Grid Architecture is the Key to Building the Future Grid

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Introduction

Grid Architecture is a discipline that uses advanced concepts and methods to manage the complexity involved in grid evolution and to provide insights that enable superb decision-making across the range of stakeholders involved in electricity delivery and use. It has applicability far beyond issues of data management and gets to the core questions of electricity industry and grid structure and how to modify them to address 21st Century customer-centric abundance-based opportunities. It is the key to building the future grid.

Why is Grid Architecture Important?

As described by Hawaiian Electric, "The grid we have is not the grid we need". We foresee that the electric grid will need to evolve from a centralized generation economy of scale model to a customer-centric network economy and platform model that makes extensive use of Distributed Energy Resources (DER). Driven by societal and technological mega-shifts over the preceding three decades, this will necessitate profound changes to the overarching Grid Architecture structure of power systems that were designed in the early 20th century. The grid will need to handle circuit-level two-way flow of power and N-way flows of information. Its structure will need to be flexible and able to adapt to dynamically changing conditions. It will need to be capable of operating with a mix of centralized and distributed elements (including energy storage and electric vehicles) and able to function in discrete segments (i.e., microgrids) when impacted by extraordinary events. To achieve this requires a level of enhanced operational flexibility, the ability to withstand diverse stresses and the capacity for infinitely greater market dynamics that were unforeseen by the architects of the original grid. Such shifts are structural, not peripheral, and therefore demand a holistic or architectural view to be efficiently navigated. Such a perspective is essential as it considers as a systemic whole the multiple domains that make up the ultra-complex 21st century electric grid: power circuit topologies, communications, control and coordination, and industry and market structures.

Some of the key trends that will trigger structural changes in the architecture of the grid are:

- DER penetration on circuits exceeding 15% of peak load or 50% of a circuit's daytime minimum load, signaling the need to plan for two-way power flow and for distributed coordination and control.
- Establishment of extensive renewable energy or carbon footprint reduction goals.
- Establishment of incentives for energy storage devices as core infrastructure and behind the meter equipment.
- Establishment of Local Building Code requirements that new buildings and developments support Level 2 charging and/or local EV sales approach 5% of total vehicle sales.

- Establishment of incentives for grid improvements and availability of proper metrics and decision tools for making decision on resilience measures and investments.
- Changing customer expectations for new services and for reliable and resilient grid performance

What is Grid Architecture?

A system architecture is an abstract model of a complex system that we use to reason about its structure and behavior and to predict its characteristics. In general, a system architecture is comprised of three kinds of elements:

- Black box components – elements whose internal workings are not of concern (hence "black box").
- Structure – how the components are connected or related.
- Externally visible characteristics – these include characteristics of the components, the structures, and the whole system.

Grid Architecture (as a discipline) is the application of system architecture, network theory, and control theory to the electric power grid. A grid architecture (as an artifact) 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.

The uses of Grid Architecture are many and include:

- Identifying legacy constraints.
- Removing structural barriers and refining essential limits.
- Managing system complexity (and therefore risk).
- Setting essential bounds on system behavior.
- Identifying gaps in theory, technology, organization, etc.
- Facilitating communication among stakeholders.
- Defining platforms and interfaces and informing interoperability.

That said, an architecture is not a design. An architecture admits many possible implementations, any of which must fit inside the bounds or constraints defined by the architect, whereas a design is a specific expression of an architecture that admits exactly and only one implementation. A role of the architect is to define the smallest set of constraints needed to ensure the resulting system will have the right characteristics and behavior while minimizing limitations on the grid developers, designers, and engineers as much as possible. For the electric grid, complexity makes this a challenging proposition.

The complexity of the grid goes well beyond the levels we associate with many sophisticated systems – We designate it *Ultra-Large-Scale (ULS)* complexity, using a concept developed at Carnegie Mellon University. This level of complexity arises because the grid is comprised of many already complex structures, and these structures are interconnected and interact in complex ways. Such systems have characteristics that pose special challenges, such as:

- Inherently conflicting diverse requirements.
- Decentralized data, control, and development.
- Continuous (or at least long-time scale) evolution and deployment.
- Heterogeneous, inconsistent, and changing elements.
- Operation involving wide time scales.
- Operation involving wide geographic scales.
- Normal failures (failures are common and frequent, not exception events).

