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1 Purpose and Scope

It is the policy of the United States to support the modernization of the Nation's electricity transmission and distribution system.
Energy Independence and Security Act of 2007 [1]

The National Institute of Standards and Technology shall have the primary responsibility to coordinate the development of a framework that includes protocols and model standards for information management to achieve interoperability of smart grid devices and systems.
Energy Independence and Security Act of 2007 [2]

The United States power system encompasses more than 7,000 power plants [3] feeding a distribution system with 6,000,000 miles of wire serving 150,000,000 customers [4]. This immense system, integrated into every aspect of modern life, is undergoing dramatic transformation that changes everything from where electrons come from[1] to how they are consumed [6].

The electrical grid is the tightly coupled system that manages and delivers power from where and how it is generated to where—and how—it is consumed. The Nation needs an electrical grid that is adaptable, secure, reliable, resilient, and can accommodate changing loads, generation technologies, and operating business models. Grid modernization will bring new capabilities and economic opportunity to utilities and customers through improved access to data, cyber security protections, and power flow control, but will also require new physical and informational capabilities to observe and manage the system and its emerging and increasingly complex dynamics [7]. Interoperability is the crucial enabler of these needed capabilities.

1.1 Overview and Background

Technological advances are transforming the electric grid. Over the last decade, the United States has experienced large increases in the deployment and use of nontraditional energy resources [8]. As the installed costs for technologies like solar photovoltaics (PV) continue their dramatic decline (see **Figure 1**), deployments are expected to rise significantly [9]. But generation is only one part of the system, and the largest category of distributed energy technologies in use today—demand response—is focused on optimizing electricity consumption rather than production [10]. And as the capabilities of modern power electronics expand, new sources of essential reliability services are emerging [11] and the power grid will become more resilient as these capabilities are deployed across a broadening range of applications and scales [12].

[1] In the year 2000 the United States produced more than 200 times as much electricity from oil than from solar energy. Over the next 15 years solar power generation grew by almost 30% annually while oil-based generation fell by nearly 9% per year; by 2015 the amount of electricity generated from both resources were similar. In the years since solar generation grew at nearly 40% per year while oil generation continued to decline, so that in 2018 nearly 3 kWh of solar power were generated for each kWh of oil-fueled electricity [5].

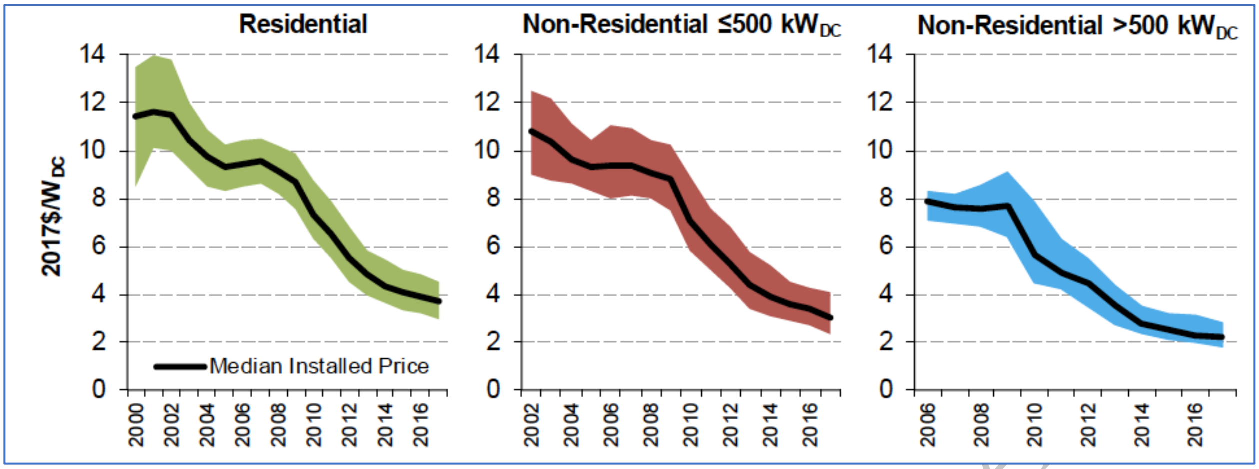

Figure 1- Installed Photovoltaic Price Trends over Time [13]

The modular and scalable nature of modern energy technologies [14] also allows for distributed implementations of grid capabilities which have historically been provided through large and centralized utility infrastructures. These changes, combined with regulatory changes that have altered the historic guarantee for a utility's return on capital investment, have over time reduced the size of newly deployed generation [7] and allowed generation and demand management capabilities to expand toward the grid edge [15]. This evolving set of resources and capabilities are conventionally referred to as Distributed Energy Resources (DERs).

Because electricity is perishable, most power is delivered at the time it is generated.[2] The supply, transmission, distribution, and consumption of electricity in the system are therefore closely coupled, and must be actively coordinated [17]. This requires the coordinated sensing, measurement, and control of devices and systems spread across the grid. Fortunately, the cost of sensors has declined even more rapidly than the cost of energy technologies, and the growth of sensing and network enabled energy devices and systems is unleashing dramatic opportunities to improve our ability to understand and operate the power grid [18]. Interoperability is the key to unlocking this potential.

1.2 The Role of Interoperability

> *These* [interoperability] *protocols and standards shall further align policy, business, and technology approaches in a manner that would enable all electric resources, including demand-side resources, to contribute to an efficient, reliable electricity network.*
>
> Energy Independence and Security Act of 2007 [2]

Interoperability is the capability of two or more networks, systems, devices, applications, or components to work together, and to exchange and readily use information—securely, effectively, and with little or no inconvenience to the user. The smart grid will be a system of interoperable systems; that is, different systems will be able to exchange meaningful, actionable

[2] Energy storage provides temporal flexibility and has an increasing role in the system. However, the scale of energy storage deployments of all kinds remains small compared to the grid's net generating capacity [16].

information in support of the safe, secure, efficient, and reliable operations of electric systems [19]. As the number of devices and systems used on the electrical grid continue to multiply [20], the interoperability requirements become more complex and the path to achieving interoperability becomes more challenging.

1.2.1 The Interoperability Value Proposition

Modern energy systems rely on an increasing array of sophisticated controls and information exchanges which are managed across diverse operational and economic systems [21]. Interoperability is therefore key to maximizing the benefits of technology investments. Yet because it is not easy to directly quantify the value of seamlessly exchanging a single bit of information in a complex system like the electrical grid, the value of interoperability is most often thought of in the context of what avoided: the expensive and time consuming set of activities necessary for one-of integrations of incompatible systems [22]. Indeed, anecdotes abound regarding the expense and functional limitations associated with integrating equipment designed to conform to the same interoperability standard [23]. For equipment designed to dissimilar standards, the challenges of achieving the intended functionality can become insurmountable.

Beyond minimizing system integration costs, grid interoperability also creates new value throughout the smart grid. As tens of billions of dollars are spent annually on communications capable electrical devices and software, the transition from isolated and siloed capabilities to interconnected systems will engender tremendous economic and operational opportunities across society [18]. Empowering consumers to better manage their energy consumption is but one of the growing set of capabilities that interoperability enables, which together will impact every aspect of how electricity is produced and managed and provide fundamentally new and different value propositions.

Beginning with individual sensors and devices found in the home, **Figure 2** depicts how the impacts of interoperability can change with the scale of interaction. Each level of the diagram represents a new set of interactions and information exchanges which can lead to new value opportunities. These include:

> **Local**: Interoperability between individual sensors, energy consuming devices, and system controllers can allow customers to better monitor their energy demand (or production) and manage consumption according to their specific needs.
>
> **Proximal:** Interoperability at the community level interoperability would create opportunity by allowing customers to interact with and potentially provide services to their neighbors or distribution utility. Specific community and local reliability needs could be met by better local management of power flow and quality issues in the system.
>
> **Regional:** Interoperability at the regional level would improve situational and state awareness for utilities, system operators, and regulators, allowing for more efficient operation and improved long-term planning. Physical interactions between the electrical

system and the local environment (e.g., managing surface water [24]) could be better managed, as well.

Global: At the societal scale, interoperability will enable expanded access to modern energy services, economic development, and environmental stewardship [25].

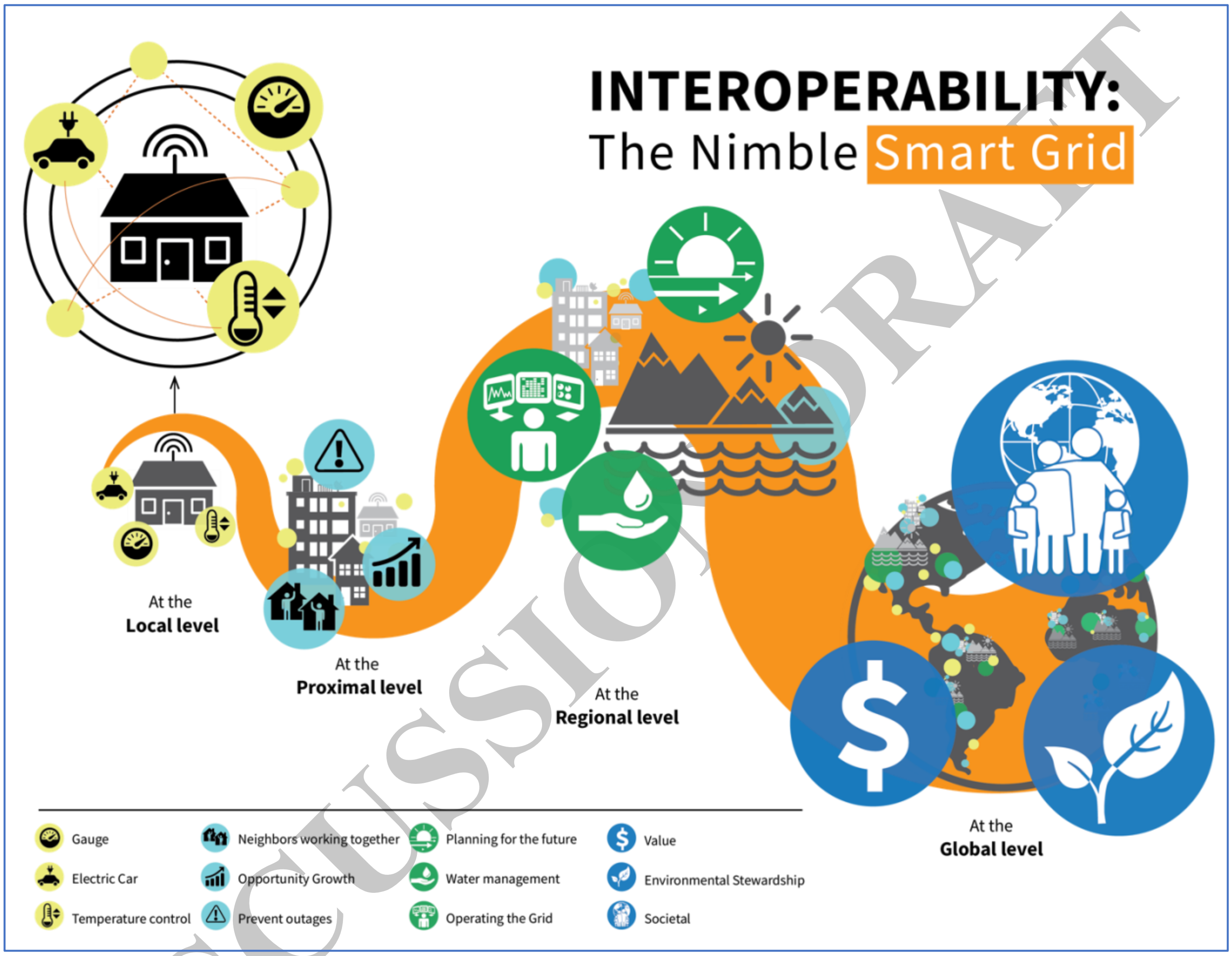

Figure 2 - Interoperability across scales

While interoperability—or lack thereof—is often considered an issue that must be addressed for utilities to maximize return on investment for specific system assets [26], **Figure 2** describes a different general concept: that interoperability *creates* value by overcoming the designed specificity of energy devices connected to the grid. Breaking this asset specificity would allow systems purchased to perform one set of tasks the ability to contribute to an entirely different set of applications by sharing information with a new set of actors.

Interoperability is therefore a tool to unlocking new value across the power system. The benefits can accrue at any scale, and for assets owned by any stakeholder. Some of the most intriguing implications relate to the role of the energy consumer.

1.2.2 The Empowered Consumer

The power grid was for decades modeled as an extremely simple set of interactions [27]. With simplicity born of a need for computationally tractable approaches to manage the system, these models codified the relationships between grid actors in similarly simple terms. In this paradigm generators produce electricity that is fed to and consumed by customers, and everything on the system is well characterized with behaviors that are both linear and consistent in their response.

Changing technologies have upended these assumptions. The new power grid is increasingly dynamic [28], few devices interact with the grid in the straightforward linear manner of old [29], and customers have long-since evolved into providers of resources that actively support grid health [30]. Indeed, expanding capabilities and falling costs for small-scale energy technologies has allowed customers and other actors to emerge as entirely new classes of asset owners.

The empowered energy consumer who can actively manage their interactions with the power grid is therefore one of the key elements of this Framework. Empowered by integration of new physical and informational capabilities, consumer devices can manage load, produce power, and otherwise support grid health[3] in ways which defy the historical customer-utility relationship. As consumer and third-party assets gain capability to respond to economic opportunity beyond the traditional tariff structure, the relationships between asset owners and electric utilities will evolve.

The empowered consumer's expanding set of roles are depicted in **Figure 2**, where the devices deployed in the home enable a diverse set of interactions and outcomes.

1.2.3 Utility and Other Benefits

Interoperability benefits are often reciprocal in nature and can accrue to multiple parties through diverse interactions. While **Figure 2** depicts a value stream emanating from customer-sited devices, utility investments in interoperable equipment would likely have similarly far-reaching impacts and provide value to a broad range of stakeholders.

Recent work has shown that utility-based interoperability investments improve system resilience, an effect which is conservatively estimated to provide $ billions in economic benefit during natural disasters and potentially savings lives (cite Irma work). This resilience benefit is different from the operational efficiencies traditionally cited as justification for utility-based interoperability investments [31].

The scope of benefits are only just beginning to be understood for utility or third-party interoperability investments that enable platforms for innovative grid management, such as through transactive market signals or peer-to-peer services [32].

[3] For example, by providing reactive power or voltage support along a distribution feeder.

1.3 Framework Content and Structure

This Framework document reflects the results of the ongoing technical work of the National Institute of Standards and Technology (NIST) in the area of smart grid interoperability, and builds on prior Framework versions [19, 33, 34]. This revision examines the impacts changing grid technologies will have on four key areas, and the associated evolution of grid interoperability requirements. The four areas are:

- Grid Operations
- Cybersecurity
- Grid Economics
- Standards Testing & Certification

The impact of interoperability on the emerging trends in each of these four focus areas is explored, and roadmaps for research, standards, and other technical work to advance interoperability in the smart grid are described.

1.3.1 The Role of Grid Architecture

Grid architecture is the highest level description of the complete grid, and is an important tool to understand and define the many complex interactions that exist in electrical system [35]. The relationships between technology, regulatory policy, and economic opportunity that govern interactions throughout the grid also guide the evolution of grid architectures.

While early grids were similar in a broad enough range of characteristics that they could generally be described by a single architecture,[4] today's environment is far more heterogeneous. Vertically integrated utilities with conventional tariff structures remain the standard for large portions of the country, whereas other regions have embraced diversified asset ownership,[5] market-driven operations, and unconventional or non-wires alternatives to traditional electricity supply [37].

This Framework uses multiple grid architectures described by the U.S. Department of Energy (DOE) [38] as inspiration for use cases to explore the different types of interactions one could expect to see in the electrical grid. No single architecture is deemed the correct architecture, and the use cases employed herein are abstractions of the detailed DOE architecture descriptions intended to elucidate specific system characteristics.

1.3.2 Updated Models

The NIST Smart Grid Conceptual Model is used to build a high-level and scalable understanding of the different physical and informational interfaces across the smart grid. In this Framework the Conceptual Model is updated to reflect evolving interface trends across the grid. The logical

[4] For example, vertically integrated utilities with conventional generation (e.g., steam cycle, hydropower, or reciprocating engine), and unidirectional power flows from generator to radial distribution networks that fed customers with similar characteristics.
[5] For example, through distribution system operators (DSOs) [36].

model of legacy systems from the previous Framework has been updated to explore interface characteristics across multiple grid architectures.

1.3.3 A Common Language for the Grid

Diversifying architectures complicates an already challenging space. As roles, responsibilities, and interfaces evolve across architectures, opportunities for miscommunication increase significantly—especially as companies engage in multiple locations and similar equipment is utilized in substantially different architectures.

Interoperability depends on a consistent understanding of the language used to describe capabilities and requirements for devices, systems, and actors. To facilitate this common understanding of the language of the grid NIST has applied a cyber-physical systems ontology [39] to the smart grid.

1.3.4 Tools to Facilitate Interoperability

Achieving interoperability is a complex challenge towards which compliance to individual communications or data model standards will yield limited progress. To maximize the benefits new devices and systems can bring to the electrical grid NIST has developed an approach to interoperability that depends on co-optimization of standards requirements related to the physical function, communications protocols, and information models.

Referred to as an interoperability profile, this approach to coordinated application of requirements which may span multiple standards is described.

1.4 Use of this Framework

The results of NIST's ongoing technical work reflected in this Framework document should assist smart grid stakeholders in future decision making. The ideas expressed in this work are foundational to information exchange and interoperability concerns across the smart grid, have gone through a full vetting process, and are expected to stand the "test of time" as the building blocks for emerging power sector issues.

It is important to note that standards for electrical grid technologies are not static—as technology evolves, so too will the relevant standards. Standards undergo continuing revisions to add new functionalities, integrate with legacy standards, harmonize/align with overlapping standards, and remedy shortcomings that are discovered as their implementations undergo interoperability testing. Standards are also deprecated when no longer useful. The concepts and gaps described in this Framework provide a foundation to guide this process moving forward.

2 Models for the Smart Grid

Several models have been developed by NIST to describe interoperability concerns in the smart grid. In this version of the Framework, these models are updated and expanded to reflect emerging power system trends. An ontology for the smart grid is also described, which can be used to model functional and requirements descriptions for actors and equipment across the grid.

2.1 NIST Smart Grid Conceptual Model

The NIST Smart Grid Conceptual Model describes the overall composition of electric grid systems and applications. It is meant to provide a high-level view of the system that can be understood by many stakeholders. Originally introduced in 2010 [33], the Conceptual Model is updated with each Framework revision. The Smart Grid Conceptual Model update in this document (see **Figure 3**) reflects large increases in the number and types of distributed energy resources (DERs) used throughout the grid, the increasing importance and automation of distribution systems, and the role of serviced providers in the Distribution system.

