

Developing an Ontology for the Smart Grid (Discussion DRAFT)

October 12, 2018

The electrical grid has been called the greatest engineering achievement of the 20th century.¹ The U.S. power system is immense, with nearly 500,000 miles of transmission lines² connecting more than 7,000 power plants³ to feed a distribution system relying on 6,000,000 miles of wires to serve 150,000,000 unique customers.⁴

Beyond the sheer scale of the infrastructure, electrical grids are complex systems of systems (SoS) where mechanical, electro-mechanical, and electronic control devices must all work together to produce and manage the electricity critical to modern society.⁵ Relying on engineered interactions between physical and computational components also means the electrical grid is a cyber-physical system,⁶ and because the grid only works when numerous systems operate in parallel⁷ the electrical grid is actually multi-layered cyber-physical system of systems.

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.⁸ Even the term interoperability, defined as the capability of two or more networks, systems, devices, applications, or components to work together,⁹ belies the complex series of interactions and requirements necessary to exchange actionable information.¹⁰ 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.

Yet any pursuit of a common set of terms, or ontology,¹¹ 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 serves as an input to a great number of systems.¹² The electrical grid is therefore but one domain in the broader universe of cyber-physical systems. Any ontology

¹ <http://www.greatachievements.org/>

² <https://www.energy.gov/epso/downloads/electricity-distribution-system-baseline-report>

³ <https://www.energy.gov/sites/prod/files/2015/12/f28/united-states-electricity-industry-primer.pdf>

⁴ <https://www.energy.gov/epso/downloads/electricity-distribution-system-baseline-report>

⁵ For example, transmission system load balancing control systems use mechanical turbines to match generation to load.

⁶ <https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1500-201.pdf>

⁷ 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.

⁸ For example, popular media will use catch-all phrases like “[intelligent grid](#)” to describe any number of complex interactions and developing system capabilities, and the term “[grid modernization](#)” in the regulatory arena can mean anything from advanced metering to utility business model reform to microgrids and demand response.

⁹ <https://www.nist.gov/sites/default/files/documents/smartgrid/NIST-SP-1108r3.pdf>

¹⁰ https://www.nist.gov/sites/default/files/documents/2018/06/25/draft_interoperability_profile_description_final.pdf

¹¹ An ontology is a set of concepts and categories in a subject area or domain that shows their properties and the relations between them (Source: <https://en.oxforddictionaries.com/definition/ontology>)

¹² A. Gopstein. “Energy Storage & the Grid—From Characteristics to Impact.” *Proceedings of the IEEE*. (2012) Vol. 100(2): 311-16.

developed for the 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.

The NIST Framework for Cyber-Physical Systems

NIST’s 2017 *Framework for Cyber-Physical Systems*¹³ provides a useful template for developing ontologies to describe key features of cyber-physical systems (CPSs). As seen in **Figure 1**, the features of a CPS derive from the set of relationships that begin with the system application and conclude with a set of activities and artifacts that can be used to assure system performance. In this implementation, the *Domains* represent different application areas of cyber-physical systems¹⁴ and *Aspects* consist of groupings of conceptually equivalent or related concerns, where concerns are expressed from stakeholder perspectives and are fundamental concepts that drive the methodology of assuring system performance.

