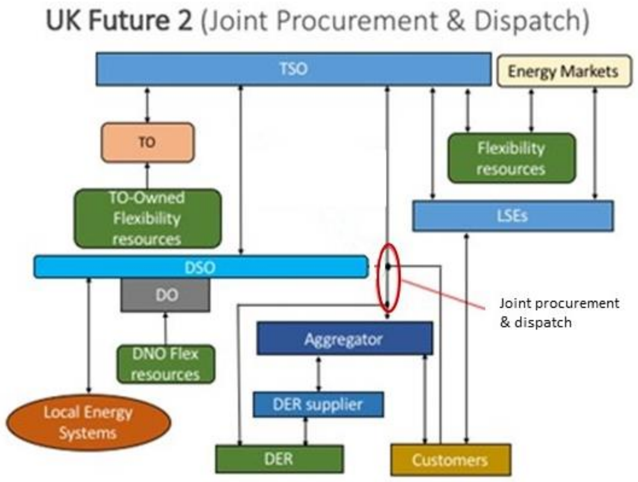
UK Option 2, the responsibility for DER coordination is shared by the DSO and TSO, leading to a more complicated arrangement involving these parties and the aggregators, although the sharing mechanism is not clear.

This model is somewhat similar to the Total DSO model, but the sharing arrangement results in a blending of roles that will require extra coordination to perform.

Option 2 partially **degrades the layered decomposition** structure and allows for **some tier bypassing**, although the proposed function-sharing ("joint procurement and activation") may prevent that from being an issue. This structure **increases the coupling** between the TSO and DSO (not hidden in this case), since the DSO cannot manage the DER in its service area alone while interfacing to the TSO in a modular fashion.

The joint arrangement results in **data flow complexity** involving the DSO, the TSO, the aggregators, the customers, and DER. This is a result of the structure shown in the red oval which comes about due to the definition of **joint roles instead of clean separation of functions**.





Source: J. Taft, L. Kristov & P. De Martini

NY Coordination Models
Current & Future Models Under Discussion

Example Grid Architectural Analysis:

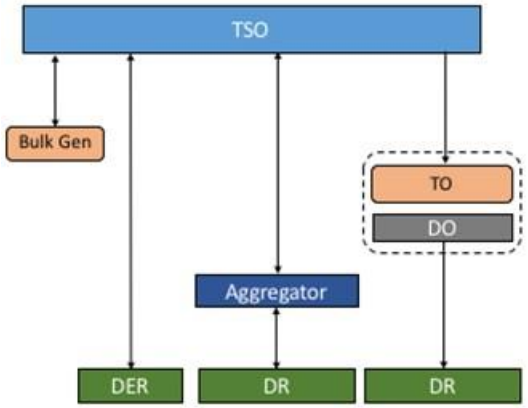
Future 2, the removal of the link between the aggregator and the TSO creates **some of the layered decomposition** structure by **eliminating one source of tier bypassing**, but the presence of a link from DER to the TSO **still allows for tier bypassing, hidden coupling, scalability issues, and cyber vulnerability** at the TSO level.

Future 2, the DSP is potentially somewhat better able to manage the DER, and if coordination between TSO and DSP is well organized, the **tier bypassing problem may be mitigated**.

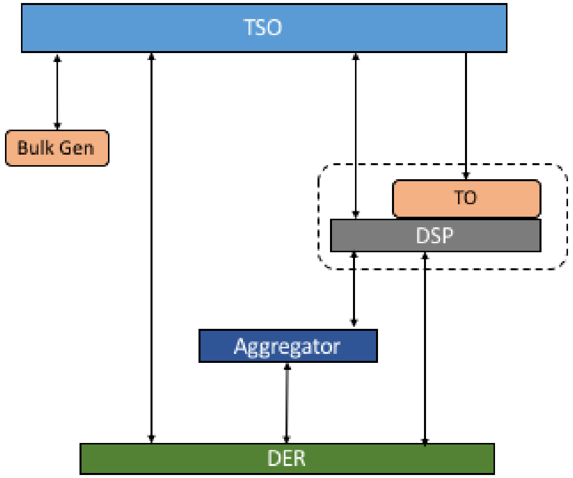
If some **DER are bidding into the wholesale markets and some into a DSP market**, for example, then the **potential for mis-coordination exists**.

