Grid Architecture

An Overview

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- Dr. Ron Melton, PNNL
- Mr. Dave Hardin, SEPA

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Agenda

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• Introduction	J Taft
• Why Do We Need Grid Architecture?	D Hardin
• What is Grid Architecture?	J Taft
• Basic Definitions	R Melton
• Underlying Principles	R Melton
• How is Grid Architecture Done?	D Hardin
• Some Results and Final Comments	J Taft

Why Is It Needed?

Grid Architecture: Tools for Insight

The US Utility Industry is in Complex Transition

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20th Century Electric Utility Mission:

21st Century Electric Utility Mission:

VER/DER Integration Is Changing Grid Structure

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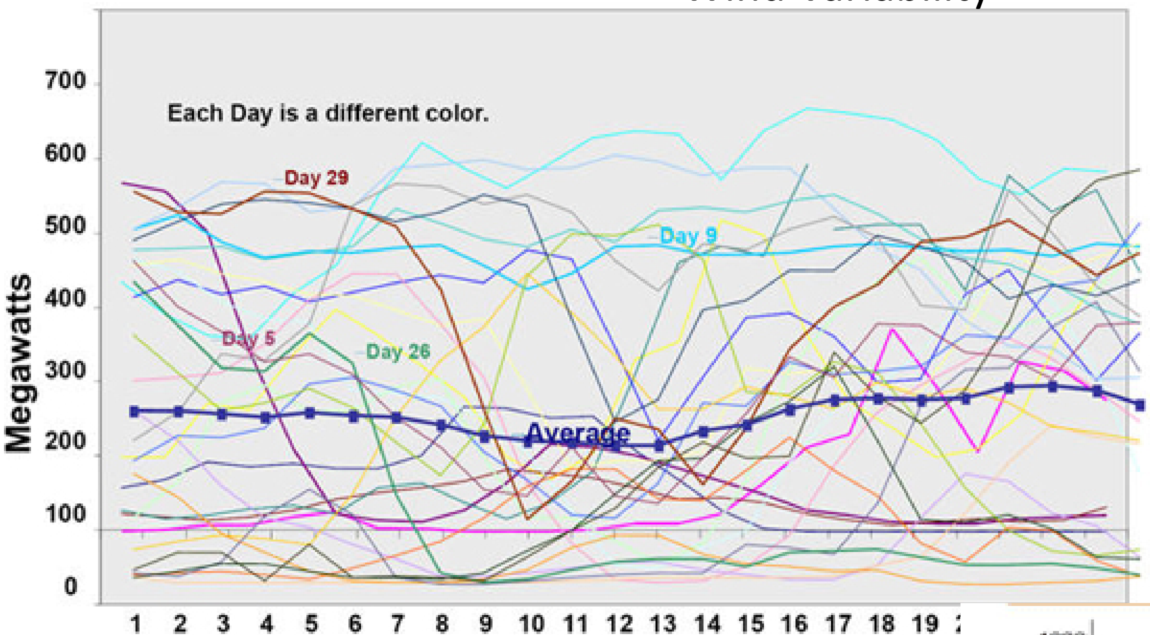
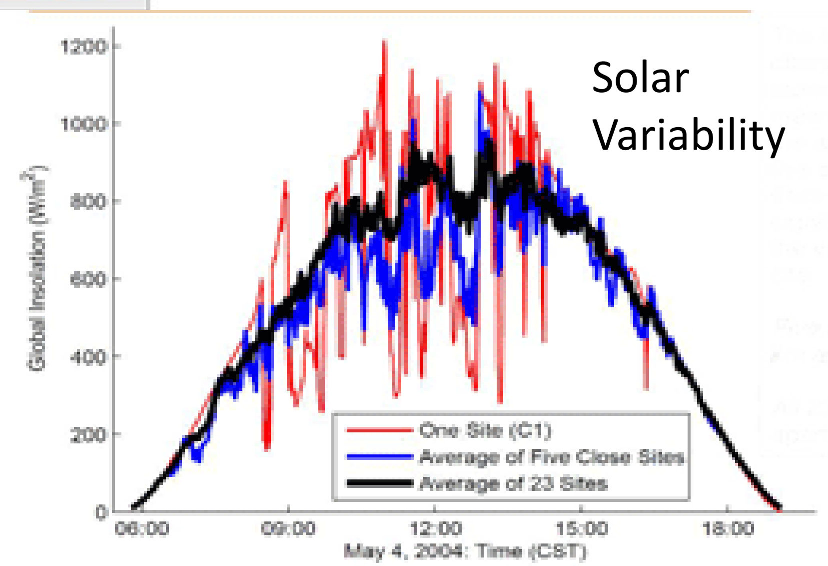
Wind Variability



Introduces new operational issues into the grid.

Resulting in new grid volatility:

- Volt/VAr regulation at distribution
- Net load vs. system flexibility
- Ramping (duck curves)



Less Time, More Endpoints. More Data

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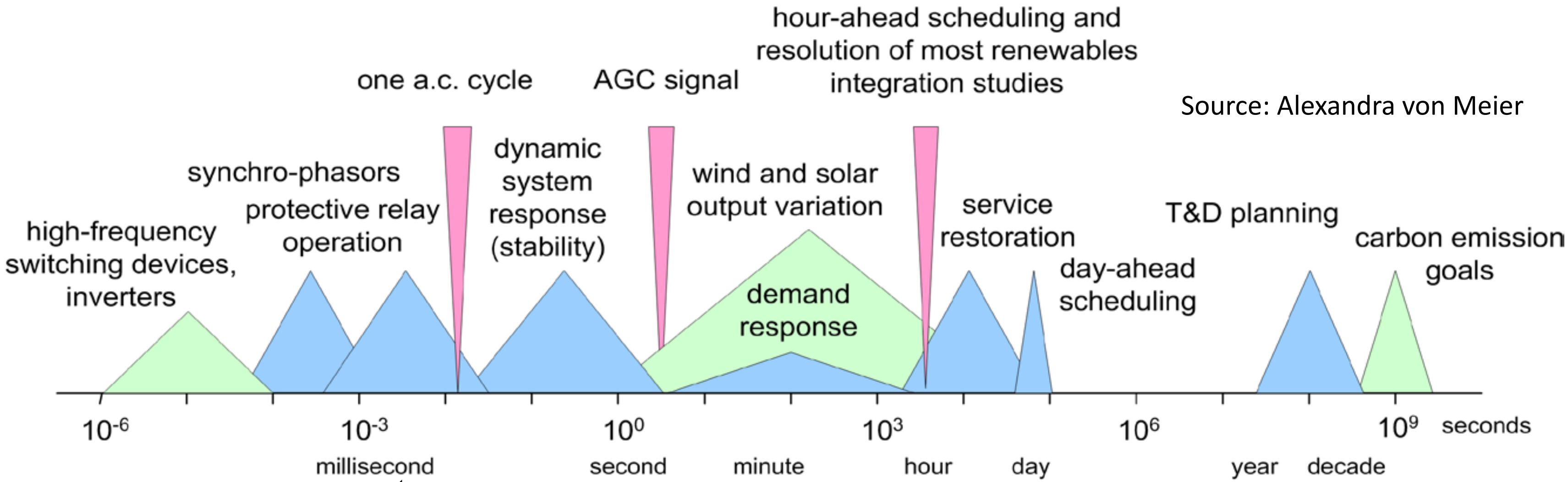

Source: Alexandra von Meier

Dynamics Trending Faster

- Increasingly faster device/system dynamics
- Moving from slow data sampling to fast streaming data
- Massive numbers of sensing and control endpoints

Thousands of endpoints → WAMS/AMI/DER/DR/networking… → Tens of millions of endpoints

Ubiquitous Connectivity Is Changing Grid Structure

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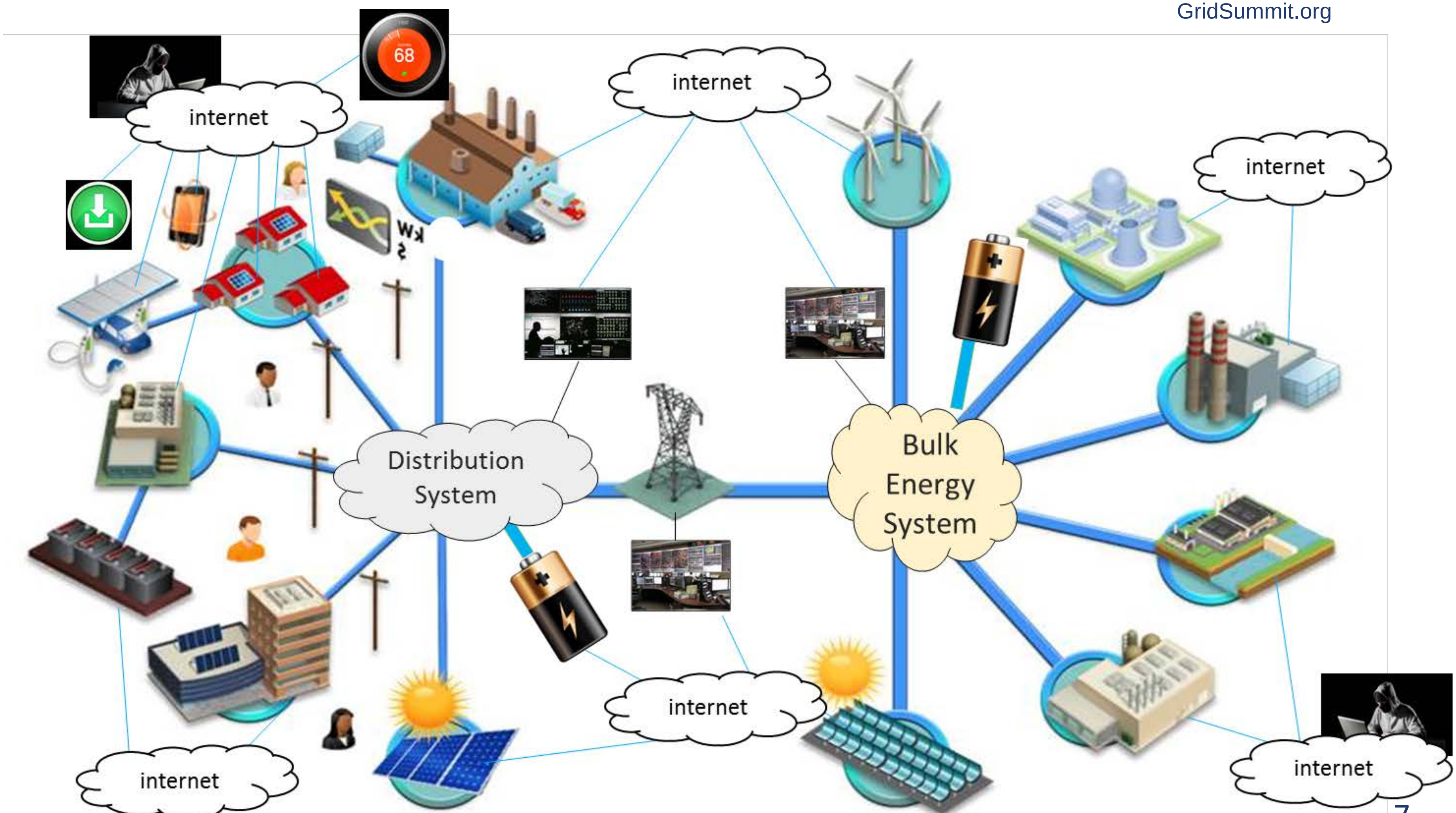

Underlying diagram source: EPRI

Legacy Principles Gave Us the Grid Structure We Have Now

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- Generation is firm dispatchable
- Generation follows load; always kept in power balance
- Distribution can be treated as a passive load attached to Transmission
- Real power flows in one direction only at Distribution
- Designed for reliability, not economy

And we are in the process of violating these principles!

Because the Grid is Being Driven to Change

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- Changing needs and expectations of consumers
- Emerging challenges to grid resilience and reliability
- Physical changes to the grid
- New services: open access
  - Information
  - Energy transactions
- New technologies
- Aging infrastructure

These changes have large structural (architectural) implications.

But the Grid Has Complex Legacy Structure

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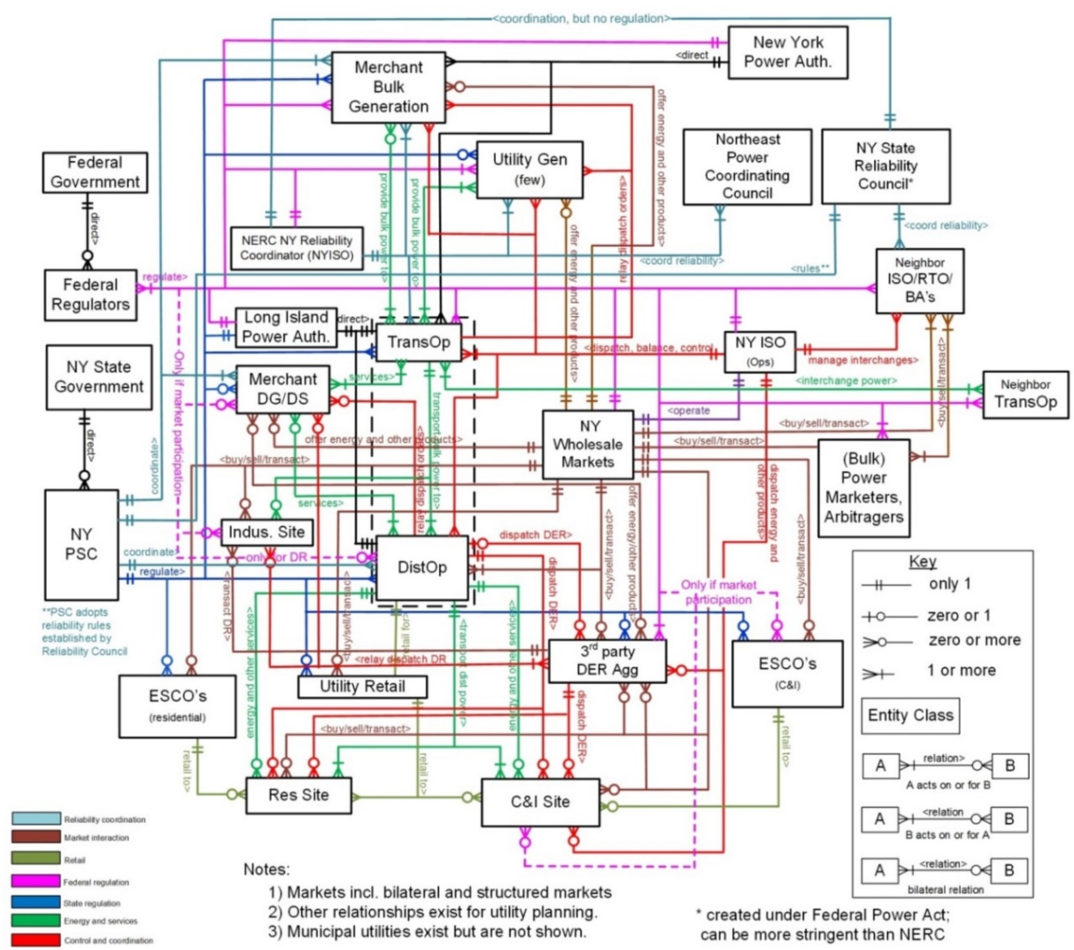
Any change exists in the context of a complex network of structures:

- Electric infrastructure
- Industry
- Regulatory
- ICT
- Control
- Coordination
- Other convergent networks (gas, transportation, etc.)

Industry Structure Model, New York 2015 *



* Model created by PNNL

And the Issues We Face Are Also Complex

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- How should the control structure for the whole grid change?
- How should distribution communication networks be structured to enable DER integration?
- How do grid controls and wholesale markets interact?
- How should DERs interact with ISO/RTO functions?
- How should storage be integrated into electric power systems?
- Are electric and gas networks converging or is generation just a downstream use of gas?
- Should distribution company roles and responsibilities be changed, and if so, how does this impact grid control, markets, and oversight?