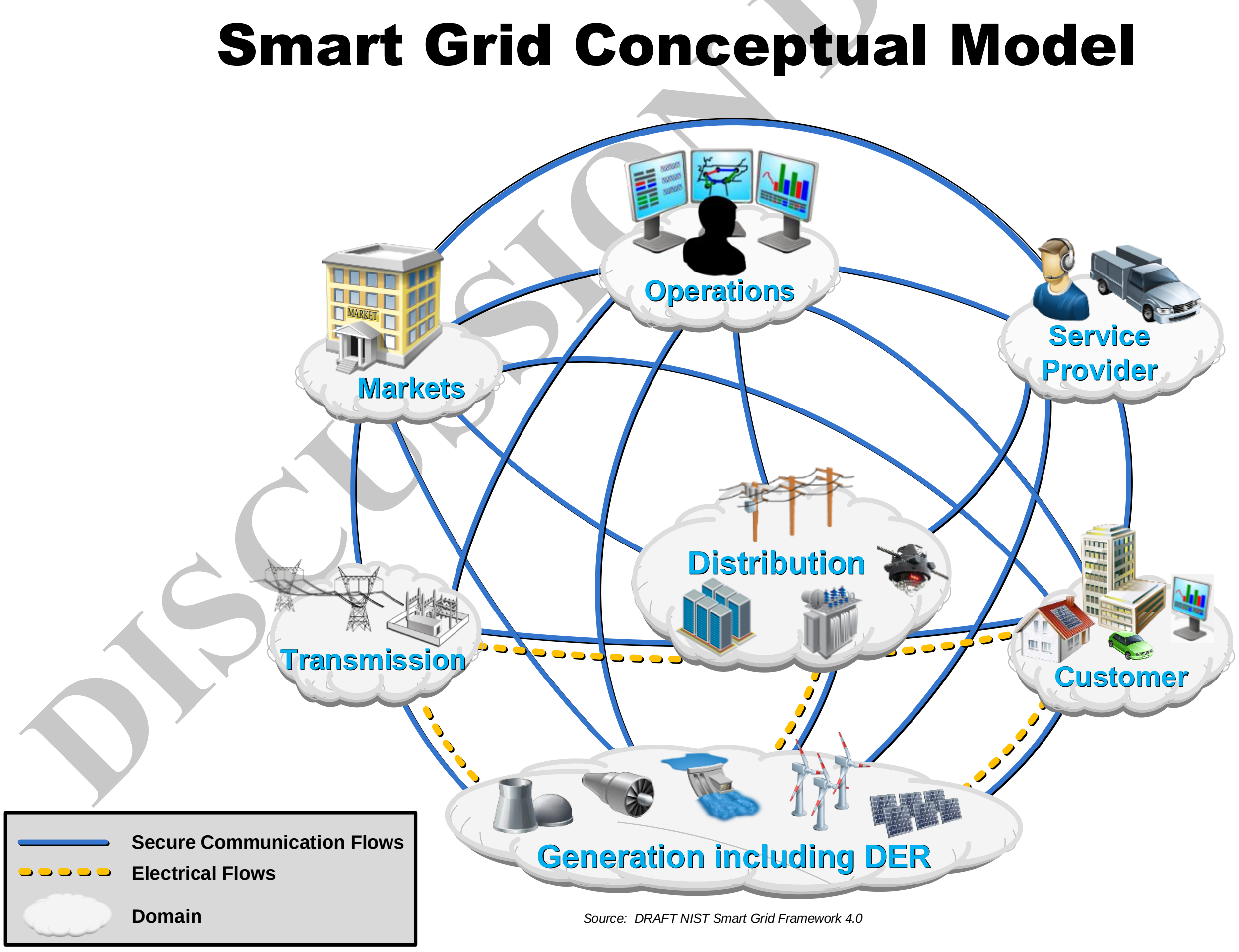

Figure 3 - Updated NIST Smart Grid Conceptual Model

The key concepts derived form the updated Conceptual Model remain broadly similar to those of previous editions. First, the roles and responsibilities for actors and equipment in the electrical grid are a function of the domain in which they are applied. Through this lens we understand that functions required of grid equipment will likely change depending onteh grid context, or domain, in which it is used.[6] Benefits associated with equipment, resource, or action will similarly vary with domain and other context.

Second, the conceptual model reinforces the contrast between the growing complexity of information exchange necessary to operate the grid, and the relatively straightforward physical exchanges of energy that actually are the grid. Producing or consuming electricity still relies on relatively few and simply physical connections, even as energy technologies diversify across the system and grid dynamics become less certain. Conversely, grid communications and data complexity are exploding as people leverage the proliferation of low-cost power electronics, snesors, and microchips to support grid operations through coordinated actions of small-scale and distributed devices—coordination that was once the exclusive purview of large generators in close proximity.[7] Whether to expand coordination of the high voltage system[8] or to prolong the life of existing distribution infrastructure,[9] communication flows are increasing everywhere across the grid.

2.1.1 Conceptual Model Updates

While the high-level concepts contained in the NSIT Smart Grid Conceptual Model have proven robust with time, the grid is also changing rapidly. The Conceptual Model and its derivatives have been updated to reflect many changes throughout the system and explore the associated impact on system interoperability requirements. These changes include:

Generation Domain

Changing scale—the domain name has been updated to *Generation including DER* to explicitly acknowledge the growing diversity in scale and utilization of grid resources.

Technology diversity—the number and types of generation technologies has been expanded, to reflect the growing diversity of U.S. generation assets [8].

Physical siting—the *Generation including DER* domain has been elongated, so that icons representing large scale generation technologies are physically closer to the *Transmission* domain, and smaller scale or more modular technologies are physically closer to the *Distribution* and *Customer* domains.

[6] For example, a photovoltaic system installed at a single-family house may have significantly different operating parameters than ones installed at commercial facilities or used for bulk power generation.
[7] For example, while energy imbalances between supply and demand used to only be managed by dispatching one of two large generators, today the same imbalance could also be addressed through the coordinated actions of many customers and their devices.
[8] For example, the Western Energy Imbalance Market [40]
[9] For example, the Brooklyn Queens Demand Management Project [37]

Customer participation—resources provided by the customer, whether generation or demand management, are included as one of the many resource options available in the *Generation including DER* domain (see **FIGURE XXX**).

Distribution Domain

Expanding role—the *Distribution Domain* has been made larger and placed more centrally within the Conceptual Model to reflect the growing responsibilities distribution systems have for optimizing grid function.

Improved sensing—sensing in distribution systems (represented by the icon of an overhead line fault detection device) is important to improving state awareness, a prerequisite for optimizing grid function.

Controllability and intelligence—computer servers represent the growing availability and use of real-time data for intelligent control of distribution grids.

New actors—historically the province of distribution utilities, service providers and other actors are increasingly providing equipment to and services for the distribution grid as indicated by the new link between the *Distribution* and *Service Provider Domains*.

Customer Domain

Distributed operations—with active energy management possible at the grid edge, operations, control and automation enter the customer domain as represented by the computer monitor replicated from the *Operations Domain*.

Customer diversification—from multi-family dwellings to commercial facilities and campuses, the *Customer Domain* has been updated to reflect many types of customers served by the electrical grid.

Even with these updates, the high-level Conceptual Model shown in **Figure 3** is useful only for exploring the electrical and communications flows *between* grid domains. Much innovation occurs *within* the grid domains, the exploration of which improves understanding of the relationships between technology, communications, and interoperability.

Underlying the Conceptual Model is a legal and regulatory framework that governs many aspects of the electrical grid. These regulations apply to actors and applications, and to their interactions, throughout the system and enable the implementation and management of policies and requirements that keep the power system safe, reliable and cost effective while maximizing the public good. Organizations that adopt these regulations exist at several levels, from federal agencies to public utility commissions at the state and local levels.

The transition to a modern grid introduces new regulatory considerations, which may transcend jurisdictional boundaries and require increased coordination among federal, state, and local lawmakers and regulators. The conceptual model is intended to be a useful tool for regulators at all levels to assess how best to achieve public policy goals that, along with business objectives, motivate investments in modernizing the nation's electric power infrastructure.

2.1.2 Conceptual Model Domains

Each domain—and its sub-domains—in the Conceptual Model describe smart grid conceptual roles and services. They include types of services, interactions, and stakeholders that make decisions and exchange information necessary for performing tasks to achieve system goals, such as: customer and demand response management, distributed generation aggregation, and outage management. Services are performed by one or more roles within a domain. For example, corresponding services may include home automation, distributed energy resource (DER) and customer demand response, load control, and wide-area situational awareness (WASA).

Each of the seven NIST Smart Grid Conceptual Model domains is described in **Table 1**.

Table 1- Domains and Roles/Services in the Smart Grid Conceptual Model

	Domain	Roles/Services in the Domain
1	**Customer**	The end users of electricity. May also generate, store, and manage the use of energy. Traditionally, three customer types are discussed, each with its own sub-domain: residential, commercial, and industrial.
2	**Markets**	The facilitators and participants in electricity markets and other economic mechanisms used to drive action and optimize system outcomes.
3	**Service Provider**	The organizations providing services to electrical customers and to utilities.
4	**Operations**	The managers of the movement of electricity.
5	**Generation Including DER**	The producers of electricity. May also store energy for later distribution. This domain includes traditional generation sources and distributed energy resources (DER). At a logical level, "generation" includes those traditional larger scale technologies usually attached to the transmission system, such as conventional thermal generation, large-scale hydro generation, and utility-scale renewable installations usually attached to transmission. DER is associated with generation, storage, and demand response provided in the customer and distribution domains, and with service provider-aggregated energy resources.
6	**Transmission**	The carriers of high voltage electricity over long distances. May also store and generate electricity.
7	**Distribution**	The distributors of electricity to and from customers. May also store and generate electricity.

To enable smart grid functionality, the roles in a particular domain often interact with roles in other domains, as shown in **Figure 3**. Moreover, as system complexity increases and communications and interoperability expand operational control beyond the locational specificity of physical connections, it is likely that organizations will contain components of multiple domains. For example, the Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs) in North America have roles in both the markets and operations domains. Similarly, a distribution utility is not entirely contained within the distribution domain—it is likely to contain roles in the operations domain, and perhaps also the markets domain as economic signals become more dynamic across the system. Vertically integrated utilities will have roles in many domains.

Appendix A – Smart Grid Conceptual Model Domains provides detailed descriptions and diagrams for each of the NIST Conceptual Model Domains.

2.2 Communication Pathways Scenarios

The updated Smart Grid Conceptual Model provides a high-level set of descriptions adequate to include the broad set of evolving trends in the smart grid. Yet interoperability requirements derive from specific system and device interfaces that are not sufficiently characterized by such high-level depictions. In this section another set of model diagrams—communication pathways diagrams—are provided wherein the domain structure of the conceptual model is used to facilitate a more detailed examination of system interfaces.

The communication pathways scenario diagrams are an update and diversification of earlier mappings drawn to provide a visual reference for legacy applications and logical interfaces within the context of the Conceptual Model. Published in earlier Frameworks, the legacy applications mappings depicted an overarching architecture and provided a static perspective on the range of system and device interfaces. Building on the emerging diversity of grid architectures and associated system interfaces, the logical application model drawing has been updated into a series of Communication Pathways Scenario diagrams to depict specific interfaces and conceptual issues inspired by the Department of Energy's reference grid architectures (see section **1.3.1 The Role of Grid Architecture**).

The architecturally inspired scenarios include:

- Legacy Communication Pathways Scenario
- High-DER Communication Pathways Scenario
- Microgrid Communication Pathways Scenario
- Hybrid Communication Pathways Scenario

These Scenarios are not mutually exclusive. Rather, they represent views of the grid emphasizing various aspects. For example, many actors such as smart meters and advanced distribution systems appear in multiple reference models.

2.2.1 Graphic Conventions

Each Communication Pathways Scenario diagram uses a common set of graphical conventions. For each diagram colored boxes represent Conceptual Model Domains (see **Table 2**), and symbols are used to define actors, gateways, communications paths, and networks (see **Table 3**).

Table 2—Domain Descriptions and Graphical Color Representation

Domain	**Domain Role/Service**	**Color Code**
Operations	The managers of the movement of electricity.	Blue
Markets	The operators and participants in electricity markets i.e. Independent System Operators (ISOs), Regional Transmission Organizations (RTOs), and Distribution System Operators (DSOs).	Purple
Distribution	The distributors of electricity to and from customers.	Light Brown
Transmission	The carriers of bulk electricity over long distances.	Maroon
Generation	Generators of electricity. Includes older generation sources such as coal and other carbon-based fuels, nuclear, hydro as well as distributed energy resources (DERs) such as wind and solar.	Plum
Customer	Electricity users.	Orange
Service Providers	Billing, Information Technology (IT), finance, procurement, regulatory and aggregation functions performed for electric grid stakeholders.	Green

Table 3—Communication Pathways Diagrams Symbol Descriptions

Symbol Name	Description	Symbol
Comm. Network	A communication network carries analog and digital information from a physical location to other locations	
Roles and Actors	Roles perform specific business activities and actors can perform multiple activities.	
Gateway Role	Role that represents a border of the communication network.	
Comms. Path	A communications path shows the route that information flows within a Domain.	
Comms. Path Changes Owner/Domain	A communications path that shows the route that information flows between domains and in some cases between the owners of the information.	

The complexity of some scenario diagrams demands a simplified approach to portraying certain interfaces. When a communication pathway would likely interact with all domain or sub-domain actors in a similar manner, one pathway is drawn that terminates at the (sub-)domain boundary rather than cluttering the diagram with redundant individual communication pathways to each actor. Although prevalent in all scenarios, this technique is most evident in the High-DER Scenario through the simplified interactions of the operations sub-domains with the "Operational Enterprise Service Bus" actor, and also in the simplified interactions of the Internet with each of the domains in **Figure 5**.

2.2.2 The Legacy Communication Pathways Scenario

The Legacy Communication Pathways Scenario (see **Figure 4**) depicts the Conceptual Model mapping to the overarching electric grid architecture from the previous revision of the NIST Interoperability Framework [19]. It serves as a baseline mapping that also depicts a structure representative of current electric grid systems. Domains and sub-domains show logical grouping of systems and applications. For example, transmission systems such as an Energy Management System (EMS) are shown in the transmission operations sub-domain within the operations domain.

The model also shows information flows and communications paths between systems. Communications paths describe interfaces where standards may be helpful in defining the required protocols and characteristics of information exchange, although the depiction in this diagram of any single communication pathway is not in-and-of-itself an indication that NIST supports standardization of that interface.

Sub-domains in the Legacy Scenario are shown to identify typical groupings within the utility business sector. The particular collection of elements (network, roles, actors, and gateway role) helps define a business[10] or department[11] in an illustrative fashion without being exhaustive.

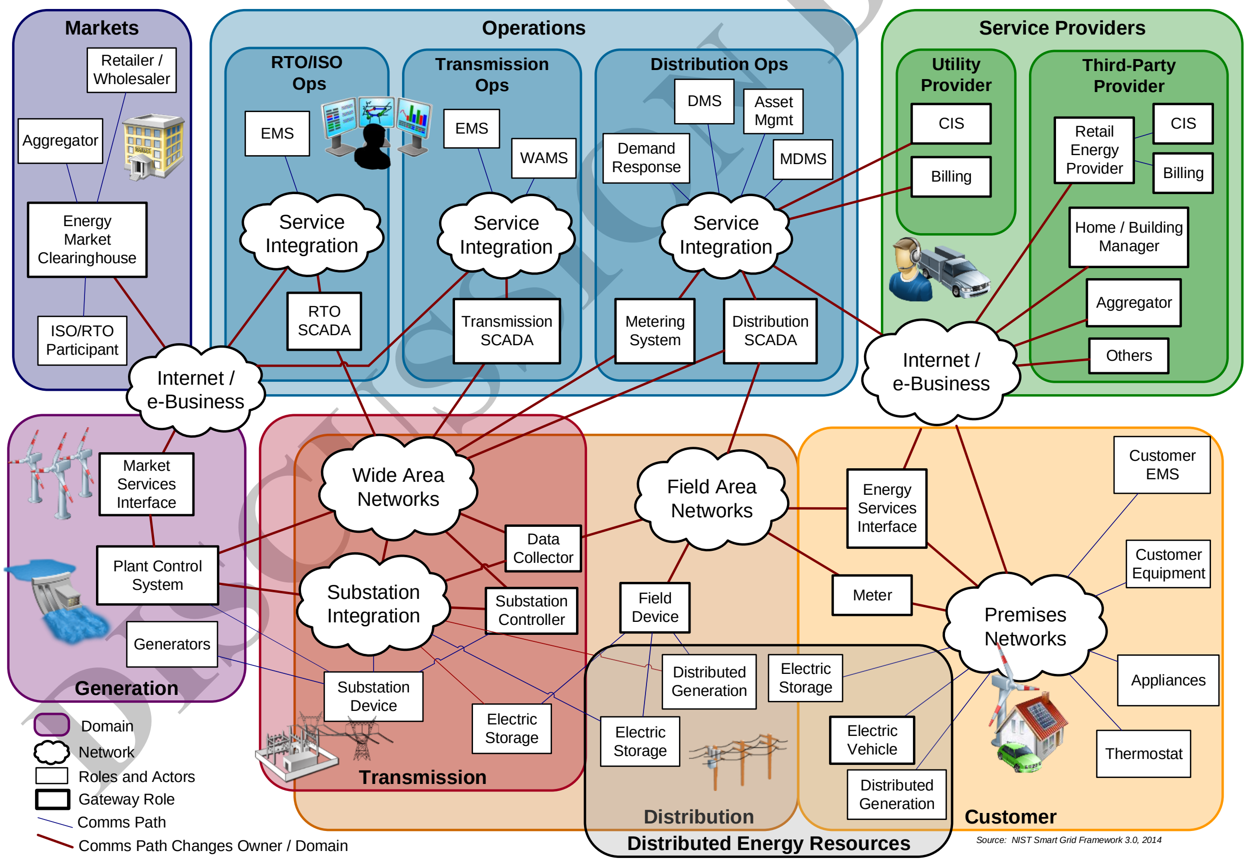

Figure 4—Legacy Communication Pathways Scenario

[10] For example: RTO/ISO, Utility Provider, or Third-Party Provider
[11] For example: Transmission Operations, Distribution Operations

2.2.3 High-DER Communication Pathways Scenario

The High-DER Communication Pathways Scenario (see **Figure 5**) represents current and future grids with DERs providing large amounts of power. In the future, market management functionality may be performed at both the distribution and transmission levels, and market makers such as Distribution System Operators (DSOs) will need to optimize for both economic factors and reliability.

As described in **Overview** and Background **1.1**, large increases in the number of DERs has occurred and are now much more common in electric grids. Distributed energy technologies are therefore not a special class of generation assets, but a typical asset that can use power generation or demand response to participate in balancing supply and demand in the electrical grid. Accordingly, DER assets can reside in numerous domains with numerous operational strategies. Some examples include:

> **Utility-owned DER assets:** These assets reside in the Generation Domain and prioritize supporting conventional markets and grid infrastructure.
>
> **Customer-sited DER assets:** These assets reside in the Customer Domain and may prioritize local or non-utility services or operational strategies over utility priorities. Although sited at the customer premises, these assets may be controlled by customers, third party aggregators, or utilities.

The High-DER Scenario in **Figure 5** depicts a paradigm where market signals can be sent over the Internet to both distribution utilities or DSOs and to customers who own DERs. In this way, non-utility assets can participate and respond to the same market or other economic incentives as conventional resources.

The colocation of customer-sited resources and loads—including demand response—means non-utility DERs could provide multiple services traditionally delivered through utility-owned assets.[12] Importantly, the internet connectivity of DERs in this scenario means the device owner/operator could choose whether to optimize function around local concerns or those of a more regional or global nature.

Another important aspect of this model are the multiple communication pathways for many actors and gateways. While many communication pathways in these scenario diagrams are intended to aid in exploring the characteristics of specific interfaces, the diversity of interfaces and control loops depicted in **Figure 5** instead highlight the complexity of interfaces for single actors, and the possibility for multiple redundant communication loops to yield conflicting information.

Other points of interest for the High-DER Scenario include combining the *RTO/ISO Ops* and *Transmission Ops* sub-domain functions from the Legacy Scenario into a combined Generation & Trans Ops sub-domain. This is done to highlight how market functions in the High-DER

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[12] For example, DERs such as solar photovoltaic or demand response can reduce peak demand during the mid-part of the day while an energy storage asset can supply reactive power.