The potential **ability of aggregators to participate at the TSO level is eliminated** in this model that **reduces tier bypassing**. However, it **does not eliminate tier bypassing** as some DERs can still bypass. The **hidden coupling problem remains** but likely at a low level.

New York Current



NYISO Proposed Future 2



Source: J. Taft, P. De Martini & L. Kristov

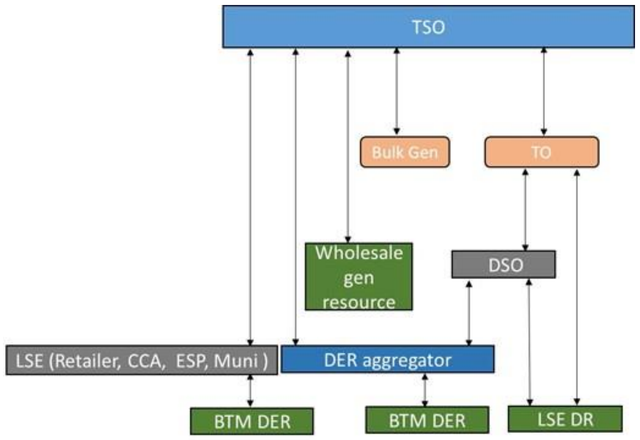
CA Coordination Models

Prior & Future Models

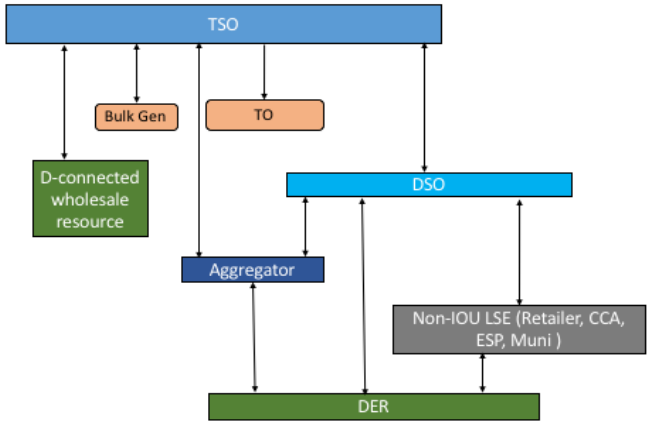
Example Grid Architectural Analysis:
The previous California structure reflects DER services provided directly to the TSO as well as the existing demand response (DR) programs that distribution utilities operate for the benefit of wholesale market operations. The resulting complexity involves a large number of entities and a somewhat **ad hoc coordination structure**. Note there are **no coordination links between the CAISO (TSO) and the DSO**.

A future **Hybrid DSO based model**, may be politically feasible in near-term. A hybrid model will **continue to exhibit tier bypassing** due to the path from DER to aggregator to TSO that bypasses the DSO. In addition, the potential for **hidden coupling exists, with some aggregators, LSEs and the DSO all connecting to DERs** unless some coordination mechanism is worked out. The presence of the direct aggregator-to-TSO connection also presents a moderate cyber vulnerability to the bulk energy system.