Diverse Array of Stakeholders
Consumers/Prosumers
Federal Regulators
ISOs/RTOs/BAs/RCs
Transmission Operators
State/Local Regulators
Distribution Operators
R&D Orgs
ESOs/Merchants
Vendors
System Integrators
Industry Orgs/SDOs

Grid Modernization Complexity Can Be Overwhelming

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Low Complexity

Medium Complexity

High Complexity

Ultra-Large Scale Complexity

- Heterogeneous, inconsistent, and changing elements
- Geographic distribution
- Wide time scales
- “Normal” failures

- Decentralized data, development, and control
- Inherently conflicting diverse requirements
- Continuous (or at least long time scale) evolution and deployment

Grid Architecture Provides Tools to Manage That Complexity

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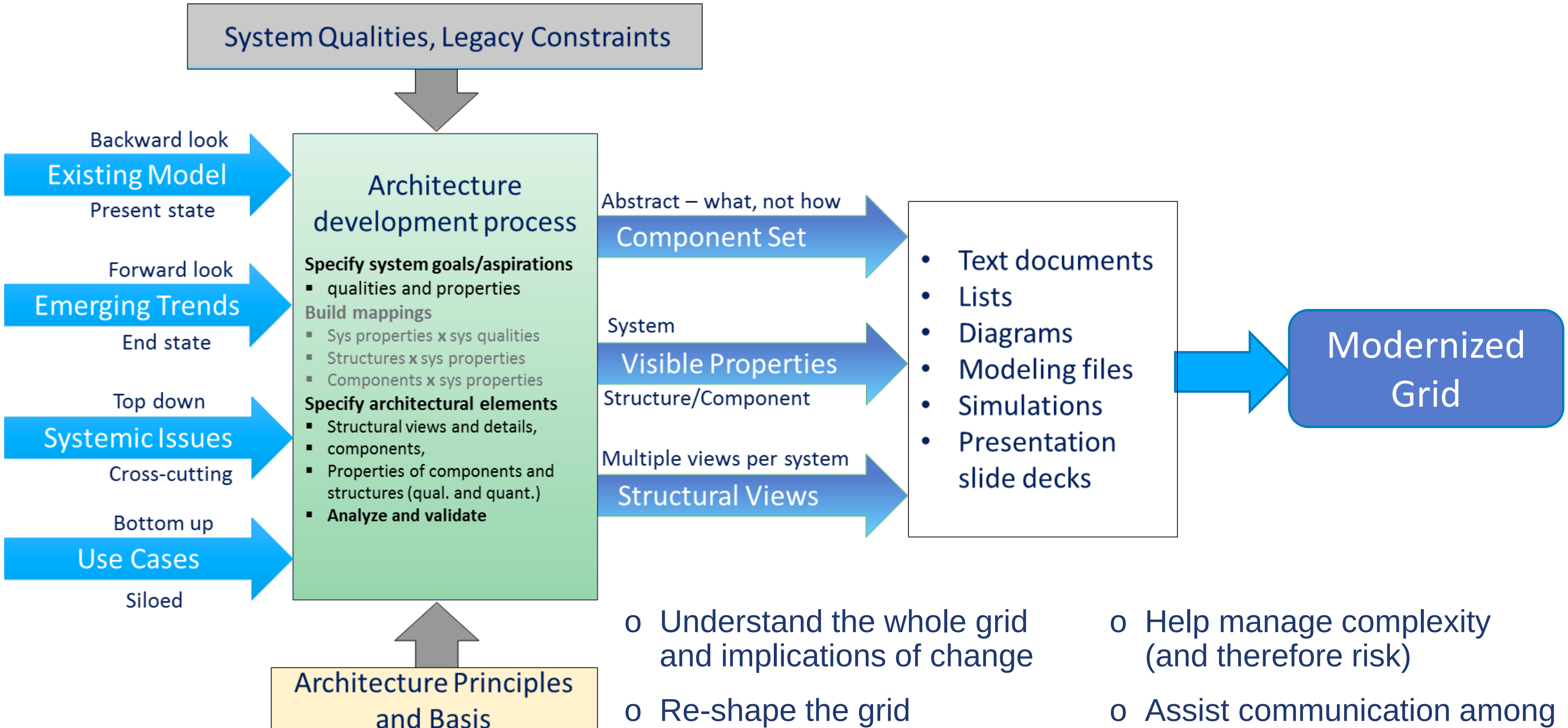

- Understand the whole grid and implications of change
- Re-shape the grid
- Remove barriers and refine essential limits
- Help manage complexity (and therefore risk)
- Assist communication among stakeholders
- Identify/define interfaces and platforms

Summary Points

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- The grid is changing due to a variety of forces and much of it is not planned
- Grid Modernization involves an amazing amount of complexity…and an amazing range of stakeholders
- Complexity is one of the biggest challenges in doing grid modernization
- Grid Architecture provides the means to make the problem manageable

What Is It?

Grid Architecture: Tools for Insight

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How to Build A House

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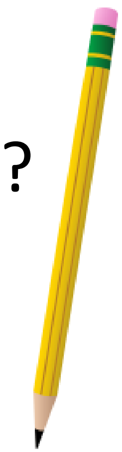
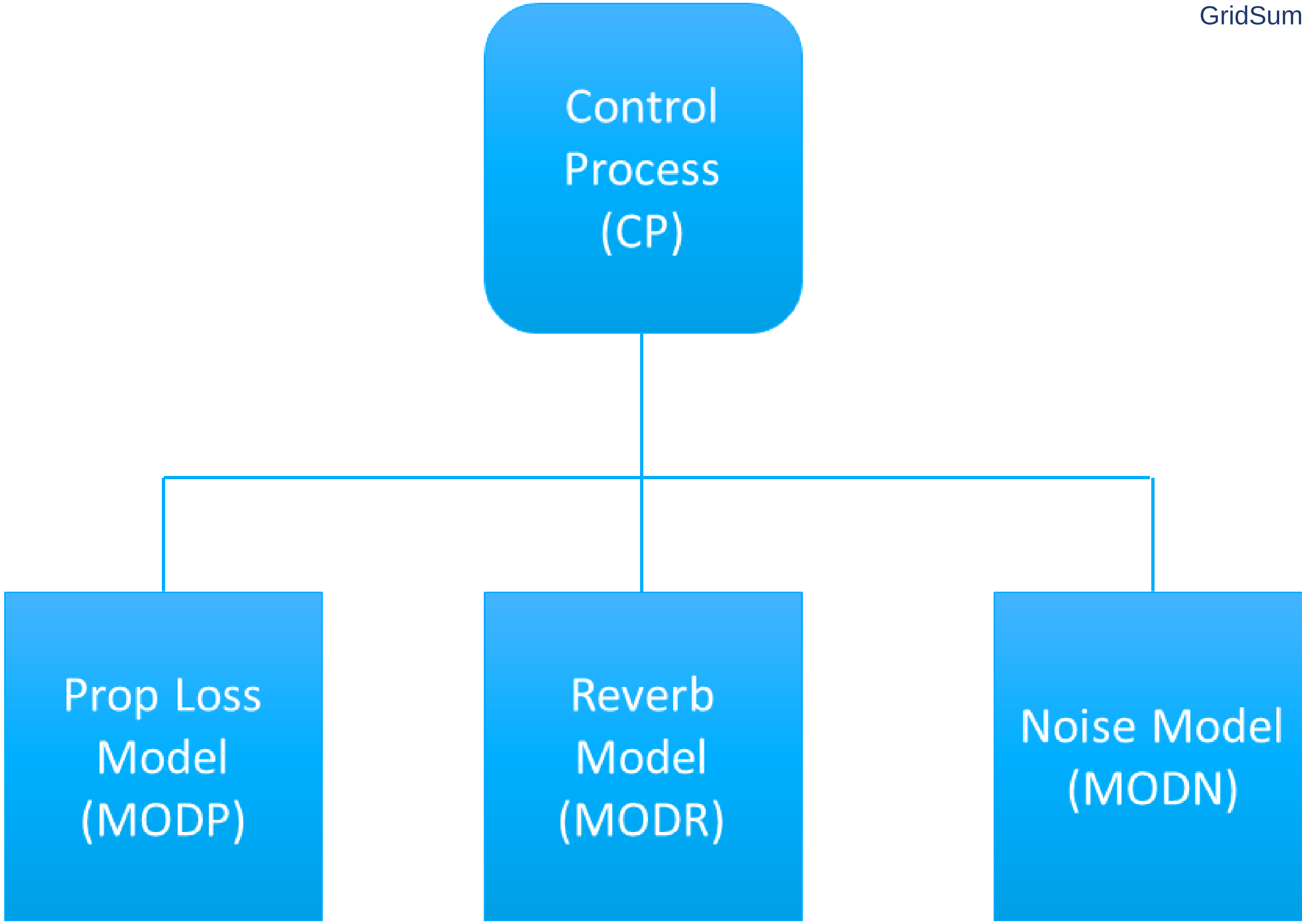
What do you pick up first:

a shovel

or a pencil?



Is This an Architecture?



Source: L Northrup, Software Architecture in Practice

Questions about that “Architecture” Diagram

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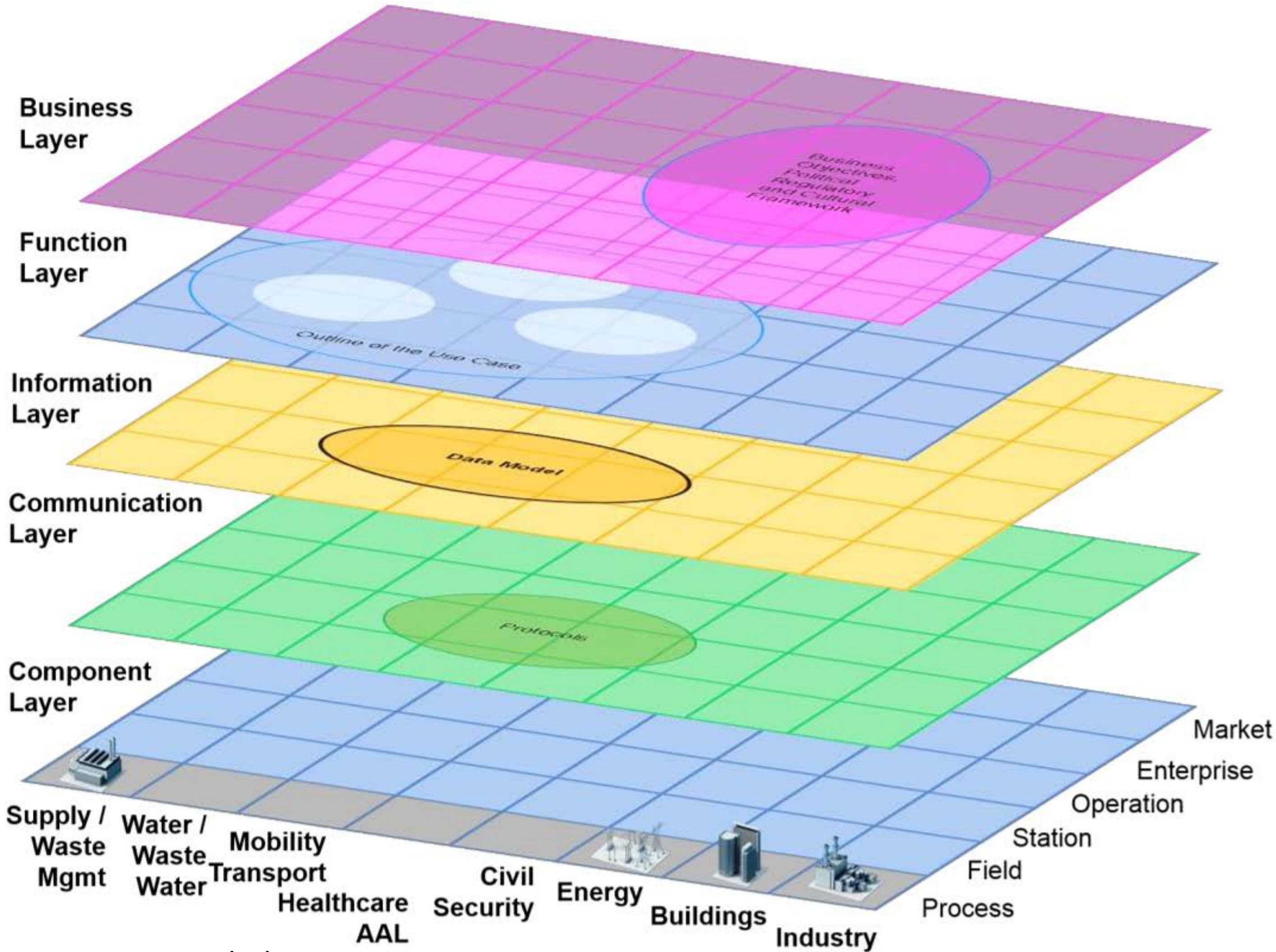
- What is the nature of the elements?
  - Run on separate processors? Run at separate times? Processes, programs, both? Runtime separation or division of design labor?
- What are the responsibilities of the elements?
- What is the significance of the connections?
  - Communicate?
  - Control?
  - Send data from one to another?
  - Use each other or invoke each other?
  - Synchronize with each other?
  - Share some information-hiding secret with each other?
  - Other?
  - What information flows, and how?
- What is the significance of the layout?
  - Why is CP on a different level? Does it call the others or are the others not allowed to call it? Does CP contain the others?
  - Was there just not room for all 4 on the same row?

Not an Architecture

SGAM



Source: Semantic Scholar

Still Not, but Getting Warmer

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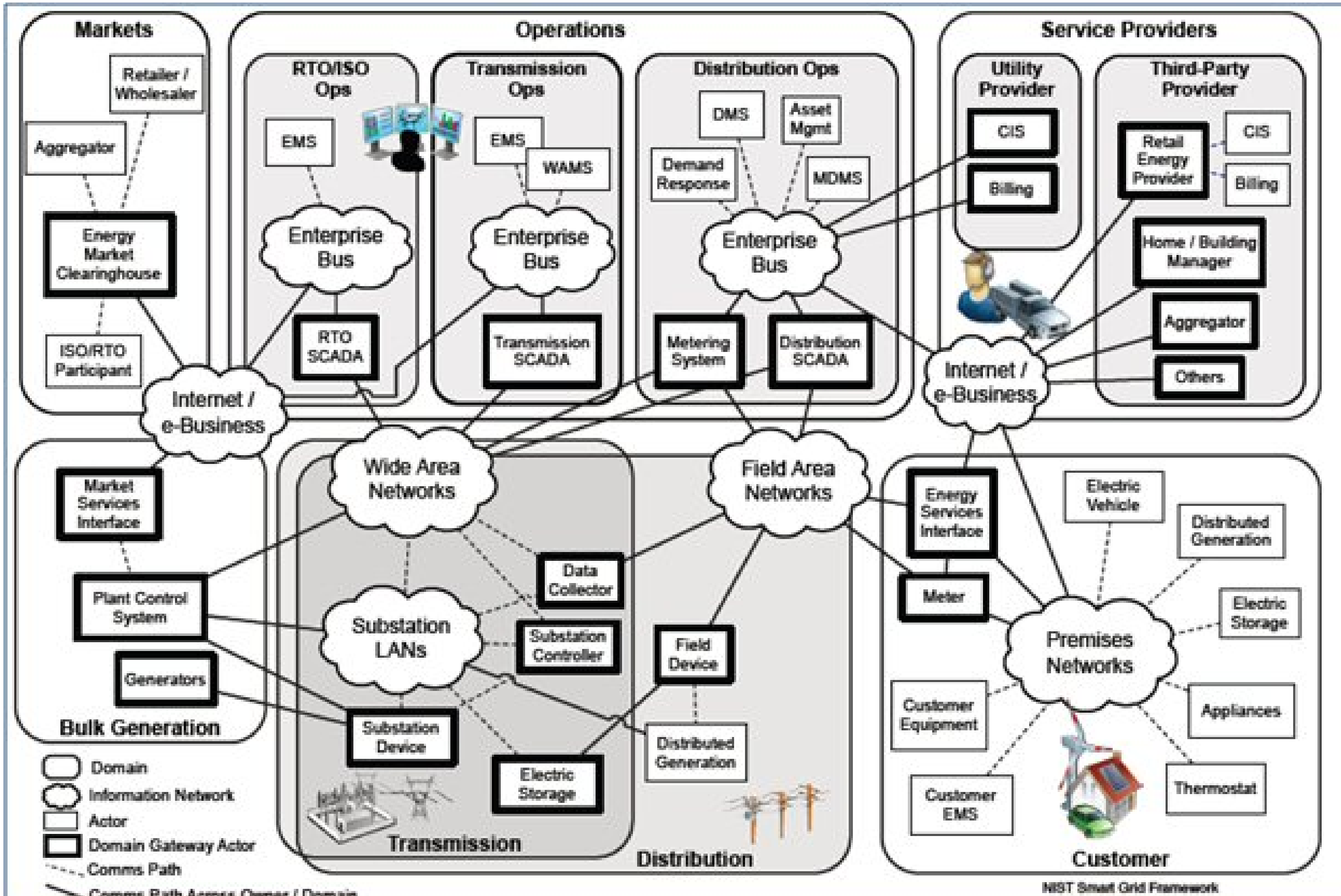

