A Practical Introduction to Common Grid Architecture Techniques

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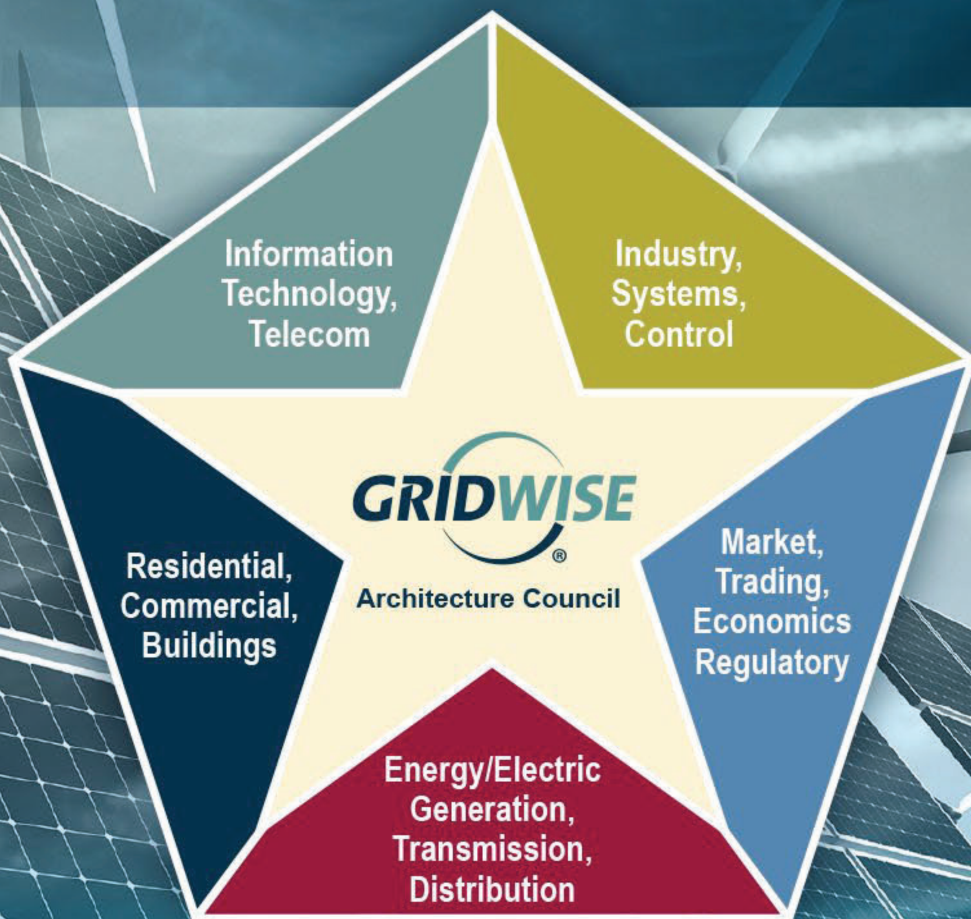

PREPARED BY THE

GRIDWISE® Architecture Council

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About this Document

The GridWise Architecture Council was formed by the U.S. Department of Energy to promote and enable ***interoperability*** among the many entities that interact with the electric power system. This balanced team of industry representatives proposes principles for the development of interoperability concepts and standards. The Council provides industry guidance and tools that make it an available resource for smart grid implementations. In the spirit of advancing the much-needed large-scale transformation of the grid in a systematic and accelerated manner, this document summarizes the uses and benefits of the practice of Grid Architecture, and introduces few selected Grid Architecture techniques. You are expected to have basic knowledge of grid operations. Those without this technical background should read the *Executive Summary* for a description of the purpose and contents of the document. Other documents, such as checklists, guides, and whitepapers, exist for targeted purposes and audiences. Please see the www.gridwiseac.org website for more products of the Council that may be of interest to you.

Executive Summary

New technologies and challenges are driving significant and rapid transformation of the electric grid. Distributed energy resources, advanced sensing technologies, and management platforms are greatly increasing the number of participants, devices, data, and control decisions involved in grid operation. In addition, the grid must meet new and traditional challenges: extreme weather events, emerging cybersecurity issues, providing equitable and affordable service, and the push for decarbonization. The increased complexity of the transforming grid must be understood, managed, and minimized to ensure its continued reliability, resiliency, affordability, and sustainability. Ensuring an appropriate grid architecture is foundational to achieving this outcome.

Grid Architecture is a discipline with roots in system architecture, network theory, control engineering, and software architecture, all of which we apply to the electric power grid. An architectural description is a structural representation of a system that helps people think about the overall shape of the system, its attributes, and how the parts interact. Such holistic understanding is key to enabling large-scale transformation of the grid in a systematic and accelerated manner. Grid Architecture principles and tools can be used and useful to a range of stakeholders: grid planners and operators; vendors; service providers; consumers; standards developing organizations; and policymakers and regulators.

Grid Architecture takes into consideration the current system with all its systemic issues and legacy constraints that inhibit grid modernization and follows a systematic approach to determine the appropriate new structures or minimal structural changes needed to the grid to achieve the desired future state. Taking a Grid Architecture-based approach helps relieve crucial constraints on new capabilities, limit undesired propagation of change effects, strengthen desirable grid characteristics, and simplify design and implementation decisions. This white paper serves as a practical introduction to Grid Architecture and presents some of the most commonly applied concepts and techniques. It is intended to provide readers with an understanding of the different ways that this discipline may benefit different stakeholders in the energy sector. The Grid Architecture techniques (industry structure modeling, market structure modeling, and laminar coordination framework) presented in this white paper have been selected based on their centrality to understanding key structural considerations and their linkage to emerging trends in electricity infrastructure.

This paper serves as an introduction to Grid Architecture, core concepts, and key techniques. There are additional concepts and techniques that are commonly used, like layered decomposition, logical energy networks, platform concept, etc. that are outside the scope of this introductory white paper. The motivation behind using an architecture-based approach and the role of Grid Architecture in industry transformation are explained in greater detail in the "Grid Architecture Primer" published by Smart Electric Power Alliance's Grid Architecture Working Group. For information about all the different Grid Architecture work products, readers are encouraged to explore https://www.pnnl.gov/grid-architecture and https://gridarchitecture.pnnl.gov.

About the GridWise® Architecture Council

The GridWise vision rests on the premise that information technology will revolutionize planning and operation of the electric power grid, just as it has transformed business, education, and entertainment. Information technology will form the "nervous system" that integrates new distributed technologies—demand response and distributed generation and storage—with traditional grid generation, transmission, and distribution assets. Responsibility for managing the grid will be shared by a "society" of devices and system entities.

The mission of the GridWise Architecture Council ("the Council") is to enable all elements of the electricity system to interact. We are an independent body that believes tomorrow's electricity infrastructure can be made more efficient and secure by integrating information technology and e commerce with distributed, intelligent networks and devices. To achieve this vision of a transformed electricity system, the Council is defining the principles for interaction among the information systems that will effectively and dynamically operate the grid. The Council, which is supported by the U.S. Department of Energy, includes 13 representatives from electric energy generation and delivery, industrial systems control, building automation, information technology, telecommunications, and economic and regulatory policy.

The GridWise Architecture Council is shaping the guiding principles of a highly intelligent and interactive electricity system—one ripe with decision-making information exchange and market-based opportunities. This high-level perspective provides guidelines for interaction between participants and interoperability between technologies and automation systems. We seek to do the following:

- Develop and promote the policies and practices that will allow electric devices, enterprise systems, and their owners to interact and adapt as full participants in system operations.
- Shape the principles of connectivity for intelligent interactions and interoperability across all automation components of the electricity system, from end-use systems, such as buildings or heating, ventilation, and air conditioning systems, to distribution, transmission, and bulk power generation.
- Address issues of open information exchange, universal grid access, distributed grid communications and control, and the use of modular and extensible technologies that are compatible with the existing infrastructure.

The Council is neither a design team nor a standards-making body. Our role is to bring the right parties together to identify actions, agreements, and standards that enable significant levels of interoperation among automation components. We act as a catalyst to outline a philosophy of inter-system operation that preserves the freedom to innovate, design, implement, and maintain each organization's role and responsibility in the electricity system.

Acronyms and Abbreviations

CAISO	California Independent System Operator
DER	Distributed energy resources
ERCOT	Electric Reliability Council of Texas
GWAC	GridWise® Architecture Council
ISO	Independent system operators
NIST	National Institute of Standards and Technology
NYISO	New York Independent System Operator
PNNL	Pacific Northwest National Laboratory

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1.0 Introduction

The North American electric grid is one of the largest integrated systems in the world. It is the critical infrastructure on which most of the other critical infrastructure sectors (e.g., emergency services, water and wastewater systems, healthcare, communications, information technology, manufacturing, transportation, etc.) are dependent for their operation (DOE/OP-0004-1 2022). It is vast in geographical expanse and connects utility-scale electric power plants and distributed energy resources (DERs) to deliver electricity through a complex system of power lines and substations. The interconnected networks consist of more than 22,000 generators, 55,000 substations, 642,000 miles of high-voltage lines, and 6.3 million miles of distribution lines that serve 153 million customers (DHS 2019). These assets are owned, operated, regulated, and managed by many different entities.