California Prior



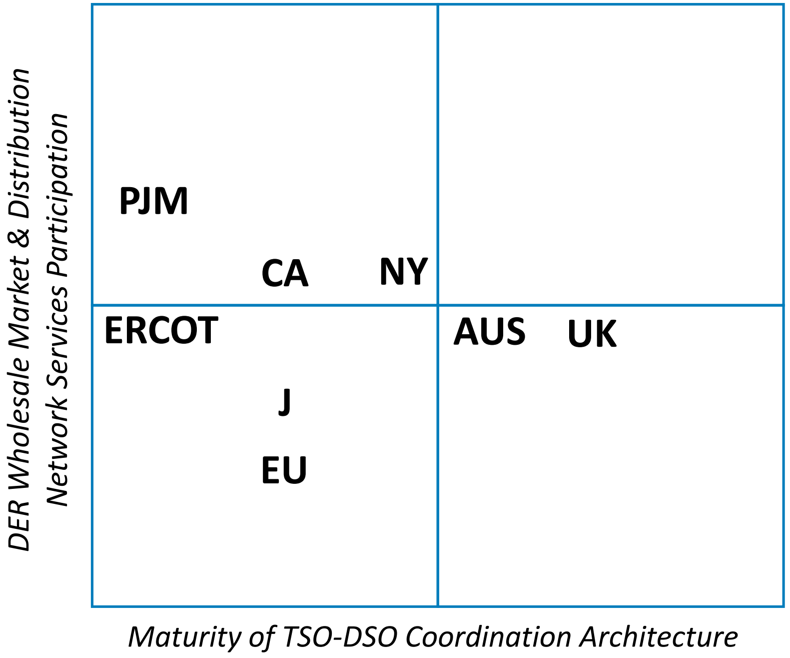
California Future



Source: J. Taft, P. De Martini & L. Kristov

2018 International TSO-DSO Comparative Assessment

Primary and secondary research supporting comparative assessment of TSO-DSO development efforts in 8 regions/countries

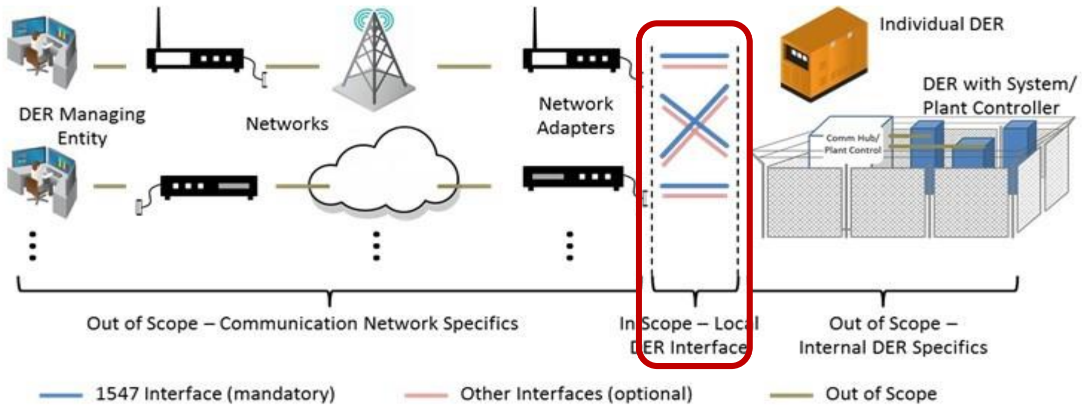


UK & AUS have the most sophisticated approaches and analysis conducted to-date. But, are hampered by a strong institutional and stakeholder bias towards real-time centralized markets despite the significant operational issues.

Distribution Grid Code

- IEEE 1547 enables, but does not directly specify, cyber security – responsibility falls on inverter manufacturers and energy service firms' to establish security for aggregated devices.
- Develop a general distribution grid code that can be adapted to individual state needs.
- Distribution Grid Code would incorporate IEEE 1547-2018 standard and related advanced inverter functions, *and* address the additional operational information, control, communication and cybersecurity requirements as well as roles and responsibilities.

Scope of DER Communications & Security



Source: IEEE 1547-2018 Standard

"When integrated with energy demand management programs and technologies, these combined technologies significantly increase the attack surface of the national power grid and opportunity for risk to system operation from malicious actors." Sandia National Lab

Takeaways

- Current DER coordination models for all locations exhibit considerable distribution operator bypassing, with the attendant issues of hidden coupling and cyber vulnerability.
  - Primarily due to use of Hybrid approaches
- Future models involve two schools of thought regarding coordination structure:
  - Centralized approach where the TSO performs all coordination, and
  - Layered approaches where a DSO has a significant role in coordination.
- Customer DER to distribution interconnection standardization and operational integration technology maturity for the provision of services is currently inadequate.

Thank You

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Coordination Principles

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