NIST Smart Grid Framework

System Architecture

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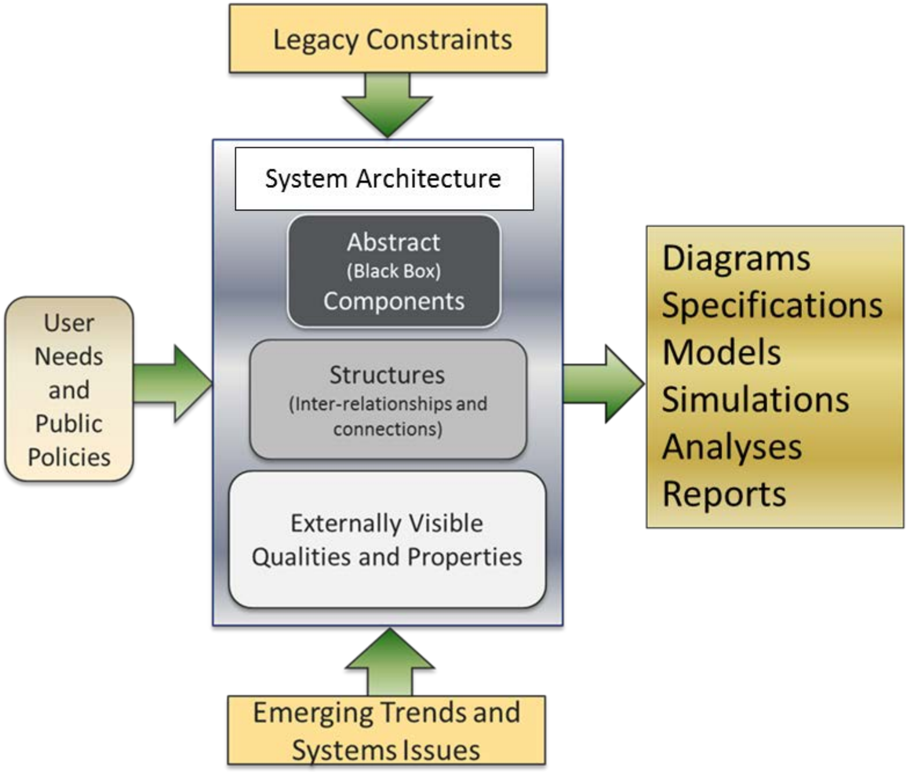
Architecture

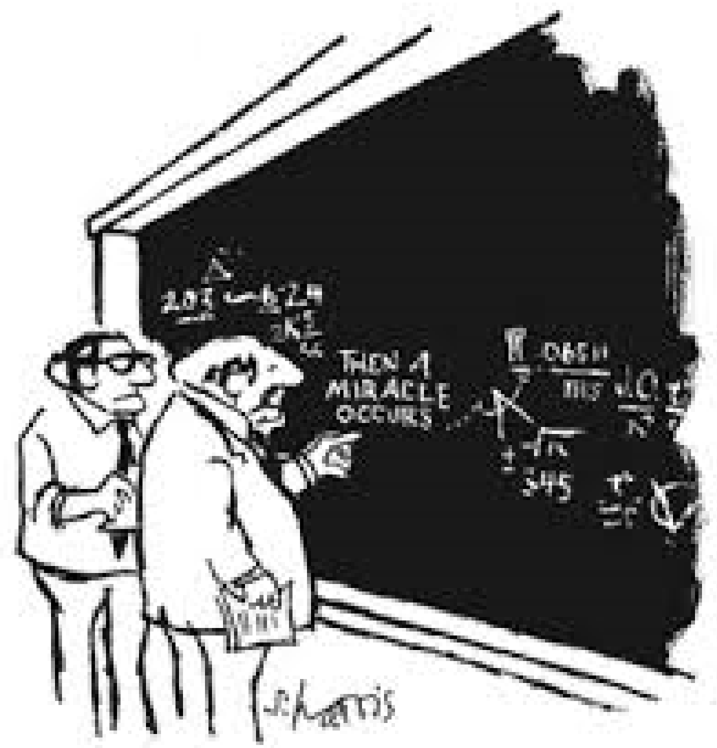
- An abstract depiction of a system, consisting of black box components, structure, and externally visible properties
- Purposes of architecture:
  - Enable reasoning about a system's structure and behavior
  - Manage system complexity
  - Facilitate communication among stakeholders (internal and external)
  - Manifest earliest design decisions/constraints
  - Identify gaps in theory, technology, organization, regulation…
  - Enable prediction of system qualities
  - Identify/define interfaces and platforms



Architecture is *not* design.
Nor is it interoperability.

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



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Source: Sidney Harris

Elements of System Architecture: Structure

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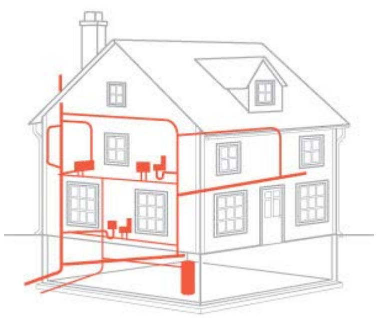
- Abstract components
  - The individual parts, viewed as “black boxes”
  - But thoroughly grounded in reality (no “magic” boxes)

- 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


Elements of System Architecture: Properties and Qualities

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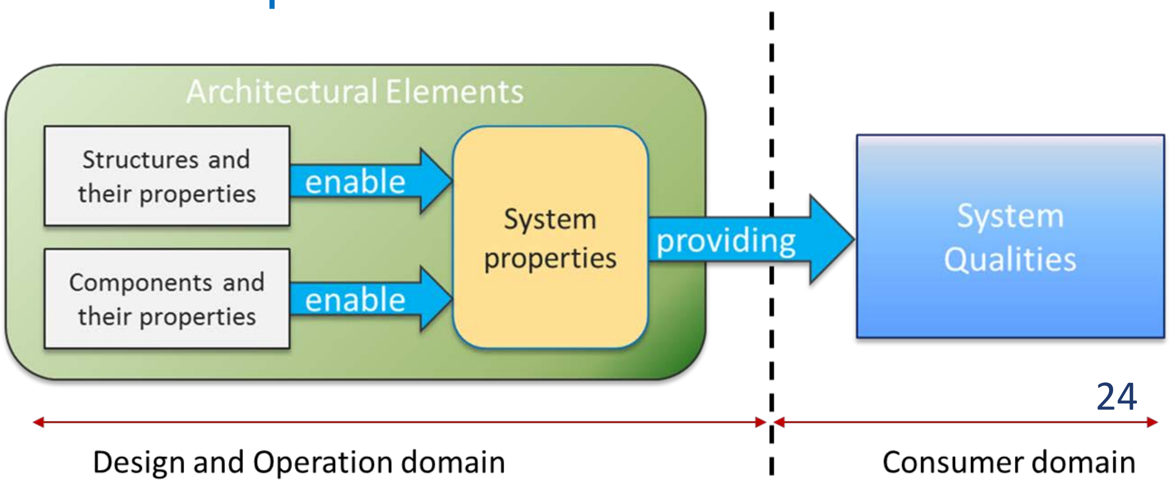
- Abstract components
  - The individual parts, viewed as “black boxes”
  - But thoroughly grounded in reality (no “magic” boxes)
- Structures
  - The overall shape of the system and how components interact
  - Any complex system has multiple structures, requiring multiple views
  - No real architecture can be represented in a single diagram
- Externally visible properties and qualities
  - Of components
  - Of structures
  - Of the whole system



Grid Architecture Definition

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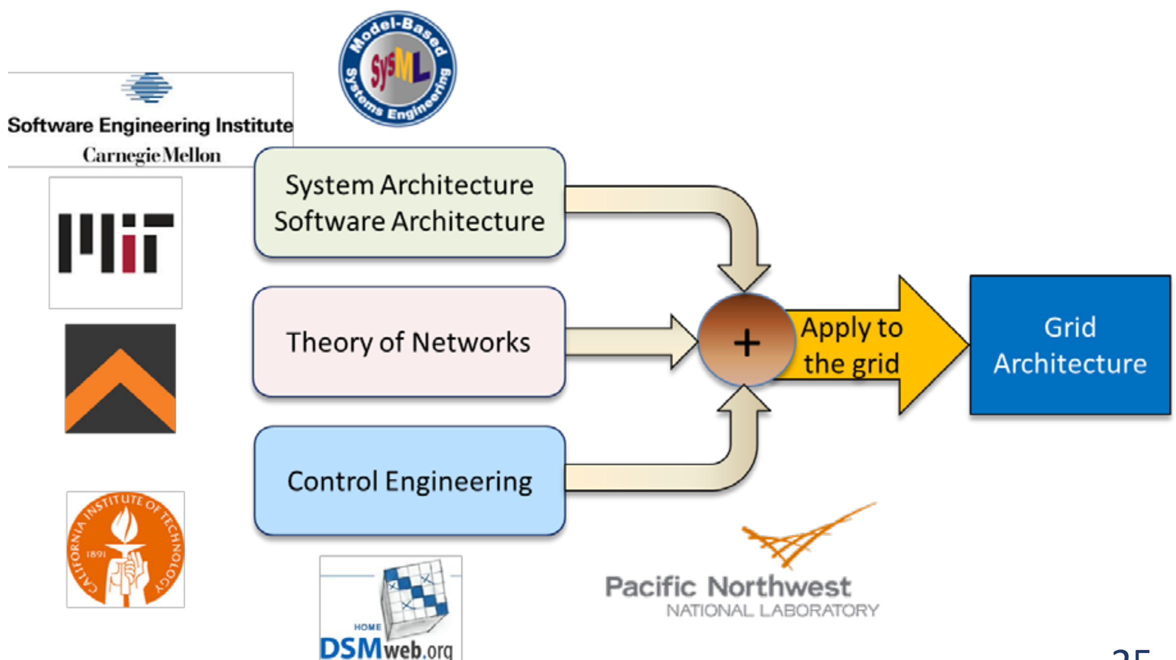
Grid Architecture is the top level view of the whole grid; it enables reasoning about the grid's properties, behavior, and performance

Grid Architecture is about ***structure*** - structure sets the essential limits on what complex systems like the grid can and cannot do

- 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



Grid Architecture Is…

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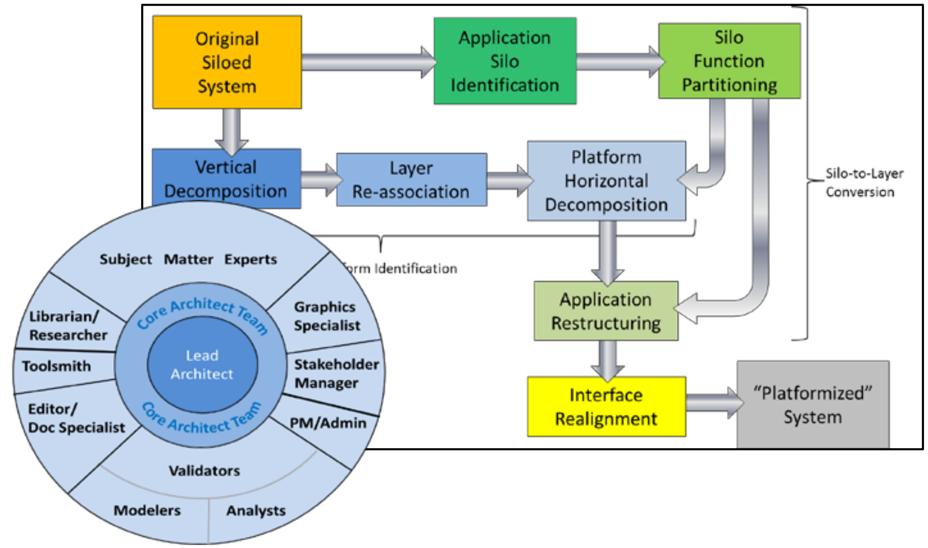
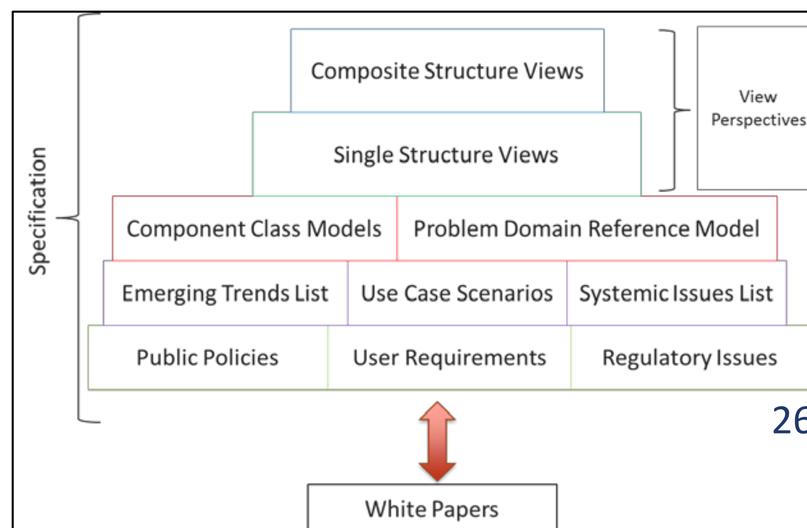
- A discipline/methodology
  - Based on system architecture
  - Plus network theory
  - Plus control engineering
  - Plus software architecture
  - Applied to electricity systems



- A work product
  - Specifications
  - Drawings and diagrams
  - Spreadsheets
  - Descriptive documents



Grid Architecture Re-Shapes the Grid

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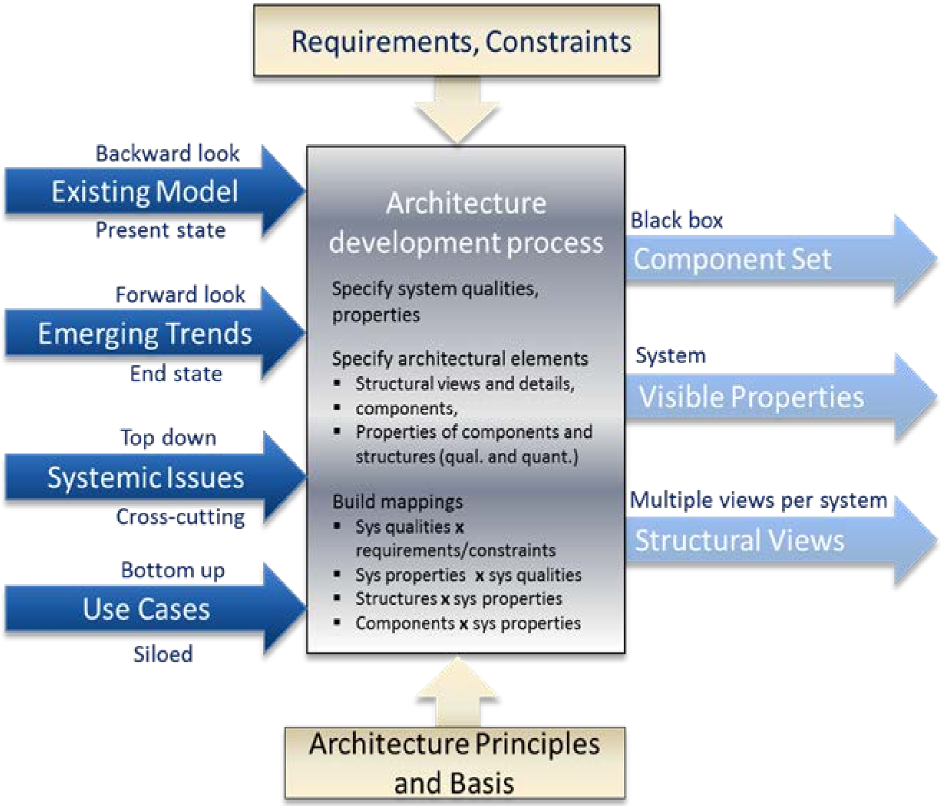
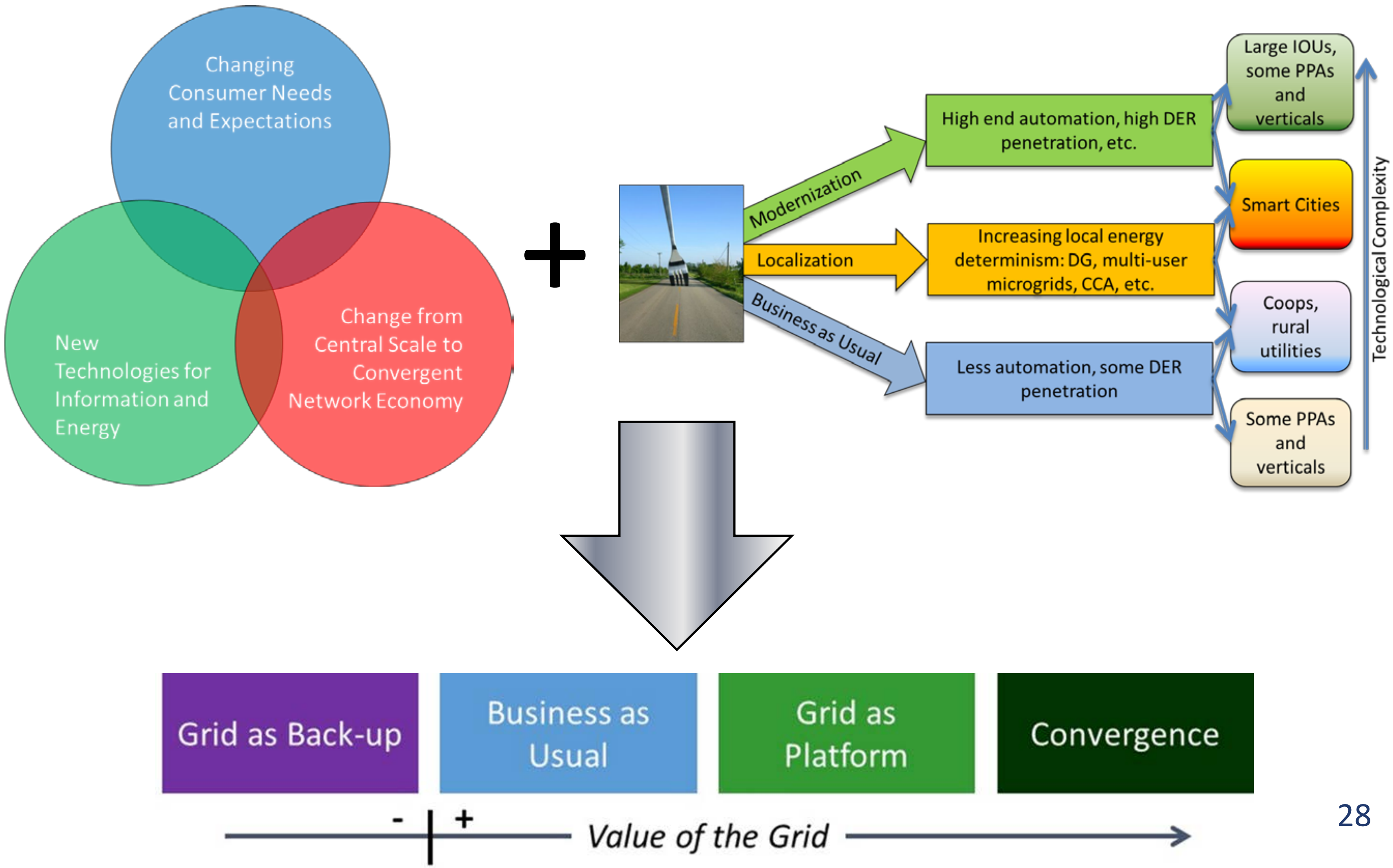