This existing system, with its typically long-lived assets, was designed and implemented over the last 100 years with traditional generation and generally passive consumers in mind. Therefore, it is progressively less able to meet the changing needs of the utilities and the evolving expectations of the customers. Bidirectional power flows are one example of the new challenges that must be accommodated with the increasing deployment of DERs. Other examples include increasing extreme weather events, emerging cybersecurity issues, the need for greater affordability, the trajectory toward a customer-driven future, and the push for decarbonization. These are together driving significant transformation of the grid. Incremental changes in the system will not be able to address all of these needs. Systemic structural changes are required for integrating changing technologies, changes in markets, and regulation in a holistic manner, which requires rethinking the grid's architecture.

Grid Architecture techniques are immensely helpful in managing the complexity of this ultra-large-scale system. One element of Grid Architecture is based on identifying the involved entities and understanding their responsibilities as well as their inter-relationships to obtain a complete picture of how these entities coordinate their activities to perform specific functions. This is a critical step toward identifying and managing the risks involved. Grid Architecture is a tool for future grid planning that assists stakeholders in communicating their shared vision and engineering solutions around it. The various Grid Architecture methodologies provide tools enabling one to create models, specifications, and diagrams to simplify the representation of the complex interactions of entities, processes, or structures in the electric power grid. These serve the crucial purpose of visualizing how the present grid operates and what the properties and qualities of the future grid will be, while taking into consideration the aggregate of the technical, environmental, social, and economic impacts of the transformation. These results provide advanced insights to stakeholders and help them in their decision-making.

Currently, the GridWise® Architecture Council (GWAC) is working with stakeholders to demonstrate the applicability and benefits of Grid Architecture in support of transforming the grid to enable decarbonization, enhance system resilience, and meet the evolving needs of customers. This white paper serves as a practical introduction to Grid Architecture and presents some of the most commonly applied concepts and techniques that will enable the much-needed large-scale transformation of the grid in a systematic and accelerated manner. It is intended to provide readers with an understanding of the different ways that this discipline may benefit different stakeholders in the energy sector.

The intended users of this document are:

- Power system engineers,
- Executives of utilities and system operators,
- Power system researchers,

- Standard development organizations,
- Public policymakers and regulators,
- Developers and vendors of energy delivery system products,
- Developers and operators of communication networks,
- Funding agents,
- Consumers and prosumers, and
- Grid Architecture enthusiasts.

The document also provides references to guide the reader to other resources for obtaining more details on each of the discussed topics.

2.0 Brief Overview Of Grid Architecture

In 2014, the concept of Grid Architecture was introduced by Pacific Northwest National Laboratory (PNNL) as a discipline that can address the grid as a whole and provide the means to manage the inherent complexity of grid modernization (Taft 2019). Grid Architecture provides the concepts, frameworks, methodologies, and tools for describing, analyzing, and communicating structural representations of ultra-large-scale electric grid systems among stakeholders (internally or externally). It enables the development of top-level views of the whole electric power system that help to understand and define the many complex interactions that exist in present and future grids. This enables reasoning about the grid's properties, behavior, and performance (PNNL n.d.). It involves a set of rigorous methodologies and techniques based on systems engineering combined with elements of network theory, optimization theory, and control engineering applied specifically to the grid as an ultra-large-scale complex system. A detailed discussion on why Grid Architecture is needed is provided in the "Grid Architecture Primer" published by Smart Electric Power Alliance's Grid Architecture Working Group.[1]

An architecture is an abstract depiction of a system that can be used to reason about the system's structure, behavior, and characteristics since "structure sets the essential limits on what the complex system of the grid can and cannot do." As shown in Figure 1, this ultra-large-scale complex system can be represented as a network of distinct structures: electric infrastructure, industry structure, regulatory structure, digital superstructure, control structure, and convergent networks, all of which are connected based on a coordination framework to form grid structures. These structures intersect with each other, subject to overt or hidden interactions, cross-couplings, and convergences. Considering the network of structures makes cross-domain interactions much easier to identify and manage. It also helps in capturing multi-structural properties in a manner such that the complexities can be decomposed to understand what the system can reliably and efficiently do. If any structural change is made without understanding the complex relationships, it can potentially lead to unintended consequences.

[1] https://sepapower.org/resource/grid-architecture-primer/

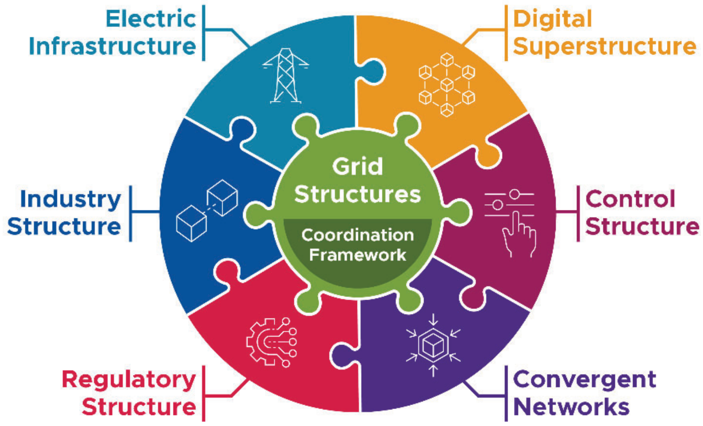

Figure 1: Network of structures representing the ultra-large-complex grid.

In this section, the various inputs that are needed for architecture development, the high-level process, and the work products developed are summarized.

2.1 Inputs

This subsection provides an overview of the inputs needed for the Grid Architecture process. When we travel in our car from one place to another with the help of GPS, we need three pieces of information: the starting location or origin, the final location or destination, and any requirements that we may have, for example, we may want to add certain route options, like “prefer fuel-efficient routes.” Similarly, for developing a road map for system transformation, we need to know the present state model (analogous to the origin), the end state model (analogous to the destination), and other requirements (like route constraints) associated with that transformation.

Figure 2 provides a graphical summary of the categories of inputs used in the process of developing Grid Architecture work products. Note that the three primary inputs already mentioned—the present state model, the end state model, and the requirements—are supported by several other inputs.

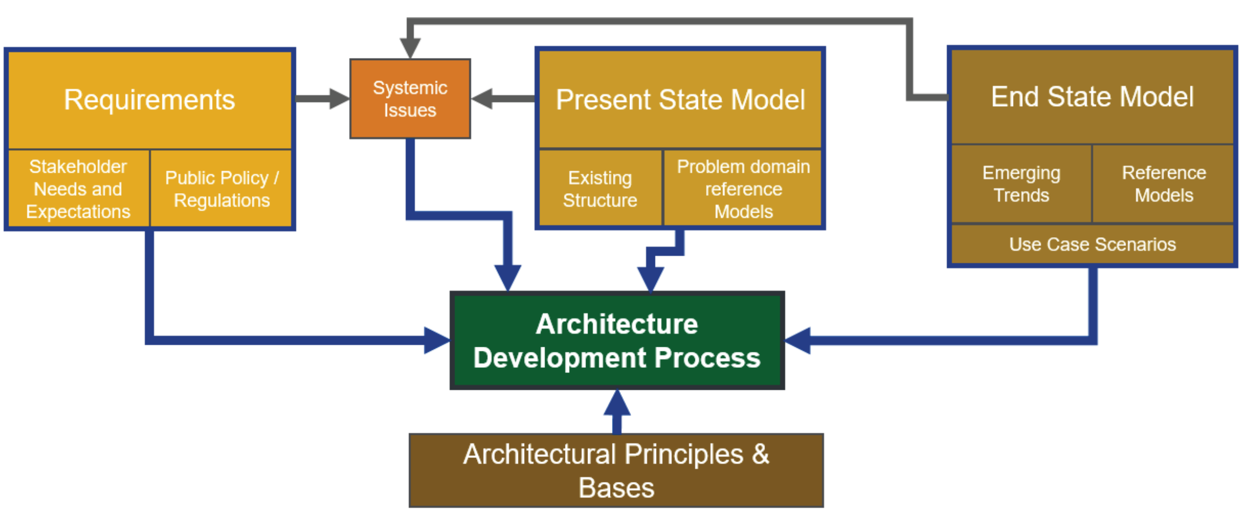

Figure 2: Inputs to Grid Architecture development process.

Below are these three and other major inputs to the architecture development process:

- **Requirements:** The starting point is a set of requirements that are informed by stakeholder needs and expectations as well as public policy and regulations. Federal, state, and local policies that affect the architecture, such as distribution system operator mandates or renewable portfolio standards mandates. Architecture development should also take into account jurisdictional constraints and requirements. Supporting documents may include traceable reference materials (including policy documents, requirement studies, user surveys and reports, and related industry white papers) and compilations of stakeholder interviews and focus group discussions and comments.
- **Present state model:** It is critical to understand the present state of the system. This is done by developing models of the existing structure of the system and a problem domain reference model. The problem domain reference model depicts the current, or "as-built," problem domain, including entities, key components, and legacy structures.
- **End state model:** The end-state model describes the future state of the system as envisioned by the stakeholders and is captured in the form of reference architectures and models.
- **Emerging trends:** Emerging trends are the specific drivers of change or industry trends that help determine the end-state model. These trends create challenges and opportunities, influence future directions in the evolution of the grid, and are therefore important when determining how the system will need to transform. These could be technology, policy, or societally driven and cause the grid to evolve and adapt if and where necessary. These are defined at the beginning of the process for determining the end-state model and guiding the development of the architectural views. A listing of the considered emerging trends along with their descriptions is developed, and such a report was developed as part of one of the Grid Modernization Laboratory Consortium projects funded by the Department of Energy (Xue et al. 2022).
- **Use case scenarios:** These are macro-use cases that are developed before the architecture is finalized and are utilized for performing validation of the architectural view being developed.
- **Systemic issues:** Systemic issues are cross-cutting issues that are inherent in the overall system based on structural and run-time considerations of grid operations that are extant in the grid. They create challenges in design and operation, thereby needing to be addressed to support new requirements and objectives that a future architecture may aim to fulfill. There may be systemic issues in the present-state model that arise from the various emerging trends in the end-state model. These are captured in the form of a list with detailed explanations for each item before the architecture development process can start (Xue et al. 2022).
- **Architectural principles and bases:** The principles and bases describe the foundational principles used in the development of the architecture to ensure the conceptual integrity of the architecture. These principles are often needed when making architectural decisions.