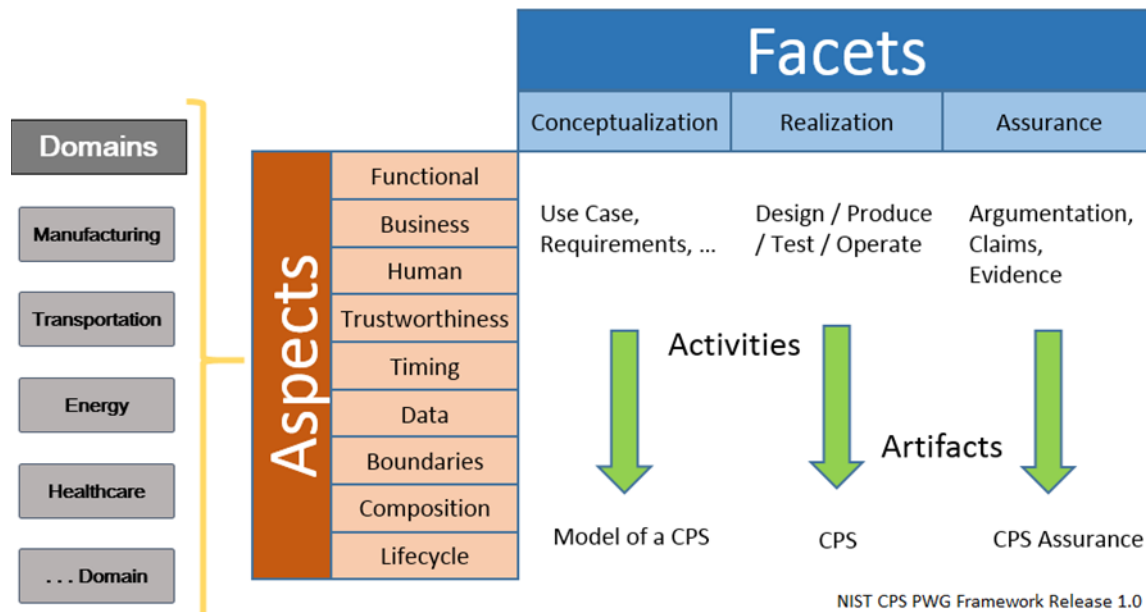


Figure 1- Key Cyber-Physical System Features

¹³ <https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1500-201.pdf>

¹⁴ The logical relationship between the “domains” in **Figure 1** and the Smart Grid Conceptual Model domains which describe roles and services within the grid, is that changing the cyber-physical system 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.

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 1** also apply to the grid. A modernized electrical grid aligns to the cyber-physical framework's aspects as follows:

Functional — Concerns about sensing, actuation, control, communications and other functions accurately describes grid modernization issues. For example, one grid modernization functional aspect is how incorporation of Distributed Energy Resources (DERs) will affect electrical distribution sensing, control and communications systems which were not designed to accommodate them.

Business — Concerns about enterprise, time to market, environment, regulation, cost, and other business areas. For the electric grid, a key business aspect is how to design a market that optimizes energy costs in what was formerly a regulated monopoly market in most locations.

Human — Concerns about human interaction with and as part of a CPS. An important aspect is how human-in-the-loop system operators will manage the grid with potentially millions of new distributed generation devices not under their direct control. An additional human aspect is now these millions of DERs devices can be controlled in real-time when there simply are not enough human operators to monitor and manage all the DERs in the time available.

Trustworthiness — Concerns about trustworthiness of CPS including security, privacy, safety, reliability, and resilience. These are key concerns and aspects of an electrical grid, especially safety, reliability, cyber-security, privacy, and resiliency. Thus trustworthiness aspects should be considered as potentially impacting and driving architectural principles for the CPS's energy domain.

Timing — Concerns about time and frequency signals, including the generation and transport of time and frequency signals, timestamping, managing latency, and timing composability. Timing aspects have long been a concern of electric grids as evidenced by the many existing electrical grid timing standards such as IEEE 1588-2008 standard "Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems."

Data — Concerns about data interoperability including fusion (situational awareness), data definitions (metadata), privacy, quality, type and identity. Data interoperability is a key aspect 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 operations.

Boundaries — Concerns related to topological, functional, and organizational separations. For electrical utilities, a persistent boundary aspect is the organizational siloes which must be integrated in order to maximize the operational efficiency of the grid. Currently the

boundaries between Information Technology (IT) and Operational Technology (OT) organization groups is a key concern.

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 concern is the ability to combine utility control systems with user-owned and controlled DER assets.

Lifecycle — Concerns related to the management and maintenance of CPS systems and components throughout their deployments including enhancements and removal of components. For electrical utilities, lifecycle concerns include reliability throughout a components lifetime which may be exceeding long e.g. that average age of power plants is over 30 years.¹⁵ Another lifecycle concern is the increased usage of grid control devices such as tap changers which may need to operate much more frequently to control voltage changes induced by distributed generation. A further lifecycle 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.

Aspects and Concerns of the Electrical Grid

The CPS Framework “aspects” and “concerns”¹⁶ 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 for the grid. This has been done in **Table 1**. Note that the Description column in **Table 1** contains a summary of the concern as defined in the CPS framework, and has been included here verbatim from that document.

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 1**, 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.

¹⁵ UtilityDIVE, <http://www.utilitydive.com/news/making-the-case-for-grid-investment-6-insights-from-the-white-houses-new/160426/>