- Identify legacy constraints
- Remove barriers and refine essential limits
- Help manage complexity (and therefore risk)
- Support early stage modernization processes
- Identify gaps
- Assist communication among stakeholders
- Define platforms
- Inform interfaces and interoperability

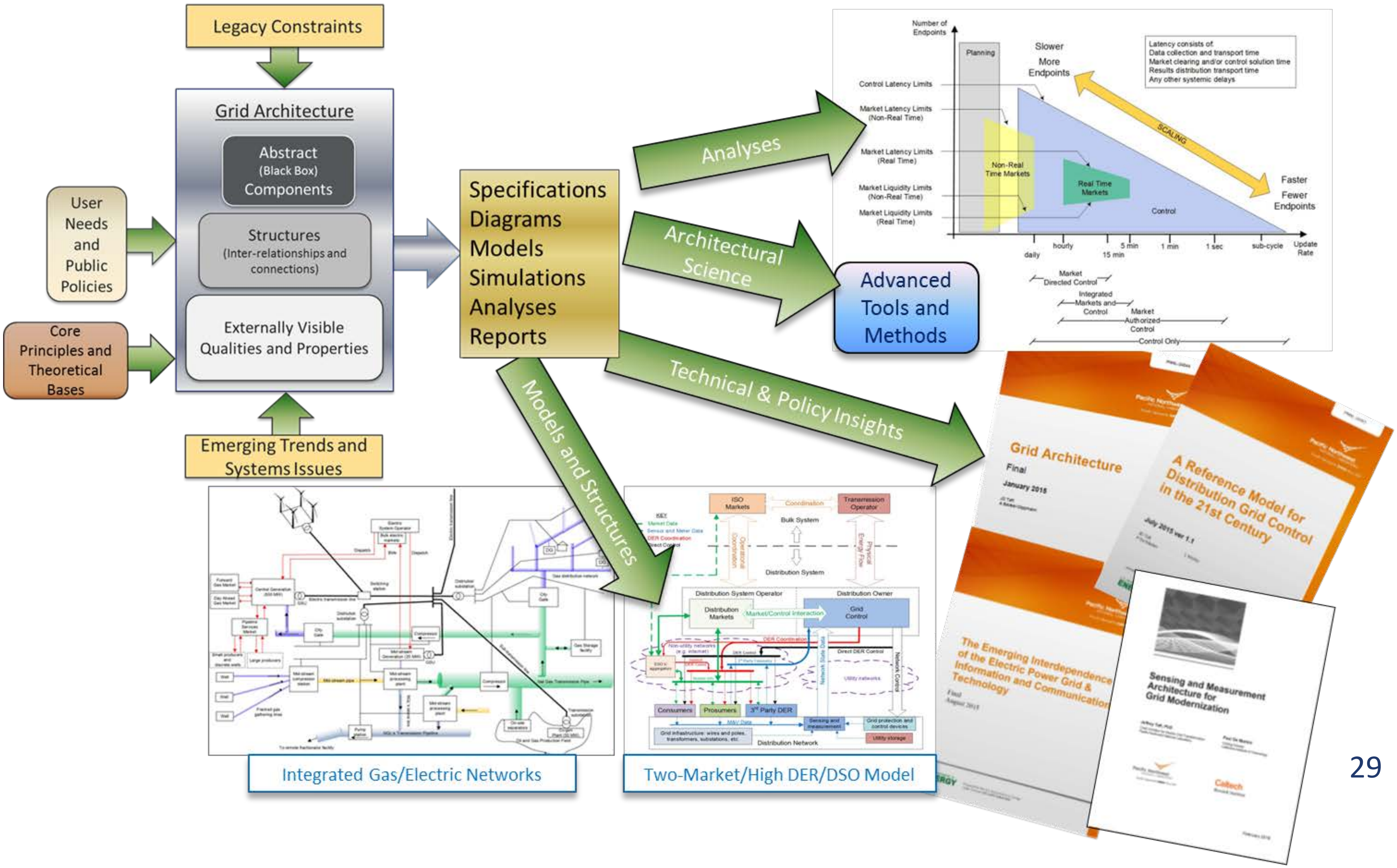
Grid Architecture shapes everything from grid communications and control to industry interactions and market products and even convergence with other infrastructure networks.

Re-Shaping of the Grid Impacts Grid Value



Value diagram source: P De Martini

Manage Complexity; Produce *Insight*



Powerful Methods –> Practical Results

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- Layered decomposition mathematics → Laminar Coordination Framework
  - → Architectures for TE and distributed control; grid codes
  - → DSO/ISO structure
  - → Architecture comparative analysis method
- Platform definition methodology
  - → Silo-to-layer conversion → Sensor/comms networks
  - → DER Planning/Operations/Markets system structure
- Industry structure modeling
  - → DER telemetry comms architecture
  - → DER/ESO/DSO/ISO roles & interaction definition

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

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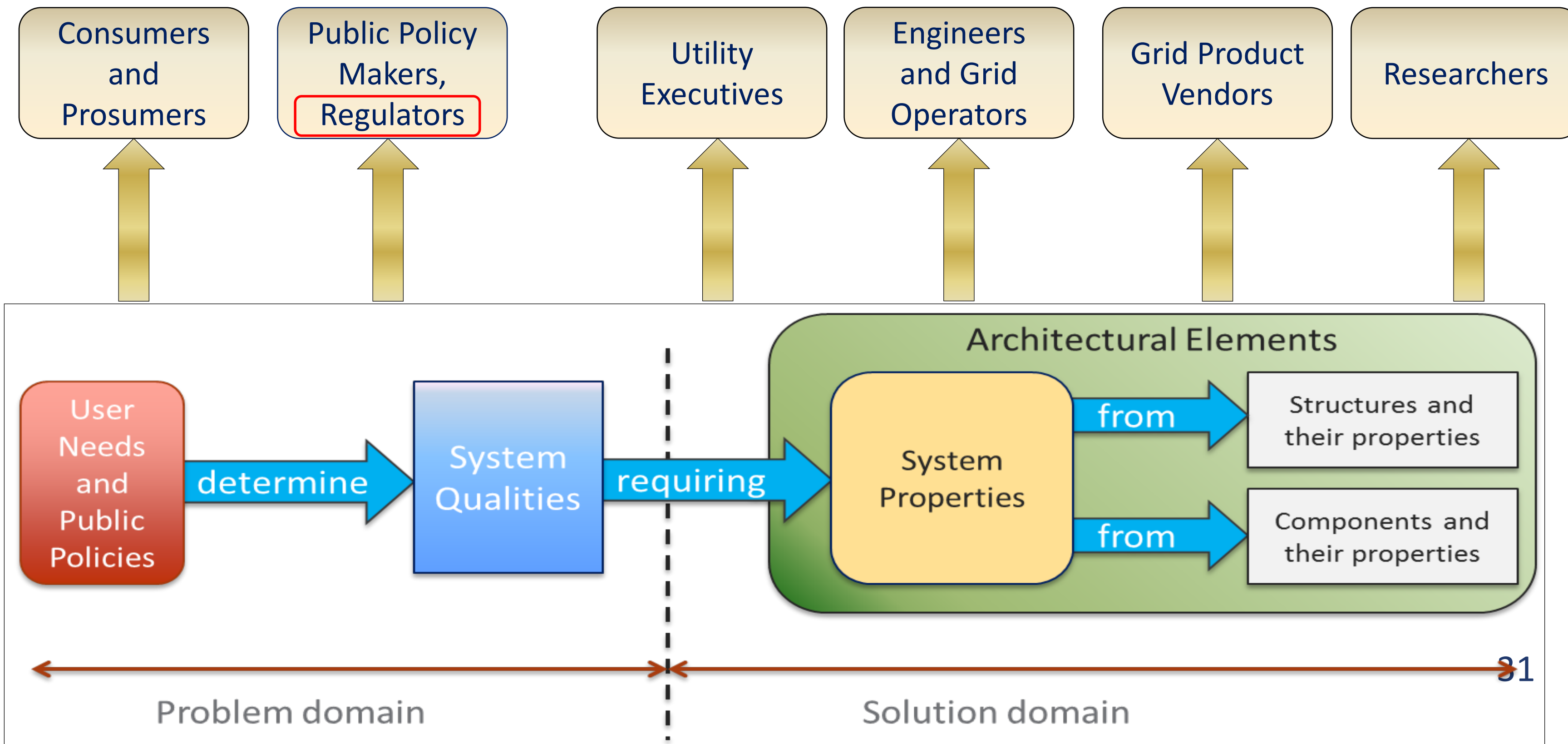
Grid Architecture supports a wide range of stakeholders, including:



Summary Points

- Grid Architecture is the top level view of the whole grid and its various parts
- Focus on *structure*
  - Get it right early and things fall into place cleanly
  - Get it wrong and costs and performance suffer
- Grid Architecture is a discipline (methodology) and a set of work products (architectural specifications)
- Powerful methods – practical results
- You don't have to be an architect to use the results

Basic Definitions

Grid Architecture: Tools for Insight

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Architecture and Design

- Architecture has been previously defined
- A *system design* is a specific expression of an architecture that is suitable for implementation
- An *architecture* allows multiple possible implementations; a design allows exactly and only one
- A goal of architecture is top specify the minimum number of (structural) constraints that simplify all the downstream decisions

Architecture is not design. It is far more than interoperability.

System

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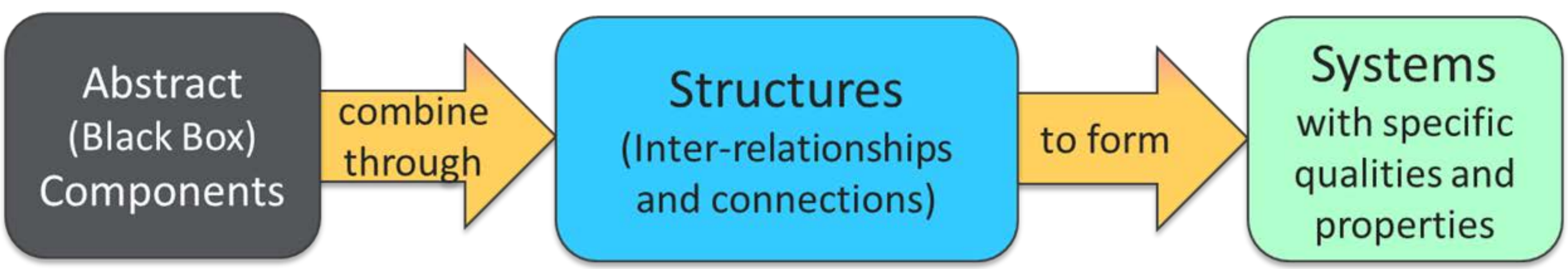
- A set of interdependent elements forming an integrated whole
  - A system has **components**: it contains parts that are directly or indirectly related to each other;
  - A system has **structure**: its components are linked by **connectivity** and **relationships**
  - A system has **behavior**: it exhibits processes that fulfill its function or purpose and respond to stimuli



Structure

- Arrangement or pattern of interlinkage of components; organization of a system; the form or “shape” of a system
- Structure is a fundamental, tangible or intangible notion referring to the recognition, observation, nature, and permanence of patterns and linkages of components. This notion may be tangible, such as a built structure, or an attribute, such as the structure of society
- **Structure has large impact on system boundaries and constraints**

Components

- Uniquely identifiable, non-trivial, nearly-independent devices, individuals, organizations, organisms, elements, building blocks, parts, or sub-assemblies that may be collected together to cooperate or to serve a common purpose
- Have **externally visible properties** but their internal details are hidden
- Exhibit **behaviors**

Behavior and Connectivity

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- Behavior
  - The set of **processes** that fulfill a specific function or purpose.
  - It is the **range of actions** and mannerisms exhibited by components in conjunction with themselves or their environment.
  - It is the **response to various inputs** or stimuli, whether internal or external.
- Connectivity
  - The state of being linked or joined together so as to **enable some form of exchange**. Connectivity is a basic form of structure.
  - For power grids, the basic elements of exchange are: energy, money, control/access, information, services, value

Relationships

- The means by which two entities are affiliated; they consist of collections of component behaviors.
- Architectural relationships consist to two classes of behaviors:

Interactions Mutual or reciprocal influences	Transfers Conveyances from one entity to another
conversation	transmission, broadcast, narrowcast
transaction	grants or takings
closed loop (feedback) control	open loop command and control

Summary Points

- Grid Architecture uses formal methodology to produce architecture work products
- Architectures are produced by organized architecture teams
  - These teams are not committees
- Stakeholder input is crucial *throughout the process*
- Some of the work products are necessarily technical and can be complex
- White papers explain the rationales and significance of the architectures for stakeholders

Underlying Principles

Grid Architecture: Tools for Insight

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Is There Just One Grid Architecture?

- No one-size-stretches-to-fit-all architecture
  - Regional concerns
  - Industry structure variations
- Multiple possible future scenarios for grid evolution
- Diverse competing approaches to various grid problems imply an unlimited number of possible architectures
  - part of the grid architecture process is to weed out the weak and identify the strong
- We use multiple *views* to accommodate appropriate regional, industry segment, and notional variations while maintaining *conceptual integrity* across the set of views

Core Principles (1)

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- A good architecture is one that meets the needs of the stakeholders (especially the users) to their satisfaction, does not violate established principles of system architecture, and takes into account the relevant qualities and properties as the customer requires

- Good architectures have conceptual integrity (clean of unnecessary complexities or 'exceptions,' similar problems are solved in similar ways, etc.)