Grid Architecture focuses largely on structure (the manner in which grid elements are related or interconnected). This is because structure determines the essential limits or bounds on what a complex system can and cannot do. Most grid system design and implementation processes and "smart grid architectures" explicitly or implicitly *assume* a structure, whereas Grid Architecture is primarily concerned with *specifying* structure. There are two reasons for this:

- Get the structure right early on and the system pieces fit into place neatly, 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.

We have inherited a massive amount of structure from the 20th Century grid and with it many structural constraints that inhibit change and limit new grid functionality. Consequently, the core problem of Grid Architecture is to determine the appropriate new structures or minimal structural changes to the grid that:

- Relieve crucial constraints on new capabilities.
- Limit propagation of undesired change effects.
- Strengthen desirable grid characteristics.
- Simplify design and implementation decisions.

The relationship between Grid Architecture and Design/Operation is related to the relationship between Strategy/Planning and Engineering/Operation, as illustrated in Figure 1.

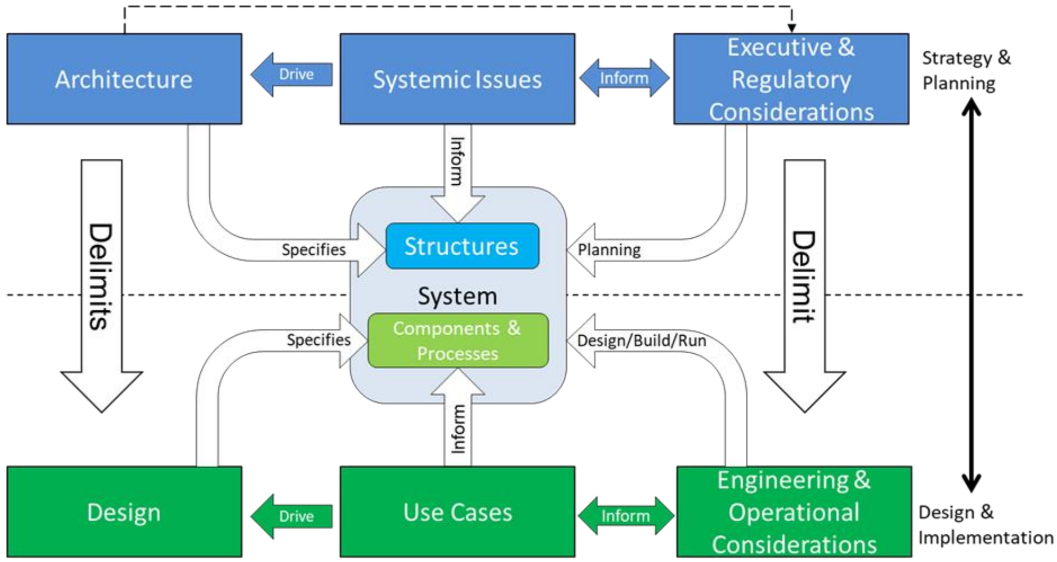

Figure 1 Architecture in Context (Source: PNNL)

Changing the Grid's Architecture

The current grid architecture has been shaped by 100 years to engineering design in response to use of the grid as a means to deliver energy from central resources to consumers. Changing the legacy structure involves addressing a number of technical, policy and economic challenges described below.

Technical Challenges

A range of emerging technical grid issues are emerging that fundamentally change the use and operation of the grid. These include:

- Changing grid coordination and control to support a highly distributed energy structure with variable energy sources (renewables).
- Changing from one-way power flow in a circuit to a two-way physical power flow architecture, including changing grid coordination and control.
- Evolving industry structure (the set of entities involved in power delivery, their roles and responsibilities, and their relationships) is a major factor in grid evolution and must be considered simultaneously with other aspects of grid architecture, as well as regulatory and business model issues.
- The need for a means to rationally quantify and understand resilience in the grid and energy systems. Distribution resilience planning generally fails to account for customer's options to address resilience themselves, and no effective means exist to trade off resilience options.