¹⁶ Framework for Cyber-Physical Systems, Release 1.0, May 2016, page xiv

Table 1- 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. | <ul style="list-style-type: none"> • Geographic mismatch between locations of power generation and demand for power requires additional electric transmission, but the increasing fast grid dynamics and rising influence of distribution systems in bulk system operations are causing the need for structural changes to the bulk energy system.¹ Similarly, the increased role of distribution grids calls for greater coordination between premise, distribution, and bulk systems. • Managing EV impact by controlling EV charger. • Reconfiguring circuits using automatic circuit configuration e.g. FLISR. | Ability to impact the power flow throughout the grid, including sources and load. | <ul style="list-style-type: none"> • Distribution systems likely to need algorithms previously only needed for Transmission systems e.g. State Estimation. Hence additional sensors and wider-geographic area communications systems needed. • Projections of demand and generation levels to optimize Distribution systems for managed/smart EV charging. • It is essential to implement Protection and Relay schemes that effectively respond to grid events. |
| Functional | Communication | Concerns related to the exchange of information internal to the CPS and between the CPS and other entities. | <ul style="list-style-type: none"> • 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 likely to be slow. | Exchange of information between internal and external networks including communications protocols, the communication network, and the exchange between interested parties. | <ul style="list-style-type: none"> • Public communications networks will likely replace private networks. • More distribution automation devices/IEDs/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. | <ul style="list-style-type: none"> • Controllability requires the condonation of sensing, processing and acting. • Multiple inputs are needed to make control decisions. • Most grid control systems and hardware were not designed to accommodate large numbers of DERs. • More dynamic monitoring and control to respond to the dynamic network. | Ability to control grid properties (sense, process and change); e.g., intentionally change a phenomenon / property. | <ul style="list-style-type: none"> • Coordination of sensing and processing functions to produce accurate control signals. • Architectures may need to support control applications that input and evaluate multiple optimization factors including 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). |
| Functional | Functionality | Concerns related to the function that a CPS provides. | <ul style="list-style-type: none"> • The constant evolution of the power system creates new grid functions. • Grid control functionality has expanded to include management of generation assets which require different functionality e.g. diverse generation assets require additional control functionality including distributed assets. | Ability to provide grid functions e.g. control functions, sensing functions, service-related functions. | <ul style="list-style-type: none"> • Innovative grid technology needed to facilitate Power Markets, DERs, Microgrids, Electric Vehicles, etc. • Architecture needs to support management of DERs constraints that differ from older types of generation. |
| Functional | Manageability | Concerns related to the management of CPS function. | <ul style="list-style-type: none"> • Need the ability to manage change across multiple devices at different grid levels. | Ability to manage change internally and externally to the grid at the cyber-physical boundary e.g. digital equipment and actuators affected by EMC. | <ul style="list-style-type: none"> • Communication topology views and key externally visible properties for multi-tier distribution communications needed for system control, substations, field operations, and Transmission/Distribution integration⁷⁴ |