Core Principles (2)

- Conceptual integrity is best achieved by a small cohesive team of like-minded architects. Architecture should be the product of a single architect or small team with an identified leader
- Essential functionality drives complexity, not architectural “elegance”
- Architectural structures should have formal bases where possible to minimize ad hoc configurations with unknown properties

Core Principles (3)

- Architecture should not depend on a particular commercial product or tool
- Architecture should produce enforceable key constraints
- The architect must be cognizant of the global system when optimizing subsystems
- Stakeholders should be involved in the process as much as possible, giving frequent and honest feedback on all aspects of the system architecture

Core Principles (4)

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- Each component should be responsible for only a specific feature or functionality, or aggregation of cohesive functionality. Components should be coupled only through explicit structure, avoiding hidden coupling where possible

- Architectures should define interfaces, not vice versa

- The system architect is not a generalist, but rather a specialist in managing complexity

Paradigm Shifting

Focus on components	Focus on structures
Structure is improvised	Structure is formalized
System of Systems	Network of Structures
Data tsunami	Ultra-Large Scale complexity
System integration	Convergence and value streams
Energy delivery channel	Energy innovation platform
Architectural “elegance”	Architecture quantification

The Grid is a Network of Related Structures

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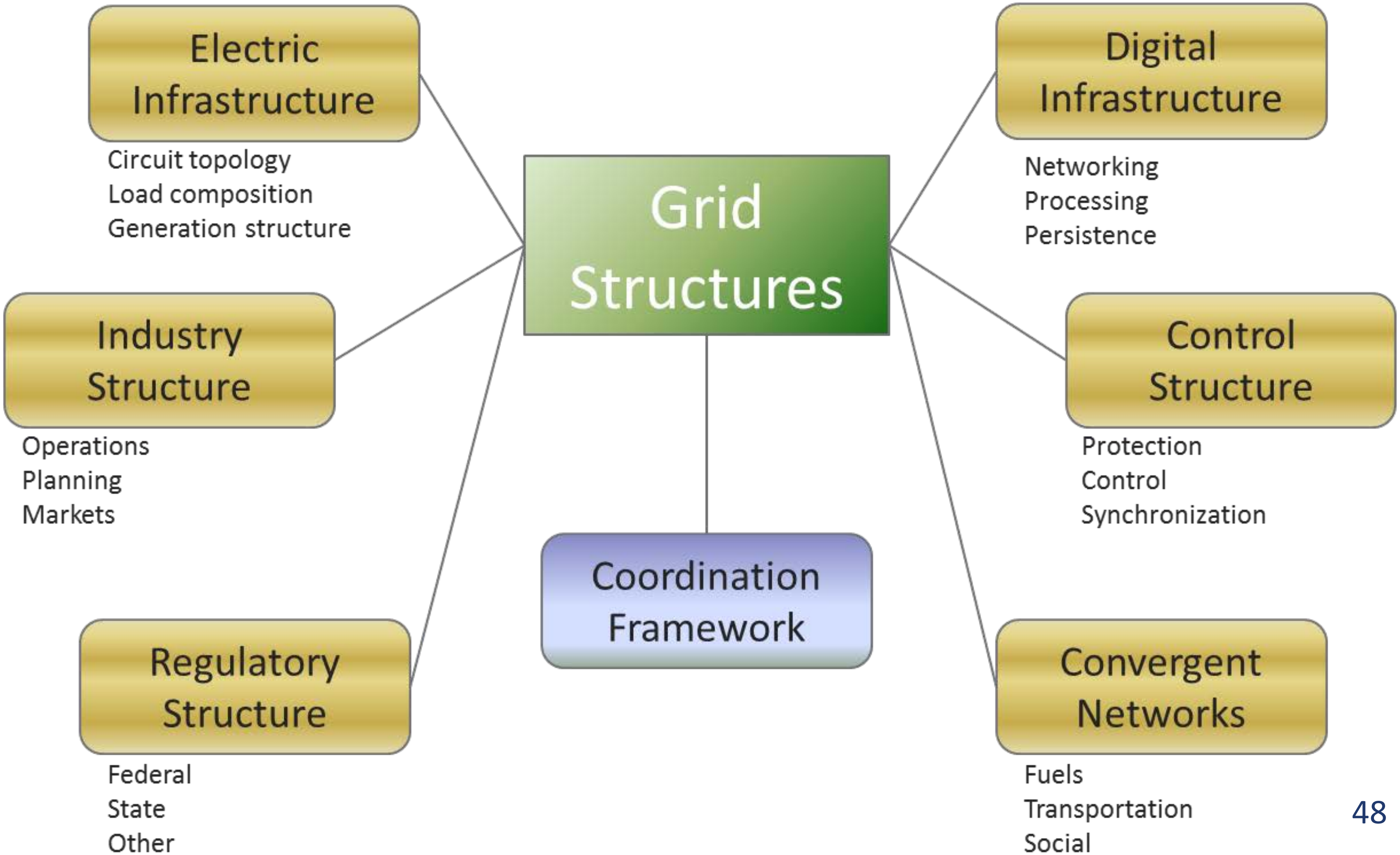

Grid Structure Relationships

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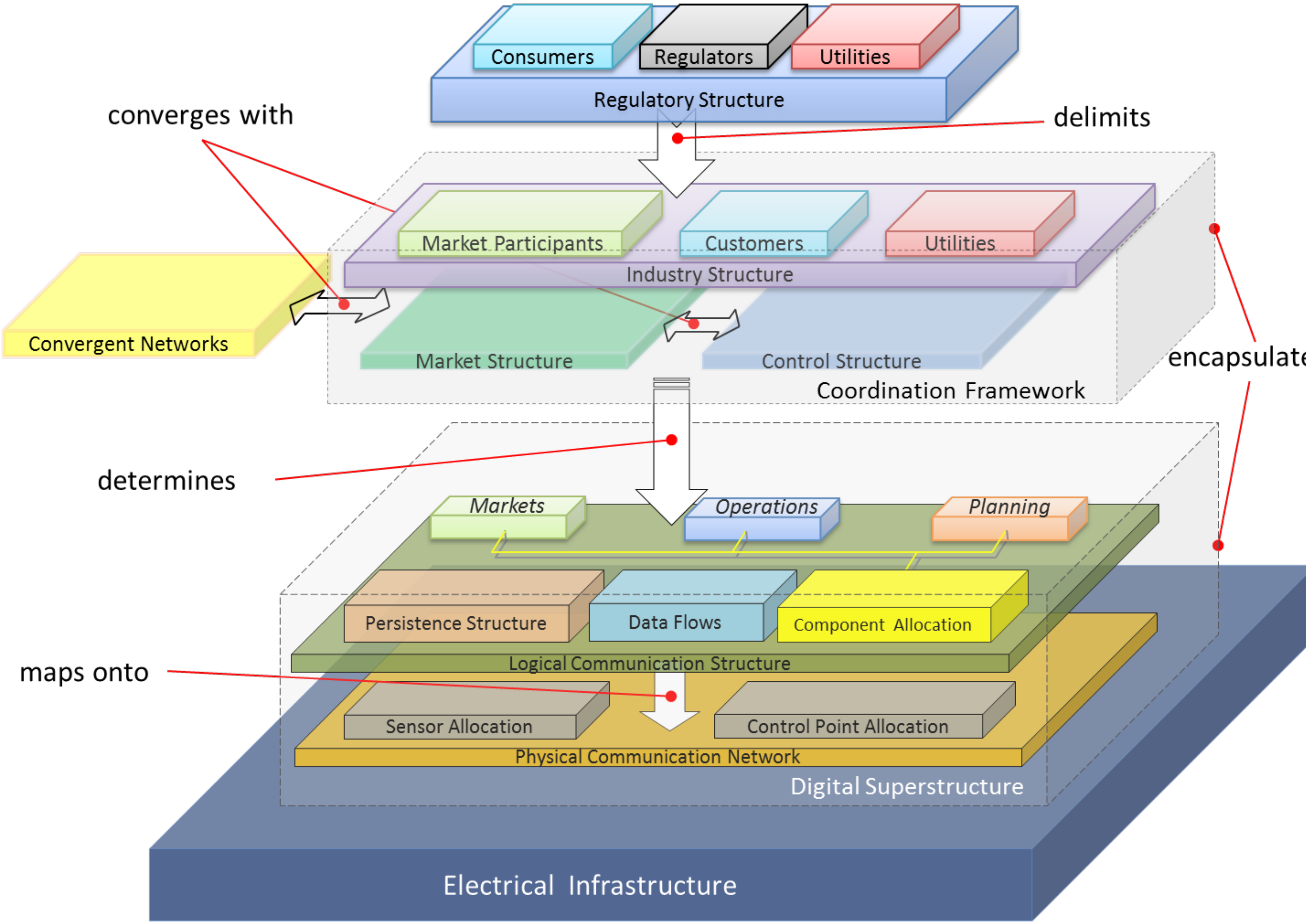

Context is Crucial

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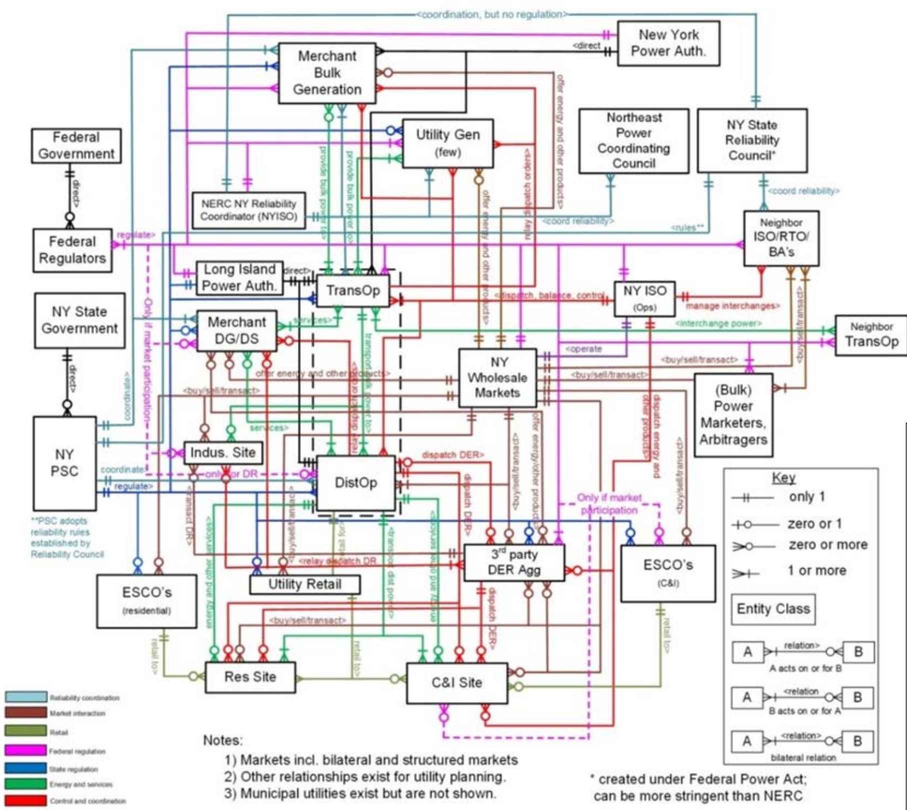
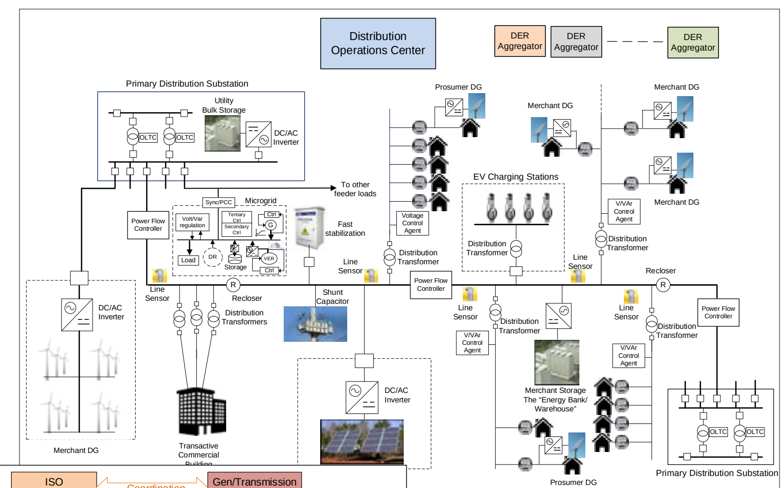
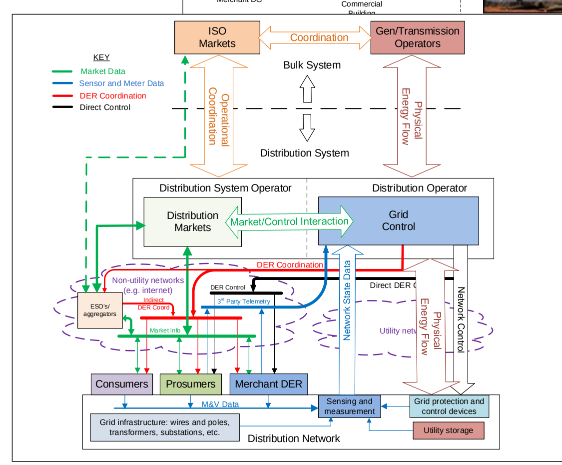
Be aware of the global system when optimizing subsystems. The architect is your guide through this maze.