Scenario may operate at different levels with fewer restrictions than those of the Legacy Scenario *RTO/ISO Ops* grouping.[13]

For this model, the *Gateway, Data Transfer, and IP SCADA Communications* role is placed across the system operations, transmission, and distribution domains, as this aligns with actual deployment and operation. Similarly, the *Cogeneration* actor is placed across the customer, distribution, and generation including DER domains because the scale and specifics of each cogeneration deployment will determine the physical and functional domain alignment.

[13] In the Legacy Scenario *RTO/ISO Ops* functions are limited to cross-region functions on the bulk power system.

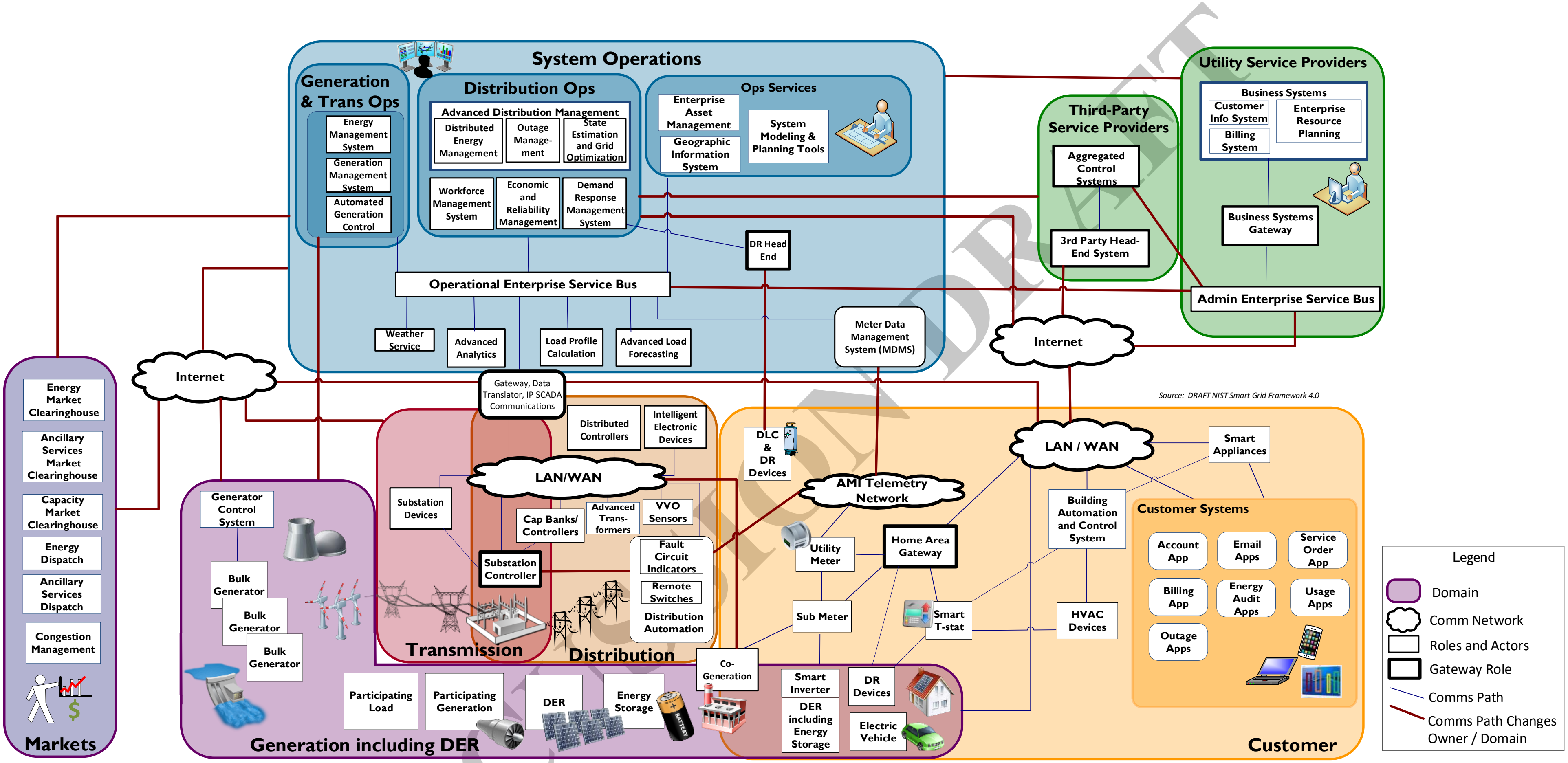

Figure 5—High-DER Communication Pathways Scenario

2.2.4 Hybrid Communication Pathways Scenario

The Hybrid Communication Pathways Scenario shown in **Figure 6** is inspired by the reference model for distribution grid control in the 21st century [41]. It depicts a high DER environment with centralized, distributed (non-centralized) and edge functionality. Grid control devices are in the Transmission and Distribution Domains.

This diagram depicts several concepts worth noting. The first is that each domain has its own edge, so the term grid-edge device immediately becomes context specific. For example, while a customer's grid-edge device may be an appliance that actively manages energy consumption, the edge of a distribution utility's grid is the smart meter behind which the entire customer domain resides. Further, the edge of the transmission grid may be the phasor measurement unit or intelligent electronic device positioned at a substation behind which exist the entire distribution and customer domains. This concept is also applied to distributed assets which lie in between the centralized systems and edge devices.

Another important concept in this diagram is one of parallel communications infrastructures. While the dedicated operational communications network and pathways between the operations domain and actors in the distribution and transmission domain implies a proprietary communications infrastructure, unseen are the implied Internet communications interfaces with each of the remaining actors in the scenario. While a DER, electric vehicle, or remote controllable appliance could be expected to be managed by a system operations domain actor in a high DER environment, it is not necessary that those operational communications utilize the same operational communications network as utility-owned critical infrastructure. This diagram is called the Hybrid Communication Pathways Scenario because it depicts a hybrid approach to operational communications that uses both public and private communication pathways.

A final concept worth noting is that market actors need not be classified as centralized infrastructure. While the classic model of an aggregator may be to bundle distributed resources for sale into centralized markets [42], aggregators can work in decentralized or local markets as can other market actors.

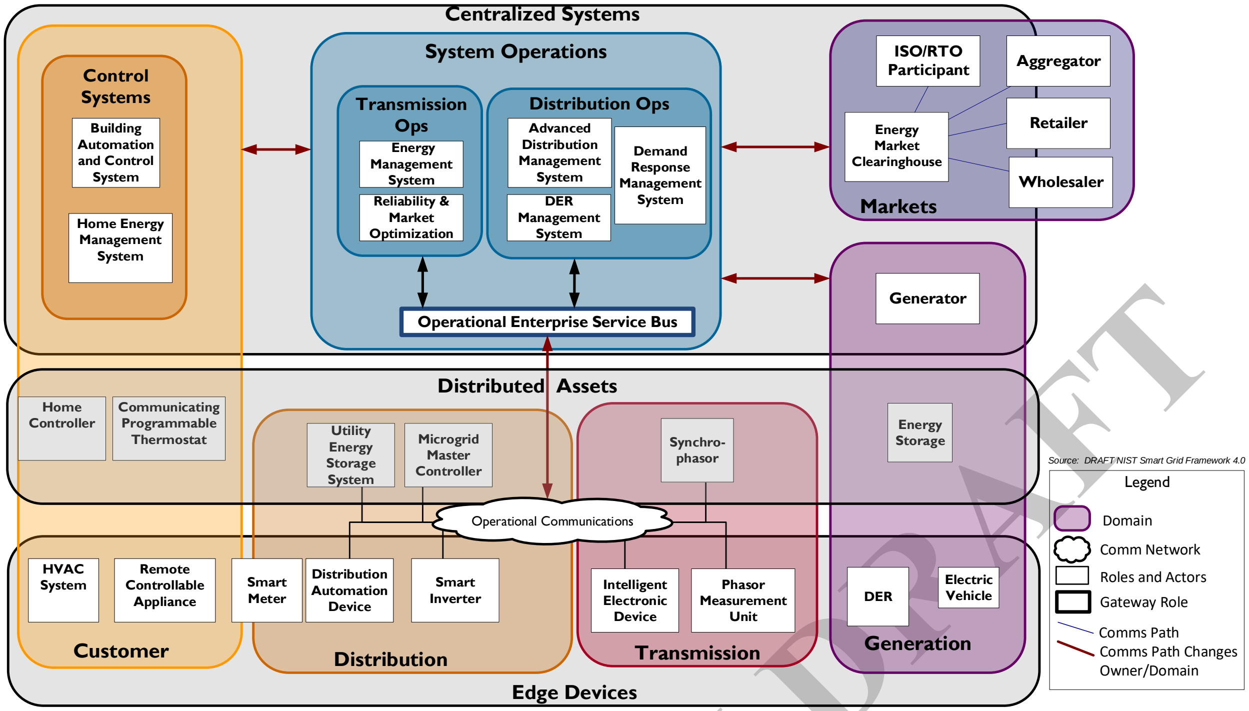

Figure 6—Hybrid Communication Pathways Scenario

2.2.5 Microgrid Communication Pathways Scenario

Microgrids vary in scope ranging from a single premise to those including substations. Ownership and control of microgrids varies, with some owned and operated by consumers and some controlled by utilities that may or may not also own the microgrid. The Microgrid Communication Pathways Scenario depicts two example microgrids, one managed and controlled by a customer, and one managed by a utility.

Microgrids have the ability to isolate the circuits under their control from the main electrical grid. Modern microgrids can also be optimized to support overall grid health or provide specific grid services when operating while connected to the main electrical grid. Although managed by different entities, both types of microgrids are used primarily to improve reliability. In particular, microgrids are often deployed in situations where mission critical functions require power to be available at all times.

The principal difference between the customer- and utility-managed microgrids is in determining which communication pathways change domains and/or transition between assets with different owners. Communication pathways that change owner or domain—colored brown in **Figure 7**—are more likely to benefit from interoperability standardization.

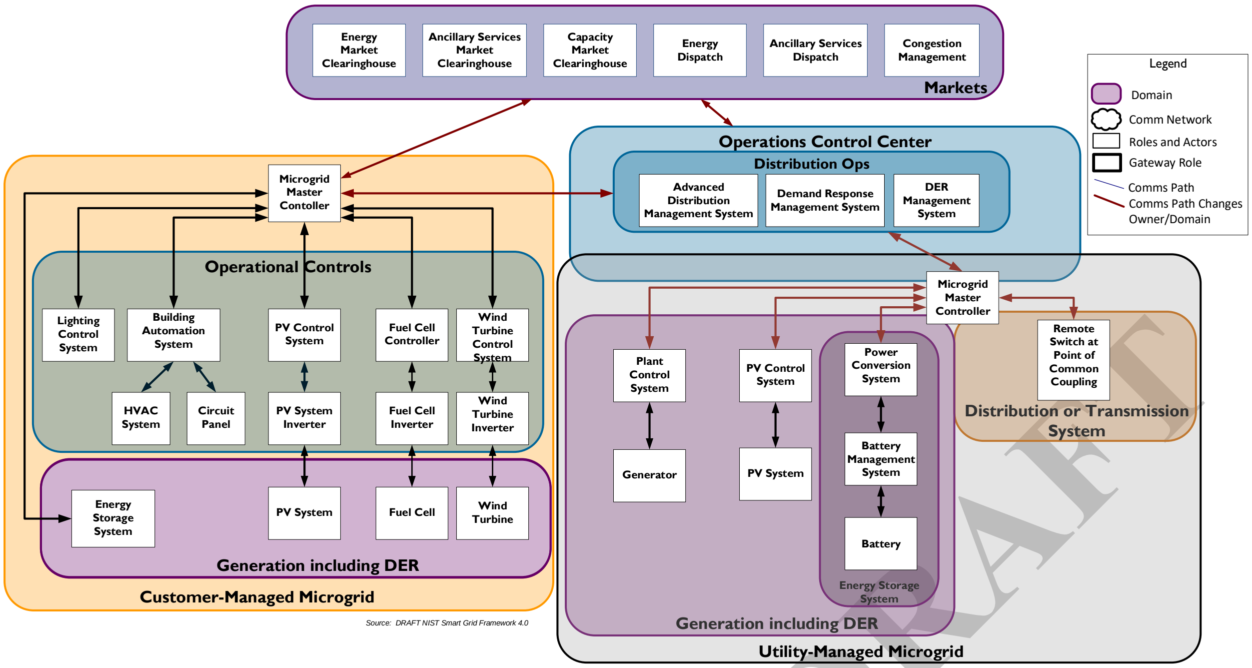

Figure 7—Microgrid Communication Pathways Scenario

2.3 An Ontology for the Smart Grid

The electrical grid has been called the greatest engineering achievement of the 20th century [43]. Beyond the sheer scale of the infrastructure, electrical grids are complex systems of systems (SoS) in which mechanical, electro-mechanical, and electronic control devices must all work together in near-real time with human oversight and intervention to produce and manage the electricity critical to modern society [4]. Relying on engineered interactions between physical and computational components also means the electrical grid is a cyber-physical system [39], and because the grid only works when numerous systems operate in parallel[14] the electrical grid is actually a multi-layered cyber-physical SoS. The design and engineering of advanced cyber-physical systems such as the smart grid can be so complex that existing approaches for performance prediction, measurement, management, and assurance are often inadequate.

In short, the electrical grid is an impossibly large and complex marvel. And yet despite this complexity, the language we use to describe the grid is often obtuse and lacks the clarity necessary to describe the specific capabilities that enable a complex SoS to operate.[15] Even the term interoperability belies the complex series of interactions and requirements necessary to exchange actionable information (see Testing & Certification Chapter). A common understanding of the relationship between individual component capabilities and the functions of the broader electrical system could improve our ability to communicate between stakeholder groups regarding objectives, concerns, and strategies for grid modernization.

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[14] For example, the transmission SoS is operated in parallel to the distribution system, which is also a SoS whose components include system operators, switches, distribution lines, and advanced inverters.

[15] For example, popular media will use catch-all phrases like "intelligent grid" [44] to describe any number of complex interactions and developing system capabilities, and the term "grid modernization" on the regulatory arena can mean anything from advanced metering to utility business model reform to microgrids and demand response [45].

Yet any pursuit of a common set of terms, or ontology,[16] for the electrical grid must address the fact that the grid is not an isolated system. Indeed, electricity is the preferred energy carrier for modern society, and as a key enabling critical infrastructure the grid serves a great number of other systems—including many that are life-critical [17]. The electrical grid is therefore but one domain in the broader universe of cyber-physical systems.

Current design and management approaches for these broader systems are often domain-specific, resulting in redundant efforts that lack the robust, formal methods for design, evaluation, verification, and validation. Any ontology developed for the electrical grid should be consistent with those ontologies already developed for other cyber-physical systems; doing so would improve interactions and enable co-optimization of the grid with the other systems it serves.

2.3.1 The NIST Framework for Cyber-Physical Systems

NIST's 2017 Framework for Cyber-Physical Systems [39] provides a useful analysis methodology and template for developing ontologies to describe key features of cyber-physical systems (CPS). Facets and Aspects are core concepts to this methodology.

> **Facets** are inclusive of all system engineering processes (conceptualization, realization, and assurance), and can be thought of as "modes of thinking" about a CPS.
>
> **Aspects** are groupings of stakeholder concerns along functional, business, human, trustworthiness, timing, data, composition, boundaries, and lifecycle concerns.

As seen in **Figure 8**, the CPS Framework's methodology provides holistic concern-driven input to guide the development of the set of activities and artifacts, regardless of the specific systems engineering approach used. In this implementation, the *Domains* represent different application areas of CPS,[17] including smart grid (Energy).

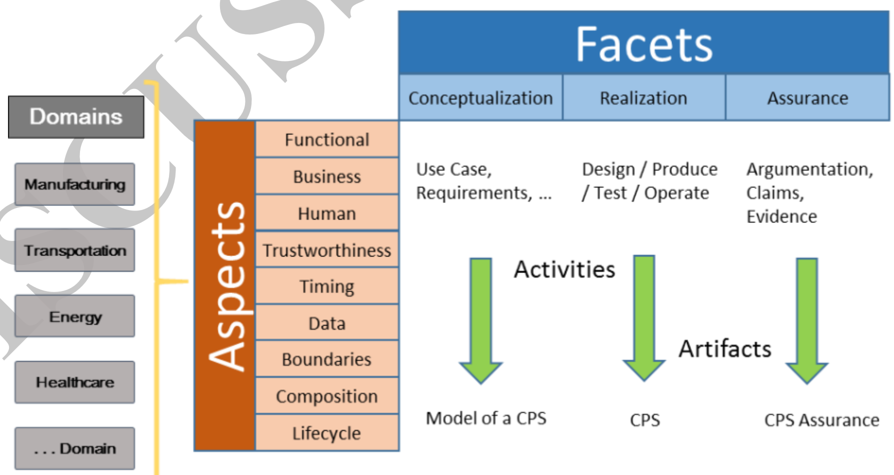

Figure 8—CPS Framework Domains, Facets, and Aspects [39]

[16] An ontology is a set of concepts and categories in a subject area or domain that shows their properties and the relations between them [46].
[17] The logical relationship between the "domains" in **Figure 8** and the Smart Grid Conceptual Model domains which describe roles and services within the grid is that changing the CPS application domain (e.g., from energy to healthcare) fundamentally alters participant roles and procured services within that system, just as the *Distribution* to the *Markets* domains of the Smart Grid Conceptual model have different participant roles and procured services.

2.3.2 The Aspects of a Modern Electrical Grid

An electrical grid is an energy-domain application of a CPS, so the aspects of a CPS shown in **Figure 8** also apply to the grid. A modernized electrical grid aligns to the cyber-physical framework's aspects as follows:

> **Functional —** Concerns about function, including sensing, actuation, control, and communications, accurately describe grid modernization issues. For example, one grid modernization functional aspect concern relates to the impact incorporating DERs on electrical distribution grids will have on the sensing, control, and communications requirements of existing systems.
>
> **Business —** Concerns about enterprise, time to market, environment, regulation, cost, and other business areas. For the electric grid, a key business aspect concern involves the ability to design markets to optimize energy costs as many locations transition from regulated monopoly markets.
>
> **Human —** Concerns about human interaction with and as part of a CPS. An important human aspect concern is whether human-in-the-loop system operators will be able to effectively manage a grid with potentially millions of new distributed generation devices not under their direct control.
>
> **Trustworthiness —** Concerns about trustworthiness of CPS including security (cybersecurity and physical security), privacy, safety, reliability, and resilience. Addressing these concerns, including understanding and managing their interrelationships, is fundamental to the electric grid. Thus the trustworthiness aspect should be considered as a key driver for grid modernization, including through its impact on development of grid architectural principals.
>
> **Timing —** Concerns about time and frequency signals, including the generation and transport of time and frequency signals, timestamping, managing latency, and timing composability. Timing aspect concerns reflect the real-time nature of electricity generation, transmission, distribution, and use, and have long been addressed by the electric industry through many existing electrical grid timing standards.[18]
>
> **Data —** Concerns about data interoperability including fusion (situational awareness), data definitions (metadata), privacy, quality, type and identity. Data interoperability is a key concern of the electric grid as evidenced by international standards such as IEC-61850 which defines configuration data for electric substation Intelligent Electronic Devices (IEDs). In addition, data accuracy, timeliness, and availability are crucial to data analytics ability to improve grid operation.
>
> **Boundaries —** Concerns related to topological, functional, and organizational demarcations and interactions. For electrical utilities, a persistent boundary aspect concern is the friction between organizational siloes which must be

[18] For example, IEEE 1588-2008 *Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems* [47]

integrated in order to maximize the operational efficiency of the grid. Examples include the boundaries between Information Technology (IT) and Operational Technology (OT) organization groups.

Composition — Concerns related to the ability to construct new systems from existing CPS systems. For electrical utilities, a current composability concern is how to effectively replace newly constructed control systems that combine Outage Management System (OMS) and Distribution Management System (DMS) features. Another key composition aspect concern is the ability to integrate utilty control systems with user-owned and controlled DER assets.