| 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. | <ul style="list-style-type: none"> • Changing dynamics of the grid require faster measurement of grid characteristics to gain visibility to facilitate active management versus historically passive approaches, e.g. through physical inertia of generation. • SCADA systems typically report data at slow rates e.g. once every 4 seconds while IoT control systems can operate in the millisecond or microsecond time frame. • Behind the meter (BTM) generation typically not measured. | Ability to quantify a phenomenon / property against a known reference or fundamental definition. | <ul style="list-style-type: none"> • Architecture needs to support applications and sensors with different data rates. • Behind the meter (BTM) generation can be monitored with separate meters, and estimates of non-metered generation can be estimated. |
| 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. | <ul style="list-style-type: none"> • Increasing complexity of bulk energy systems combined with reduced operating margins, results in new and more complicated grid control problems.⁸ • Prosumers who both use and generate electricity require increased monitoring. • Prosumers increase difficulty of forecasting supply and demand. • Distribution State estimation algorithms require measured distribution grid data to be useful. | Measuring a phenomenon / property over a period of time. | <ul style="list-style-type: none"> • Architecture support for increased input of grid sensor data and control messages. • Architecture support for increased input of DER data. • Forecasting algorithms that input historical prosumer net load or generation as well as near-real time production data. • State Estimation Algorithms that produce accurate results with minimal error. |
| Functional | Performance | Concerns related to whether a CPS can meet required operational targets. | <ul style="list-style-type: none"> • Geographic and temporal mismatches between supply and demand are growing in some areas. • IoT devices typically natively run on DC power. But end-point delivery is AC. Energy is lost during the DC to AC and then AC to DC conversion. Energy lost during the conversion decreases performance. | Ability to deliver power as required by consumers. | <ul style="list-style-type: none"> • Architecture needed to enhance supply and demand balance, for example, installation of DERs with Energy Storage in problem areas. • Architecture needed to support DC networks 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 | Sensing | Concerns related to the ability of a CPS to develop the situational awareness required to perform its function. | <ul style="list-style-type: none"> IoT-related grid technology changes include 1) small systems and solutions rather than large centrally controlled solution, 2) flexible solution rather than fixed solutions needed, and 3) wireless used whenever possible.¹⁸ Complexity of grid limits ability to understand grid conditions/status. | Ability to detect a phenomenon/ of the physical grid over time. | <ul style="list-style-type: none"> Smart devices needed to increase level of information, monitoring, and control at various points of the distribution system. Sensors and communications for distribution observability are needed as core infrastructure⁷³ |
| Business | Enterprise | Concerns related to the economic aspects of CPS. | <ul style="list-style-type: none"> Grid control algorithms need to be much more complex in order to consider market economics, efficient energy usage, and managing reliability with a variety of resources, such as storage and demand response, in areas with high penetrations of wind and solar generation. The grid in addition to delivering electricity also generates large amount of income 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 scale economies to network economies³⁵ More dynamic grid conditions requires more dynamic markets New distribution-level markets need to be created. Need for Distribution System Operators (DSOs) to maintaining reliability in the future grid with a much higher degree of uncertainty and complexity. | Long term economic viability of maintaining the grid. | <ul style="list-style-type: none"> Distribution grid can be used as an open-access network for energy transactions.⁷⁵ Architecture and communications needed for transactive energy approaches to distribution grid coordination and control.⁷⁷ Economic and societal benefits of architecture changes must be quantifiable as allocation of funds must meet rigorous regulatory/stakeholder analyses in order secure authorized funding. Network convergence of electric, gas, and water distribution, traffic lights, emergency services, and public safety systems leads to need for a common platform for sensing, communications, and control.⁴⁴ Transactive Energy Market architecture needed Architecture support for algorithms that incorporate uncertainty (unpredictability) and complexity. Transparent market/economic business models that expose business factors driving decisions. |
| Business | Cost | Concerns related to the direct and indirect investment or monetary flow or other resources required by the CPS throughout its lifecycle. | <ul style="list-style-type: none"> Different amortization schedules for grid components such as generation which can range from 6 years or less for solar to 20 years or more for other generation assets. Changing nature of capital to OM&M expenditures is affecting everything from grid operations to bankability. | Direct and indirect lifecycle costs of electric grid components. | <ul style="list-style-type: none"> 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 | Environment | Concerns related to the impacts of the engineering and operation of a CPS on the physical world. | <ul style="list-style-type: none"> • Outcome-oriented regulation like CO₂ Performance Incentives Mechanisms (PIMs) or a revenue cap can align utility motivation directly with societal goals. | Concerns related to the impacts of the engineering and operation of the grid on the physical world. | <ul style="list-style-type: none"> • Architecture support for carbon-based factors in addition to economic factor. |
| Business | Policy | Concerns related to the impacts of treaties, statutes, and doctrines on a CPS throughout its lifecycle. | <ul style="list-style-type: none"> • Large amounts of renewable energy are being required by legislation⁹ Hawaii legislated 100% renewable by 2040. California requires 50% by 2030. Vermont 75% by 2032.¹⁰ In addition, corporations such as Google, Apple, and Amazon state their goal is 100% renewable energy. | Concerns related to grid policies such as enterprise goals e.g. adherence to established standards and protocols. | <ul style="list-style-type: none"> • Architecture needs to support operational system controls to control 100% renewable energy. Currently key operational consideration is the need to include some combination of large amounts of battery storage and 100% renewable bio-fueled spinning DER generation assets |
| Business | Quality | Concerns related to the ease and reliability of assessing whether a CPS meets stakeholder (especially customer) expectations. | <ul style="list-style-type: none"> • Customer expectations are changing as customers become increasingly aware. • 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 changes in control structures.³⁴ • Changing expectations of customers with respect to the provision and other grid services. | Concerns related to customer satisfaction or perceived quality of grid services. | <ul style="list-style-type: none"> • Coordination structures that facilitate integration of community energy resources such as multi-user microgrids and solar gardens into overall resilience strategies needed.⁶⁸ • New hybrid central/distributed control structures needed for distribution control to facilitate functional flexibility and grid resilience.⁴⁵ • Potential need for city distribution grid as an open-access network for energy transactions.⁴⁶ • Architectural support for needed for EV services and vehicle charging networks.⁴⁸ • To provide building to grid integration, coordination and communication structures for enablement of grid services supplied from buildings.^{49,78} • Sensor networks for distribution and urban environment observability and situational awareness.⁵⁰ • Inherent need for defense against social network-based cyber-physical attacks requires architecture for resilience buffering against social network-coordinated or induced threats.⁵¹ • Architecture needed for distribution system platforms with support for distribution planning, operations, and where appropriate, markets.^{52,72} |