Industry Structure Model







Problem domain reference models

New Architecture Informs New Interfaces

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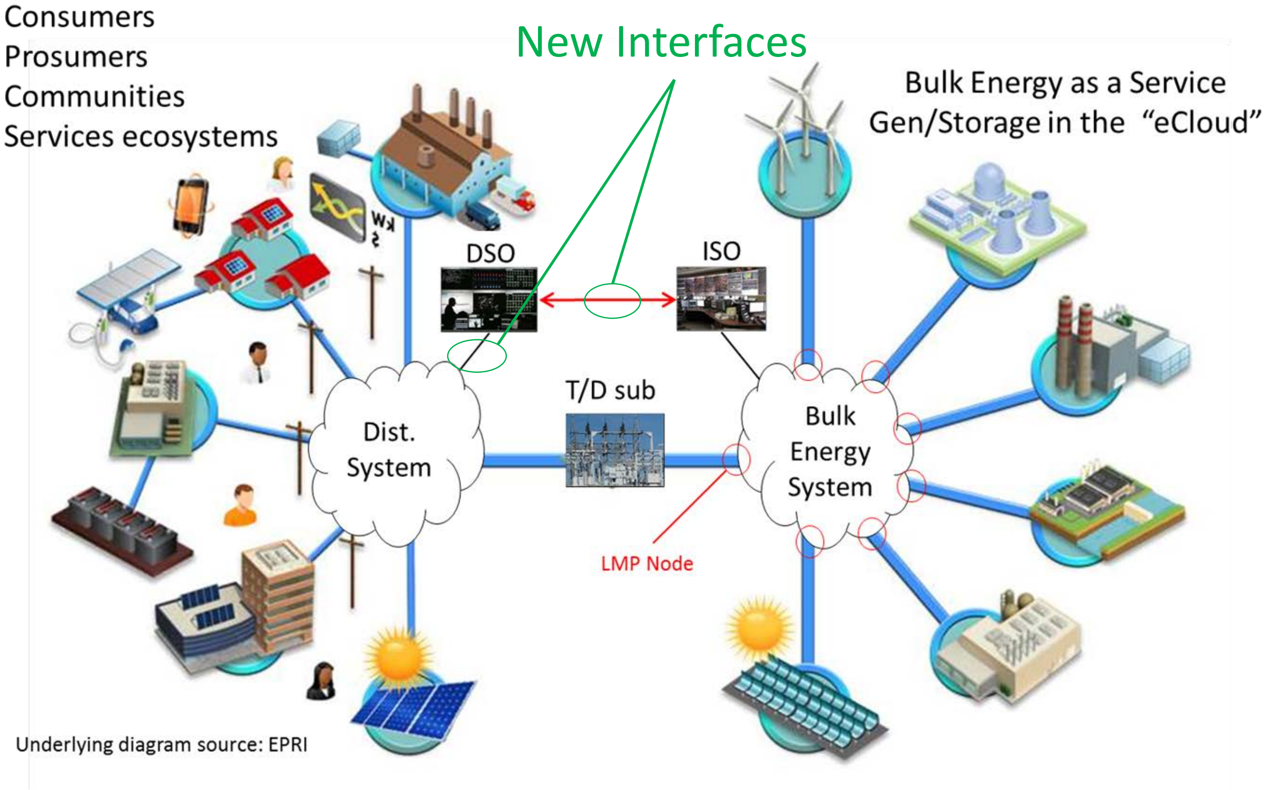
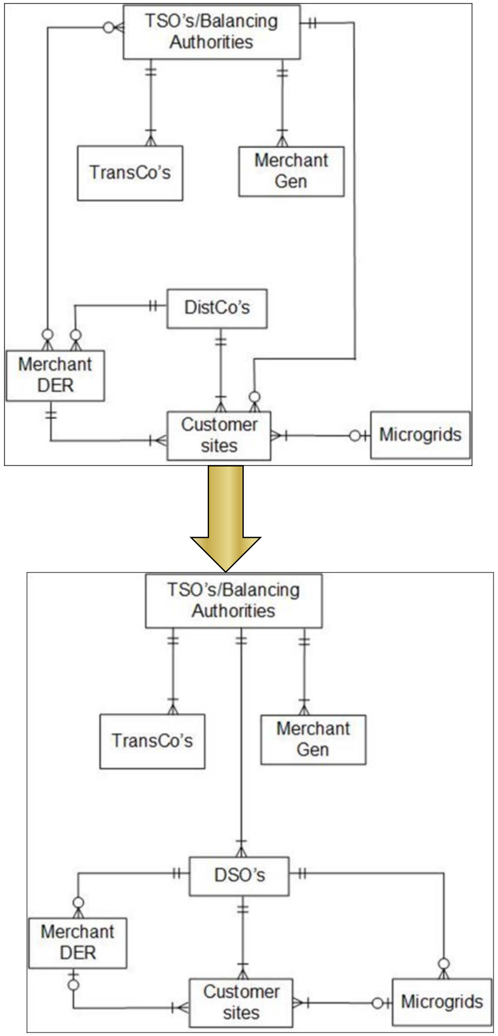
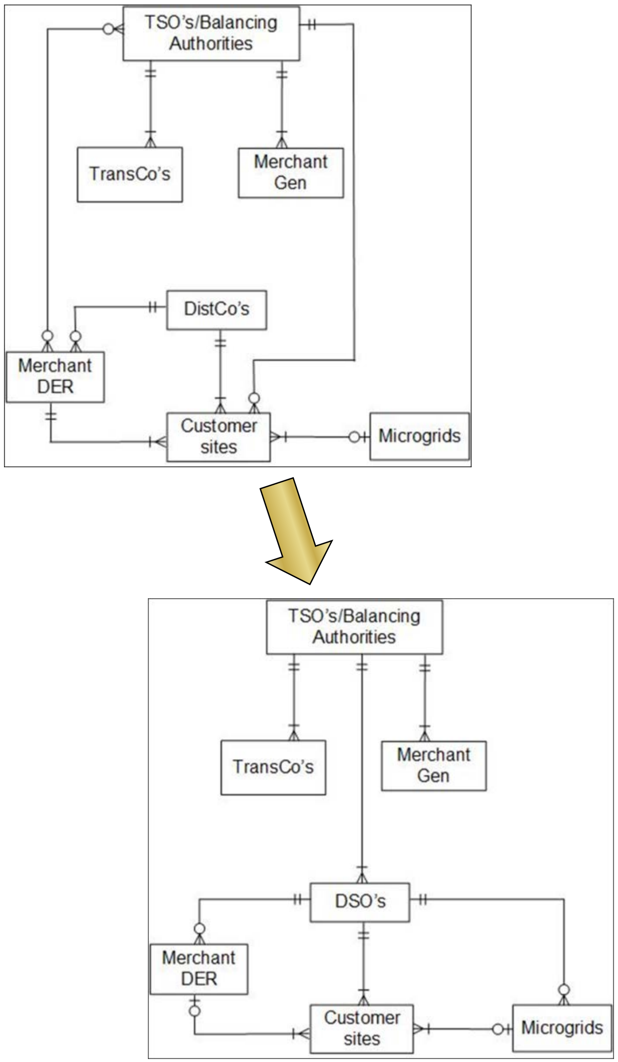
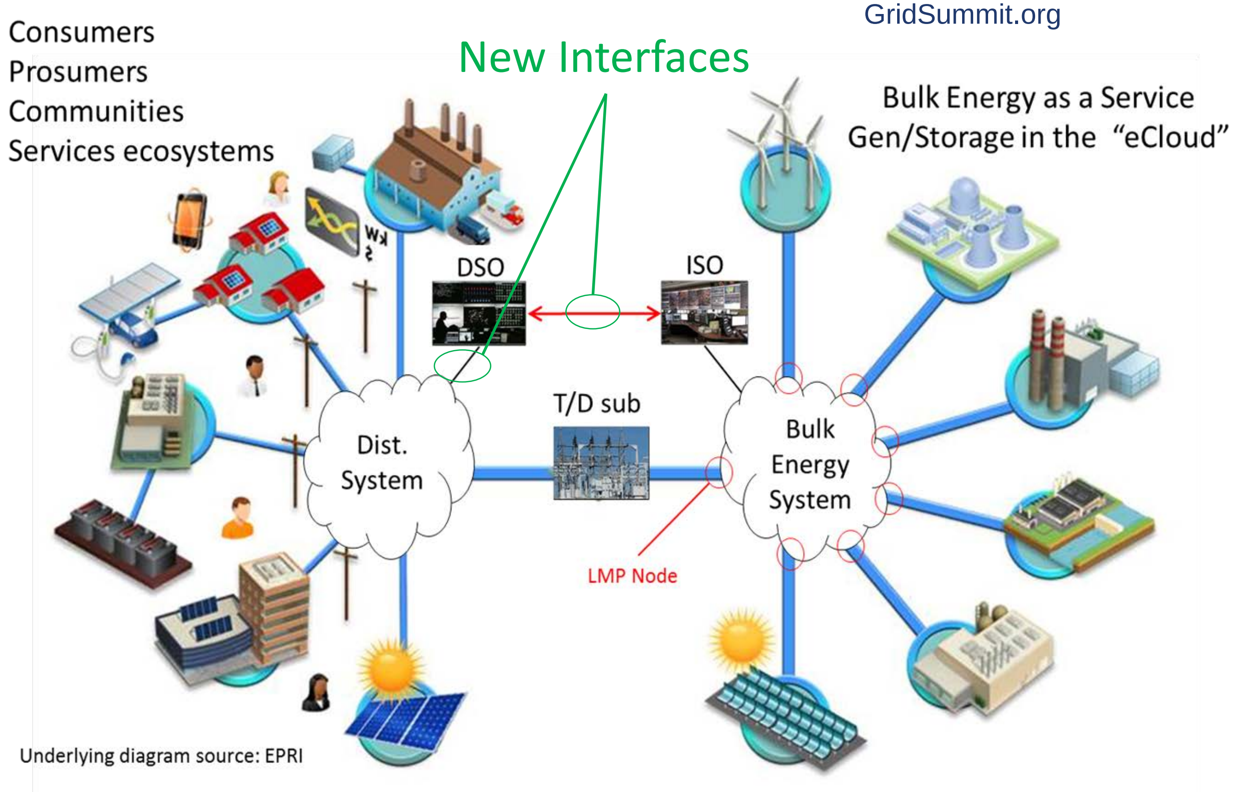




Grid architectures *inform* interfaces and therefore interoperability.

Architectural Consequences





Complexity

- Roles and Responsibilities
- Grid observability
- Distributed coord/control
- T/D coordination
- Scalability, granularity
- Functional flexibility
- Distribution platforms
- Cyber security

Summary Points

- Grid Architecture is a discipline, not just a collection of notions
- Solid foundation of core principles from system architecture, network theory, etc.
- It introduces some new paradigms into thinking about the grid
  - Grid as network of structures
- There is no one-size-fits-all grid architecture so many views are needed
- Architecture is not design

How Is It Done?

Grid Architecture: Tools for Insight

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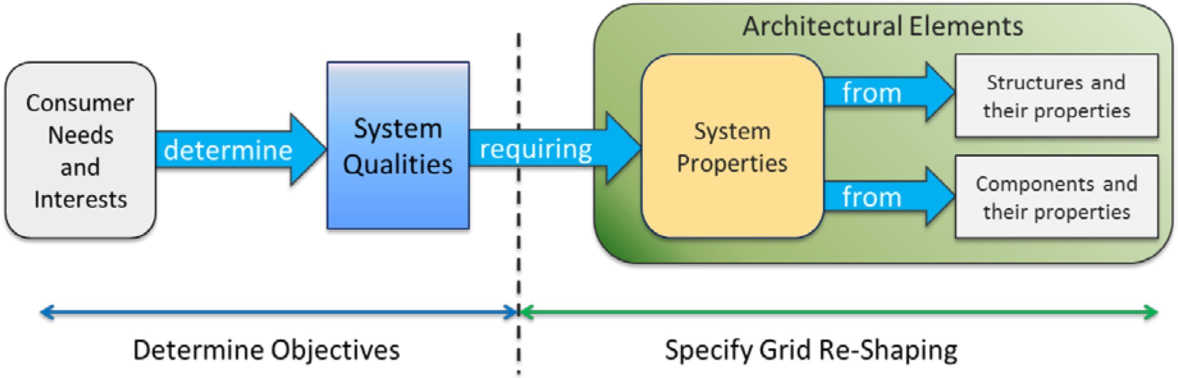
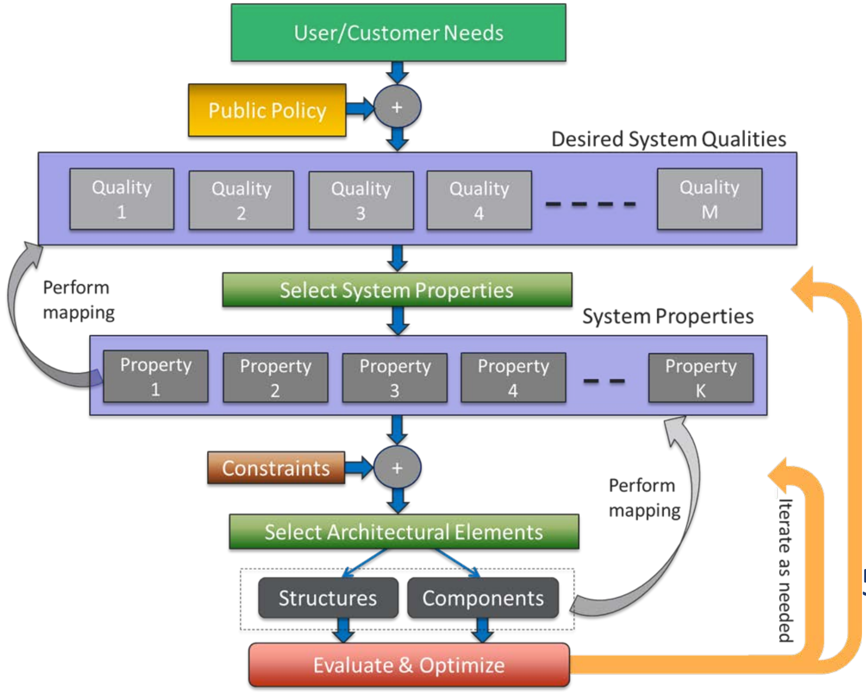
Start From the Objectives

Don't Try to Hang the Windows First



- Start from objectives, not technology
- Define the desired system qualities
- Determine necessary system properties
- Understand the problem environment
- Identify systemic issues and legacy constraints
- Validate the proposed architecture
- The architect is your guide through the complexity maze



Conceptual Integrity and the Core Team

- The conceptual integrity of an architecture measured by how well it conforms to a unified set of principles

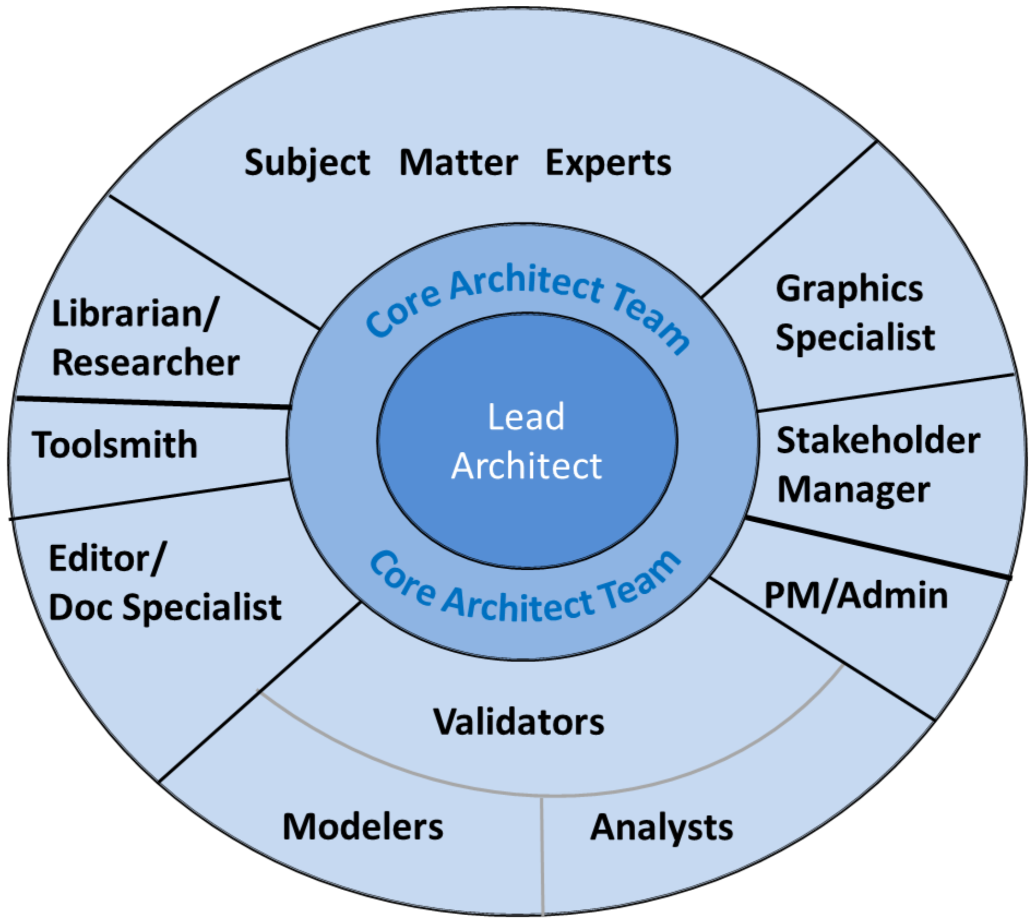
Conceptual integrity must proceed from one mind or from a very small number of agreeing resonant minds. A single chief architect (or a small number of architects), acting on behalf of the stakeholders, should develop a vision of what the architecture should be and make sure that this vision is understood by the rest of the team

Better to reflect a consistent set of architectural views than to try to incorporate many good but independent and uncoordinated ideas.