2.2 Approach

Any Grid Architecture development work starts with the end goals in mind. What do the consumers (users of the system) need or desire? These consumer requirements are defined in the form of system qualities. These qualities can, however, be attained only if the system has certain properties that are intrinsic to it and represent the viewpoints of the providers and provisioners (or, in other words, the developers and operators of the system). The system properties in turn help in identifying the component classes and determining the interactions between them, which provide the connected structures. The logical steps from the user's needs to the architectural elements are shown in Figure 3.

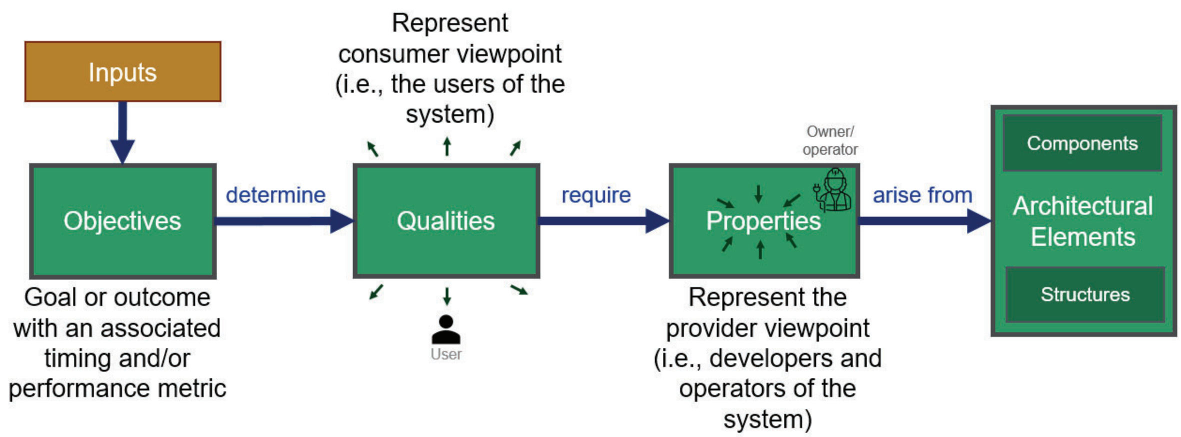

Figure 3: High-level approach used in Grid Architecture.

This approach helps to map the consumer objectives to the architectural components. The mapping can be shown by creating a tripartite graph that then forms the foundation for architectural development. Figure 4 shows an example of a tripartite graph in which contributions are mapped with lines from the key properties to the qualities. Consumer viewpoints determine the system's qualities. Developers and operators of the system are consulted to develop the list of desirable system properties that achieve the desired qualities; formal definitions may need to be developed or existing definitions may need to be leveraged to elaborate on these properties. One property may contribute to multiple qualities, as shown in Figure 4. Qualities should be independent and decoupled; however, properties need not be strictly orthogonal. If the key components are known, then the methodology can be extrapolated to include mappings between these key components and the properties. These components will be architected to connect in certain ways to achieve specific desirable structures. The resultant mapping, if done in a thorough manner, may look messy with several crisscrossing lines.

One of the core applications of Grid Architecture is to determine appropriate new structures or structural modifications for supporting the outcomes as follows:

- relieve crucial constraints,
- minimize the propagation of undesired effects of changes,
- strengthen desirable grid characteristics and
- simplify design and implementation decisions.

The approach to accomplishing these outcomes is shown in Figure 5. It helps in identifying the systemic issues, understanding the complexities, and resolving the constraints of the existing system.

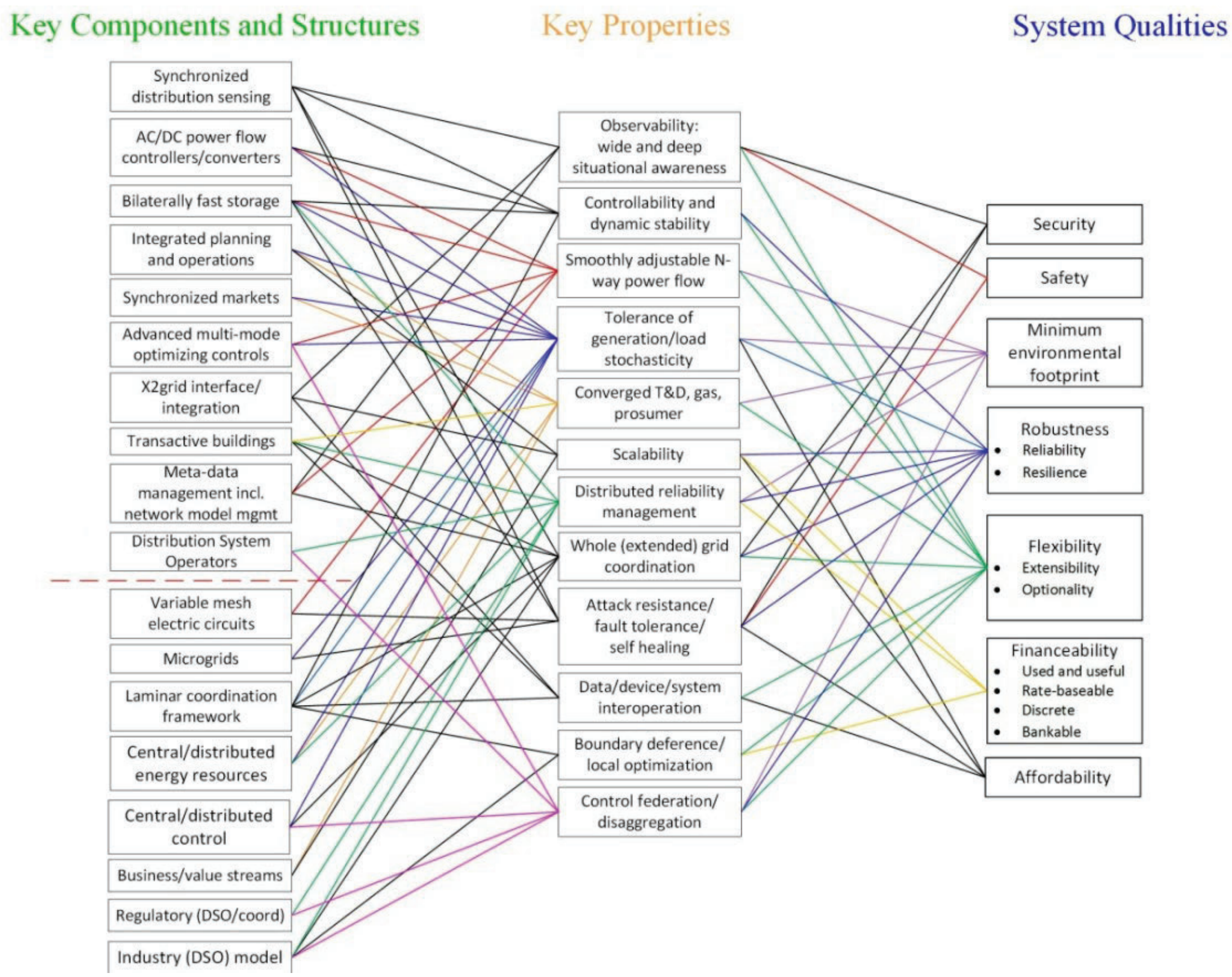

Figure 4: Mapping showing components, properties, and qualities.

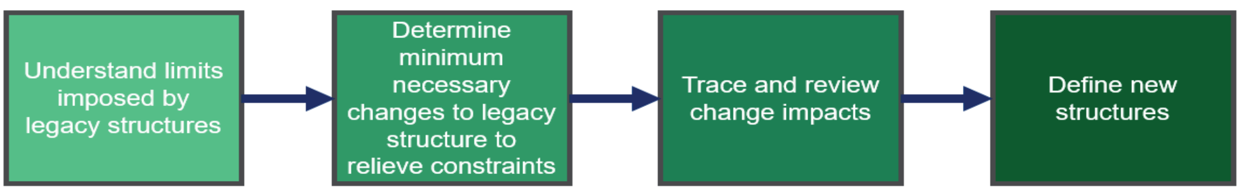

Figure 5: Approach for defining verified structural changes.

In summary, Grid Architecture helps in determining the existing structures and how the different structures interact with each other. It not only helps in managing complexity in existing structures but also assists in identifying ambiguity, dependency issues, and conflicts in functions or relationships. This is a critical step toward identifying risks in the existing structure and planning a future-facing system that will be able to accommodate changes for the next several decades. If the structure is right, then all pieces will be more easily integrated, downstream decisions will be simpler, and investments will be future-proofed.