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| Business | Regulatory | Concerns related to regulatory requirements and certifications. | <ul style="list-style-type: none"> • 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 • Many different Public Utility Commissions e.g. one per state make it difficult to develop solutions which can be deployed nation-wide. • Renewable energy goals rarely account for the grid changes that must be made in order to meet the renewable energy goals.¹² • Architecture concerns include city’s budget management needs such as the need to finance new project.³⁷ • Architecture concerns include the need to create safe and efficient urban environments due to mass urbanization (including waste management, traffic management).³⁸ • How to design a market that optimizes energy costs in what was formerly a regulated monopoly market in most locations. • Method to fairly compensate DER owners for their contributions to the grid needed. • Authority of individual state commissions affect the asset investment strategies and business model of grid participants. | Concerns related to the regulation of the grid. | <ul style="list-style-type: none"> • Standardization of interfaces across US Distribution System Operators (DSO) would reduce level of effort needed to implement DSOs nationwide. • Operational architecture needed for 100% renewable systems. • Architecture structure needed to calculate costs on a year-by-year basis to support budget analysis. • Integrated electric grid and Smart City architecture needed. • Market architecture models needed. • Economic models need to consider DER costs and economic benefits as well. |

| Aspect | Concern | Description | Grid Context for CPS Concern | Grid CPS Concern Description | Architecture Significance |
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| Business | Time to Market | Concerns related to the time period required to bring a CPS from need realization through deployment. | <ul style="list-style-type: none"> • Mismatch between speed to market of information technology vs. operational technology. Cultures of utilities vs telecommunications companies (30-year vs 3-year innovation cycles and depreciation schedules). • Technical barriers to DER integration with utility control systems. • High costs of DER interconnections including costs of connection to utility communications network. | Concerns related to the time to implement new grid technology from realization to deployment within the constraints of legacy systems. | <ul style="list-style-type: none"> • Telecommunications and other non-utility communications and interoperability solutions likely to be implemented first followed later by utility solutions. Thus architecture likely to be impacted more quickly by non-utility solutions. • Standardization of utility-DER interfaces needed. • Support for automated interconnection applications for consumers needed. • Standardization of interconnection agreements needed. |

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|-----------------|----------------|--|--|---|---|
| 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. | <ul style="list-style-type: none"> • Unclear which improvements provide the most value among 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). • 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 needs to consider use of DERs as an option. • Different business models for the vendors, commercial control system developers, generation owners, and utilities which themselves have multiple business models (IOUs, municipalities, co-ops, government-owned) cause misunderstanding which make collaboration difficult. • Unmetered Behind the Meter (BTM) generation may not be accurately valued. | Ability to reliably supply electric power to consumers. | <ul style="list-style-type: none"> • Assessment of least cost alternative needs to include new infrastructure, customer-owned assets, and non-wires alternatives such as Demand Response. • Distribution feeder structures needed to facilitate adaptation to stress conditions and sharing of localized energy resource.⁶⁴ • Assessment of least cost alternative needs to consider multiple revenue streams from DER and other non-wires including energy shifting, load shifting, ancillary services and reliability improvements/detriments. • Architecture needs to support distribution planning applications that consider DER assets in the set of potential options for new projects • New regularity 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 tariffs⁹¹ e.g. Time of Use (TOU) rates. |

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|--------|---------------|---|---|--|---|
| Human | Human Factors | Concern about the characteristics of CPS with respect to how they are used by humans. | <ul style="list-style-type: none"> • Some stakeholders have little understanding of what a kWh is or its economic value. Hence market constructs that deal in kWhs or MWhs are difficult for consumers to grasp. Consumers “have a hard time estimating the costs and benefits of their actions.”¹³ • Primary factors driving increased automation with large amounts of DER include consumer choice including local energy choice.²⁹ • Architecture concerns include interaction/convergence with social networks and social media.³⁶ • Need for simpler/better/intuitive user interfaces. • How to automate control of millions of DERs as it’s not possible for humans to manually control them. | Ability of power system users to comprehend grid concepts and functions. | <ul style="list-style-type: none"> • Develop regulatory tariffs whose benefits are clear to consumers • Allow consumers to select their energy providers, to select an option for all renewable energy, and to form Community Choice Aggregation (CCA) districts. • Architectural support for interfaces with social media e.g. provide energy price information and outage status. • Include human factors assessments and inputs in application development process. • Use preset or interactive device level controls as well as aggregation of DER assets to reduce need for direct control of each DER. |
| 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. | <ul style="list-style-type: none"> • Impact of outage events on electric service can have significant negative economic consequence as well as implications for safety, comfort, and productivity.⁴² • Primary factors driving increased automation with large amounts of DER include rising consumer expectations for functionality.²⁸ • Situational awareness applications needed for consumers, market management organizations, market participants, utilities and other stakeholders. | Ability of power system users to understand, interact with, and apply grid technology. | <ul style="list-style-type: none"> • Need to ensure that system operators monitor, measure and encourage increases in electric system reliability and resiliency for both the overall system and for consumers, e.g. microgrids. • Support for aggregated services capable of leveraging individual DER capabilities to increase customer benefits e.g. through demand response, charging of EVs when generation is most abundant. • Architecture needed to support 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. | <ul style="list-style-type: none"> • High-frequency data collected for the purpose of energy monitoring unintentionally leaks confidential information. In addition, the data has the potential to infer information from an individuals' behaviors, such as their search of information repositories and their general day-to day-interactions with CPS systems.³⁹ • Collecting pieces of information from various sources and then using algorithms or machine learning, makes it possible to take "safe" data from many sources to create "unsafe" results (e.g. privacy concerns). • An additional privacy concern in addition to those listed is simply one of confidentiality of customer data. | 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. | <ul style="list-style-type: none"> • Architecture needs to support using algorithms 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. | <ul style="list-style-type: none"> • A lack of understood, or trustworthy, reliability 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. • Reliability of microgrids can improve grid reliability • Reliability of DERs impacts grid reliability e.g. effects of intermittent/non-dispatchable DER generation on reliability. | Concerns related to the ability of the grid, or components within a grid, to deliver stable and predictable performance in expected conditions. | <ul style="list-style-type: none"> • 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 understood, or trustworthy, reliability 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. |