- adapted from F. Brooks, The Mythical Man Month

Grid Architecture Team Structure

- Multi-ring structure
- Various roles – not all are architects
- **Not a committee**
- Architect is a specialist in complexity management
- Conceptual integrity is crucial



Stakeholder Input is Crucial Throughout the Process

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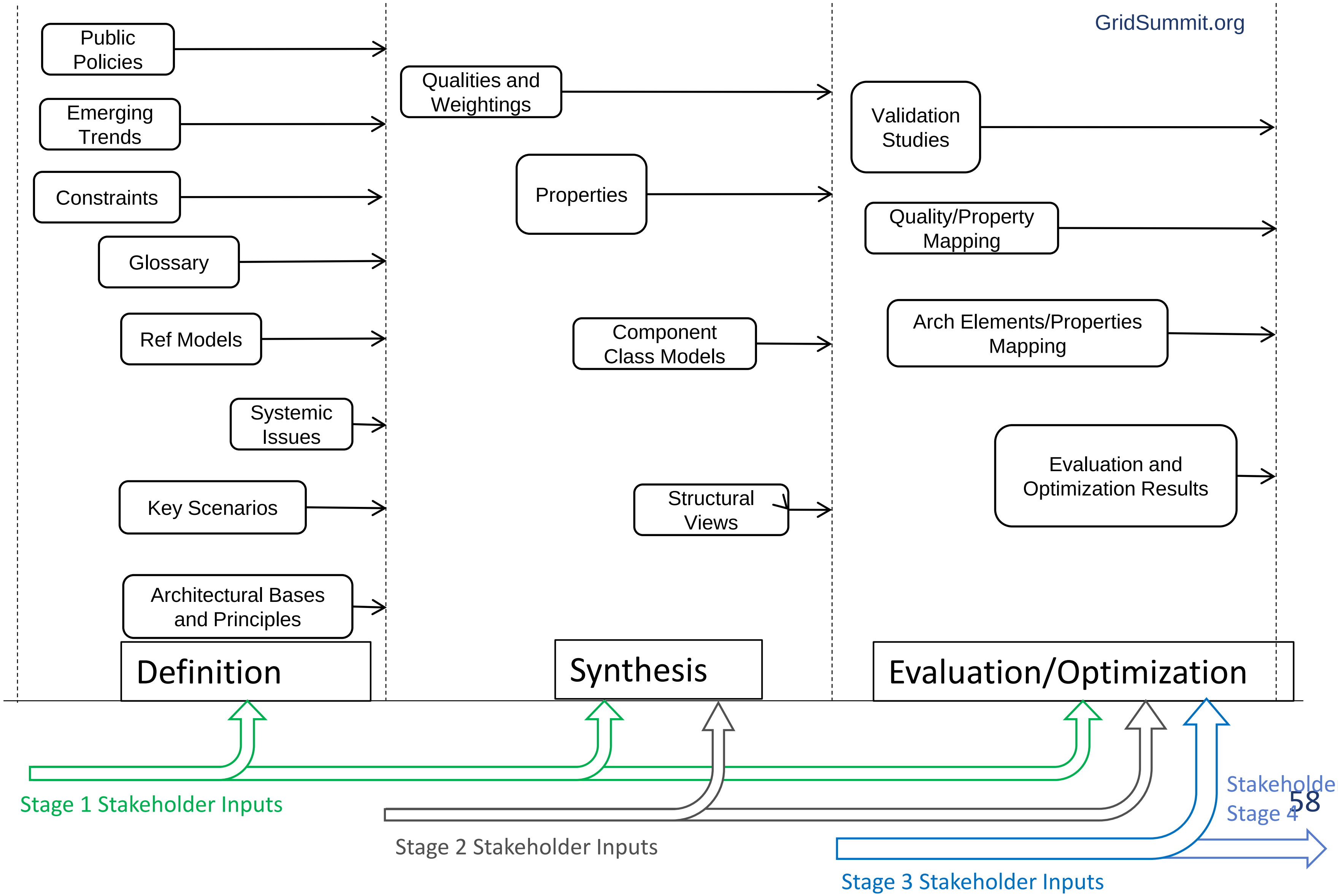
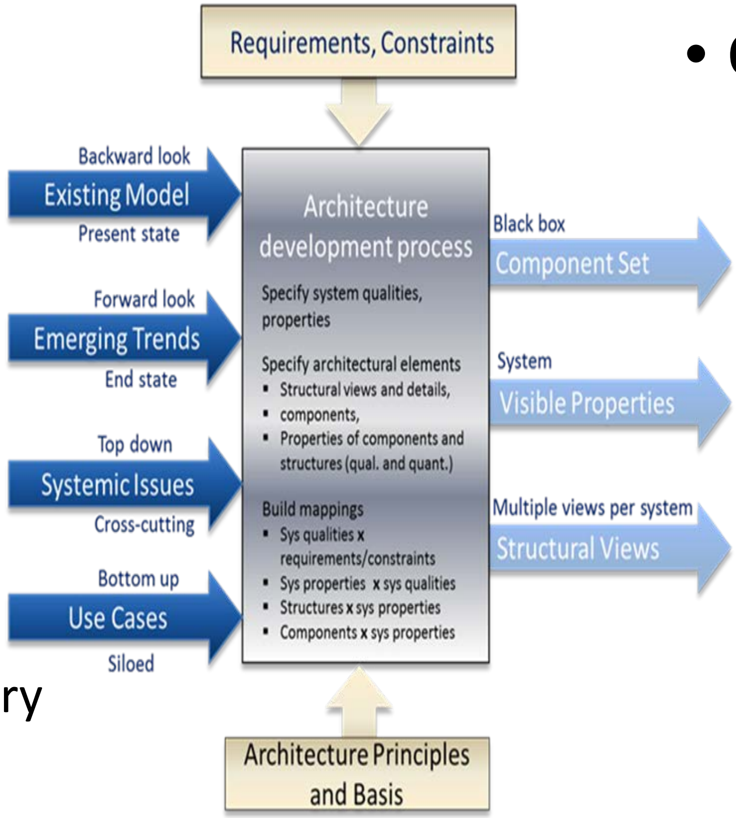


Work Products

- Inputs
  - User Requirements and Public Policies
  - Emerging Trends and Constraints Lists
  - Reference Models and Systemic Issues Lists
  - Use Case Documents
  - Architectural Bases and Principles List
  - Architecture and Industry Technical Glossary



- Outputs
  - System Qualities, Properties, and Elements Mappings
  - Component class models and external properties
  - Structures and external properties
  - Validation Studies and Analyses
  - Reports and Presentations

Grid Architecture Specification Packages Are Technical

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Specification

Composite Structure Views

Single Structure Views

Component Class Models	Problem Domain Reference Model

Emerging Trends List	Use Case Scenarios	Systemic Issues List

Public Policies	User Requirements	Regulatory Issues

SME White Papers

Architecture Insight Papers

Especially for non-technical stakeholders

Example Drawings/Diagrams

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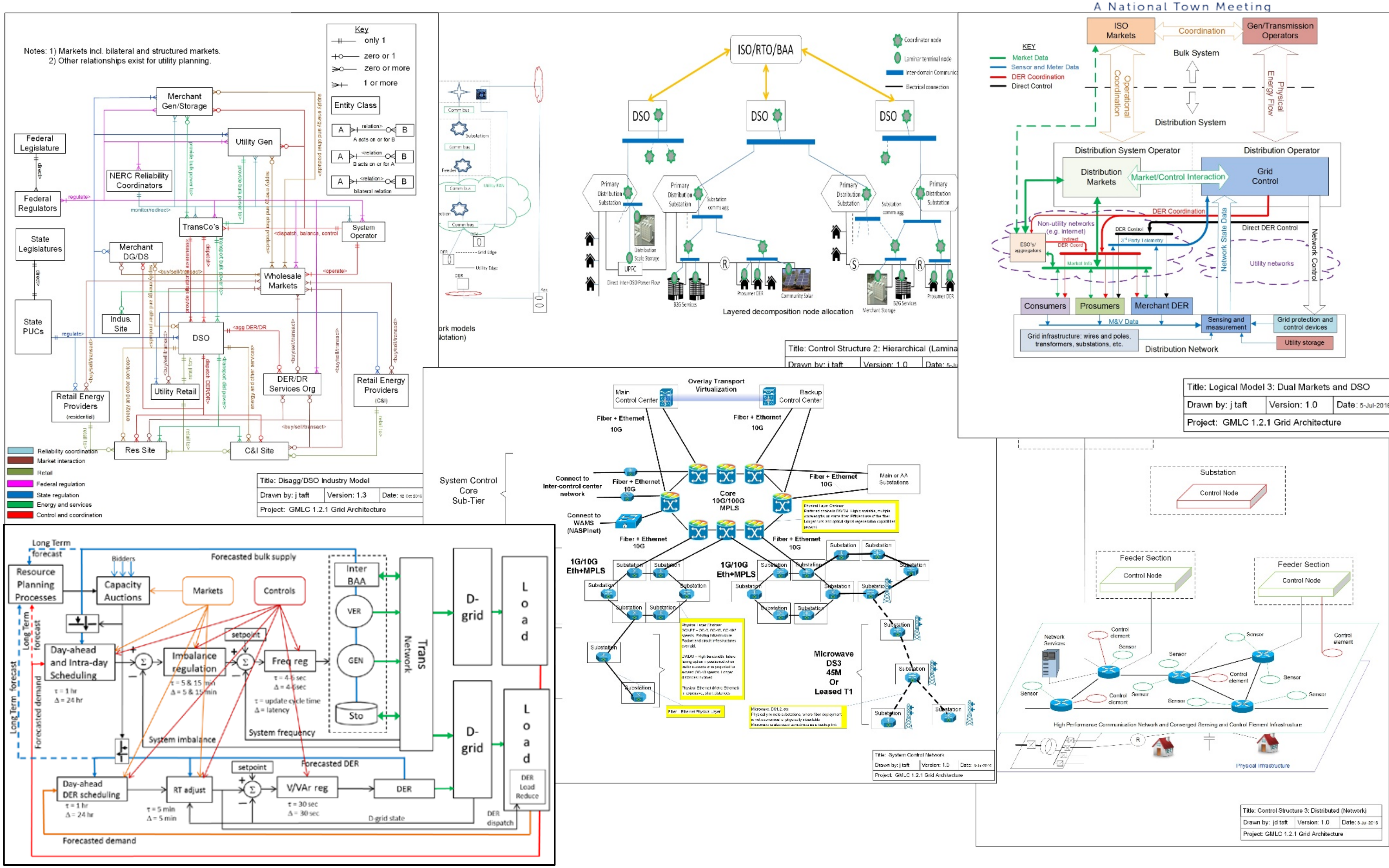

The White Papers Explain the Architectures

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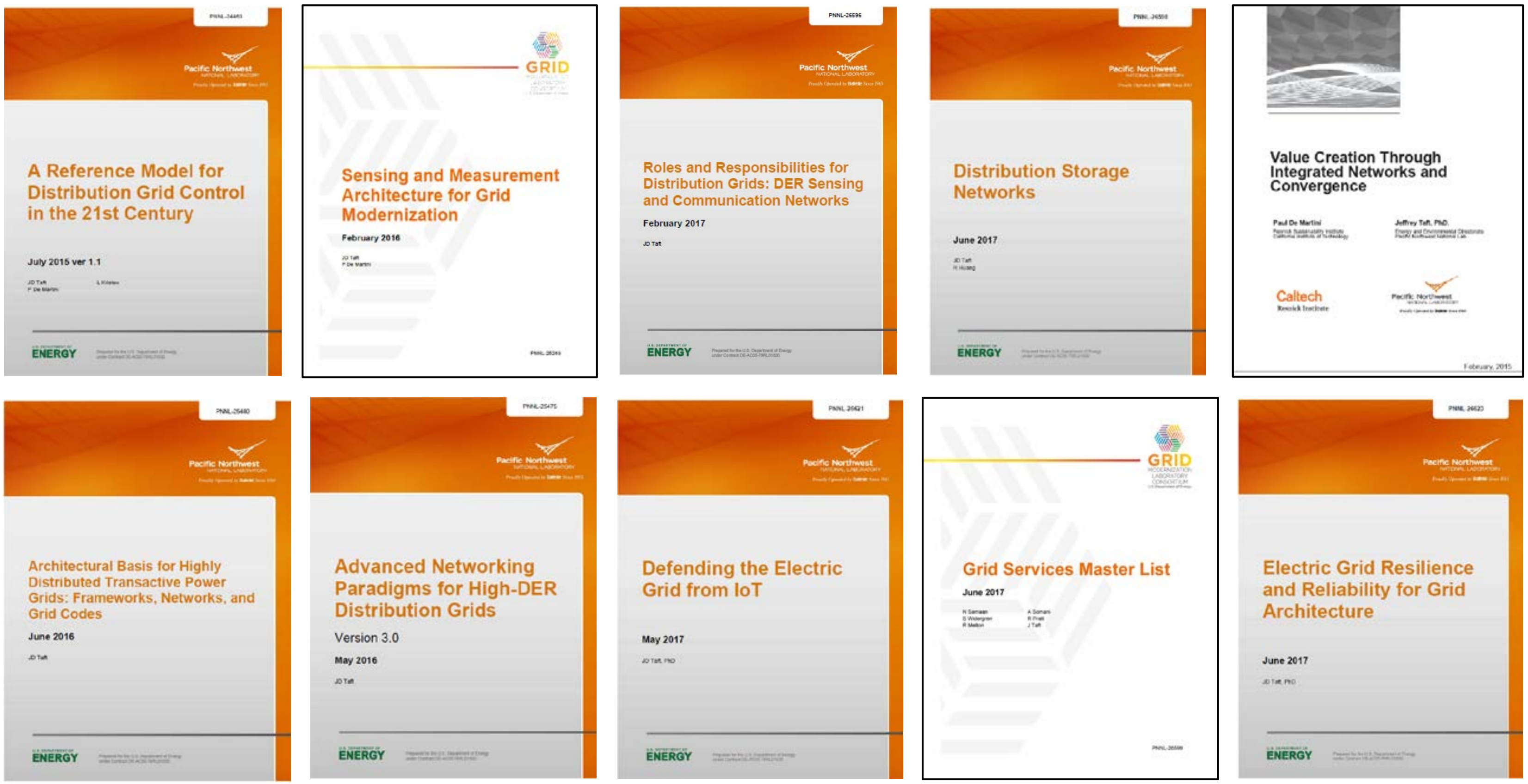

You can find many examples at:

http://gridarchitecture.pnnl.gov/

especially on the Advanced Concepts page

Summary Points

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- Grid Architecture uses formal methodology to produce architecture work products
- Architectures are produced by organized architecture teams
    - These teams are not committees
- Stakeholder input is crucial *throughout the process*
- Some of the work products are necessarily technical and can be complex
- White papers explain the rationales and significance of the architectures for stakeholders

Some Results

Grid Architecture: Tools for Insight

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Silo to Layer Conversion

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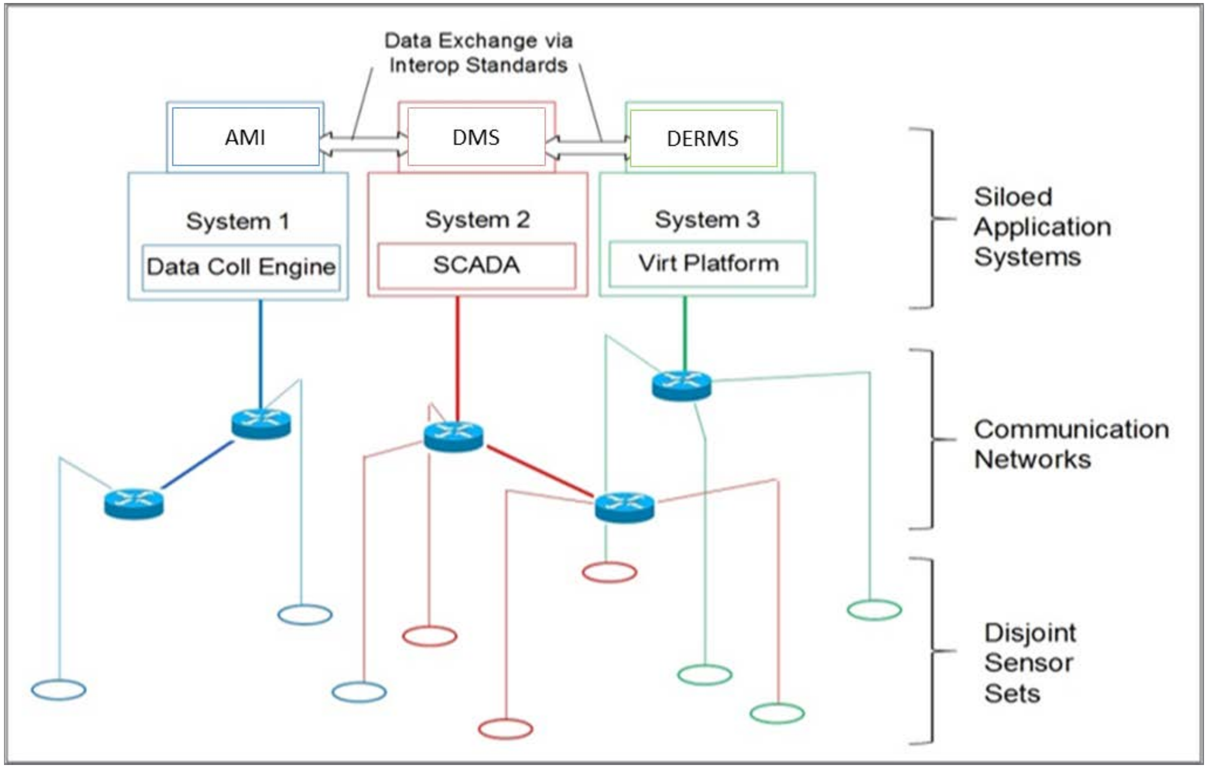

- Siloed, coupled apps
- Long latency
- Poor flexibility
- Expensive integration

- Break up silos ad re-slice into layers
- Use layered structure to:
  - Improve performance
  - Increase flexibility
  - Reduce stranded investment (future-proof)