2.3 Work Products

Figure 6 provides a graphical summary of common Grid Architecture work products and the relationships between them. Work products in Grid Architecture are typically in the form of foundational concepts, methodologies, frameworks, specifications, diagrams, and tools. They are intended to be technology-agnostic, so it is common to develop abstract conceptualizations that precede the physical design of the system. Once the necessary architectural solution has been determined, the interested stakeholder can assess the different potential technologies based on the specifics of their system needs. Future-facing reference architecture packages are often developed in which different types of energy futures are assumed. Work products may also include simulation study results, spreadsheets, and descriptive documents.

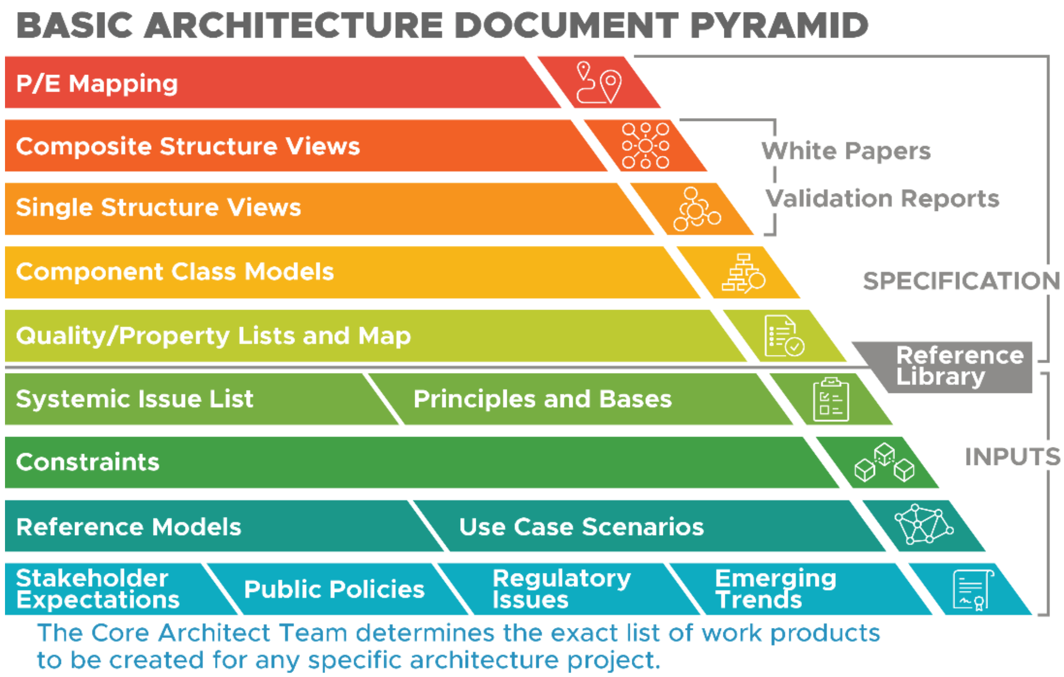

Figure 6: Different types of work products from Grid Architecture development process. (P/E is properties and elements; mapping of the properties to their sets of elements is shown in the tripartite graph in Figure 4)

2.4 An Example

Consider the kinds of questions that Grid Architecture can help answer. It is well known that Federal Energy Regulatory Commission Order 2222 calls for plans to enable DER aggregators to compete in regionally organized wholesale energy markets (FERC 2020). The regional transmission organizations and independent system operators (ISOs) are required to revise their tariffs to establish the rules and processes for enabling DERs access to the wholesale energy markets. However, the DERs in the grid edge are typically not owned by the grid operators and, most often, cannot be directly controlled by them. Utilities need to enable DER integration in the grid, while ISOs need to consider their variable and uncertain generation appropriately in the market processes to be able to administer the market fairly and ensure safe operation. This brings up many questions around how the ISO, utilities, aggregators, DER owners, and regulators of any region should be working in coordination toward sharing responsibilities for connecting, monitoring, and dispatching these devices. What should be the coordination framework between these organizations so that there are no conflicts or lack of operational transparency for the distribution operator due to direct interactions with the ISO? Which entities should be included in the structural model, and who should communicate with whom? How can control be decentralized while enabling global optimization of the market? There are many more possible questions, and these are merely a few examples.

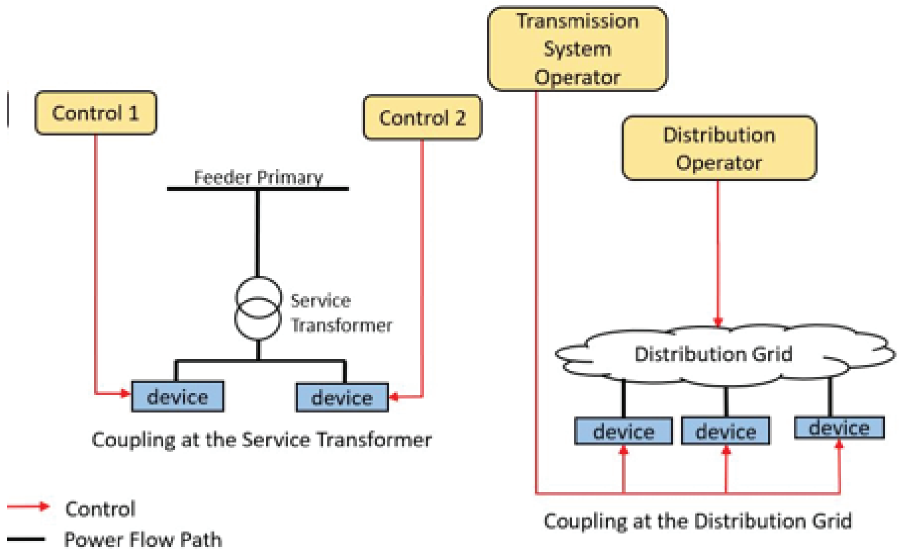

Figure 7: Figure shows different ways in which hidden coupling can happen. (Taft, Melton, and Harden 2019)

Answering questions such as these is critical and requires explicit industry and market structure models to better understand today's situation as context for future changes. Therefore, industry and market structure modeling (discussed in a later section) of the existing system is an important first step to capture all the different entities involved, map their interactions, relationships, and functions, and identify the constraints.

It also requires determining the necessary changes and analyzing their direct and indirect impacts. For the example in hand, if a DER is proposed to be coordinated directly with the ISO or aggregated through third parties and the distribution utility is unaware of the plan (e.g., dispatch decisions), then it can lead to what is called "tier-bypassing." For example, if the ISO dispatches an energy storage resource to charge and consume power because wholesale prices are negative and the utility would like to dispatch the same resource to inject power because of power quality or availability issues at that specific location, then this conflict in coordination can potentially degrade the system's performance. However, the utility is still responsible for the safe and reliable operation of the distribution grid and its assets (including DERs under its purview), so it is apparent that there is a hidden coupling. Figure 7 shows two graphical examples of hidden coupling. Hidden coupling occurs, for example, when two separate systems attempt to manage or control a third common element or asset but do not coordinate their actions. The Grid Architecture concept of layered decomposition can be applied to create a layered structure in such a way that there is no tier-bypassing or hidden coupling.

3.0 Benefits Of Grid Architecture To Different Stakeholders

Identification of stakeholders and understanding of their perspectives, concerns, and requirements are important early steps in any architectural endeavor. In this context, stakeholders broadly include those with an interest in grid modernization (and those who should have such an interest) and those who can affect or be affected (both positively and negatively) by objectives, policies, actions, and outcomes related to grid modernization. Some representative questions commonly used to identify stakeholders include:

- Who is making decisions?

- Who will design, plan, and operate the system?
- Who will use or consume it?
- Who will research or evaluate outcomes?
- Who will regulate?
- Who will be affected by any proposed changes to the system?
- Who will standardize?
- Who in government and policy is interested and engaged?

It is often useful to group stakeholders into conceptual categories. A good starting point for characterizing stakeholders is the seven smart grid domains, identified in the National Institute of Standards and Technology (NIST) Smart Grid Interoperability Framework (Gopstein et al. 2021), that conceptually organize grid participants, roles, and services:

1. Markets;
2. Generation, including DER;
3. Transmission;
4. Distribution;
5. Operations;
6. Service Providers;
7. and Customers.

Each domain is a high-level grouping of organizations, buildings or facilities, individuals, systems, software, devices, or other actors that have the capability to make decisions to exchange information with other actors; organizations may have actors in more than one domain. Augmenting the direct domain-based stakeholders (including customers who interact with the grid), there are many indirect stakeholders. With this conceptual understanding, NIST identified 22 stakeholder categories[1] in the original Smart Grid Interoperability Panel, including multiple types of utilities, manufacturers, and customers, which was useful for achieving representational balance among disparate stakeholders with different goals but perhaps unwieldy for other uses. Later, for comparison, SGIP 2.0, Inc. identified a much shorter list of Interest Categories: Asset Owners; Service Providers and Systems Administrators; Manufacturers; Consumers, Policy and Government; and Standards Development Organizations and Consortiums. However, this shorter list may be too short and overly combine stakeholders with otherwise unique perspectives and goals.