- The use of energy storage as core 21st Century grid infrastructure components raises structural and control/coordination issues. Using embedded storage raises issues of how to control storage to improve intrinsic grid operational flexibility and resilience and facilitate DER and microgrid integration.
- Transforming the grid from an electricity delivery channel to a customer-centric energy platform raises issues of T/D/C coordination, grid control, distributed intelligence, and convergence with other infrastructures, such as transportation, buildings, seaports, etc.

Policy & Regulatory Challenges

In addition to technical issues, it is necessary to consider how public policy and regulation constrain grid change and how architecture can inform how public policy makers and regulators can deal with the vast complexity of modernizing the grid. Some key issues are:

- Policy makers and regulators must understand and clearly establish the end-state objectives before roadmaps and transformational changes to Grid Architecture can be developed.
- Regulators need to accept that implementation of a large policy change will be made in incremental steps because of technical limitations and key system architectural issues.
- Regulators will need to support foundational distribution grid investments, even if they do not have a Benefit/Cost ratio greater than 1, in order to achieve a two-way power flow grid.
- Regulators must adopt a viewpoint informed by Grid Architecture to re-frame and understand emerging trends and key (systemic) issues related to large scale changes, even when the implementation of these changes may involve incremental steps.

Economic Challenges

Changing customer expectations and availability of new technologies raise issues of financeability, and affordability and therefore quantification and valuation of grid structural changes. Some structural changes are happening organically while others are being planned, but without comprehensive structural (architectural) considerations, many economic issues will be difficult to resolve, such as:

- Shift from 20th Century supply side economies of scale to 21st Century demand side network economies and what will this shift mean for grid and energy system structure.
- Lack of metrics for valuing resilience that are broadly acceptable to regulators. As a result, resilience value is addressed subjectively but not objectively.
- Failure to create the distribution network as a platform will continue to perpetuate barriers for customers that will seek alternatives and may lead to grid defection.
- The grid's transition from a physical wires structure to a more of an electric network (platform) leads to questions about how this type of service will be monetized and what role the grid will take on.

Key Grid Architecture Principles

Grid architecture development focuses largely on structure and is driven by consideration of user expectations, public policies, and emerging trends. It is a top-down whole-system approach and is agnostic to specific products, tools, and business plans. The discipline takes a methodical approach to understanding and synthesizing architectures by determining the key systemic (cross-cutting) issues to be addressed by structural change, as illustrated in Figure 2.