Layered Sensing and Measurement Structure

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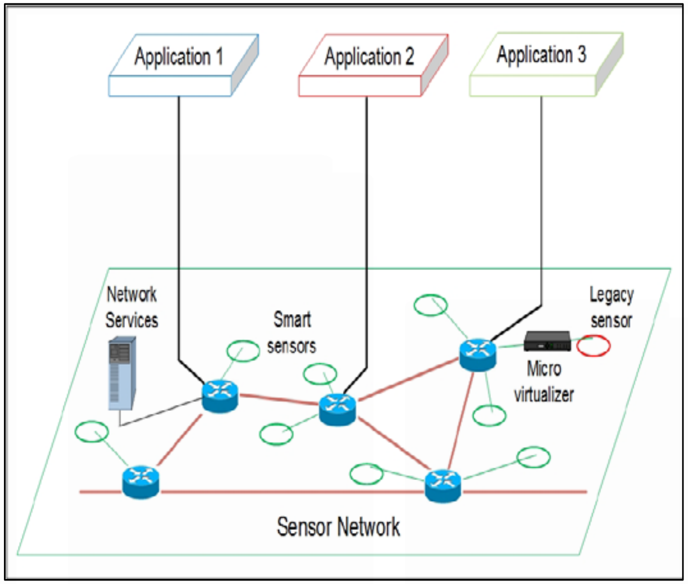
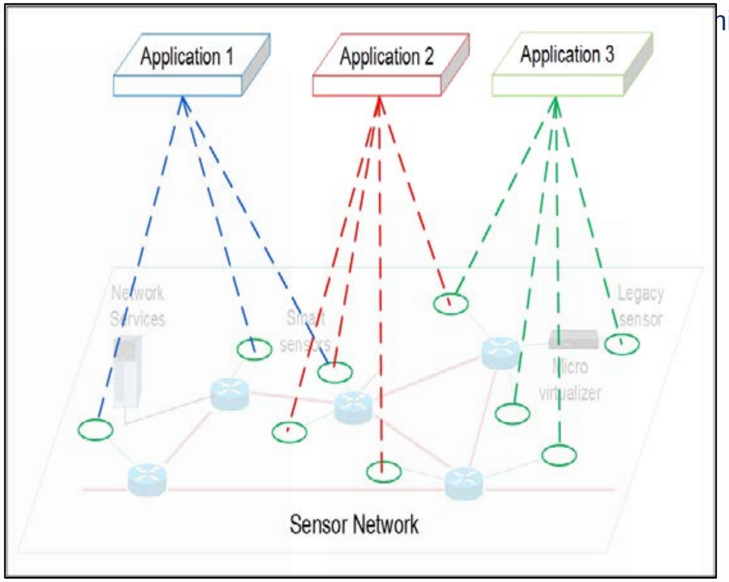


Physical View

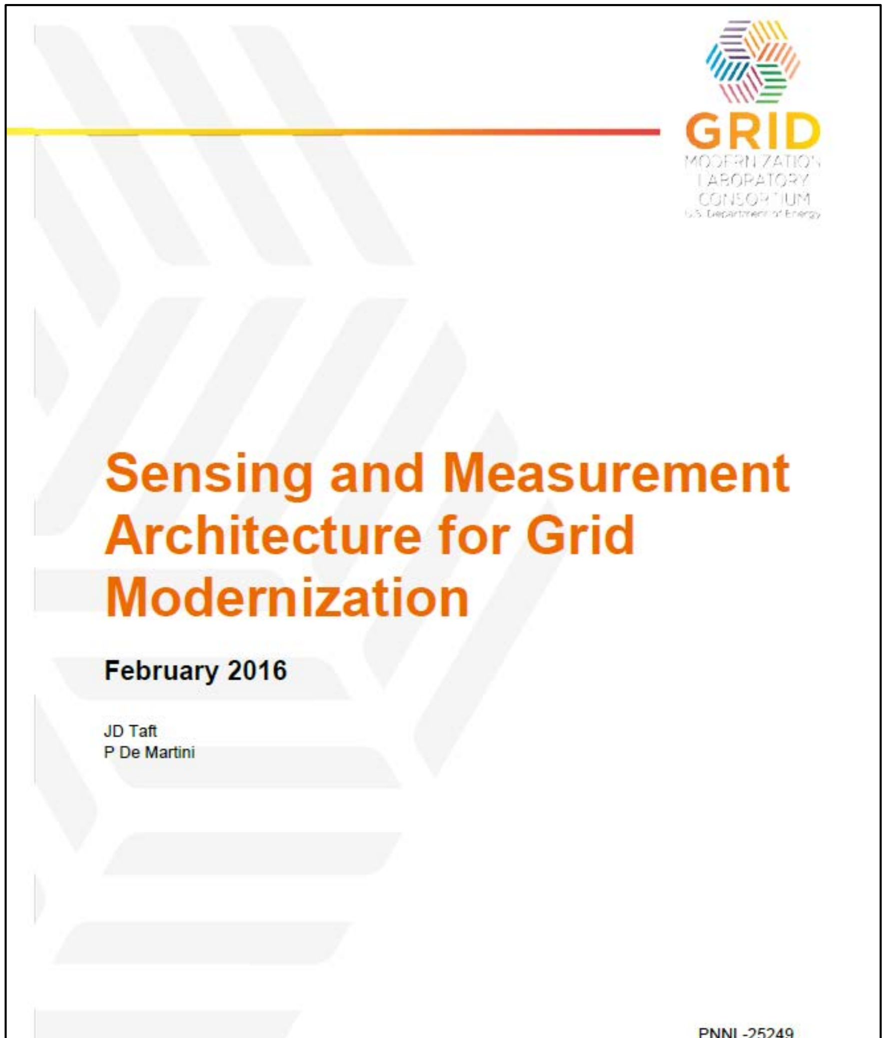


Logical View

- Streaming data
- Dynamic binding
- Multiple use of sensor data
- Low latency available

- Independent apps
- Low latency
- High flexibility
- Low cost integration
- Better business cases

Result: Sensor Networks as Infrastructure Layers


GRID
MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

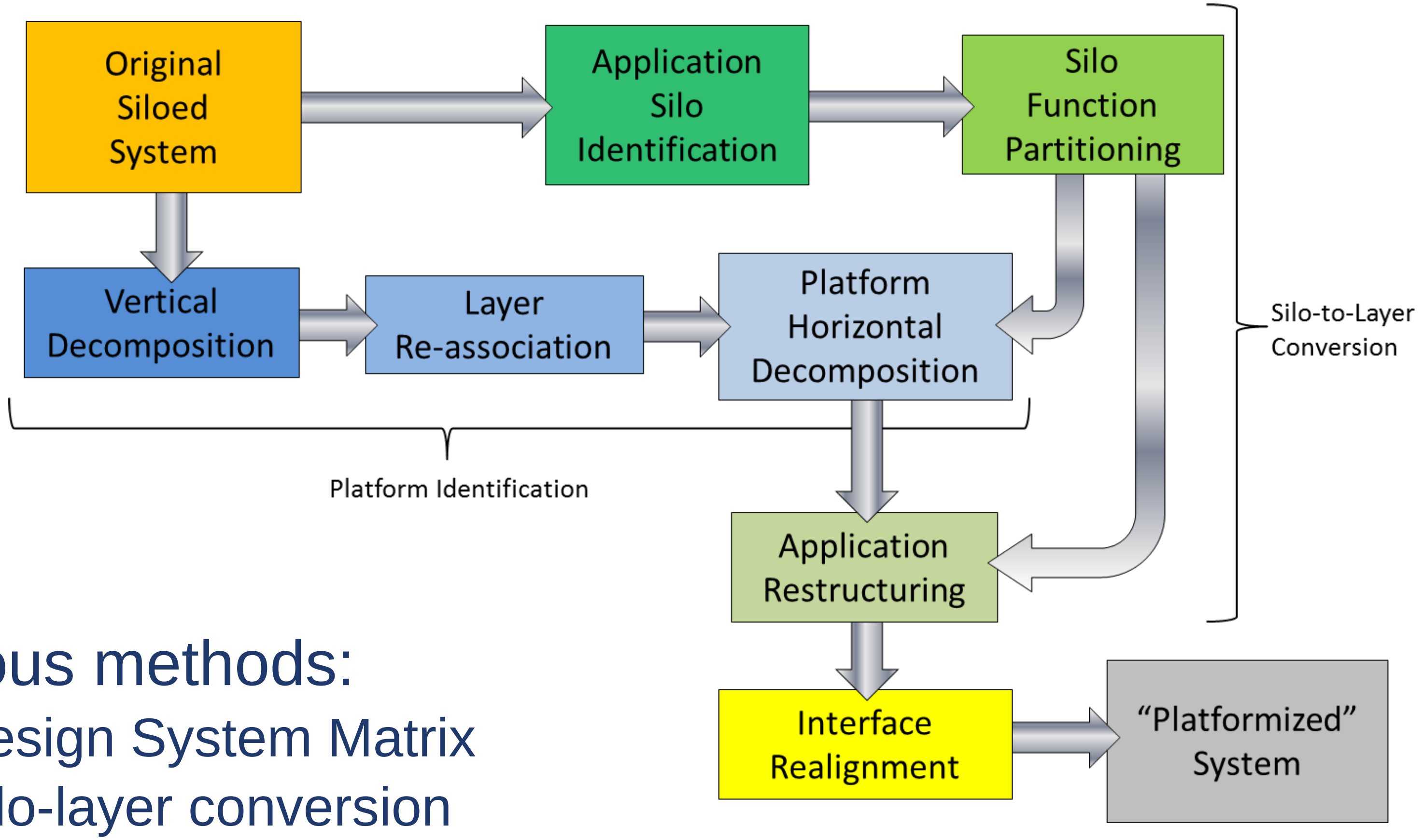
Sensing and Measurement Architecture for Grid Modernization

February 2016

JD Taft
P De Martini

PNNL-25249

Platform Synthesis



- Various methods:
  - Design System Matrix
  - Silo-layer conversion
  - Decomposition and re-composition

DSPx Project

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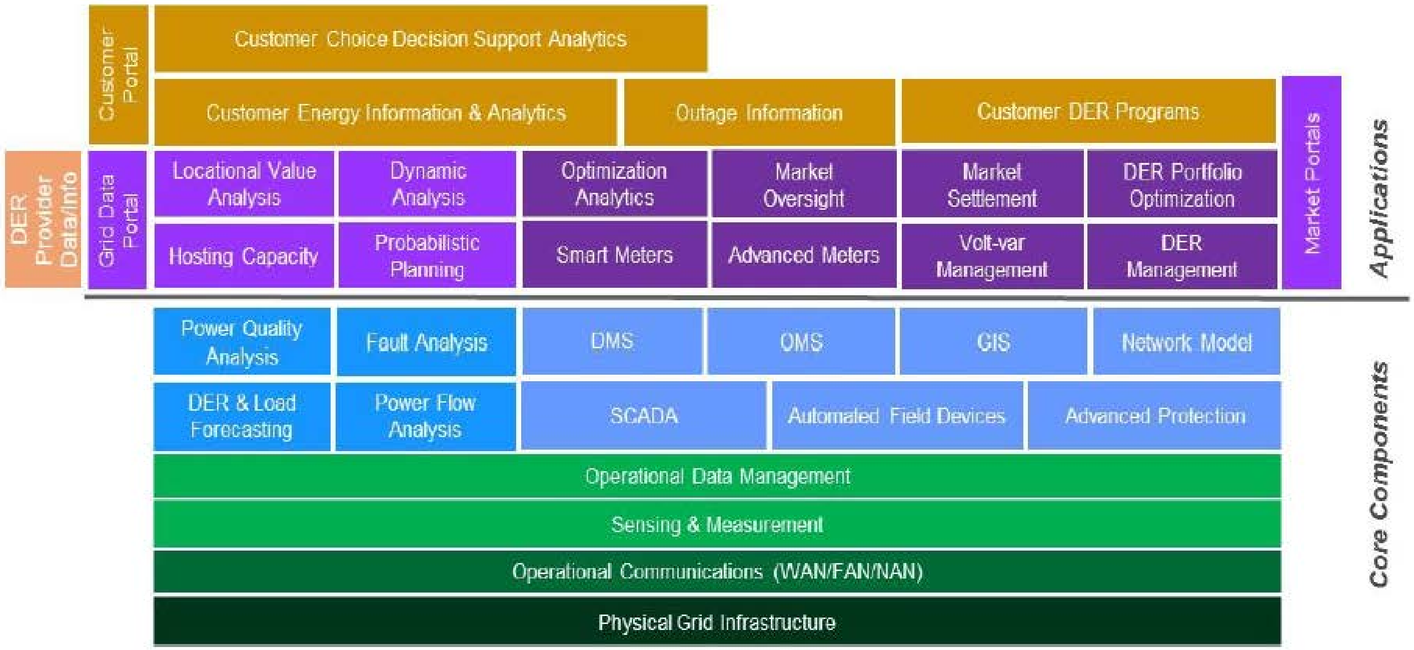
- Definition of Distribution System Platforms for High DER grids
- https://doe-dspx.org/



Source: Modern Distribution Grid Volume 3 (DSPx Project)

Uptake of Grid Architecture

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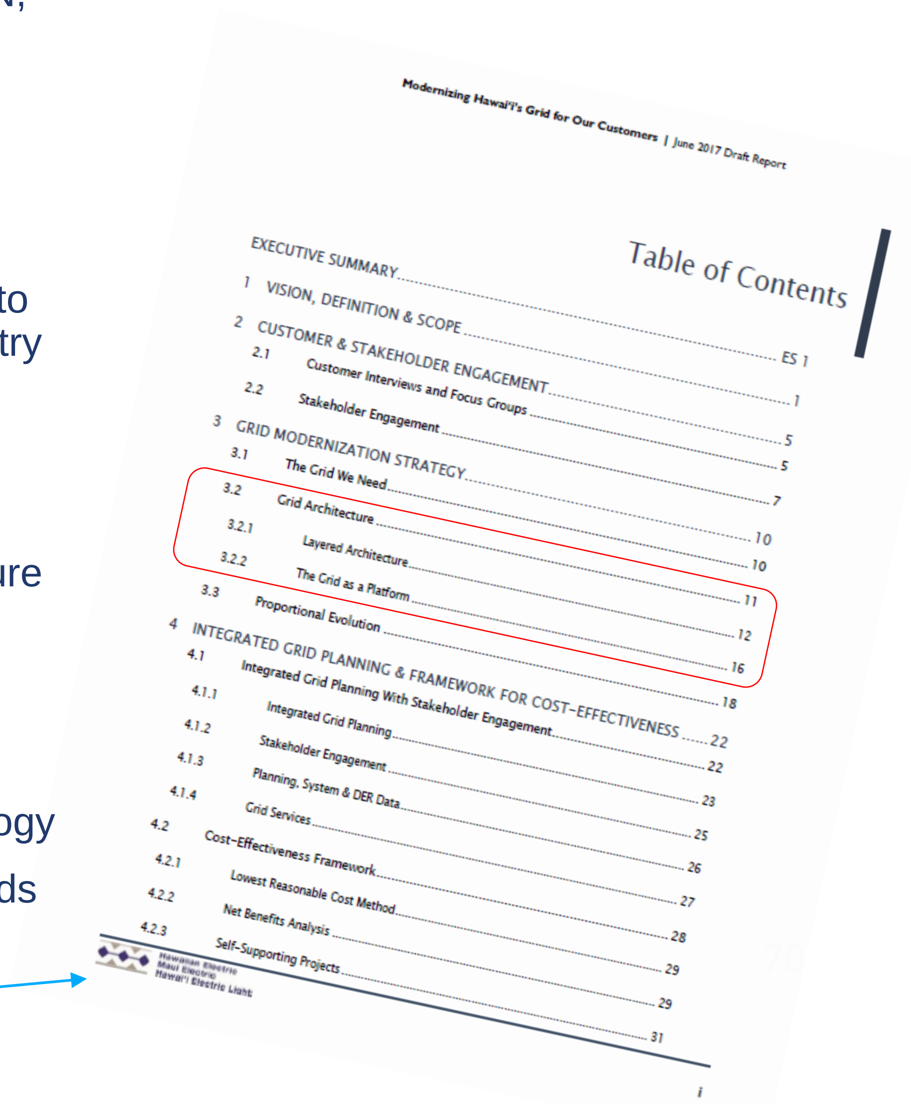
- DSPx project – five state commissions: NY, CA, MN, HI, DC
  - define Distribution System Platforms (planning, operations, markets)
- PUCO PowerForward process – advise the Commission (manage complexity)
- CSIRO – apply laminar framework and other work to inform re-organization of the Australian utility industry
- Laminar Coordination Framework
  - Three IOUs and two private companies pursuing
  - Alliander – use for comparative architecture analysis
- NY REV - GA methods & communication architecture
  - Order NY PSC Order Adopting Distribution System Implementation Plan Guidance
  - DER telemetry architecture development (WIP)
  - Upcoming utility architecture workshop (August)
- SCE 2018 Rate Case – grid architecture methodology
- Sensor network infrastructure & general GA methods
  - HPUC Order 34281 (January 4, 2017)
  - HECO Draft Grid Mod Plan (June 30 2017)


Modernizing Hawai'i's Grid for Our Customers | June 2017 Draft Report

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Hawaiian Electric
Maui Electric
Hawai'i Electric Light

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Without Grid Architecture You Get…

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Grid Architecture

An Overview

http://gridarchitecture.pnnl.gov/

https://doe-dspx.org/

https://gridmod.labworks.org/projects/1.2.1

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