[1] NIST Smart Grid Interoperability Panel (1.0) Stakeholder Categories included: Appliance and consumer electronic providers; Commercial and industrial equipment manufacturers and automation vendors; Consumers (residential, commercial, and industrial); Electric transportation; Electric utility companies—investor owned utilities and federal and state power authorities; Electric utility companies - municipal and investor owned; Electric utility companies—rural electric associations; Electricity and financial market traders; Independent power producers; Information and communication technologies infrastructure and service providers; Information technology application developers and integrators; Power equipment manufacturers and vendors; Professional societies, user groups, trade associations, and industry consortia; Research and development organizations and academia; Relevant government entities; Renewable power producers; Retail service providers; Standards and specification development organizations; State and local regulators; Testing and certification vendors; Transmission operators and independent system operators; and Venture capital.

For architecture outreach and education purposes, it is advantageous to pursue a middle path and identify two categories of Grid Architecture stakeholders: direct Grid Architecture practitioners (e.g., in domain-based organizations) and indirect Grid Architecture influencers (e.g., research, standards, government organizations, and others). Figure 8 illustrates the categories of stakeholders and their relationship to the Grid Architecture processes.

For the first category of Grid Architecture stakeholders, i.e., direct Grid Architecture practitioners, it is useful to consider Grid Architecture layers (conceptual, logical/functional, and physical) as a backdrop for understanding different roles in Grid Architecture development. Executives within organizations are likely to gravitate toward the conceptual layer, which will help determine improvements to the overall business processes. Grid Architecture-based work products will enable superior decision-making aimed at reducing the risk of stranded assets and therefore lead to better investment choices. Operators and System Integrators are likely to start at the logical and functional layers but extend to the physical layer. For broader insights, market structure diagrams will help operators get a better understanding of how the individual market-related processes fit together and what needs to change in order to support the grid transformation. Engineers will tend to extend into individual areas of expertise in logical and physical aspects. They will use the reference architectures as a starting point in order to design the technical requirements of the system and implement them. This characterization is not meant to be prescriptive, just pragmatic; the level of Grid Architecture understanding and training can then be tailored to the interests of Executives, Operators and System Integrators, and Engineers.

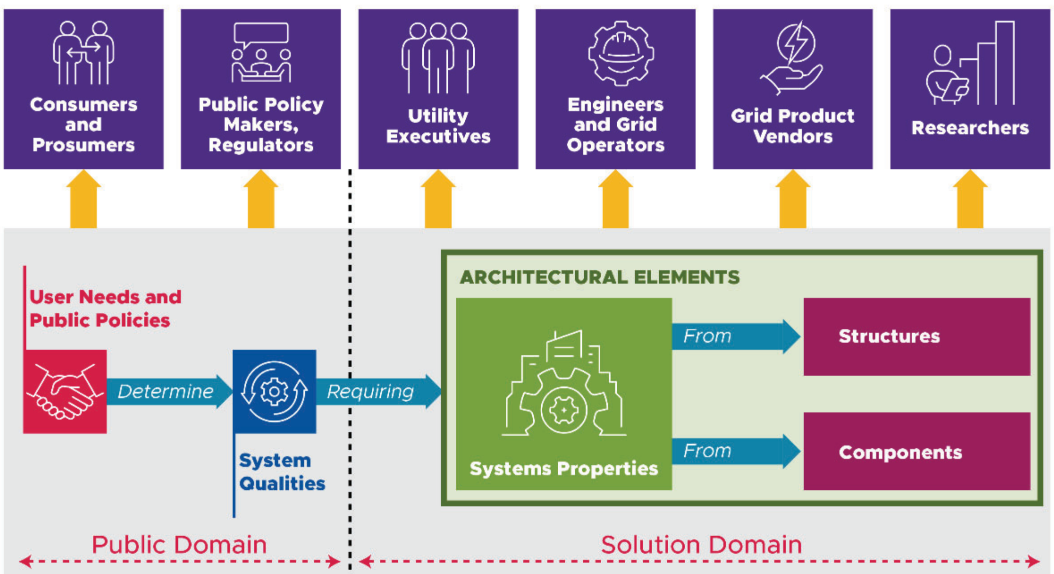

Figure 8: Grid Architecture stakeholders.

For the second category of Grid Architecture stakeholders, the indirect Grid Architecture influencers include: Manufacturers/Vendors; Service Providers; Consumers; Consumer Advocates; Standards Developing Organizations; Policy Makers and Regulators; and Research/Funding Agencies. Note that Manufacturers/Vendors and Consumers may fit into both categories of stakeholders, depending on their degree of involvement and criticality to domain-based services and operational systems. An architectural focus is essential to designing standardized specifications and interfaces in various products, all of which help make products integrate more simply and reliably. Research and Funding Agencies should be considered for inclusion depending on the relevant agency mission space, the degree of researchers' proximity to markets, system planning, operations, and the architectural complexity of research schemes. Researchers may have a breadth of interest in Grid Architecture across the range of conceptual, logical/functional, and physical layers, with varying depths of interest in each layer depending on specific research domains. Grid Architecture will help determine the standardization needs and therefore influence the standards being developed. It will also assist in the identification of issues that may have public policy implications and can be leveraged by regulatory bodies to verify that proposed changes are achievable and do not have any unintended negative implications.

4.0 Grid Architecture Techniques – Select Examples

In this section, a few examples of Grid Architecture methodologies and approaches are discussed that are highly relevant and applicable to activities aimed at grid modernization. For additional information on existing Grid Architecture work products and their relevance to accelerating the grid transformation, readers are encouraged to explore the website https://gridarchitecture.pnnl.gov/.

4.1 Industry Structure Modeling

Industry structure diagrams are diagrams depicting how different entities within the industry interact (Melton and Pal 2019). They may represent an "as-built" structure or a future proposed structure. Entity-relationship diagram techniques are used to represent the connectivity, value, ownership, and coordination in these models and create a viable hybrid information model that is of special interest to stakeholders. Entity classes are representative of entire groups of organizations or entities. They are represented by boxes with labels indicating their names. For example, all residential customers can be treated as an entity class and shown by a box labeled "Residential Customer," as shown in Figure 9. There are exceptions, like North American Electric Reliability Corporation, which, unlike any of the other entity classes, is treated as a separate entity class of its own.

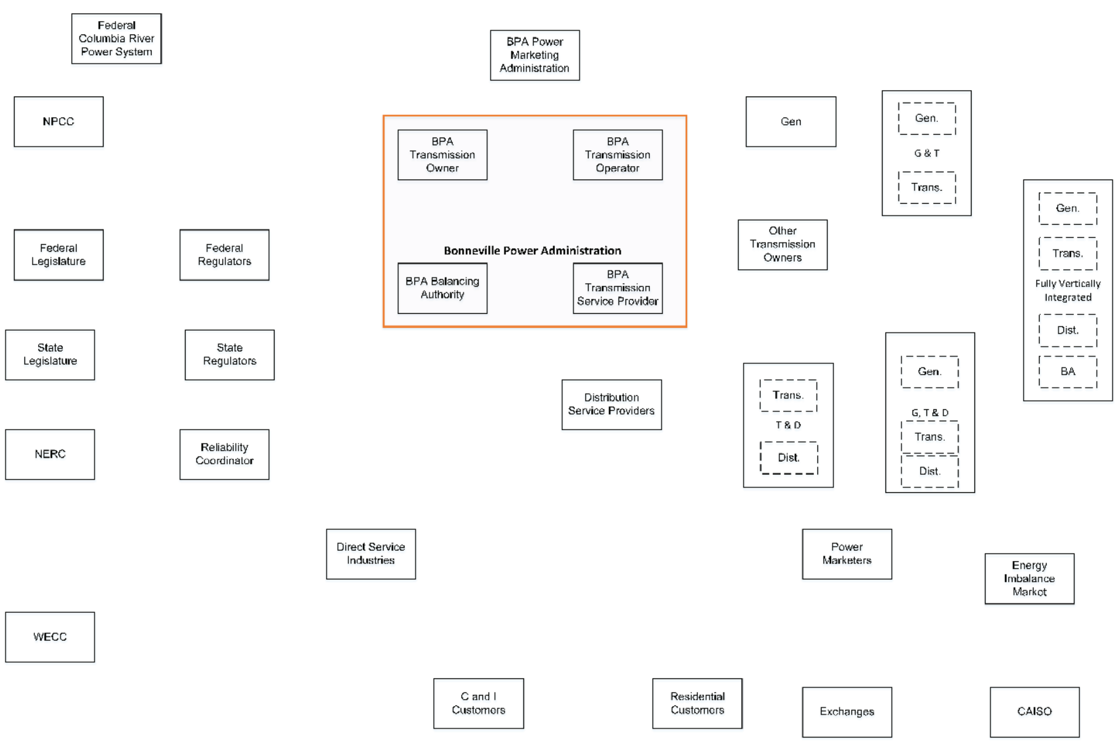

Figure 9: Initial version of industry structure diagram showing only entity classes.

The relationship between any pair of entity classes is a group of behaviors, which are represented by a line connecting their boxes. The line terminates in symbols, as shown in Figure 11, which indicate how many members of the entity class can be involved in that relationship. These lines are labeled with a summarized description of the primary relationship, as shown in Figure 10. The angle brackets at the ends of this text indicate its directionality.

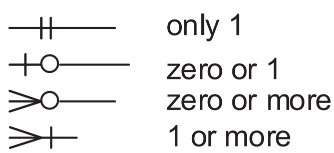

Figure 10: Symbols used for defining cardinality.