Lifecycle — Concerns related to the management and maintenance of CPS systems and components throughout their lifecycle, including design, deployment, operation, enhancement, and ultimately disposal. For electrical utilities, lifecycle concerns include the need to maintain system and component performance time periods as expectations of system lifetimes are often measured in decades rather than years.[19] Another lifecycle concern is the need to manage increased repetitive usage of grid control devices such as tap changes which may need to operate much more frequently to control voltage changes induced by modern loads and distributed generation. A further lifecycle aspect concern is how to upgrade firmware in existing devices to support new features such as the ability of advanced inverters to control voltage and frequency.

2.3.3 Aspects and Concerns of the Electrical Grid

The CPS Framework "aspects" and "concerns" apply to all cyber-physical domains and can be mapped to a modern electric grid. The first step in this mapping is to evaluate the grid context for the existing set of CPS concerns, and if necessary to clarify the description of the CPS concern in the context of the electric grid. The results of this exercise are presented in **Table 11** of **Appendix B**—Mapping CPS Aspects and Concerns to the Electrical Grid.

CPS concerns relate directly to system performance, and the domain-driven context for these concerns characterizes the relationship between the concern and system function. The relationships between these concepts form the basis of a system ontology. In **Table 11**, the "Architecture Significance" column provides some examples of how each concern relates to activities or emerging trends in power systems as well as changes that could arise as new architectures are introduced. The architecture significance column therefore may help clarify the importance of CPS concerns to the electrical grids of today and tomorrow.

[19] The average age of power plants is over 30 years [48].

3 Appendix A – Smart Grid Conceptual Model Domains

3.1 Customer Domain

The customer is ultimately the stakeholder that the entire grid was created to support. This is the domain where electricity is consumed, but is increasingly a domain where electricity is actively managed and generated as well (see **Figure 9**). Actors in the *Customer* domain enable customers to manage their energy usage and generation. Some actors also provide control and information flow between the *Customer* domain and the other domains. The boundaries of the Customer domain are typically considered to be the utility meter and the energy services interface (ESI). The ESI provides a secure interface for utility- or service provider-to-customer interactions. The ESI in turn can act as a bridge to facility-based systems, such as a building automation system (BAS) or a customer's premise management system.

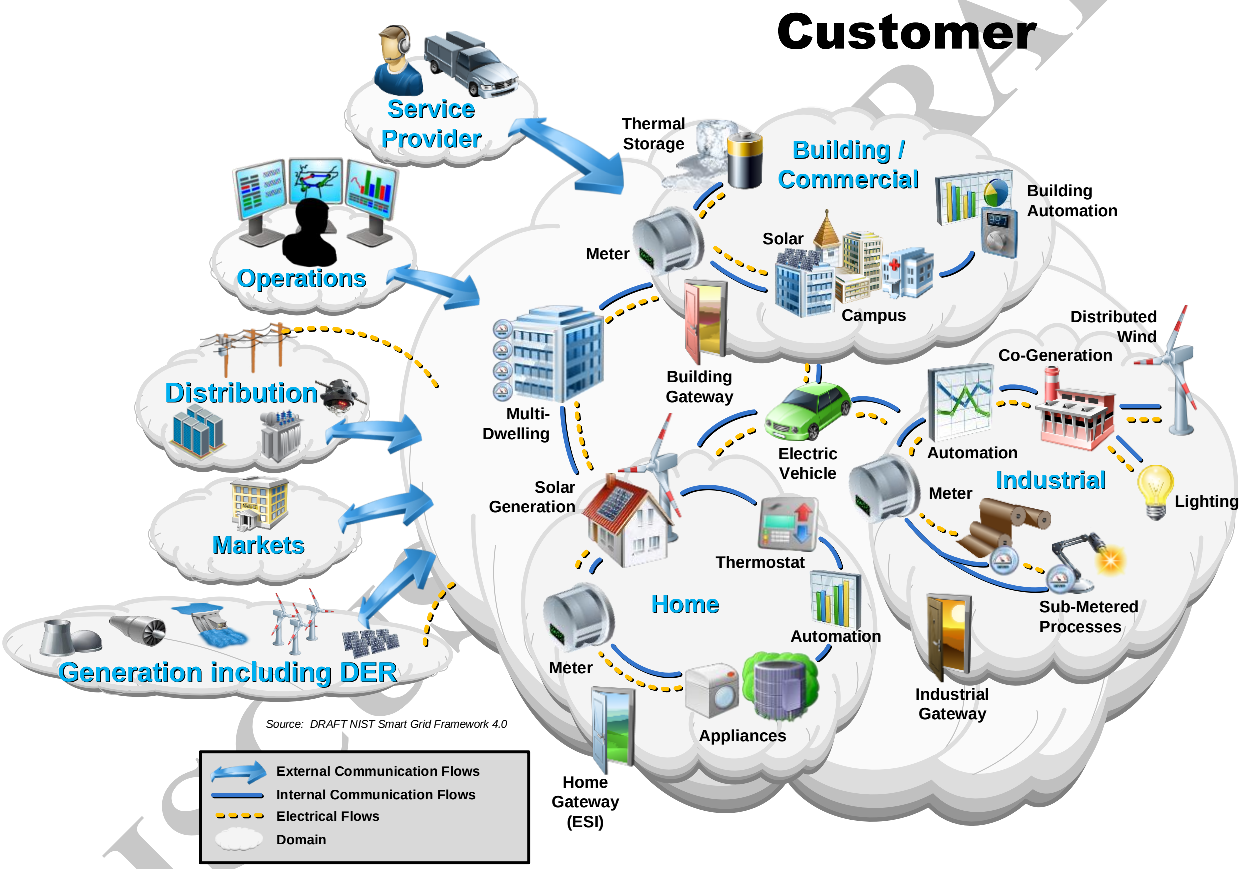

Figure 9—Overview of the Customer domain

The Customer domain is usually segmented into sub-domains for home, building/commercial, and industrial. The energy needs of these sub-domains are typically less than 20kW of demand for a residence,[20,21] 20-200 kW for commercial buildings, and over 200kW for industrial. Each sub-domain has multiple actors and applications, which may also be present in the other sub-domains.

[20] Most residences have either 100A or 200A service, or 24kVA and 48kVA maximum, respectively, at 240VAC. A single EV can introduce loads up to 2.4kVA (Level 1) or 19.2kVA (Level 2) when running at maximum output.
[21] Peak demand for large multi-family dwellings can exceed 1MW, although the per-residence energy consumption can be 60% less than that of single family homes [49].

Each sub-domain has a meter actor and includes an energy services interface (ESI), which is the primary service interface to the *Customer* domain. The ESI may reside at an end-device, in a premise-management system, in the meter, or outside the premises, and may communicate with other domains via the advanced metering infrastructure (AMI) or other means, such as the internet. The ESI provides the interface to devices and systems within the customer premises, either directly or via a home area network (HAN), other local area network (LAN), or some other mechanism in the future.

There may be more than one communications path per customer. Entry points may support applications such as remote load control, monitoring and control of distributed generation, in-home display of customer usage, reading of non-energy meters, and integration with building management systems and the enterprise. They may provide auditing/logging for cybersecurity purposes.

In this revision, the *Customer* domain is electrically connected to the *Distribution* and *Generation Including DER* domains. This reflects the potential to connect, in a behind the meter fashion, up to the service rating of DER (up to 320A, nominally for single-phase services), as well as the potential for community energy storage and other DER connected to the distribution system. This diversity in scale and siting highlights a challenge in slotting DER into a specific role within the Conceptual Model, as DERs satisfy different needs depending upon the point of connection.

This *Customer* domain communicates with the *Generation including DER*, *Distribution*, *Operations*, *Market*, and *Service Provider* domains. Examples of typical application categories in the *Customer* domain are in **Table 4**.

Table 4—Typical application categories in the Customer domain

Example Application Category	Description
Building or Home Automation	A system that is capable of controlling various functions within a building, such as lighting, temperature control and appliance usage.
Industrial Automation	A system that controls industrial processes such as manufacturing or warehousing. These systems have very different requirements compared to home and building systems.
Micro-generation	Includes all types of distributed generation including: solar, wind, and hydroelectric generators. This generation harnesses energy for electricity at a customer location. May be monitored, dispatched, or controlled via communications.
Storage	Means to store energy that may be converted directly or through a process to electricity. Examples include thermal storage units, and batteries (both stationary and electric vehicles)

3.2 Markets Domain

Markets are where grid assets and services are bought and sold.[22] Some markets yet to be created may be instrumental in defining the smart grid of the future, particularly with DER and aggregated DER.[23] Entities in the *Markets* domain exchange price information and balance supply and demand within the power system (see **Figure 10**). The boundaries of the *Markets* domain include the edge of the *Operations* domain where control happens, the domains supplying assets (*Generation including DER*, *Transmission*, and *Distribution*), the *Service Provider* domain, and the *Customer* domain. In short, the *Markets* domain interfaces with all domains of the smart grid.

Communication flows between the *Markets* domain and the domains supplying energy are critical because efficient matching of production with consumption is dependent on markets or their proxies. Energy supply domains include the *Generation Including DER*—and more recently the *Customer*—domains. The North American Electric Reliability Corporation (NERC) Critical Infrastructure Protections (CIP) standards consider suppliers of more than 300 megawatts to be bulk generation; most DER is smaller and is typically served through aggregators.

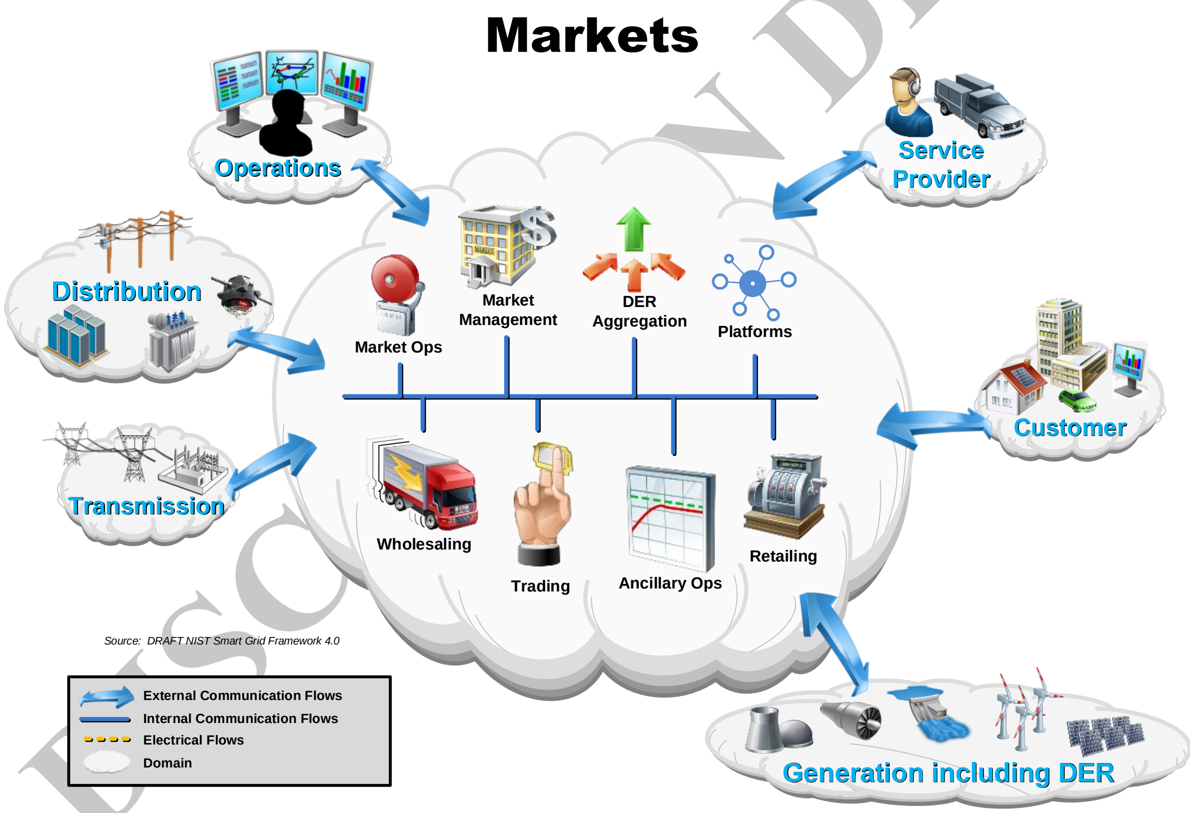

Figure 10—Overview of the Markets domain

DERs have an active and growing role in several wholesale markets through aggregation, and will participate to a greater extent as the smart grid becomes more interactive. Hyper-local markets based on peer-to-peer principles such as Transactive Energy have been demonstrated to

[22] Entities within the electric power sector have engaged in markets for inputs such as equipment, labor, and fuel since the outset of the sector's development.
[23] Some utilities utilize market concepts to determine the avoided operational and infrastructure costs associated with deploying DER on their grid.

work for a variety of applications and services, and appear poised to significantly expand the design and role of market interactions with the *Customer* domain. This is in addition to the active and growing role that DER, via aggregation, will have in wholesale markets.

This revision of the *Markets* domain introduces the “Platform” icon to represent emerging opportunities for interactions among nontraditional grid actors to create value. Fundamentally markets are formed of sets of actors, which collectively establish the price of goods and services [50]. Advances in information and communication technologies have reduced the costs of coordinating and facilitating many types of trades, uncovering new economic opportunity as falling transaction costs improve the value propositions offered by entities at the edge of the grid. Organizational structures such as platforms are increasingly pivotal to the erosion of transaction costs and the formation of decentralized markets for services. The economic potential for the emergence of distribution level platforms is growing with the number and diversity of organizations attempting to pursue opportunities on the electric grid [28].

A major uncertainty remains the relationship between wholesale markets and distribution markets, including the information flows between market operators and participants at each level. The economic fundamentals and legal structures governing market activities and price levels in each market segment (retail and wholesale) co-evolve over time. That is, prices in distribution level markets influence wholesale prices, and vice versa.

Conventionally, prices are determined by rate designs and tariffs adopted by the applicable regulatory authority. These rates include flat rate, time of use rates, or other more dynamic rate designs, such as real time pricing. Rates are primarily a means by which the utility recovers its authorized revenue requirement. Furthermore, rates can also provide a signal to customers on when it is more or less costly to consume electricity thereby encouraging customers to shift consumption to other hours. Emerging technologies that can dynamically and autonomously interpret customer preferences while responding to signals of price, resource availability, and service provision will enable customers to adopt more active strategies for engaging with the electric grid.

Communications for *Markets* domain interactions must be reliable, traceable, and auditable. Also, these communications must support e-commerce standards for integrity and nonrepudiation. As the percentage of energy supplied by small DER increases, requirements for the allowed latency in communications with these resources will have to be formally established.

The high-priority challenges in the *Markets* domain are: extending price and DER signals to each of the *Customer* sub-domains; simplifying market rules; expanding the capabilities of aggregators; ensuring interoperability across all providers and consumers of market information; managing the growth (and regulation) of retailing and wholesaling of energy; providing access to actionable data about the customer and the grid to support these new technologies and resources; and evolving communication mechanisms for prices and energy characteristics between and throughout the *Markets* and *Customer* domains.

Table 5—Typical Applications in the Markets domain

Example Application	Description
Market Management	Market managers include ISOs for wholesale markets or New York Mercantile Exchange (NYMEX)/Chicago Mercantile Exchange (CME) for forward markets in many ISO/RTO regions. Markets can be used to identify transmission, resource, capacity, and other service needs. These markets may also treat non-traditional resources, like storage and demand response, similar to traditional dispatchable generation.
Retailing	Retailers sell power to end-customers and may in the future aggregate or broker DER between customers or into the market. Most are connected to a trading organization to allow participation in the wholesale market.
DER Aggregation	Aggregators combine smaller participants (as providers, customers, or curtailment) to enable distributed resources to participate in the larger markets.
Trading	Traders are participants in markets, which include aggregators for provision, consumption, curtailment, and other qualified entities. There are a number of companies whose primary business is the buying and selling of energy.
Market Operations	Market operations make a particular market function smoothly. Functions include financial and goods-sold clearing, price quotation streams, audit, balancing, and more.
Ancillary Operations	Ancillary operations provide a market to provide frequency support, voltage support, spinning reserve, and other ancillary services as defined by FERC, NERC, and the various ISOs. These markets normally function on a regional or ISO basis, although local implementations may become more prevalent as new capabilities continue to be introduced to the *Distribution* and *Customer* domains.
Platform	A governance structure or mechanism for connecting potentially diverse organizations and actors that seek to create and deliver value through interaction (including interoperation).

3.3 Service Provider Domain

Actors in the Service Provider domain perform services to support the business processes of power system producers, distributors, and customers (see **Figure 11**). These business processes range from traditional utility services, such as billing and customer account management, to enhanced customer services, such as management of energy use and home energy generation.

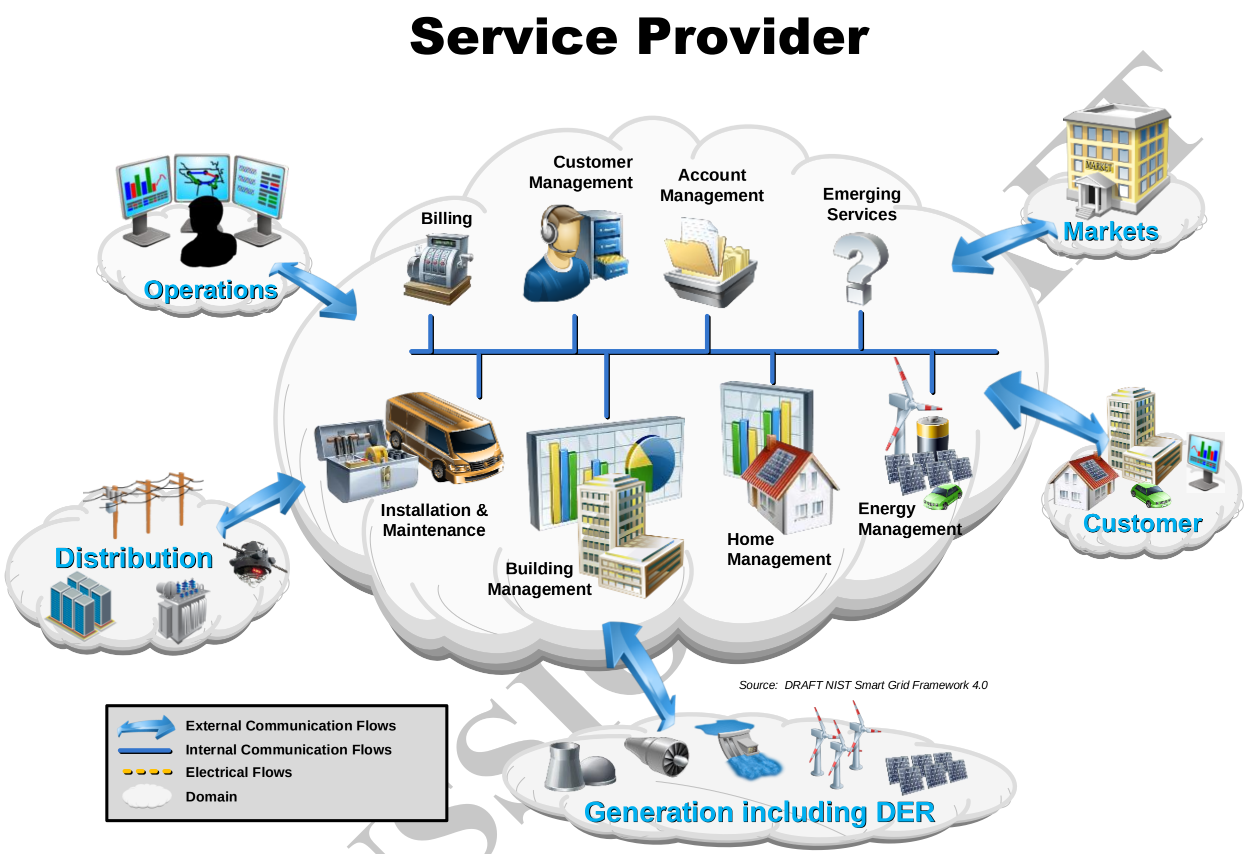

Figure 11—Overview of the Service Provider domain

Service providers create new and innovative services and products to meet the requirements and opportunities presented by the evolving smart grid. Services may be performed by the electric service provider, by existing third parties, or by new participants drawn by new business models. Emerging services represent an area of significant new economic growth.