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| 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. | <ul style="list-style-type: none"> • Different from reliability, in which normal services are provided, 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 intense⁵³ increasing risk of damage to electric grid infrastructure. • For many industries an outage of 15 seconds or 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. | <ul style="list-style-type: none"> • Coordination, communication, and sensing structures that facilitate use of Distributed Generation (DG) for grid resilience purposes needed.⁶⁶ • Grid and communication/coordination structures that enable fast use of the results of contingency planning needed.⁶⁵ • Condition-Based Maintenance (CBM) projects require additional communications bandwidth. • Storage at the distribution level can be used for resilience.⁷⁶ • Effective use of bellwether meter/AMI data requires for outage detection requires faster higher bandwidth communications networks. • Charging of Electric Vehicles needs to support resilience e.g. charging must support both customer charging needs and grid availability of power. |
| 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. | <ul style="list-style-type: none"> • The potential for device (and substation) controllability to be compromised through malicious intent via a cybersecurity attack can have catastrophic implications. • As distributed devices incorporate and rely on grid-forming capabilities to enhance system reliability and resilience, traditional safety practices are no longer relevant. | 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. | <ul style="list-style-type: none"> • 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. |

| Aspect | Concern | Description | Grid Context for CPS Concern | Grid CPS Concern Description | Architecture Significance |
|-----------------|----------|--|--|--|--|
| 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. | <ul style="list-style-type: none"> • Most substation systems were designed as isolated non-connected systems. Thus connecting them to the IoT requires that cyber security be added to the device. • Adding security later, which is required for most legacy substation and field devices results in less effective security. • Primary factors driving increased automation with large amounts of DER include access for carrying out energy transactions in some areas.³⁰ • 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 (including those only temporarily) connected to a substation communications bus, 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 • Most substation systems were designed as isolated non-connected systems. Thus connecting them to the IoT requires that cyber security be added to the device. • Adding security later, which is required for most legacy substation and field devices results in less effective security. • Proliferation of additional DER and distributed automation devices requires additional physical security to protect these assets. • Most substation systems were designed as isolated non-connected systems. Thus connecting them to the IoT requires that cyber security be added to the device. • Adding security later, which is required for most legacy substation and field devices results in less effective security. • Primary factors driving increased automation with large amounts of DER include access for carrying out energy transactions in some areas.³⁰ | Concerns related to physical and cyber processes and mechanisms impacting trustworthiness. | <ul style="list-style-type: none"> • Architecture for resilience buffering against edge device induced power flow volatilities needed for defense against IoT-based cyber-attacks.⁸¹ • Cybersecurity architecture needed to consider the inherent risks of connecting devices to a network/the Internet. • Security architecture for DERs needed. • Security architecture to protect against timing-denial cyber-attack needed. • Security architecture to protect substations against spoofing attacks needed. • Security architecture to protect against DoS cyber-attacks needed. • Security architecture for securing legacy electric grid systems needed. • Security architecture for securing substations needed. • Security architecture needs to support input and monitoring of physical devices. • Distribution-level cyber securability approaches needed for information flow, coordination, and control that are inherently defendable.⁷⁹ • Security architecture for transactive energy needed. |

| Aspect | Concern | Description | Grid Context for CPS Concern | Grid CPS Concern Description | Architecture Significance |
|--------|-----------------|--|--|---|---|
| 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. | <ul style="list-style-type: none"> • Rising importance of coordination across the transmission and distribution systems, results in increasing need for synchronization on fine time scale over wider areas. • Integrity of the time is uncertain given the reference sources and communication mediums are subject to failure at times. • Awareness and seamless mapping of different time scales and time (Daylight savings time, local time). | Concerns that all nodes and devices connected to the grid have timing signals traceable to the same time scale with accuracies as required. | <ul style="list-style-type: none"> • Synchronized timing allows for localized data analytics and simpler data communications. • Communication structures needed for timing distribution over distribution grids, in conjunction with or independent of satellite-based methods.⁸⁰ • Architecture needs to support applications alignment of time stamps subject to communications failures. • Architecture needs to support applications alignment of time from different time zones, local time and daylight savings. |
| 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. | <ul style="list-style-type: none"> • Efficient protection functions require synchronized time, either locally or globally.²¹ • Timeliness of data availability, computation, and communication in order to meet the system constraints to provide accurate state estimation and precise control automation. • Ability to specify and validate timing constraints • Grid operations uses 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 acquire a sufficiently accurate time signal | <ul style="list-style-type: none"> • Architecture needs to support synchronous time for protection schemes • Architecture needs to support applications validation of timing constraints • Architecture needs to support sufficiently accurate time stamping. |