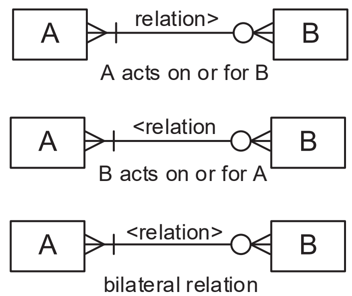

Figure 11: Examples of relationships with different directionality between entity classes.

Each relationship is assigned to a specific functional group based on the primary function served. Typical functional groups included in industry structure diagrams are reliability coordination, market interaction, retail, federal regulation, state regulation, energy and services, and control and coordination, as shown in Figure 12. These are distinguished by using specifically colored lines. Each functional group can be visualized as a separate layer in the diagram (using the layering feature in Visio or PDF formats) in order to decompose the complexity of the structure and focus on specific functions. Figure 12 also provides a couple of examples on the right of how different relationships can be colored appropriately to indicate their specific layers.

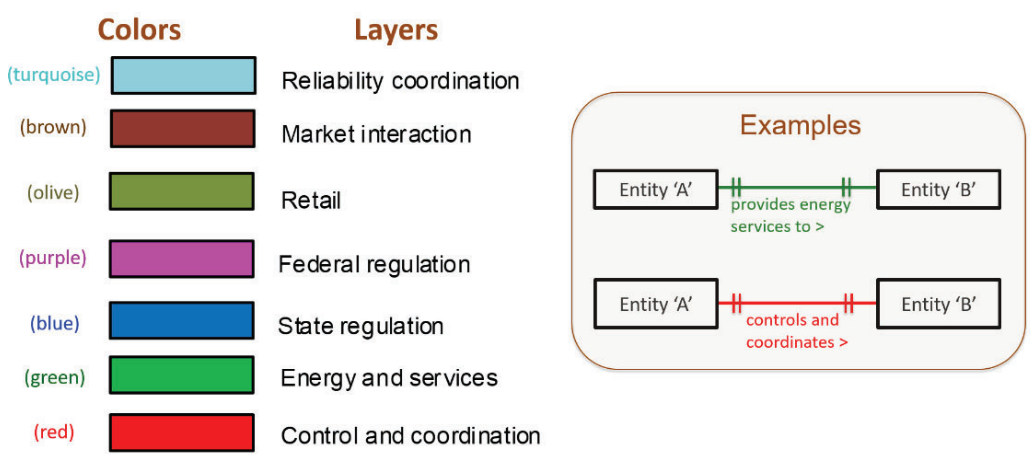

Figure 12: Colors and usage of different colored layers.

Industry structure diagrams often serve as the baseline in grid-related planning, development, and operation. They assist in identifying which organizations are involved in providing the mentioned functions (federal regulation, state regulation, reliability coordination, control and coordination, energy and ancillary services, market, and retail) in the grid and how they interact with each other for the seamless delivery of that function. A model of this kind helps identify the current dependencies between entity classes and legacy structural constraints. When system changes are proposed, they can be inserted into the current industry structure model for tracing and analyzing the propagation of those specific changes. Modeling and visualization of the industry structures of the regional grids using industry structure diagrams is of great benefit to stakeholders in the electric industry and beyond.

Industry structure diagrams have been developed for California (California Independent System Operator [CAISO] service area), New York (New York Independent System Operator [NYISO] service area), Texas (Electric Reliability Council of Texas [ERCOT] service area), and the Pacific Northwest (Bonneville Power Administration service area). Figure 13 is an example of the industry structure diagram of the regional grid in the Pacific Northwest. Interactive versions of the industry structure diagrams for ERCOT and the Pacific Northwest are available as part of the Industry Structure Diagram Viewer app[1]. Intermediate static versions of these diagrams are also included in the Reference Grid Architecture Packages[2]. Such models have been developed for the Central American regional electric grid, also based on the as-built system models, and include the systemic issues and trends for which recommendations have been provided toward enhancing the system.

[1] https://gridarchitecture.pnnl.gov/grid_diagram/default.aspx
[2] https://gridarchitecture.pnnl.gov/library.aspx

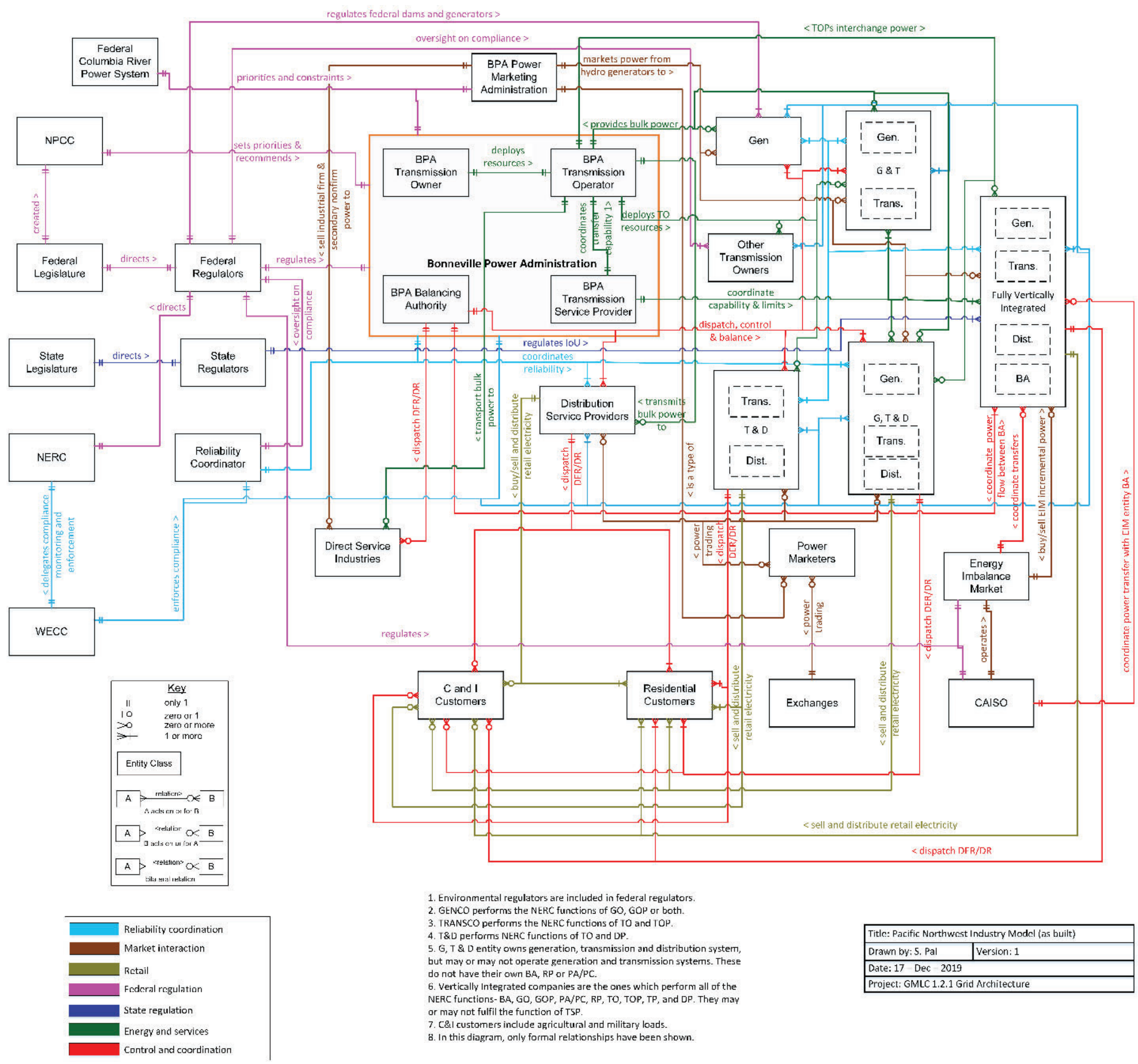

Figure 13: Industry structure diagram for the Pacific Northwest region of the U.S. (Melton and Pal 2019)

4.2 Market Structure Modeling

A market structure diagram is a one-line visual representation of any regional grid that shows how the data provided by the various entities is collected and utilized for the business applications that are run by the market operator to generate the outputs. These outputs include both grid control signals (e.g., dispatch instructions) as well as market signals (e.g., locational marginal prices). The market structure diagram also shows the timeline and provides information on the look-ahead of the different processes included in the market operations.

It should be noted that market structure in the Grid Architecture context does not refer to market rules. Instead, it provides a holistic view of the market mechanisms to help answer questions like the following:

- What are the different processes that are part of the markets?
- What are the sequences of the market processes?
- Who are the operators of the markets?
- Who are the participants in the markets?
- What kind of information is needed to be exchanged as part of the market processes?

Market structure diagrams have also been developed that show the processes that are implemented by ERCOT, CAISO, and NYISO to operate the wholesale electric market. Figure 14 shows the market structure diagram for ERCOT.