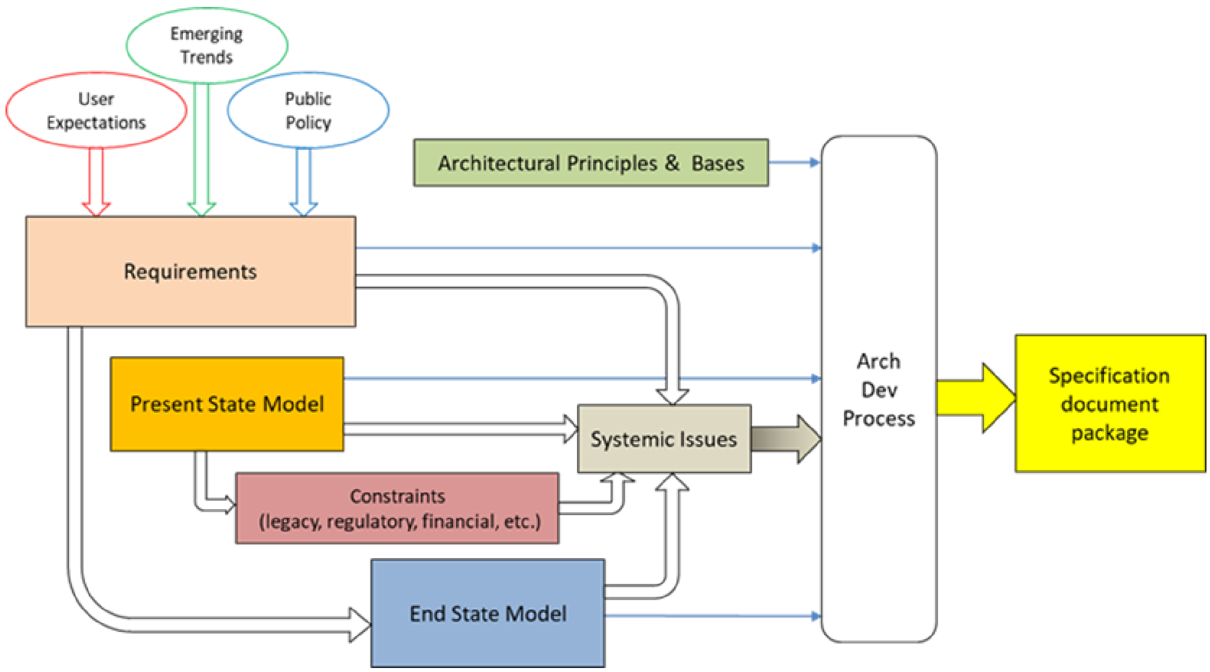

Figure 2 Grid Architecture Paradigm (Source: PNNL)

In addition, grid architecture development is driven by a set of architectural principles and formal bases, as opposed to being ad hoc creations. These principles and bases derive from several sources, including mathematical formalism where available. This leads to architectures that have predictable intrinsic properties and result in practical specifications. It also leads to architectures that have conceptual integrity; a key characteristic that makes complex architectures understandable to stakeholders.

A few of the key principles are summarized here:

<u>Network of structures</u> – electric power grid consists of seven types of structures: electrical infrastructure, industry structure (including market structure), regulatory structure, information and communication superstructure, control structure, coordination framework, and convergent (adjacent) structures (such as transportation, fuels, and social networks).

Multi-scale structure – use of structural models that apply at various (preferably all) scales, consistent with the general principle of solving similar problems in similar ways for conceptual integrity.

Distributed operation – increasing customer centricity means reshaping the grid from a centralized hierarchical delivery channel to a distributed energy platform, with consequent new structures such as localized energy transaction hubs, buffered infrastructure, and dynamically adjustable circuit, control, and coordination. New and modified grid structures can enable such changes in an incremental and orderly fashion.

Layered decomposition – use of structure derived from mathematical optimization theory to solve problems related to multi-scale coordination of centralized and distributed resources, resulting in a layered structure that is scalable and applies equally well from the device level up to the Transmission/Distribution coordination level thus informing entity role/responsibility definitions and interfaces.

Structural resilience – quantification of the effects of component characteristics and the grid structures in which they reside on grid resilience, leading to analytical support for decisions on choice of structures and resultant issues such as data flows and functional interactions.

Market-control spectrum – real time markets and grid operational controls are related in terms of regions of applicability in a cycle time-endpoints domain.

Note that these principles apply across the entire set of grid structure classes. This includes industry structure and therefore has applicability to electricity markets and to business models.

Grid Architecture Principles for Markets and Business Models

While some Grid Architecture work focuses on physical and cyber aspects of grid structure, the discipline also provides useful concepts and methods for future electricity markets and business models.

Layered decomposition is valuable in thinking about how resource coordination can be accomplished at all scales on the grid, leading to definition of the roles and responsibilities of Distribution System Operators (DSOs) and the interactions between DSO and Transmission System Operators on one end of the scale, and between DSOs and DER operators (including aggregators and other parties) on the other. This leads to structural concepts that help frame future business models. For regulators, the layering concept helps to focus on appropriate constraints that allow for faster dynamics (change) at the level of roles and functions for individual entities and entity groups while maintaining properly balanced oversight, as per the mission of the regulator, thus enabling growth of business models benefiting consumers.