| Aspect | Concern | Description | Grid Context for CPS Concern | Grid CPS Concern Description | Architecture Significance |
|--------|---------------------------|---|--|--|--|
| Data | Data Semantics | Concerns related to the agreed and shared meaning(s) of data held within, generated by, and transiting a system. | <ul style="list-style-type: none"> • Efforts to fuse data from multiple energy generation and distribution, sources face significant data interoperability challenges.⁴⁰ • Data interoperability is key need for grid modernization. • Data models and many data standards for smart grid devices allow for many different use cases which means that 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. | <ul style="list-style-type: none"> • By collecting pieces of information from various sources and then using algorithms or machine learning, it will be possible to take “safe” data from many sources to create “unsafe” results (e.g. privacy concerns). • Standardization of communication interfaces and data harmonization needed. • As ownership of devices responsible for communicating about and actuating across the grid diversifies, it is not clear that data context (i.e., semantic interoperability) will be maintained across devices without additional effort. |
| 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. | <ul style="list-style-type: none"> • Network convergence is manifesting in the evolution of natural gas/electric system harmonization efforts.¹¹ • 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 accuracy of Distribution State Estimation | Concerns related to the relationships of grid and external data and the value or harm that can be derived from those associations. | <ul style="list-style-type: none"> • Joint control structure needed for converged natural gas/electric power systems.⁵⁵ |

| Aspect | Concern | Description | Grid Context for CPS Concern | Grid CPS Concern Description | Architecture Significance |
|-------------------|-----------------------|--|--|--|---|
| Boundaries | Behavioral | Concerns related to the ability to successfully operate a CPS in multiple application areas. | <ul style="list-style-type: none"> • Multiple value stacks for energy storage systems must respect organizational boundaries. • Operational siloes within utilities especially between Informational Technology (IT) and Operational Technology (OT) increase difficulty of managing CPS devices.⁸⁹ | Concerns related to successful operation at boundaries including geographic and system boundaries. | <ul style="list-style-type: none"> • Architecture must support operational and market uses for energy storage systems. • Architecture practices e.g. TOGAF need to consider differing IT and OT perspectives. |
| 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. | <ul style="list-style-type: none"> • Proliferation of DERs invalidates the long-held assumptions that the grid will be controlled in a top-down fashion. In particular, protection schemes need to be re-assesses⁶. Failure to account for two-way power flows will result in additional outages. | Incorporation of newer technology and updated systems models at various grid levels while maintaining the integrity of the grid network. | <ul style="list-style-type: none"> • More advanced control systems needed to protect grid systems from two-way power flows. |

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| Aspect | Concern | Description | Grid Context for CPS Concern | Grid CPS Concern Description | Architecture Significance |
|-------------------|-----------------------|--|---|--|---|
| Boundaries | Responsibility | Concerns related to the ability to identify the entity or entities authorized to control the operation of a CPS. | <ul style="list-style-type: none"> • Business model changes for utilities driven by distributed generation likely will create Distribution System Operators who may earn income from distribution services not the sale of electricity.¹⁷ • Coordination of microgrids with the larger grid and coordination of microgrids with other microgrids³¹ • Boundary determinations between Distribution System Operators (DSO) and RTOs/ISOs needed. • Boundary interfaces between utility resource planning and DERs needed. • Customers are able to vary power consumption using Demand Response measures. | Determination of ownership and control of grid components. | <ul style="list-style-type: none"> • Transmission/distribution coordination via Distribution System Operator models needed.⁷¹ • Circuit structure, protection and control structure needed for multiple cooperating microgrids.⁸³ • Architectures for multi-scale (e.g. single building versus multiple circuit) coordination of microgrid networks needed.⁸⁴ • Architecture needed for CCAs and aggregated community resources.⁸⁵ • Architecture needed for segmentable and coordinated grid “pieces” and for coordination to facilitate agile re-segmentation and cooperation for different microgrid scales (e.g. single building versus multiple circuit).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, but it’s more likely they would be provided by third-party aggregators.⁸⁷ • Standardization of interfaces between utility resource planning tools and DERs would increase effectiveness of DERs. • Clearly defined guidelines for customer participation and benefit realization. |