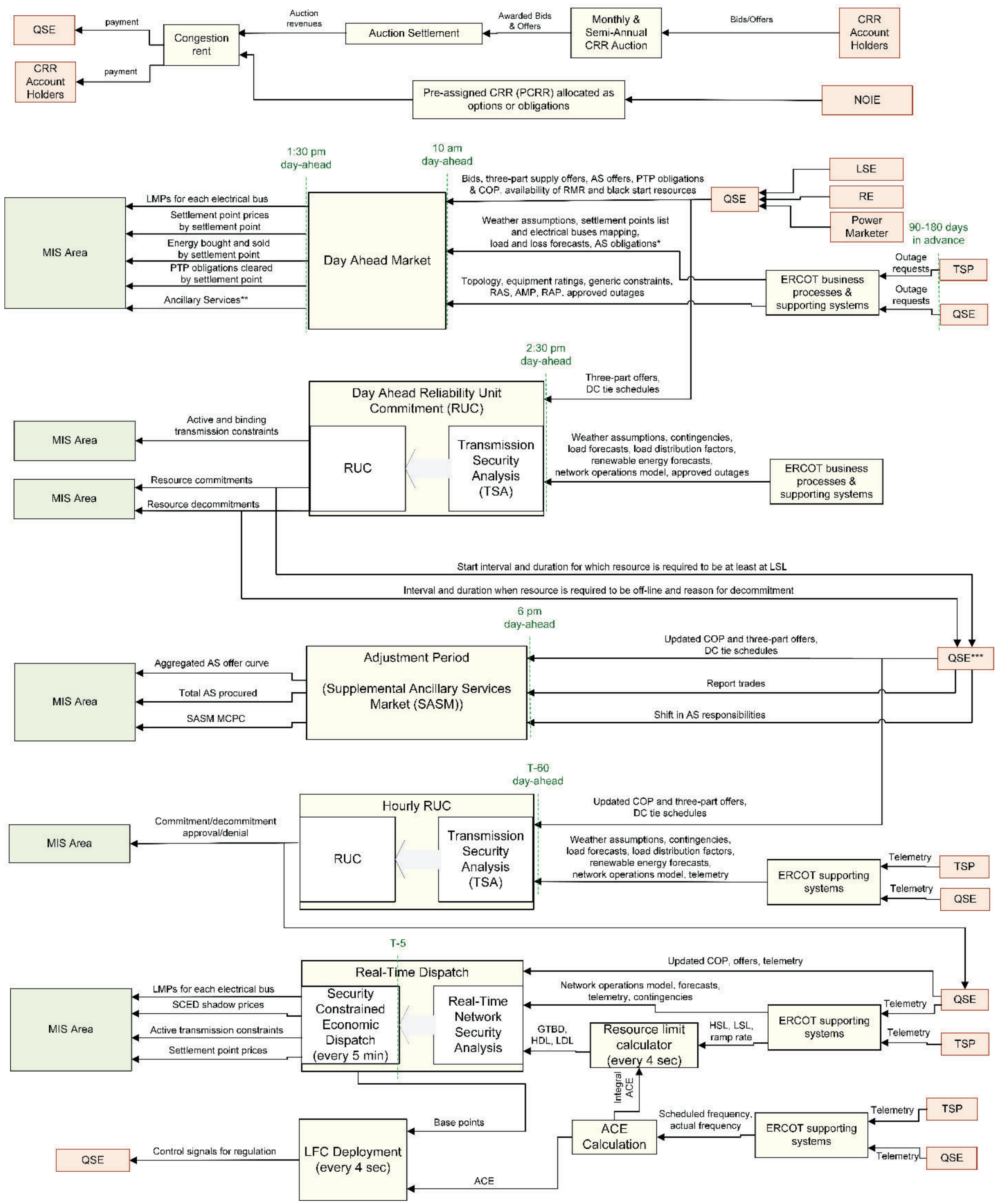

Figure 14: Market structure diagram for ERCOT.

4.3 Laminar Coordination Framework

The operation of geographically dispersed and temporally varying systems is challenging without a formalized coordination mechanism. A laminar coordination framework is a mechanism for generating coordination architectures via layered decomposition for electric power systems and is critical for multi-scale grid operation (Taft 2016).

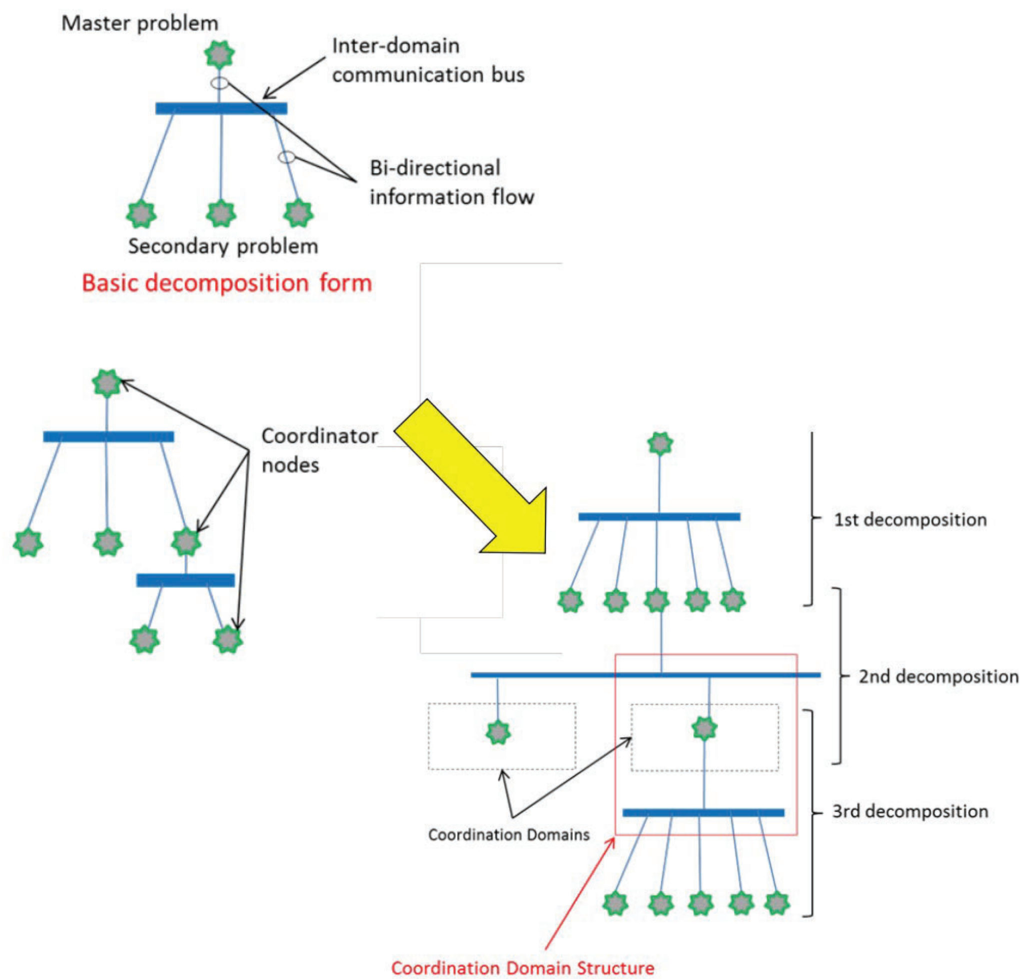

Figure 15: Underlying layered decomposition structure in laminar coordination network.

The basic approach to layered decomposition starts with decomposing the overall problem with coupled constraints problems into a primary problem and several subproblems with the aim of decoupling those constraints. The primary problem and subproblems are all solved sequentially and iteratively until they collectively reach convergence, so that a solution to the original optimization problem is produced. The primary and sub-problems are coordinated by the exchange of signals referred to as coordination signals. In the basic approach, two decompositions are used: primal decomposition, which yields coordination signals that resemble resource allocations, and dual decomposition, which yields coordination signals that resemble prices.

To illustrate, Figure 15 shows an example of a layered decomposition structure with three levels of decomposition. In the upper left, a basic structure with a single level of decomposition is shown. It consists of a coordination node for the primary problem, a coordination node for each of the three subproblems, and a communication bus for coordination signal exchange. In the lower left, a structure with two-stage decomposition is shown. One sub-problem has been further decomposed, so that there are now two communication buses for two levels of coordination signals. Finally, on the right-hand side, a three-stage decomposition is shown. From this, we can now identify a basic element, which we designate the coordination domain, and a structure associated with it. This can be used as a composable building block to assemble complete coordination structures with "vertical" chains of coordination domains, which we designate as laminar coordination frameworks (Taft 2016).

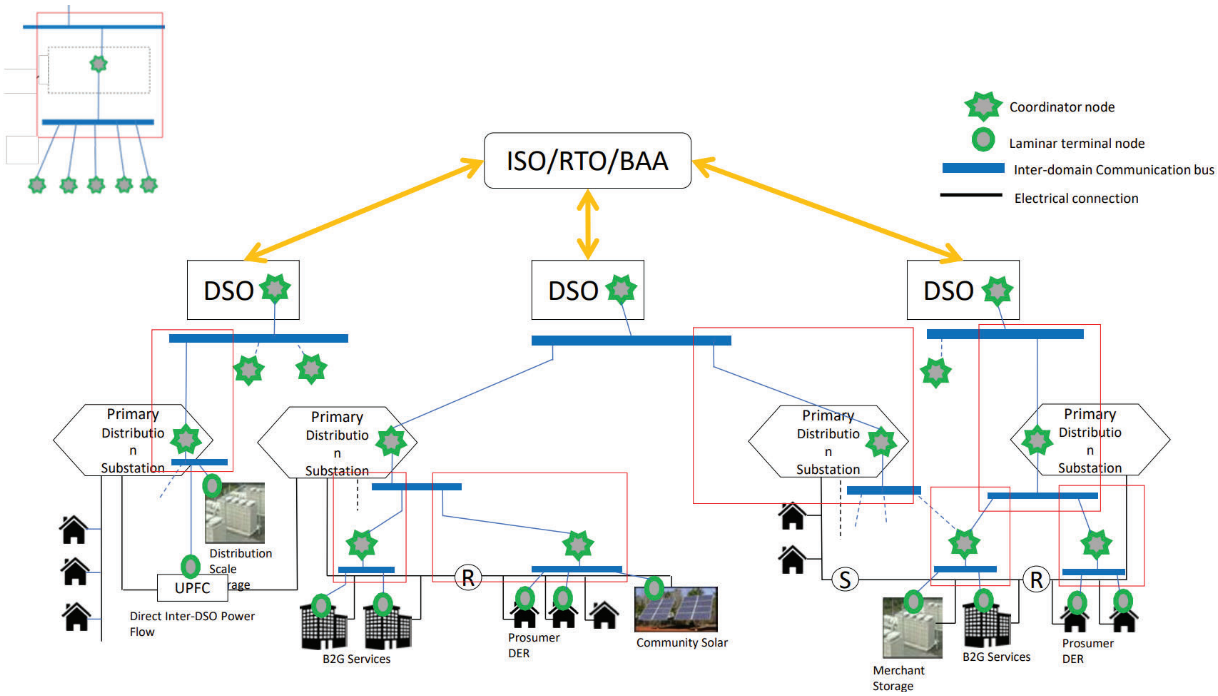

Figure 16: Mapping of laminar coordination framework to grid structure. (Taft 2020)