The relationship between system control and market functions at various scales is illustrated in Figure 3. This principle is crucial to an understanding of how and where markets and controls apply to grid operations and where they should exist in combined form vs. in separate forms. Understanding this concept and the related process architecture charts for planning-market-control functions at various scales (time and endpoints) provides insight into how to incorporate price as a practical element of coordination/control for physical systems and how to use this to encourage new business models, creation of new value streams, and, in combination with structural resilience principles, how to form future grids to better serve customers with increased reliability, resilience, and operational flexibility.

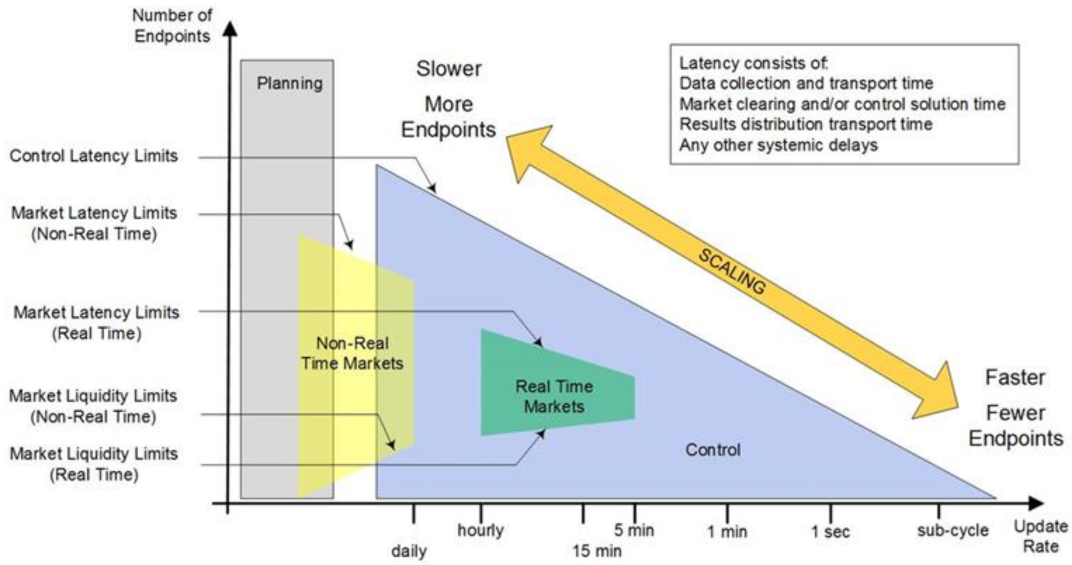

Figure 3 Market-Control Relationships (Source: PNNL)

The use of grid architectural methods helps manage the complexity of the use of price and control to shift from traditional grid constraint thinking to abundance thinking of the type that is highly successful for creating customer value in other industries, but within the fundamental limits of physical electrical operation.

Summary

Grid Architecture not only provides valuable new insights into grid modernization planning and design, but it also provides the means to future-proof technological investments and to reduce integration costs – two issues that concern regulators and utility executives alike. Proper structure creates intrinsic grid characteristics that bolster resilience, capability, and affordability and help safeguard investments by limiting change effects. Well-planned grid structure simplifies downstream decisions and frees up architects and engineers working on individual components or systems to employ creativity with assurance that unintended consequences will not crop up to hamper or even invalidate their work. For these reasons, it is not just important, but crucial, that the structural issues addressed by Grid Architecture be considered before other aspects of grid modernization are undertaken.

While traditional smart grid architecture is limited to information systems considerations, Grid Architecture provides the means to simultaneously consider all grid structures and the impacts of proposed changes to them. By providing tools for managing complexity and understanding whole grid systems, it is possible to not only understand specific issue solutions and end state grid architectures, but more importantly to provide an architecture to manage the transition from present grid to the grid of 2035 by structuring the evolution of an electricity industry ecosystem.