The priority challenge in the Service Provider domain is to develop key interfaces and standards that will enable a dynamic market-driven ecosystem while protecting the critical power infrastructure. These interfaces must be able to operate over a variety of networking technologies while maintaining consistent messaging semantics. The service provider must not compromise the cybersecurity, reliability, stability, integrity, or safety of the electrical power network when delivering existing or emerging services.

The *Service Provider* domain is updated here to include an explicit focus on system-level issues that keep the electrical grid running. Where earlier versions of the *Service Provider* domain focused on managing specific assets and functions for their customers,[24] this revision reflects the expanding focus of third-party and other service providers towards co-optimizing energy and infrastructure requirements across multiple customers and value streams.[25] The introduction of an energy management icon and communications flows with additional domains reflects the expanding service provider roles.

The *Service Provider* domain shares interfaces with the *Generation including DER*, *Distribution*, *Markets*, *Operations*, and *Customer* domains. Communications with the *Operations* domain are critical for system control and situational awareness; communications with the *Markets* and *Customer* domains are critical for enabling economic growth through the development of "smart" services. For example, the *Service Provider* domain may provide the interface enabling the customer to interact with the market.

The addition of communications to the *Distribution* and *Generation including DER* domains reflects the importance of higher DER penetration into utility portfolios, a condition that is likely under all regulatory and market structures given the scalability and rapidly declining costs of many distributed energy technologies [53]. Regardless of whether these new communication flows are from connecting directly to a single large DER or to an aggregation of DERs behind an interface in the *Distribution* or *Customer* domains, these connections represent new challenges for system actors.

Some benefits to the service provider domain from the deployment of the smart grid include:

- The development of a growing market for non-utility providers to provide value-added services and products to customers, utilities, and other stakeholders at competitive costs;
- The decrease in cost of business services for other smart grid domains;
- A decrease in power consumption and an increase in power generation as customers become active participants in the power supply chain; and
- Better aligning consumption with service conditions, such as price or scarcity, and shifting consumption to optimize the operation of the electric grid.

[24] For example, managing a building or facility for a commercial or residential customer, or certain functions such as customer account management for utility customers.
[25] As value and benefits for third-party-managed DERs like storage are stacked, the focus and interactions of service providers will naturally expand beyond traditional single-customer relationships [51]. Furthermore, as third-party service providers assume larger roles in retail energy services, the provider's responsibility to manage impacts on grid infrastructure will grow [52].

Table 6—Typical Applications in the Service Provider domain

Example Application	Description
Customer Management	Managing customer relationships by providing point-of-contact and resolution for customer issues and problems.
Installation & Maintenance	Installing and maintaining premises equipment that interacts with the smart grid.
Building Management	Monitoring and controlling building energy and responding to smart grid signals while minimizing impact on building occupants.
Home Management	Monitoring and controlling home energy and responding to smart grid signals while minimizing impact on home occupants.
Energy Management	Managing assets—often sited at multiple locations—to co-optimize for requirements and objectives at multiple scales and for multiple customers.
Billing	Managing customer billing information, including providing billing statements and payment processing.
Account Management	Managing the supplier and customer business accounts.

3.4 Operations Domain

Actors in the *Operations* domain are responsible for the smooth operation of the power system. Today, the majority of these functions are the responsibility of a regulated utility (see **Figure 12**).

The smart grid will enable more of these functions to be provided by service providers. No matter how the *Service Provider* and *Markets* domains evolve, there will still be functions needed for planning and operating the service delivery points of a regulated "wires" company.

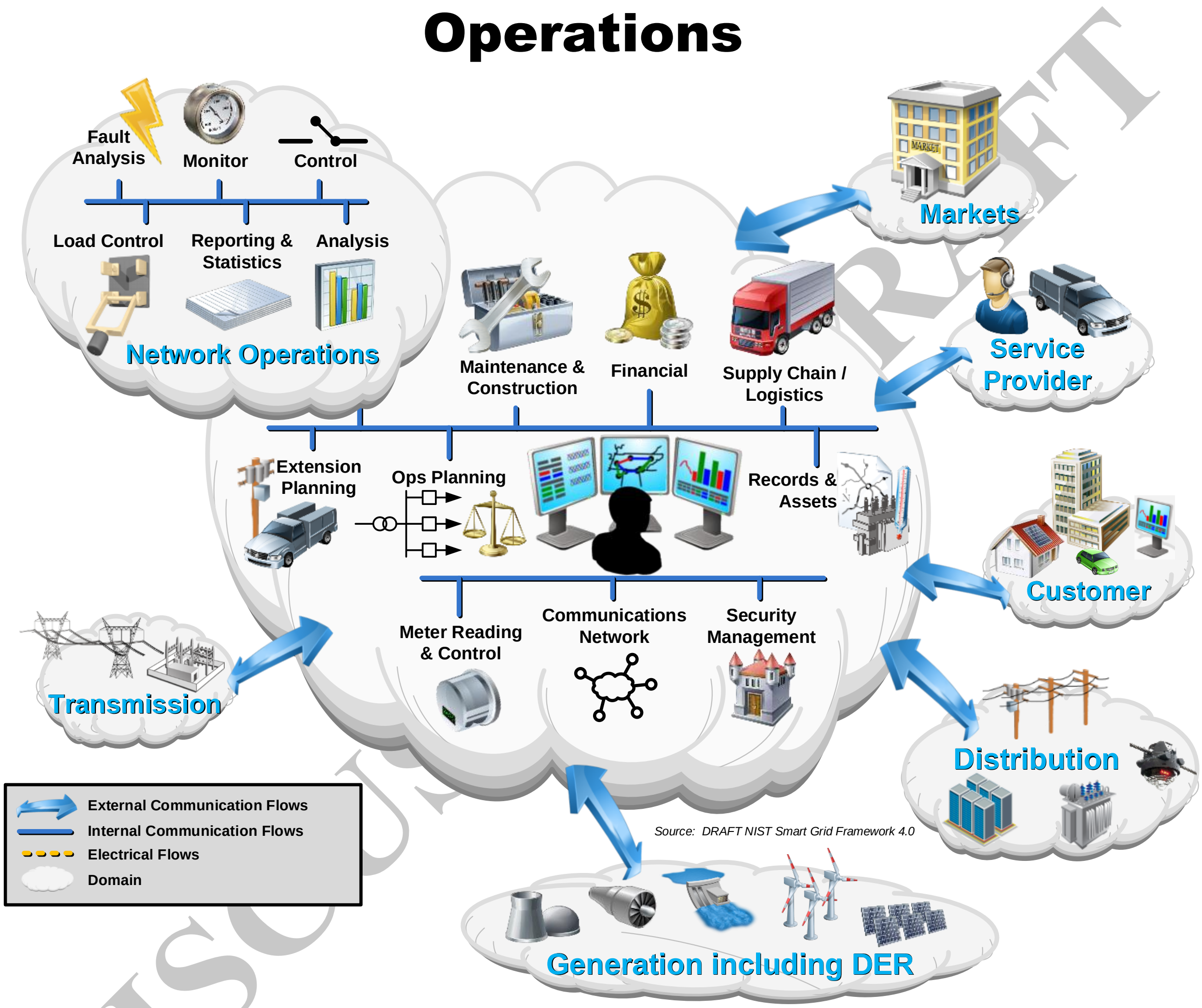

Figure 12—Overview of the Operations Domain

Currently, at the physical level, various energy management systems are used to analyze and operate the power system reliably and efficiently. The *Operations* domain is updated here to include communication flows with the *Generation Including DER* domain to highlight the importance of resource awareness—including for DERs—in state awareness.

Representative applications within the *Operations* domain are described in (**Table 7**). These applications are derived from the International Electrochemical Commission (IEC) 61968-1 Interface Reference Model (IRM) for this domain.

Table 7—Typical applications in the Operations domain

Example Application	**Description**
Monitoring	Network operation monitoring roles supervise network topology, connectivity, and loading conditions, including breaker and switch states, as well as control equipment status and field crew location and status.
Control	Network control is coordinated by roles in this domain. They may only supervise wide area, substation, and local automatic or manual control.
Fault Management	Fault management roles enhance the speed at which faults can be located, identified, and sectionalized, and the speed at which service can be restored. They provide information for customers, coordinate workforce dispatch, and compile information statistics.
Analysis	Operation feedback analysis roles compare records taken from realtime operation related with information on network incidents, connectivity, and loading to optimize periodic maintenance.
Reporting and Statistics	Operational statistics and reporting roles archive online data and perform feedback analysis about system efficiency and reliability.
Network Calculations	Real-time network calculations roles (not shown) provide system operators with the ability to assess the reliability and security of the power system.
Training	Dispatcher training roles (not shown) provide facilities for dispatchers that simulate the actual system they will be using.
Records and Assets	Records and asset management roles track and report on the substation and network equipment inventory, provide geospatial data and geographic displays, maintain records on non-electrical assets, and perform asset-investment planning.
Operation Planning	Operational planning and optimization roles perform simulation of network operations, schedule switching actions, dispatch repair crews, inform affected customers, and schedule the importing of power. They keep the cost of imported power low through peak generation, switching, load shedding, DER or demand response.
Maintenance and Construction	Maintenance and construction roles coordinate inspection, cleaning, and adjustment of equipment; organize construction and design; dispatch and schedule maintenance and construction work; and capture records gathered by field technicians inform and perform their tasks.
Extension Planning	Network extension planning roles develop long-term plans for power system reliability; monitor the cost, performance, and schedule of construction; and define projects to extend the network, such as new lines, feeders, or switchgear.
Customer Support	Customer support roles help customers to purchase, provision, install, and troubleshoot power system services. They also relay and record customer trouble reports.
State Estimation	A process by which Network Calculation algorithms are applied to real-time measured parameters across the electrical grid to produce the information necessary to operate and optimize the system.

3.5 Generation Including DER Domain

Electricity generation is the process of creating electricity from other forms of energy and is the first process in delivering electricity to customers. This conversion may include a wide variety of primary energy resources and conversion technologies ranging from chemical combustion and nuclear fission, to flowing water, wind, solar radiation, and geothermal heat. As the primary electricity supply for the electrical grid, the *Generation Including DER* domain is electrically connected to the *Transmission* or *Distribution* or *Customer* domain, and shares communications interfaces with the *Operations*, *Markets*, *Transmission*, and *Distribution* domains.

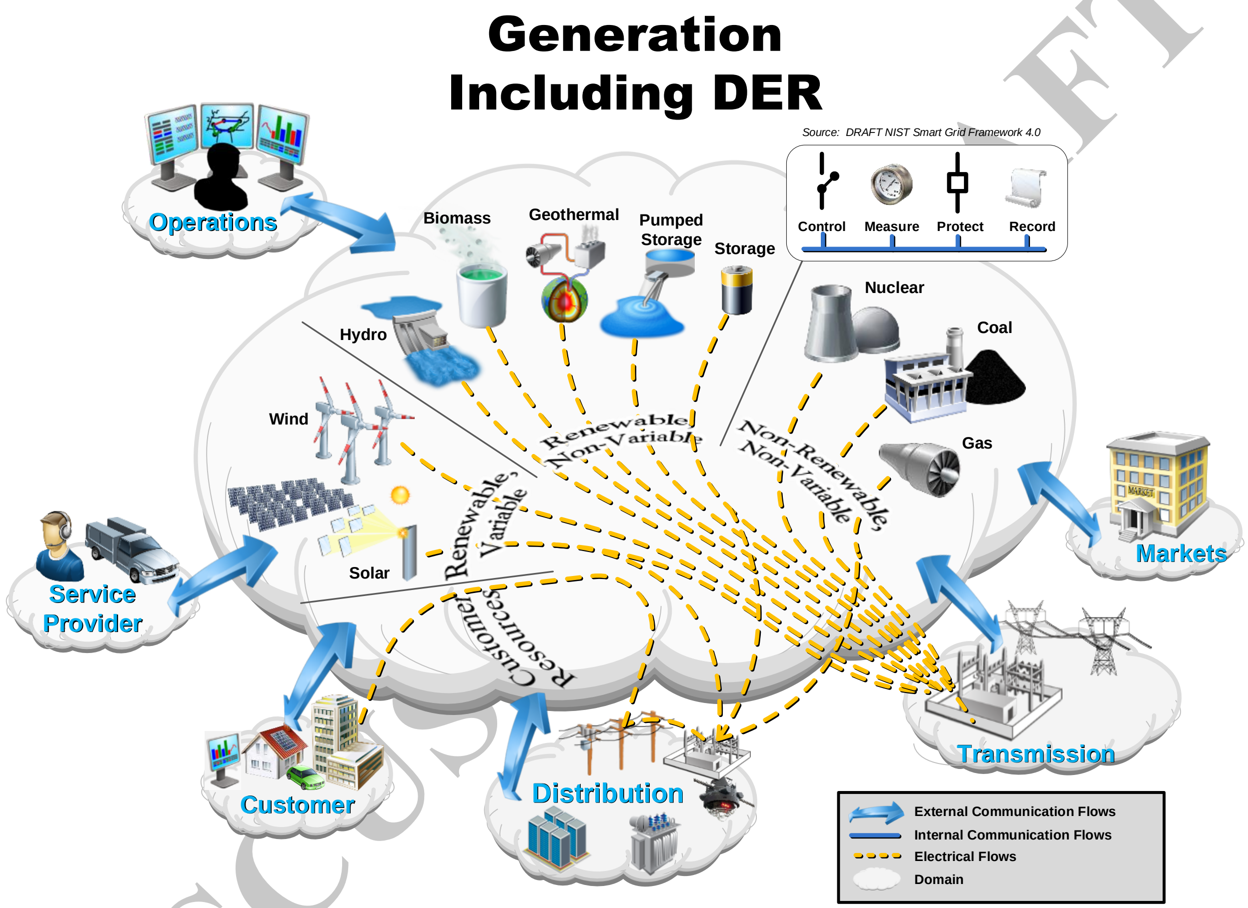

Figure 13—Overview of the Generation Including DER Domain

Historically provided by large generators that fed only the high-voltage transmission system, the scalability and modularity of modern generating technologies alters the physical relationship and points of coupling between generation assets and the grid, as well as the distribution of generation assets. Accordingly, this domain has been updated to reflect direct electrical interconnection with the distribution system that smaller scale and distributed generation assets may utilize. The domain has also been renamed *Generation Including DER*.

Communications with the *Transmission* and *Distribution* domains are critical, because without a delivery mechanism, customers cannot be served. The *Generation Including DER* domain should communicate key performance and quality of service issues such as scarcity and generator failure. These communications may cause the routing of electricity from other sources, or trigger an increased reliance on customer-cited measures described below. A lack of sufficient supply is addressed directly (via *Operations*) or indirectly (via *Markets*).

For this revision, NIST has introduced a *Customer Resources* segment which includes an electrical flow that passes through the *Generation Including DER* domain to connect the *Customer* and *Distribution* domains. Aligning the *Customer Resources* electrical flow with the electrical flows from the broader set of generation resources is a visual indication of the growing participation of customer-sited generation resources in conventional settlement and dispatch processes. Initiating the customer resource in the *Customer* domain—which includes distributed generation, demand response, and other load-management technology—reflects the growing number of market structures which treat demand management similarly to generating capacity [54] and/or energy production [55]. Beginning the electrical flow in the *Customer* domain and terminating it on a secondary feeder in the *Distribution* domain highlights the unique physical conditions and control requirements for customer-sited resources when compared to conventional generation assets.

Communication are extremely critical to the increasingly pervasive DER at the bulk system and distribution levels, including behind-the-meter installations. The *Generation Including DER* domain has therefore been updated in this revision to explicitly identify necessary communications flows with the *Distribution*, *Customer*, and *Service Provider* domains. These external communications flows (shown as bidirectional arrows in **Figure 13**) represent the inter-domain communications flows previously drawn in **Figure 3**Error! Reference source not found., a nd are not intended to describe specific interactions among roles or actors.

Evolving requirements for the *Generation Including DER* domain may include priorities such as controls for greenhouse gas emissions [56], increases in renewable energy sources [57], and provision of storage [58] to manage the variability of renewable generation or defer infrastructure obsolescence. To the extent that some of these goals require coordination across multiple domains, this complexity and associated interoperability requirements can be examined through the Conceptual Model communications flows. Roles in the *Generation Including DER* domain may include various physical actors, such as protection relays, remote terminal units, equipment monitors, fault recorders, user interfaces, and programmable logic controllers.

Examples of typical functions within the *Generation Including DER* domain that depend on communications flows and require interoperability are shown in **Table 8**.

Table 8- Typical applications requiring interoperability in the Generation Including DER domain

Example Application	Description
Control	Performed by roles that permit the Operations domain to manage the flow of power and the reliability of the system. Currently a physical example is the use of phase-angle regulators within a substation to control power flow between two adjacent power systems.
Measure	Performed by roles that provide visibility into the flow of power and the condition of the systems in the field. In the future, measurement might be built into increasingly more discrete field devices in the grid. Currently, an example is the digital and analog measurements collected through the supervisory control and data acquisition (SCADA) system from a remote terminal unit and provided to a grid control center in the Operations domain.
Protect	Performed by roles that react rapidly to faults and other events in the system that might cause power outages, brownouts, or the destruction of equipment. Performed to maintain high levels of reliability and power quality. May work locally or on a wide scale.
Record	Performed by roles that permit other domains to review what happened on the grid for financial, engineering, operational, and forecasting purposes.
Asset Management	Performed by roles that work together to determine when equipment should have maintenance, calculate the life expectancy of the device, and record its history of operations and maintenance so it can be reviewed in the future for operational and engineering decisions.

3.6 Transmission Domain

Transmission is the bulk transfer of electrical power from generation sources to distribution through multiple substations (see **Figure 14**). A transmission network is typically operated by a transmission-owning utility, Regional Transmission Operator or Independent System Operator (RTO, ISO respectively), whose primary responsibility is to maintain stability on the electric grid by balancing generation (supply) with load (demand) across the transmission network. Examples of physical actors in the Transmission domain include remote terminal units, substation meters, protection relays, power quality monitors, phasor measurement units, sag monitors, fault recorders, and substation user interfaces.