The laminar coordination framework attempts to create this layered form where a system may be divided up into domains with their associated coordination nodes. The specified domains may be based on the way a mathematical problem is decomposed or a result of geographic distances between subcircuits of a larger power system. For example, it may encompass an entire distribution service provider's territory, a primary distribution substation service area, a microgrid, or a feeder section and the devices connected to that section. Accordingly, the coordination node may be responsible for certain subproblems that may involve optimization or local controls. Coordination domains can be nested recursively as needed, and the structure is scalable.

There are several benefits to using the laminar coordination framework. It provides a clean interface, avoids tier bypassing, and separates roles and responsibilities for the various entities that are involved. It allows for solving a wide class of optimization problems with multiple coupled constraints and is able to support both centralized, decentralized, distributed, or hybrid implementations. Laminar coordination networks can be mapped to the grid structure, as illustrated in Figure 16, to clearly define the coordination nodes, coordination signals, and the control/coordination structure. This approach will help clarify the roles and responsibilities of each of the entity classes and therefore prevent hidden coupling.

5.0 Conclusions

Power grids have been mostly conceived and built in a bottom-up manner as different needs have arisen over the decades, as opposed to being designed with a systems-wide view. This has led to a situation where system stability has been a result of different disjointed efforts that are not always coordinated or optimized on the economic, control, and operational fronts, often leading to operational or design conflicts. The resulting electric power systems of today are exceedingly complex. Following the same bottoms-up approach as we engineer the inclusion of large quantities of DER, electrification of new classes of loads, and other measures supporting decarbonization will fail unless the growth in complexity is managed.

Grid Architecture is a discipline for managing such complexity. It provides different frameworks, methodologies, and tools for analyzing the complex structures and generating relevant views at the system level that benefit different stakeholders. This, in turn, enables coordination to design and implement the electric power systems of the future capable of supporting decarbonization goals.

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Working Group Participants

Seemita Pal, Pacific Northwest National Laboratory (PNNL)

Ron Melton, PNNL

Ron Cunningham, American Electric Power

David Wollman, National Institute of Standards and Technology (NIST)

Ron Bernstein, Ron Bernstein Consulting Group, LLC

Ahlmahz Negash, Tacoma Power

Larisa Dobriansky, General Microgrids Inc.

David Forfia, Utilicast

Mark Paterson, Strategen

Ron Ambrosio, Utopus Insights, Inc.

Lorenzo Kristov, Independent Consultant

Kay Aikin, Dynamic Grid

Aaron Snyder, EnerNex

Farrokh Rahimi, Open Access Technology International, Inc.

Rahul Bahadur, VMware, Inc.

Gerald Gray, Electric Power Research Institute

Timothy Schoechle, Colorado State University

Jeffrey Morris, Schneider Electric North America

Leonard Tillman, Balch & Bingham, LLP

Andrew Bordine, Anterix

Chris Villarreal, Plugged In Strategies

Rohit Jinsiwale, PNNL

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7.0 References

DHS – Department of Homeland Security. 2019. "Energy Sector." Available at: https://www.dhs.gov/cisa/energy-sector, Accessed: 01/14/2019.

DOE/OP-0004-1. 2022. Achieving American Leadership in the Electric Grid Supply Chain. Department of Energy. Office of Electricity. https://www.energy.gov/sites/default/files/2022-02/Electric%20Grid%20Supply%20Chain%20Fact%20Sheet.pdf.

FERC – Federal Energy Regulatory Commission. 2020. "FERC Opens Wholesale Markets to Distributed Resources: Landmark Action Breaks Down Barriers to Emerging Technologies, Boosts Competition." Docket No. RM18-9-000, Item No. E-1. Latest updated: September 28, 2020. https://www.ferc.gov/news-events/news/ferc-opens-wholesale-markets-distributed-resources-landmark-action-breaks-down, Date of Access: 3/28/2022.

Gopstein C. Nguyen, C. O'Fallon, N, Hastings, and D. Wollman. 2021. *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 4.0*. NIST Special Publication 1108r4. National Institute of Standards and Technology, U.S. Department of Commerce. https://doi.org/10.6028/NIST.SP.1108r4 (2021).

Melton R.B. and S. Pal. 2019. *Problem Domain Reference Model: Functional Groups and Reference Architectures for the Electric Grid*. PNNL-28399. Pacific Northwest National Laboratory, Richland, WA.

PNNL. n.d. "Tutorials and Advanced Concepts for Architecture of Electric Power Grids." Grid Architecture. Last updated June 2022. Accessed: 01/14/2019. https://gridarchitecture.pnnl.gov/.

Taft J.D. 2016. *Architectural Basis for Highly Distributed Transactive Power Grids: Frameworks, Networks, and Grid Codes*. PNNL-25480. Pacific Northwest National Labortory, Richland, WA. https://gridarchitecture.pnnl.gov/media/advanced/Architectural%20Basis%20for%20Highly%20Distributed%20Transactive%20Power%20Grids_final.pdf.

Taft J. D. 2019. "Grid Architecture: Shaping Our Energy Future." *Power & Energy Magazine* - Volume 17: Issue 5 - Sep/Oct 2019. IEEE Power &Energy Society.

Taft J. D. 2020. *Architectural Models for Distributed Grid Structures and Grid Virtualization*. PNNL-SA-151709, Pacific Northwest National Laboratory, Richland, WA. https://s3.wp.wsu.edu/uploads/sites/2217/2020/03/Virtualization-2B-2-J-Taft.pdf.

Taft J., R. Melton, and D. Harden. 2019. "Next-Gen Grid Architecture Part 3: A peek into industry structure." https://www.power-grid.com/executive-insight/next-gen-grid-architecture-part-3-a-peek-into-industry-structure/#gref,.

Xue Y., G. Liu, J.D. Taft, and M. Shankar. 2022. *Emerging Trends and Systemic Issues Influencing Today's U.S. Electric Grid – Context for Grid Architecture Development*. GMLC-1.2.1. Oak Ridge National Laboratory, Oak Ridge, TN. https://info.ornl.gov/sites/publications/Files/Pub173902.pdf.

8.0 For Future Reading

https://gridarchitecture.pnnl.gov/library.aspx

Melton R.B. and S. Pal. 2019. *Problem Domain Reference Model: Functional Groups and Reference Architectures for the Electric Grid*. PNNL-28399. Pacific Northwest National Laboratory, Richland, WA.

Taft J. D. 2019. "Grid Architecture: Shaping Our Energy Future." *Power & Energy Magazine* - Volume 17: Issue 5 - Sep/Oct 2019. IEEE Power &Energy Society.

J. Taft, R. Melton, and D. Hardin, "Laying the foundation for a next gen grid architecture," Part I – Next-Gen Grid Architecture, Powergrid International, July 2018., Available: https://www.power-grid.com/executive-insight/laying-the-foundation-for-next-gen-grid-architecture/#gref.

J. Taft, R. Melton, and D. Hardin, "A prerequisite for grid modernization," Part II – Next-Gen Grid Architecture, Powergrid International, April 2019, Available: https://www.power-grid.com/executive-insight/next-gen-grid-architecture-a-prerequisite-for-grid-modernization/#gref.

J. Taft, R. Melton, and D. Hardin, "A peek into industry structure," Part III – Next-Gen Grid Architecture, Powergrid International, May 2019, Available: https://www.power-grid.com/executive-insight/next-gen-grid-architecture-part-3-a-peek-into-industry-structure/#gref.

J. Taft, R. Melton, and D. Hardin, "A grid coordination primer," Part IV – Next-Gen Grid Architecture, Powergrid International, August 2019, Available: https://www.power-grid.com/executive-insight/nextgen-grid-architecture-a-grid-coordination-primer/#gref.

D. Hardin, "Next-Gen Grid Architecture: How to use the High Resilience Grid Architecture at any utility," Part V – Next-Gen Grid Architecture, Powergrid International, September 2019, Available: https://www.power-grid.com/der-grid-edge/next-gen-grid-architecture-how-to-use-the-high-resilience-grid-architecture-at-any-utility/#gref.