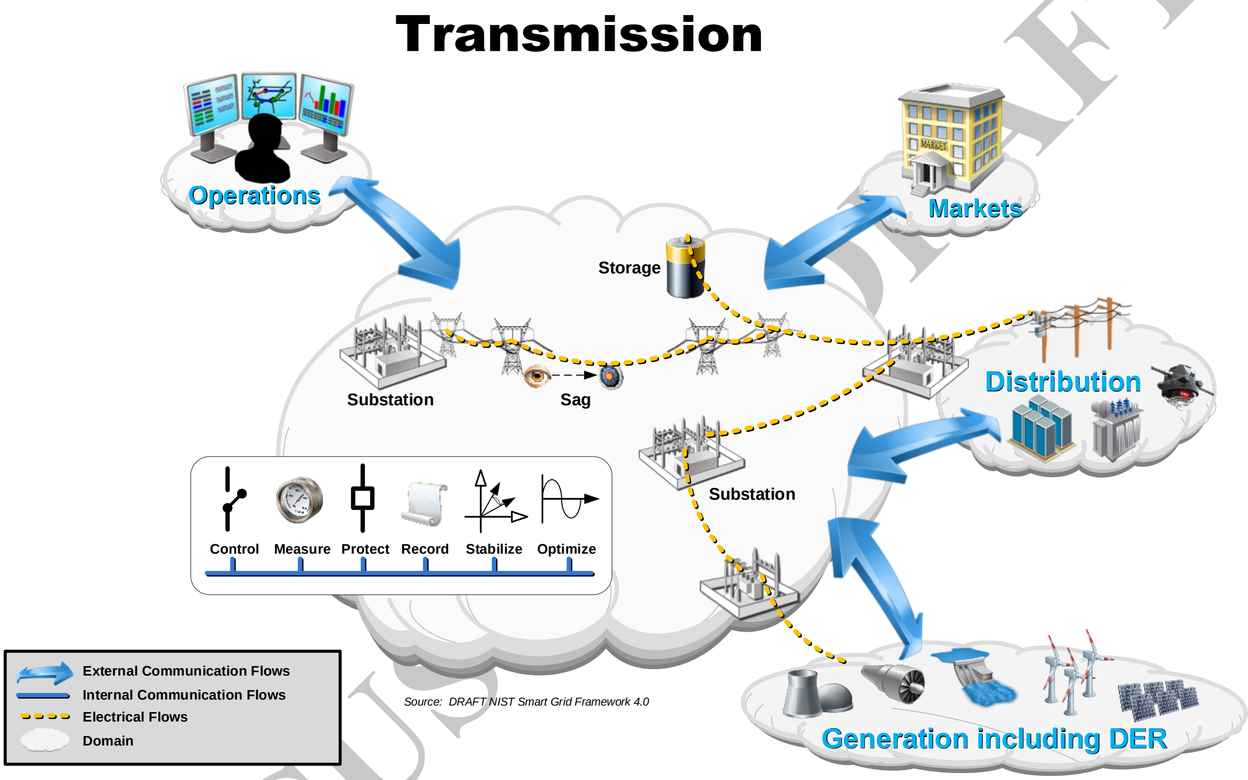

Figure 14—DRAFT Overview of the Transmission domain

Roles in the *Transmission* domain typically perform the applications shown in the diagram (**Figure 14**) and described in the table (**Table 9**). The Transmission domain may contain DER, such as electrical storage or peaking generation units.

Energy and supporting ancillary services (capacity that can be dispatched when needed) are procured through the *Markets* domain; scheduled and operated from the *Operations* domain; and finally delivered through the *Transmission* domain to the *Distribution* domain and ultimately to the *Customer* domain.

A transmission electrical substation uses transformers to step up or step down voltage across the electric supply chain. Substations also contain switching, protection, and control equipment. **Figure 14** depicts both step-up and step down substations connecting generation (including peaking units) and storage with distribution. Substations may also connect two or more transmission lines.

Transmission towers, power lines, and field telemetry (such as the line sag detector shown) make up the balance of the transmission network infrastructure. The transmission network is typically monitored and controlled through a SCADA system that uses a communication network, field monitoring devices, and control devices.

Table 9—Typical applications in the Transmission domain

Example Application	Description
Substation	The control and monitoring systems within a substation.
Storage	A system that controls the charging and discharging of an energy storage unit to bridge temporal mismatches in supply, demand, and infrastructure capabilities.
Measurement & Control	Includes all types of measurement and control systems to measure, record, and control, with the intent of protecting and optimizing grid operation

3.7 Distribution Domain

The *Distribution* domain is the electrical interconnection between the Transmission domain, the Customer domain, and the metering points for consumption, distributed storage, and distributed generation (see **Figure 15**). As does the *Generation including DER* domain, the *Distribution* domain may contain DER, such as electrical storage, peaking generation units, or other medium-scale assets such as community solar installations.

The electrical distribution system may be arranged in a variety of structures, including radial, looped, or meshed. The reliability of the distribution system varies depending on its structure, the types of configuration and control devices that are implemented, and the degree to which those devices communicate with each other and with entities in other domains.

Historically, distribution systems have been radial configurations, with little telemetry, and almost all communications within the domain was performed by humans. The primary installed sensor base in this domain was previously the customer with a telephone, whose call would initiate the dispatch of a field crew to restore power. Many communications interfaces within this domain have been hierarchical and unidirectional, although they now generally can be considered to work in both directions, even as the electrical connections are just beginning to support bidirectional flow. Distribution actors may have local inter-device (peer-to-peer) communication or a more centralized communication methodology. The use of higher speed communications to manage and optimize power flow and electricity generation and consumption in real time is an emerging concern for all stakeholders, particularly with higher penetration of DER (grid or behind-the-meter).

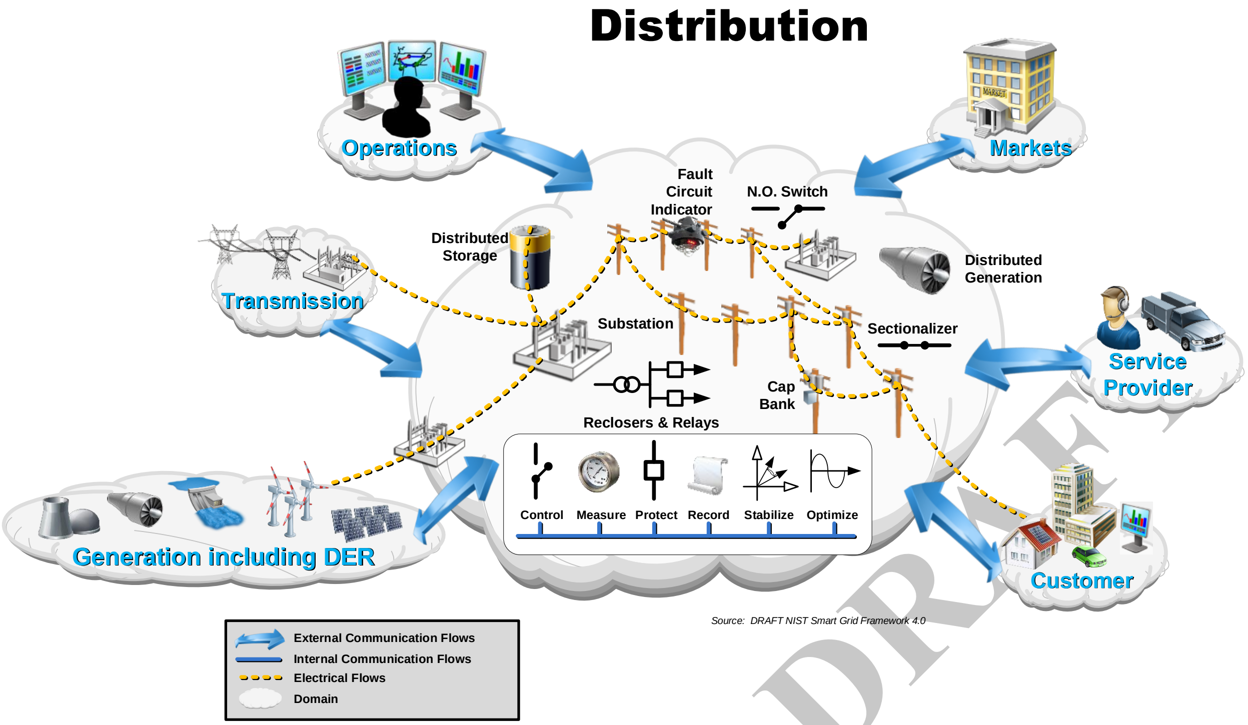

Figure 15—DRAFT Overview of the Distribution domain

In the smart grid, the Distribution domain will have increased sensing and control capabilities and communicate in a more granular fashion with the *Operations* domain in real-time to manage the complex power flows associated with new technologies, a more dynamic *Markets* domain, and other environmental and security-based factors. In general this dynamic indicates a need for improving distribution system observability and awareness, and the *Distribution* domain model in Figure 15 has been updated to include additional sensing devices (e.g., fault circuit indicator) as well as domain operational functions (e.g., stabilize) which had been limited to the *Transmission* domain in previous Conceptual Models.

The *Markets* domain will communicate with the *Distribution* domain in ways that will affect localized consumption and generation. In turn, these behavioral changes due to market forces may have electrical and structural impacts on the *Distribution* domain and the larger grid. Under some models, service providers may communicate with the *Customer* domain using the infrastructure of the *Distribution* domain, which would change the communications infrastructure selected for use within the domain.

It should be noted that DER can be considered both a *Transmission* and *Distribution* asset, so the model has been updated to reflect this reality from the electrical and communications standpoints. Examples of typical application categories in the *Distribution* domain are in

Table 10.

Table 10—Typical applications within the Distribution domain

Example Application	Description
Substation	The control and monitoring systems within a substation
Storage	A system that controls the charging and discharging of an energy storage unit to bridge temporal mismatches in supply, demand, and infrastructure capabilities.
Distributed Generation	A power source located on the distribution side of the grid.
Non-Wires Alternatives	DER, either individually or aggregated, that are used to replace or defer distribution infrastructure upgrades.
Measurement & Control	Includes all types of measurement and control systems to measure, record, and control power flows, with the intent of protecting and optimizing grid operation.

4 Appendix B—Mapping CPS Aspects and Concerns to the Electrical Grid

This appendix presents the evaluation of grid context for the existing set of CPS concerns as described in **Section 2.3**. Note that the Description column in **Table 11** contains a summary of the concern as defined in the CPS framework, and has been included here verbatim from that document. The "Architecture Significance" column provides some examples of how each concern relates to activities or emerging trends in power systems, as well examples of changes that could arise as new architectures are introduced. The architecture significance column therefore may help clarify the importance of CPS concerns to the electrical grids of today and tomorrow.

Table 11 - Mapping CPS Aspects and Concerns to the Electrical Grid

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Functional	**Actuation**	Concerns related to the ability of the CPS to effect change in the physical world.	• Geographic separation between power generation and its use requires sufficient electric transmission and improved bulk power control systems, including structural changes to existing systems to better manage the increasing fast grid dynamics and rising influence of distribution systems in bulk system operations.[1] In addition, the increased role of distribution grids requires greater coordination between premise, distribution, and bulk control systems and their operators. • Examples of new and anticipated control capabilities to address these power system actuation needs include better managing electric vehicle (EV) impact by monitoring and controlling EV chargers, and reconfiguring circuits using automatic circuit configuration, e.g. FLISR.	Ability to impact the power flow throughout the grid, including sources and load, by means of controlled, often remote, actuation of power systems equipment.	• To support overall grid system control through improved actuation capabilities, distribution systems are likely to need additional capabilities such as situational awareness and algorithms, previously needed only for transmission systems, e.g. state estimation. • To optimize distribution systems for new capabilities such as managed/smart EV charging and automatic circuit reconfiguration, projections of EV demand and generation levels and implementation of new Protection and Relay schemes that effectively respond to grid events are needed.

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Functional	**Communication**	Concerns related to the exchange of information internal to the CPS and between the CPS and other entities.	•Architecture concerns include sharing of infrastructure for communications.[33] • Legacy communications systems are widely deployed, trusted, tested, and represent billions of dollars of investment, thus transition to modern communications is likely to occur over an extended time period.	Exchange of information between internal and external networks including communications protocols, the communication network, and the exchange between interested parties.	• Additional sensors and wider-geographic area communications systems are needed to support the broad range of new functional communications requirements, including for enhanced situational awareness at the Distribution level. • Use of public communications networks will likely increase. • The addition of new distribution automation devices/intelligent electronic devices/meters will require more communications capabilities, e.g. higher bandwidth. •Architecture must support both rapid and slow transitions from legacy SCADA over IP devices/communications.

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Functional	**Controllability**	Ability of a CPS to control a property of a physical thing. There are many challenges to implementing control systems with CPS including the non-determinism of cyber systems, the uncertainty of location, time and observations or actions, their reliability and security, and complexity. Concerns related to the ability to modify a CPS or its function, if necessary.	• Controllability requires coordination of sensing, processing and acting. • Multiple inputs, including from multiple systems, are needed to inform control decisions. • Most grid control systems and hardware were not designed to accommodate large numbers of distributed energy resources (DERs). • More dynamic monitoring and control is needed to be able to respond to dynamic grid conditions.	Ability to control grid properties (sense, process and change); e.g., intentionally change a property.	• To provide the required controllability, distribution systems are likely to need situational awareness and algorithms previously only needed for transmission systems, e.g. state estimation. • Coordination of sensing and processing functions is needed to produce accurate control signals. • Architectures may need to support control applications that use multiple optimization factors including those based on carbon usage and market prices. • Architectures may need to support use of group commands (e.g., DNP3 settings groups) and third party aggregator control of DERs. • Architecture support of faster input of sensor data from traditional SCADA devices and newer devices including phasor measurement units (PMUs) is needed.
Functional	**Functionality**	Concerns related to the function that a CPS provides.	• The constant evolution of the power system requires continual development and integration of new grid functionality. • Grid control functionality has expanded to include increased management of generation assets, including with diverse ownership, varying control capabilities, and distributed locations, all of which which require different control functionality.	Ability to provide grid functions, e.g. control functions, sensing functions, service-related functions.	• Innovative grid technology is needed to facilitate development and implementation of a range of new grid functionalities, including in power markets, DERs, microgrids, Electric Vehicles, and others. • Architecture needs to support management of DERs with new control capabilities that differ from that of older types of generation.
Functional	**Manageability**	Concerns related to the management of CPS function.	• New functionalities are needed to improve effective management of an ever-changing portfolio of devices and systems that are deployed and operated at different grid levels.	Ability to develop and implement new functionality to manage change internally and externally to the grid.	• Communication topology views and key externally visible properties based on multi-tier distribution communications are needed for system control, substations, field operations, and Transmission/Distribution integration.[74]

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Functional	**Measurability**	Concerns related to the ability to measure the characteristics of the CPS.	• Changing dynamics of the grid require faster measurement of grid characteristics to gain visibility and situational awareness needed to enable active management instead of historically passive approaches, e.g. through physical inertia of generation. • SCADA systems typically report data at slow rates, e.g. once every 4 seconds, compared to new IoT control systems that can operate in the millisecond or microsecond timeframe. • Behind the meter (BTM) generation is typically not measured.	Ability to quantify a phenomenon / property against a known reference or fundamental definition.	• Architecture needs to support applications and sensors with a broad range of data rates. • Behind the meter (BTM) generation can be characterized through measurements with separate meters, or by using other techniques to estimate non-metered generation.
Functional	**Monitorability**	Concerns related to the ease and reliability with which authorized entities can gain and maintain awareness of the state of a CPS and its operations. Includes logging and audit functionality.	• Increasing complexity of bulk energy systems, combined with reduced operating margins, results in new and more complicated grid control issues[8] and increased need for multi-tier situational awareness. • Additional visibility and monitoring, including to better forecast supply and demand, is needed to support increased deployment of prosumer systems, which both use and generate electricity and may be located behind the meter. • Distribution state estimation will require consistent monitoring of measured distribution grid data to be useful.	Measuring a property over a period of time.	• Architecture support will be needed for increased input of grid sensor data and control messages, including DER. • Improved forecasting algorithms will be needed that use historical prosumer net load or generation as well as near-real time production data. • State Estimation algorithms that produce consistent, accurate results will be needed.
Functional	**Performance**	Concerns related to whether a CPS can meet required operational targets.	• Geographic and temporal mismatches between supply and demand are growing in some areas. • Energy efficiency and overall energy use of ubiquitous IoT devices, when powered using alternating current (AC) power, may be improved by taking advantage of the capability to run natively on direct current (DC) power to avoid losses due to AC-DC conversion.	Ability to deliver power as required by consumers.	• Architecture support is needed to provide additional balance between supply and demand, for example, supporting installation of DERs with Energy Storage in areas with challenges to support increased DER. • Architecture advances are needed to support new DC networks, such as in homes and commercial buildings, for lighting systems, electric vehicles, and distributed solar PV systems.

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Functional	**Physical**	Concerns about purely physical properties of CPS including seals, locks, safety, and EMI.	• Grid devices and systems have specific physical requirements for operation, protection, and safety. • There are requirements for hardening of devices, e.g., physical enclosure, immunity to EMI, and others.	Ability to ensure proper physical configuration in the operating environment.	• For architectures in which the active operating environment is designed to extend further towards the edge of domains, proper configuration and physical properties of new assets must be assured (e.g., edge devices may need additional physical security to ensure consumer safety).
Functional	**Physical Context**	Concerns relating to the need to understand a specific observation or a desired action relative to its physical position (and uncertainty.) While this information is often implied and not explicit in traditional physical systems, the distributed, mobile nature of CPS makes this a critical concern.	• The physical context, including geographical location of the device in the system as well as its location in the topology, is important for managing functional capabilities including monitoring and control. • The need for local optimization of grid assets increases with physical decentralization of distributed resources towards the edges of systems. Increased congestion (e.g. at the edge) may affect operations of aging infrastructure when load reaches or exceeds the originally designed physical limits of distribution systems.	Concerns relating to the need to understand information on the geographic and topological location of the physical asset.	• Architecture element will need to include physical location as well as network location for the devices. • Architectures should accomodate temporal changes in physical context as new asset deployments and system contingencies impact topology.
Functional	**Sensing**	Concerns related to the ability of a CPS to develop the situational awareness required to perform its function.	• Internet of Things (IoT)-related grid technology changes include small systems and solutions rather than large centrally controlled solution, flexible solution rather than fixed solutions, and wireless communications increasingly used whenever possible.[18] • Increasing complexity of the grid may impact the ability to sense grid conditions and status.	Ability to detect a property of the electrical grid over time.	• Additional smart devices and distributed sensors are needed to increase the level of information, monitoring, and control at various points of the distribution system. • Sensors and communications for distribution observability are needed to be architected as core infrastructures. [73]

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Functional	**States**	Concerns related to the states of a CPS. For example, the functional state of a CPS is frequently used to allow for variation in the CPS response to the same set of inputs. Variation in response based on state is sometimes referred to as functional modes.	• State estimation is one of the most important functions performed by system operators, and its use is extending from the bulk system to distribution systems. Proper state estimation allows control signals to be adjusted to optimize system operations and economics, and is important to maintaining system reliability and resilience by ensuring contingencies are available and activated when grid systems are operated beyond the designed capabilities or fail. • The proliferation of connected devices and systems in the grid will introduce new capabilities and provide new input data for state estimation. This will also require greater situational awareness across the system. • The ability to monitor and control devices is crititial in the modernized grid.	Concerns related to the abitlity to know the operating status and conditions of the grid and connected assets.	• Architectures must clearly identify which smart devices and sensors are important to state estimation, what information is required from those devices, and how that information should be communicated. • As the granularity of state estimation changes over time, architecture elements should define the systems with which smart devices must communicate operational and state information. • Smart devices and sensors with multiple capabilities can affect the ability to measure local system states, and networked devices can impact state estimation across wider areas. With increasing technological diversity, communications about operating status must match the needs and informational capacity of the interfacing systems.
Functional	**Uncertainty**	Managing the effects of uncertainties is a fundamental challenge in CPS. Sources of uncertainty in CPS can be grouped into statistical (aleatoric), lack of knowledge (epistemic) uncertainty, or systematic uncertainty. In CPS, statistical uncertainty is caused by randomness of accuracy of sensing and actuation, often caused by uncertainty of manufacturing processes. Systematic uncertainty is caused by incomplete knowledge either due to limits of acquired knowledge or due to simplification in modeling. Typical manifestations of epistemic uncertainty are limited validity of models of physical processes or limits of computability of properties of mathematical models.	• Fundamental limitations in the spatial and temporal ability to observe the electrical grid create uncertainty between model forecasts and actual operations. As sensors are deployed that can observe previously unmonitored aspects of the grid, this uncertainty can be minimized. Uncertainty can be reduced but not fully eliminated for a system as large and complex as the electric grid. • High penetration of variable generation renewable technologies and other DERs broadens the drivers of uncertainty that must be accounted for by grid operators. • Improved understanding uncertainty propagation would benefit grid operators.	Concerns related to the ability to characterize and mitigate uncertainty in the system for improved operations. Sources of uncertainty in the grid can include forecast error; randomness of individual actions affecting supply, load, or infrastructure; sensor limitations; and incomplete knowledge of the system.	• Architecture elements will need to include uncertainty thresholds related to operational schemes.

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Business	**Cost**	Concerns related to the direct and indirect investment or monetary flow or other resources required by the CPS throughout its lifecycle.	• Different amortization schedules exist for grid components, such as for generation, which for solar generation can range from 6 years or less, compared to 20 years or more for other generation assets. • The financial environment for grid investments, including capital expenditures (capex) and operation, maintenance and monitoring (OMM) expenditures, affects utilities' business practices and decisions broadly, from viability and bankability of individual projects to potential long-term underinvestment in grid operations and maintenance.	Direct and indirect lifecycle costs of electric grid components.	• Consideration of grid asset uniqueness with respect to amortization schedules.

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Business	**Enterprise**	Concerns related to the economic aspects of CPS.	• Grid control algorithms will likely increase in complexity in order to manage market economics, efficient energy usage, and reliability factors based on an increasing variety of resources, such as storage and demand response resources in areas with high penetrations of wind and solar generation. • Investments in energy production (generation) and delivery infrastructure generate a return on investment for utilities and energy producers; grid infrastructure enhancements need to also produce economic value or they will not be built. [14] • Architecture concerns include network convergence and transition from economies of scale to network economies. [35] • Increasing dynamic grid conditions will require more dynamic markets. • New distribution-level markets and market structures are likely to be created, including the introduction of Distribution System Operators (DSOs) to manage distribution system operations and maintain reliability and increase resilience under much higher levels of uncertainty and complexity.	Long term economic viability of maintaining the grid.	• The Distribution grid of the future may be designed as an open–access network for energy transactions.[75] • Architecture and enhanced communications are needed to enable new transactive energy approaches to distribution grid coordination and control.[77] • Economic and societal benefits of architecture changes must be quantifiable to support rigorous regulatory/stakeholder analyses to secure authorized funding. • Network convergence of electric, gas, and water distribution, traffic lights, emergency services, and public safety systems is likely to increase development of common platforms for sensing, communications, and control.[44] • New Transactive Energy Market architectures are needed. • Architecture support is needed to enable development and implantation of algorithms that incorporate uncertainty (unpredictability) and complexity. • Transparent market/economic business models should be developed to understand business factors that are driving decisions.
Business	**Environment**	Concerns related to the impacts of the engineering and operation of a CPS on the physical world.	• Outcome-oriented or performance-based regulation, including, for example, Performance Incentives Mechanisms (PIMs), have the potential to align utility motivations with societal goals related to the envirnoment.	Concerns related to the impacts of the engineering and operation of the grid on the physical world.	• Architecture support is needed to enable system-level consideration of additional environmental factors (e.g., carbon use) in addition to economics.

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Business	**Policy**	Concerns related to the impacts of treaties, statutes, and doctrines on a CPS throughout its lifecycle.	• Increased use of renewable energy is being required by legislation in many states.[9] including Hawaii, which is requiring 100% renewable usage by 2040, and California (50% by 2030) and Vermont (75% by 2032.) [10] In addition, a growing number of large corporations (including Google, Apple, and Amazon) are stating that their goal is 100% renewable energy use.	Concerns related to grid policies such as enterprise goals (e.g. adherence to established standards and protocols) or societal goals (e.g., renewable portfolio standards).	• Architecture support is needed to enable new operational system controls for systems with high (up to 100%) renewable energy usage. Currently key operational considerations include use of significant amounts of battery storage, and use of advanced DER generation assets with new functionality.
Business	**Quality**	Concerns related to the ease and reliability of assessing whether a CPS meets stakeholder (especially customer) expectations.	• Customer expectations are changing as customers become increasingly aware of energy issues and also want ease of interaction with utilities and energy services providers based on their experiences with mobile phones, banking systems, and other modern conveniences. • The emergence of new types of local energy choice and formation of community energy related entities (community choice aggregation/CCAs, community "solar garden" co-ops, etc.) will require operational changes in control systems to maintain customer quality expectations.[34]	Concerns related to customer satisfaction or perceived quality of grid services.	• Coordination structures and customer outreach are needed to facilitate integration of community energy resources such as multi-user microgrids and solar gardens into overall resilience strategies.[68] • New hybrid central/distributed control structures are needed for enhanced distribution control to facilitate functional flexibility and grid resilience.[45] • New concepts in grid architecture (e.g. potential for city distribution grid to support an open–access network for energy transactions[46]) will require significant customer outreach to ensure quality of energy services is maintained. •

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Business	**Regulatory**	Concerns related to regulatory requirements and certifications.	• Many state regulatory bodies are developing grid modernization guidance for distribution utilities in their jurisdictions (NY – NY REV, CA – MTS, MN – E21, OH – PowerForward, etc.).[43] Such regulatory guidance, and more generally the overall practices and environments of individual state commissions, have significant effects on the asset investment strategies and business models of grid participants. • Utilities with large geographic extent may be under the jurisdiction of several Public Utility Commissions (e.g. in different states) and may face additional difficulties in developing and deploying enterprise-wide solutions while meeting expectations of multiple regulatory bodies. • Renewable energy goals may be articulated at a high level such that the connection to specific grid changes necessary to meet the goals is not well understood.[12] • Utilities and energy service providers working with governmental organizations, such as cities, need to work work within local regulatory systems and authorities, and understand local conditions such as a city's budget management needs and processes for financing new projects.[37] • The electric grid directly supports many other infrastructures, such as transportation, waste management, and public safety, that are critical to the creation of safe and efficient urban environments in smart cities. [38]	Concerns related to the regulatory oversight of the grid.	• Additional standardization of interfaces across US Distribution System Operators (DSO) may be helpful to reduce level of effort needed to implement DSOs nationwide, including under differing regulatory environments. • Significant operational architecture support is needed for design and implementation of 100% renewable systems. • Architecture support needed to design grid systems for which one can calculate costs (e.g. on a year-by-year basis) to support budget analysis needed for regulatory oversight. • Integrated electric grid and smart city architecture is needed to support effective integration of infrastructures. • Market architecture and economic models are needed that support value exploration and communications between regulators and utilities/energy sector participants, including to consider costs and economic benefits of new assets such as DER.

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Business	**Time to Market**	Concerns related to the time period required to bring a CPS from need realization through deployment.	• There is an overall mismatch between speed to market of information technology compared to operational technology in the energy sector. An illustration of this mismatch is found in a comparison of typical 30-year innovation cycles and depreciation schedules in utilities with typical 3-year innovation cycles and depreciation schedules in telecommunications companies. • Technical barriers to DER integration with utility control systems, and high costs of DER interconnections including costs of connection to utility communications network, can lead to delayed time to market.	Concerns related to the time to implement new grid technology from realization to deployment within the constraints of legacy systems.	• Telecommunications and other non-utility communications and interoperability solutions are likely to be implemented on a shorter time scale, followed later by utility solutions. Thus architectures are likely to be impacted more quickly by non-utility solutions and should accommodate different development time cycles. • To reduce time to market for new innovative products, standardization of utility-DER interfaces and interconnections are needed, including support for automated interconnection applications for consumers.
Business	**Utility**	Concerns related to the ability of a CPS to provide trusted benefit or satisfaction through its operation. Utility reflects a business concern, especially when considered as the numerator when computing value, which equals utility divided by costs.	• Additional information is needed to understand the comparative value provided by installed infrastructure, T&D, or customer owned assets. • New energy services (volt/VAR, synthetic inertia, demand response, storage, etc.) will provide expanded range of sources of usefulness (value). • Significant changes in energy cost by source have occurred in recent years. For example, the lowest levelized cost of energy from any source (without subsidiaries) is now wind followed by utility-scale solar PV.[88] • In order to realize all DER benefits, distribution planning should consider use of DERs as an option. • Different business models of vendors, commercial control system developers, generation owners, and utilities (which themselves have multiple business models for IOUs, municipalities, co-ops, government-owned utilities) and different understandings of utility (business value) may impede collaborations. For example, unmetered Behind the Meter (BTM) generation may not be accurately valued.	Ability to reliably supply electric power (as a business value) to consumers.	• Assessment of least cost alternative should include new infrastructure, customer-owned assets, and non-wires alternatives such as Demand Response. • New Distribution feeder structures are needed to facilitate adaptation to stress conditions and sharing of localized energy resources.[64] • Assessment of least cost alternative should consider multiple revenue streams from DER and other non-wires alternatives, including energy shifting, load shifting, ancillary services and reliability improvements/impacts. • Distribution planning applications should consider DER assets in the set of potential options for new projects • New regulatory tariffs will require BTM and other systems to include the ability to schedule services, e.g. battery's ability to provide energy at specific time periods, based on tariffs[91] e.g., Time of Use (TOU) rates.

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Human	**Human Factors**	Concern about the characteristics of CPS with respect to how they are used by humans.	• Some stakeholders have difficulties in understanding what a kWh is or its economic value, which may prevent consumers from effectively participating in market constructs that deal in kWhs or MWhs. Without needed context and information, consumers "have a hard time estimating the costs and benefits of their actions." [13] • Consumer choice including local energy choice[29] are among the primary factors driving increased automation with large amounts of DER. • Architecture concerns related to human factors range from system operator ergonomics to interaction/convergence with social networks and social media.[36] These concerns, and additional concerns related to human performance, also apply to human operators in grid control center environments	Ability of power system users to understand and respond to grid concepts, functions and operational requirements.	• Value propositions (including regulatory tariffs) are needed in which benefits and costs are clear to consumers and presented at the time that consumer decisions are anticipated to be made. • Additional consumer education is needed to support consumers to select their energy providers (if available), to select an option to request all renewable energy, and to join with others to form Community Choice Aggregation (CCA) districts. • Human factors assessments and inputs in application development process are needed, including for example, evaluation of human factor concerns in control centers to improve the performance of humans-in-the-grid-control-loops. Architectural support is needed for development of interfaces with social media, including to provide easy-to-understand energy price information and outage status to customers.
Human	**Usability**	Concerns related to the ability of CPS to be used to achieve its functional objectives effectively, efficiently, and to the satisfaction of users (adapted from ISO 9241-210.) The combination of physical and cyber into complex systems creates challenges in meeting usability goals. Complexity is a major issue. The diversity of interfaces creates a significant learning curve for human interaction.	• Improved (simpler/better/intuitive) user interfaces are needed to support human-grid interactions.For example, the inability (and disinterest) of humans to manually control grid-connected equipment requires user-friendly interfaces (and effective automation) to help manage these devices, e.g. millions of DERs, in coordination with grid management systems. • Situational awareness applications are needed to improve system visability and usability for consumers, market management organizations, market participants, utilities and other stakeholders.	Ability of power system users to understand, interact with, and apply grid technology.	• Improved interfaces including preset or interactive device level controls, as well as aggregation of DER assets, can be used to increase usability and reduce need for direct control of each DER. Such interfaces would help to reduce human-based concerns about difficulties and complexity of managing grid-responsive equipment. • Architecture support is needed for effective delivery of relevant data to stakeholders to include consumers, market management organizations, market participants and utilities.

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Trustworthiness	**Privacy**	Concerns related to the ability of the CPS to prevent entities (people, machines) from gaining access to data stored in, created by, or transiting a CPS or its components such that individuals or groups cannot seclude themselves or information about themselves from others. Privacy is a condition that results from the establishment and maintenance of a collection of methods to support the mitigation of risks to individuals arising from the processing of their personal information within or among systems or through the manipulation of physical environments.	• The availability of high-frequency energy usage data collected for the purpose of energy monitoring may facilitate the unintentional release of private, confidential information. For example, the data has the potential to reveal information about an individual's behavior, such as when he or she arrives home at night, and what are his or her general day-to day-interactions with CPS systems.[39] • Collecting pieces of information from various sources and then using algorithms or machine learning to analyze this information, makes it possible to combine "safe" (privacy-protected) data from many sources to create "unsafe" results that reveal confidential information about individuals (e.g. privacy concerns). • An additional privacy concern is simply one of confidentiality of customer data, including data of commercial and industrial customers.	Concerns related to the ability of the grid to prevent entities (people, machines) from gaining access to data stored in, created by, or transiting a CPS or its components such that individuals or groups cannot seclude themselves or information about themselves from others. Privacy is a condition that results from the establishment and maintenance of a collection of methods to support the mitigation of risks to individuals arising from the processing of their personal information within or among systems or through the manipulation of physical environments.	• Methods and algorithms can be developed for removing Personally Identifiable Information (PII) and sensitive personal information (SPI) from monitored electric usage data.

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Trustworthiness	**Reliability**	Concerns related to the ability of the CPS to deliver stable and predictable performance in expected conditions.	• Reliability can be understood as the ability of the electric power system to deliver electricity in the quantity and with the quality needed to satisify demand, typically measured by interruption indices appropriate for normal operation. • Increased onsite generation (including renewables and backup generation), often in the context of a user-controlled microgrid, is a common approach by customers to address their own site-specific concerns about reliability. These assets may also be aggregated and can participate in markets to provide compensated grid reliability resources. • The reliability of intermittent/non-dispatchable DERs (as individual generation assets) can significantly impact the reliability of the connected grid system.	Concerns related to the ability of the grid, or components within a grid, to deliver stable and predictable performance in expected conditions.	• If assets other than those owned by the utility are trusted and compensated to support grid reliability, what happens if reliability norms are violated (e.g. how is the utility or other affected parties informed), and how would organizations be responsible for the localized and regional impacts of the violation? • The ability of grid segments or devices, possibly owned by groups other than the utility, to provide autonomous corrections to system operation (i.e., those corrections not controlled by the central utility) will reduce communications requirements and associated costs for deploying DER, and also increase the speed with which corrective action can be taken throughout the system. An example of this is the automated function of reclosers. • Multi-user microgrids and microgrid networks may require coordination with distribution grids and need for microgrid-to-grid services.[47] • A lack of verified reliability for individual asset performance could lead grid operators and/or utilities to require direct observability of asset behavior, especially when controllable assets are grouped to provide specific operational characteristics through processes opaque to the utility.

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Trustworthiness	**Resilience**	Concerns related to the ability of the CPS to withstand instability, unexpected conditions, and gracefully return to predictable, but possibly degraded, performance.	• Different from reliability, in which normal services are provided, resilience includes the ability to prepare for and adapt to changing circumstances, and to withstand and recover rapidly from distruptions. Resilience may include a graceful degradation of performance. The interconnected nature of grids means degradation will likely affect more than just those stakeholders which negotiated (or agreed to) the degraded operating solution. The authority to determine the operating solution had previously resided with utilities and similar load serving entities; the significance of assigning these decisions to others is not yet clear. • The determination (or negotiation) of the degraded state is an unclear process right now, and care must be taken to ensure all stakeholders can participate and have their interests represented accurately in the final solution. • When trustworthy resilience is provided by operating in a degraded state, the communications necessary to external entities must be clarified. • Scientific studies indicate that extreme weather events such as heat waves and large storms are likely to become more frequent and intense[53] increasing risk of damage to electric grid infrastructure. • For many industries, a momentary outage of 15 seconds, or an extended outage of 15 hours, results in the same economic loss.[5]	Concerns related to the grid, or components within a grid, to withstand instability, unexpected conditions, and gracefully return to predictable, but possible degraded, performance.	• Coordination, communication, and sensing structures that facilitate use of Distributed Generation (DG) for grid resilience purposes are needed.[66] • Grid and communication/coordination structures that enable fast use of the results of contingency planning are needed.[65] • Condition-Based Maintenance (CBM) projects require additional communications bandwidth. • Storage at the distribution level can be used to improve resilience.[76] • Effective use of smart meters at high-priority sites (such as hospitals and first stations) with enhanced outage detection alerts requires faster higher bandwidth communications networks. • Electric Vehicles charging may be able to provide additional resilience support for grid systems, in addition to meeting customer charging needs.

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Trustworthiness	**Safety**	Concerns related to the ability of the CPS to ensure the absence of catastrophic consequences on the life, health, property, or data of CPS stakeholders and the physical environment.	• Utilities and energy service providors/operators ensure that safety is prioritized within their operations and for the protection of customers. • Potential impacts on safety arise from multiple concerns, many of which are grouped in Trustworthiness. For example, the potential for device (and substation) controllability to be compromised through malicious intent via a cybersecurity attack can have catastrophic life-safety implications. • Safety must be evaluated and maintained or improved throughout all grid system evolution processes. For example, as distributed devices are increasingly deployed to enhance system reliability and resilience, traditional safety practices may no longer be relevant and must be updated.	Concerns related to the ability of the electrical grid to ensure the absence of catastrophic consequences on the life, health, and property due to electrical hazard to consumers, installers, and maintenance workers.	• Dynamic reorganization of system architectures to provide the greatest level of system performance and net economic benefit will create uncertainties in status and safety requirements as workers from multiple organizations work to restore what could be competing architectures of service.

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Trustworthiness	**Security**	Concerns related to the ability of the CPS to ensure that all of its processes, mechanisms, both physical and cyber, and services are afforded internal or external protection from unintended and unauthorized access, change, damage, destruction, or use.	• Most substation systems were designed as isolated non-connected systems. Thus connecting IoT-enabled devices and systems within substations requires reevaluation of security concerns, including implementation of device-level cybersecurity in addition to other measures. • Adding cybersecurity later, which is required for most legacy substation and field devices, results in less effective security than designing in and implementing cybersecurity at the beginning. • A timing-denial cyber-attack could be conducted either via Global Navigation Satellite System (GNSS) denial or using interference with communications network traffic. Such an attack could lead to a grid or substation failure.[22] • A spoofing cyber-attack could be initiated by any device connected to a substation communications bus (including those only temporarily connected), or via an external device that reaches the substation via a poorly protected gateway. Such an attack would provide individual or all subsystems with false time, therefore resulting in an infringement of local or global time synchronization.[23] • Denial of Service (DoS) cyber-attacks over extended time periods could lead to grid or substation failures. [24] • Proliferation of additional DER and distributed automation devices requires additional physical security to protect these assets.	Concerns related to physical and cyber processes and mechanisms impacting trustworthiness.	• Architecture for resilience buffering against edge device induced power flow volatilities is needed for defense against IoT-based cyber-attacks.[81] • Cybersecurity architecture is needed to address the inherent risks of connecting devices to a network/the Internet. • Security architecture is needed to address multiple concerns, including for DERs, and to protect against timing-denial and DoS cyber-attacks, and to protect substations against spoofing attacks. In addition, security architecture for securing legacy electric grid systems and securing substations is needed.Security architecture is also needed to support input and monitoring of physical devices, and for transactive energy. • Distribution-level cyber securability approaches are needed for information flow, coordination, and control that are inherently defendable.[79]

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Timing	**Logical Time**	Concerns related to the order in which things happen (causal order relation) or event driven.	• Protection and safety schemes for the grid require sequential operation in time and close coordination across a number of physical events and actuations. • As grid automation increases, especially on distribution systems, these coordinated and sequential operations will become more common within—and important to—daily operations and system optimization. • Hardware in the loop testing and simulation is prevelant among grid operators, especially for modeling distributed energy resources in the system. These efforts depend on logical time steps that enable faster-than-real-time simulation and are conducive to meeting the operational and planning needs of various grid stakeholders.	Concerns related to the ability to specify and coordinate time sequences for operations, simulation and testing.	• Architeture is needed to support logical time sequencing to meet operational, testing, and simulation requirements.

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Timing	**Synchronization**	Concerns for synchronization are that all associated nodes have timing signals traceable to the same time scale with accuracies as required. There are three kinds of synchronization that might be required: time, phase, and frequency synchronization, although frequency synchronization is also called syntonization.	• The increasing importance of coordination across the transmission and distribution systems results in greater need for synchronization on more granular time scales and accurately disseminated over larger physical areas. • Maintaining integrity of time synchronization is can be difficult because reference sources and communication mediums are subject to interruption and failure. For example, loss of GPS timing synchronization for Supervisory Control and Data Acquisition (SCADA) systems and synchrophasors data can compromise grid state estimation and impact the situational awareness and control capabilities of the power system. Redundant time synchronization systems provide benefits of continuity of timing infrastructure during such interruptions and failures. • Awareness and seamless mapping of different time scales and local time are needed to accommodate adjustments (e.g., introduction of leap seconds and daylight savings time)	Concerns that all nodes and devices connected to the grid have timing signals traceable to the same time scale with accuracies as required.	• Synchronized timing allows for localized data analytics and simpler data communications. • Communication infrastuctures for timing and alternatives (redundant systems) are needed for timing distribution over distribution grids, in conjunction with or independent of satellite-based methods.[80] • Architecture is needed to support applications ability to rely on accurate time stamps while recognizing that they can be subject to interruptions and communications failures. • Architecture support is needed to facilitate applications to recognize and account for timing issues including different time zones, local time and daylight savings, as well as technical time synchronization issues such as introduction of leap seconds.
Timing	**Time Awareness**	Concerns that allow time correctness by design. The presence or absence of time explicitly in the models used to describe, analyze, and design CPS and in the actual operation of the components. This is a life- cycle concern as well as a concern for the ability to build devices without the need for extensive calibration of the timing properties.	• Efficient protection functions require synchronized time, available either locally or globally. [21] • Timeliness of data availability, computation, and communication is needed in order to meet the system constraints to provide accurate state estimation and precise control automation. • Ability is needed to specify and validate timing constraints. • Grid operations use distributed equipment, which often includes time-aware capabilities based on the availability of timing as an infrastructural resource maintained by utilities.	Concerns related to the ability to design systems and components are are time aware and can acquire and use sufficiently accurate time signals.	• Architecture needs to support time awareness and synchronous time for protection schemes. • Architecture needs to support the ability within applications to apply and validate timing constraints. • Architecture needs to support sufficiently accurate time stamping ideally using designed-in and widely available timing infrastructures.

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Timing	**Time-Interval and Latency**	Specifying requirements for timing generally involves requirements for time-intervals between pairs of events. A time-interval is the duration between two instants read on the same timescale. CPS timing requirements are generally expressed as constraints on the time intervals (TI) between pairs of system significant events. These can be categorized in terms of bounded TIs or latency, deterministic TIs, and accurate TIs.	• As grid applications evolve, time-interval and latency requirements (including bounded latencies, and to prevent system destabilization) are becoming more stringent and complex. • Time-interval specificity is central to many new grid applications, from control systems to cybersecurity protections.	Concerns related to the ability to specify time interval and latency requirements for system events and communications.	• Architecture is needed to support multiple application-driven requirements for time-interval performance and latency.
Data	**Data Semantics**	Concerns related to the agreed and shared meaning(s) of data held within, generated by, and transiting a system.	• Efforts to combine data from multiple sources in the electric grid system face significant data interoperability challenges.[40] • Data interoperability is a key need for grid modernization. • Data models and many data standards for smart grid devices support many different use cases; as a consequence, data semantics are not always seamless across systems.	Concerns related to the agreed and shared meaning(s) of data held within, generated by, and transiting a system.	• Standardization of communication interfaces and data harmonization is needed. • As the ownership of grid devices for communication, sensing and actuation diversifies, additional effort will be needed to maintain data context (i.e., semantic interoperability) across devices and systems.
Data	**Data Velocity**	Concerns related to the speed with which data operations are executed.	• The operational constraints of the electric grid demand that supply and demand be continuously balanced in real time, which creates significant requirements for data velocity to support real-time operations. • The increasing volumes of data inherent to the smart grid will challenge the ability to perform timely data operations.	Concerns related to the speed with which data operations are executed, andn the ability to process data within specified requirements.	• Architecture will need to accommodate different data processing speed requirements as a function of application and device type. • Architecture will need to ensure data processing speed requirements for a given element are consistent with the employed control theory and system/device physical capabilities.

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Data	**Data Volume**	Concerns related to the volume or quantity of data associated with a CPS' operation.	• The proliferation of smart sensors in the grid and other new data sources could overwhelm the data processing and analytics capabilities of the system. • Grid operators may need to selectively manage datastreams to prioritize information that is most relevant to their operational goals. • The dramatic growth in data availability from distributed sensing may create an archival data storage problem, in which so much data is stored that useful information may become obscured and access constrained.	Concerns related to the ability to store the growing volume or quantity of data from grid devices and systems.	• Architecture support will be needed to meet growing data requirements for grid systems. • Architecture elements will need to include the ability to address data capacity requirements from different types of devices and applications.
Data	**Identity**	Concerns related to the ability to accurately recognize entities (people, machines, and data) when interacting with or being leveraged by a CPS.	• Identity management is crucial to grid communications and operations. • As ownership of grid assets diversifies, and as customers increasingly bring their own devices and expect to connect with any and all available communication systems, identity management schemes will have to be developed which allow for effective management of large numbers of diverse devices. • Identity management of physical assets is critical to trustworthiness, cybersecurity, and grid operations.	Concerns related to the ability to uniquely identify devices in the system.	• Grid systems need the ability to identify and incorporate devices subject to diverse constraints and capabilities of distinct organizations, systems, and components. • Highly distributed architectures will need to support device self-identification and registration.
Data	**Operations on Data**	Concerns related to the ability to create/read/update/delete system data and how the integrity of CPS data and behaviors may be affected.	• The quantity of data available to grid operators is increasing dramatically as sensing and communications capabilities are incorporated into all types of equipment. But the ability to use data is limited by data incompatibility, often driven by conflicts in format and structure. Ensuring appropriate data management, including data compatibility through uniform use of data models or other formatting, is critical to ensuring utilities can process, store, maintain and utilize the data according to their applications.	Concerns related to the ability to define data compatibility and data management requirements, including format, processing, storing and monitoring schemes.	• Architecture will need to support various data operations related to their applications.

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Data	**Relationship between Data**	Concerns related to how and why sets of data must, may, or may not be associated with each other and the value or harm that can be derived from those associations.	• Network convergence, such as referenced in natural gas/electric system harmonization efforts,[11] will lead to complex and interconnected data streams, which will need to be managed in coordination to support cooperative operational management of integrated infrastructures. • Utilities and grid operators manage large quantities of sensor data generated by numerous equipment, to inform and improve grid operations efficiency, reliability and other attributes. By itself, or when associated with other data (commercial, residential), this information may add value or cause harm if not managed in an appropriate way. Internally, for example, data on power flows (state estimation) may reveal energy-market-relevant decisions and data that are to be protected. Externally, data about individual customers is typically protected from unauthorized disclosure within a state regulatory construct. • Data from many sources impacts the accuracy of Distribution state estimation and other data analytics applications, and the relationship of disparate data sources will need to be evaluated to identify and enhance the value of such data to meet requirements of many applications.	Concerns related to the relationships of grid data and external data and the value or harm that can be derived from those associations.	• Integrated data management and analysis capabilities are needed effective coordinated operation of grid systems and other interacting systems, e.g. to support operational management of converged natural gas/electric power systems.[55]
Boundaries	**Behavioral**	Concerns related to the ability to successfully operate a CPS in multiple application areas.	• Multiple value stacks for responsive grid support systems, e.g. energy storage systems, motivate maximal utilization of equipment and systems to meet multiple application objectives. These potentially overlapping applications are often subject to the requirements and expectations of multiple organizations, including those related to organizational boundaries. • Operational siloes exist within utilities, such as between Informational Technology (IT) and Operational Technology (OT), and often lead to organizational boundaries which may increase the difficulty of managing CPS/IoT devices.[89]	Concerns related to successful operation at boundaries including geographic and system boundaries.	• Architecture must support diverse operational and market uses for grid responsive systems, such as energy storage systems. • Architecture practices need to consider differing IT and OT perspectives.

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Boundaries	**Networkability**	Concerns related to the ease and reliability with which a CPS can be incorporated within a (new or existing) network of other systems.	• Increasing growth of edge-connected devices and systems, e.g. DERs, is requiring development of network capabilities to manage and readily accommodate the incorporation of such devices. Positive attributes, such as ease of connection and reliability of edge devices, are accompanied by the need to reassess existing capabilities and processes, including protection schemes[6] to prevent negative impacts such as outages that may result from unanticipated two-way power flows.	Ease and reliability of incorporation of newer technology and updated systems models at various grid levels while maintaining the integrity of the grid network.	• With increased networkability and ease of incorporation of new devices and systems into the grid, advanced control systems are needed to manage such systems and protect grid systems from unintended consequences.

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Boundaries	**Responsibility**	Concerns related to the ability to identify the entity or entities authorized to control the operation of a CPS.	• Business model changes for utilities, including those driven by the availability of significant distributed generation, may include creation of new Distribution System Operators with stakeholder expectations that income will result from from distribution services instead of the volumetric sale of electricity. [17] These new organizations and structures will result in new organizational responsibilities, which will need to be understood, communicated and agreed with applicable system participants. • Additional coordination will be needed between microgrids and the larger grid and between microgrids and other microgrids[31] • Greater understanding and coordinated management of responsibilities between Distribution System Operators (DSO) and RTOs/ISOs will be needed. • Utility resource planning and accomdation of increasing DERs will need to incorporate recognitions of boundary interfaces and associated responsibilities of authorized grid operators. • Customers may have opportunities and responsibilities based on their use of grid-responsive equipment (e.g. demand response) with the ability to vary power consumption to meet multiple objectives.	Identification and determination of the responsibilities of authorized grid organizations and participants, including with respect to ownership and control of diverse grid components.	• Transmission/distribution coordination via Distribution System Operator models is needed.[71] • Circuit structure, protection and control structures are needed for multiple cooperating microgrids.[83] • Architectures for multi-scale (e.g. single building versus multiple circuits) coordination of microgrid networks needed.[84] • Architecture needed for CCAs and aggregated community resources.[85] • Architecture support is needed for segmentable and coordinated grid sub-systems and for coordination of responsibilities to facilitate agile re-segmentation and cooperation at different microgrid scales (e.g. single building versus multiple circuits).[86] • Under one proposed framework, the DSO would serve as a system optimizer on the local level, calling on least-cost resources to meet distribution system goals. The least-cost resources could be provided directly by customers or, more likely, by third-party aggregators.[87] • Standardization of interfaces between utility resource planning tools and DERs would increase effectiveness of DERs. • Consumers would benefit from development of clearly defined guidelines for customer participation, costs, benefits and responsibilities related to the integration of grid-responsive devices and systems.

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Composition	**Adaptability**	Concerns related to the ability of the CPS to achieve an intended purpose in the face of changing external conditions such as the need to upgrade or otherwise reconfigure a CPS to meet new conditions, needs, or objectives.	• Grid components are supplied by various vendors. It can be challenging for components from different vendors to communicate with one another in the power system network, and to be reconfigured as needed to meet new objectives. • Grid control algorithms need to be much more flexible and adaptable in order to consider varying market economics, efficient energy usage, and managing reliability with a diversity of resources, such as storage and demand response, and in areas with high penetrations of wind and solar generation.	Ability to update, adapt or reconfigure grid technology to meet power system needs.	• Interoperability standards for grid components continue to be needed to support composition and integration of components into systems that are adaptable and able to meet system requirements. • Preparedness for future grid technology including attention to its adaptability and reconfigurability to meet new objectives is needed. • Architecture is needed for integration of large scale energy storage distribution connected resources and grid operations.[58] • Balancing and stabilization of grids with wide area bulk wind and solar resources is needed.[59] • Distributed intelligence computations and communication network structures are needed to support distributed analytics, and control.[69] • Coordination, communication, and sensing structures that facilitate use of Demand Response for grid resilience purposes are needed.[67] • New hybrid central/distributed control structures are needed for distribution control to facilitate functional flexibility and grid resilience.[70]
Composition	**Complexity**	Concerns related to our understanding of the behavior of CPS due to the richness and heterogeneity of interactions among its components, such as existence of legacy components and the variety of interfaces.	• The grid is so complex, no-one can understand or plan for the entirety of it.[15]	Concerns relating to complexity in grid functionality.	• Movement of control/management/optimization to lower levels will help to manage complexity. • Grid partitioning, coordination and communication are means to adapt to grid complexity and stresses.[61]

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Composition	**Constructivity**	Concerns related to the ability to combine CPS modular components (hardware, software, and data) to satisfy user requirements.	• Integrating hardware, software and data components in complex systems is a difficult endeavor, and particularly so in grid systems with their legacy systems and operational requirements. For example, replacing an Outage Management System (OMS) and Distribution Management System (DMS) with an Advanced DMS (ADMS) poses complex deployment issues, including how to replace both the OMS and DMS at the same time, optimize data alignment/transfer, maintain consistency in calculating reliability metrics, and complete operator training.	Integration of power system components of various types and configurations.	• Architectures need to be developed with interface design and considerations to support modular composition of components, including the ability to address use of the same data by multiple applications, varying data rates, and standardized data definitions, e.g. CIM.
Composition	**Discoverability**	Concerns related to the ease and reliability with which a CPS component can be observed and understood (for purposes of leveraging the component's functionality) by an entity (human, machines). Concerns related to the ease and reliability with which a CPS component's functions can be ascertained (for purposes of leveraging that functionality) by an entity (human, machines).	• The grid has increasing needs for system observability and discoverability, including with respect to communication (data flow) and information handling. • System operators want greater visibility into the operation and status of DER assets and other assets that may be owned or controlled by other parties.	Concerns related to the observability of power systems components needed to leverage component data.	• Automated discoverability of edge-connected devices and sensors and their performance characteristics, communications and data models is a need to enable improved visibility, integration, and device management to support grid operations. • Fault tolerant communication structures are needed to enable reliable distributed intelligence.[62] • Architecture support is needed to enable discoverability and visibility of DERs and to support centralized and decentralized control of DERs.

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Lifecycle	**Deployability**	Concerns related to the ease and reliability with which a CPS can be brought into productive use.	• The mission-critical nature of the grid limits the ability to test new systems, as outages are unacceptable. Thus models, simulations, and testable versions of the grid are needed to test new systems, algorithms, markets capabilities and understand and mitigate factors affecting their deployability on the functioning grid. • Utility-scale wind and solar power often generated in sparsely populated areas with little grid infrastructure. Hence long-distance transmission lines must be built to move wind/solar generation to areas where power is needed, which may lead to additional concerns such as initial deployability of these assets. • Reduction of system inertia, including that associated with inverter-based generation in some cases, may require additional control actions by regulator tap changers and capacitors[54] and which may affect deployability of these assets.	Concerns related to the implementation of grid technology to meet power system needs.	• Architectural support is needed for new or updated models and simulation of the electric grid including DERs. • Bulk energy systems require closed loop secondary protection and System Integrity Protection Schemes (SIPS).[56] Sensors and communications are needed for transmission state determination and situational awareness.[57] • Structures are needed for integration of inertia augmentation methods, devices, and systems.[60]
Lifecycle	**Disposability**	Concerns related to the impacts that may occur when the CPS is taken physically out of service.	• There is an ongoing need to plan for retirement and eventual disposal/deconstruction of large power plants at the end of their lifecycle. • Planning is needed to support identification and disposal of faulty grid equipment, and to enable recycling of out-of-service grid components that may be of use elsewhere.	Concerns related to the disposal of obsolete, aged, or damaged physical grid components.	• Architecture is needed to support environmental-friendly recycling practices. • Improved quality checks are needed to minimize faulty equipment. Architecture support is needed to enable use of recycled grid components elsewhere in the grid.

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Lifecycle	**Engineerability**	Concerns related to the ease and reliability with which a CPS design concept can successfully be realized via a structured engineering process.	• There are multiple systems engineering approaches and methodologies available to support architecture development and a variety of structured engineering processes. Within systems engineering processes applied at the grid component level, the broader perspective of the grid at-scale is beneficial to identify and address engineerability issues. Included in this approach is research and development needed to better understand and improve the behavior and performance of new innovative products, to ensure that these concepts can be realized and deployed at scale and are likely to function in grid environments. • Microgrid engineering issues have been studied, but architecture coordination issues remain.[32] • Time lags may exist in translating new concepts into standards and implementation, which should be identified and mitigated as needed, e.g., through initiating testing and certification development based on earlier working versions of a standard.	Ability to develop theoretical concepts into applicable grid technology.	• Common structured engineering processes should be identified and used broadly across the electric sector to help improve engineerability and integration of new components and systems into the operational power grid. • Microgrid architecture models are needed.
Lifecycle	**Maintainability**	Concerns related to the ease and reliability with which the CPS can be kept in working order.	• The aging grid means that many assets are reaching or have already surpassed their designed lifetimes, and maintenance of these assets and systems is a growing concern for keeping the system operational. • The introduction of smart devices in the grid are changing maintenance processes and procedures. For example, the different classes of devices require different monitoring schemes (e.g. traditional grid devices may require visual inspection while smart devices could be monitored remotely). • Smart devices and systems may enable predictive maintenance to replace some preventive and reactive maintenance regimes.	Concerns related to the ease and reliability with which the grid and its assets can be kept in working order.	• Architecture needs to support different maintenance intervals for different classes of devices. • Architecture needs to accommodate a variety of emerging maintenance regimes, including predictive .

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Lifecycle	**Operability**	Concerns related to the operation of the CPS when deployed.	• Electric system components are often designed with long lifetimes that may exceed 30 years[90] and must maintain operability over this time period. • Like other critical infrastructures, the electric grid is aging, and must be kept operational through upgrade or replacement by new systems. These upgrade or replacement events represent opportunities to introduce additional system advances such as incorporating an IoT-based infrastructure. • The increasing complexity of grid controls requires a more skilled workforce to maintain operability of grid systems. • Firmware upgrades in existing devices provide opportunity to deploy new features such as the ability of advanced inverters to control voltage and frequency.	Concerns related to continuous, effective operation of grid components.	• Architecture needs to accommodate both new and legacy devices. • Architecture needs to support rollout of new Internet connectivity when systems are added or replaced. • Architecture needs to support integrated training/operations simulation. • Architecture needs to support field upgrades of device firmware.
Lifecycle	**Procureability**	Concerns related to the ease and reliability with which a CPS can be obtained.	• Historically, performance requirements for grid assets or devices have been locally determined, and drivened by interfaces with legacy systems or capabilities. This situation often leads to procurement issues as equipment often requires customized configurations to match capabilities with the legacy requirements. Grid operators are moving towards open-source standards-based device requirements, which allows for easier specification in the procurement process. • Common reference procurement language could be useful for purchasers to specify and procure devices that minimize integration overhead.	Concerns related to the ability to specify performance and communication requirements for a device.	• Architecture needs to support standardized device requirements to support procureability. • Common reference language for procurement documention and examples of standards-based performance requirements should be developed

Aspect	Concern	Description	Grid Context for CPS Concern	Grid CPS Concern Description	Architecture Significance
Lifecycle	**Producibility**	Concerns related to the ease and reliability with which a CPS design can be successfully manufactured.	• The grid itself is not manufactured, but instead it results as the product of many individual design, procurement, and installation activities. • Absent a comprehensive master design, devices manufactured to meet open standards improves the likelihood that grid components will be manufactured to conform with grid design requirements.	Concerns around the ability to translate grid designs into successful products and installations.	• Architeture needs to support standardized device requirements to support producibility.

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