| 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. | <ul style="list-style-type: none"> • 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. • Grid control algorithms need to be much more complex in order to consider market economics, efficient energy usage, and managing reliability with a variety of resources, such as storage and demand response, in areas with high penetrations of wind and solar generation. | Ability to update or reconfigure grid technology to meet power system needs. | <ul style="list-style-type: none"> • Need for interoperability standards for grid components. • Preparedness for future grid technology. • Architecture needed for integration of large scale energy storage distribution connected resources for operation.⁵⁸ • Balancing and stabilization of grids with wide area bulk wind and solar resources.⁵⁹ • Distributed intelligence computations and communication network structure needed to support distributed analytics, and control.⁶⁹ • Coordination, communication, and sensing structures that facilitate use of Demand Response for grid resilience purposes needed.⁶⁷ • New hybrid central/distributed control structures 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. | <ul style="list-style-type: none"> • The grid is so complex, no-one can understand nor plan for the entirety of it.¹⁵ | Concerns relating to complexity in grid functionality. | <ul style="list-style-type: none"> • Movement of control/management/optimization to lower levels will reduce complexity. • Grid partitioning as a means to adapt to stresses needed, along with coordination and communication.⁶¹ |
| Composition | Constructivity | Concerns related to the ability to combine CPS modular components (hardware, software, and data) to satisfy user requirements. | <ul style="list-style-type: none"> • Replacing an Outage Management System (OMS) and Distribution Management System (DMS) into an Advanced DMS (ADMS) poses complex deployment issues including how to replace both the OMS and DMS at the same time, data alignment/transfer, consistency in calculating reliability metrics, and operator training. | Integration of power system components of various types and configurations. | <ul style="list-style-type: none"> • Architectures need to address use of the same data by multiple applications, varying data rates, and standardized data definitions e.g. CIM. |

| Aspect | Concern | Description | Grid Context for CPS Concern | Grid CPS Concern Description | Architecture Significance |
|--------------------|------------------------|--|--|--|---|
| 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). | <ul style="list-style-type: none"> Increasing need for system observability, resultant communication (data flow) and resultant information handling. System operators want visibility of DER assets operation they neither own nor control. | Concerns related to the observability of power systems components needed to leverage component data. | <ul style="list-style-type: none"> Fault tolerant communication structures needed for distributed intelligence.⁶² Need for architecture to support centralized and decentralized controls for DERs. |
| Lifecycle | Deployability | Concerns related to the ease and reliability with which a CPS can be brought into productive use. | <ul style="list-style-type: none"> Grid is mission-critical for most industries and people. Limits 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. 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. American health care, military, manufacturing, emergency service, and financial institutes run on electricity, not gas, oil, coal, solar or wind. Thus electricity is essential to the age of information and to the IoT.² Reduction of system inertia caused by inverter-based generation in some cases requires additional control actions by regulator tap changers and capacitors.⁵⁴ | Concerns related to the implementation of grid technology to meet power system needs. | <ul style="list-style-type: none"> Architectural support 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 needed for transmission state determination and situational awareness.⁵⁷ Structures for integration of inertia augmentation methods, devices, and systems.⁶⁰ |

| Aspect | Concern | Description | Grid Context for CPS Concern | Grid CPS Concern Description | Architecture Significance |
|-----------|-----------------|---|--|--|--|
| Lifecycle | Disposability | Concerns related to the impacts that may occur when the CPS is taken physically out of service. | <ul style="list-style-type: none"> • Retirement of large power plants at the end of their lifecycle. • Disposal of faulty grid equipment. • Recycling of out-of-service grid components. | Concerns related to the disposal of obsolete, aged, or damaged physical grid components. | <ul style="list-style-type: none"> • Architecture needed to support environmental-friendly recycling practices. • Improved quality checks to minimize faulty equipment. |
| Lifecycle | Engineerability | Concerns related to the ease and reliability with which a CPS design concept can successfully be realized via a structured engineering process. | <ul style="list-style-type: none"> • Scalability of grid R&D products. • Microgrid engineering issues have been studied, but architecture coordination issues remain.³² • Time lags in translating new concepts into standards and implementation, e.g. test certifications may be for earlier versions of a standard. | Ability to develop theoretical concepts into applicable grid technology. | <ul style="list-style-type: none"> • Implementation of Distribution State Estimation and Optimal Power Flow (OPF) must consider scalability and data availability. • Microgrid architecture models needed. |
| Lifecycle | Operability | Concerns related to the operation of the CPS when deployed. | <ul style="list-style-type: none"> • Exceeding long lifetimes for electric system components that may exceed 30 years.⁹⁰ • American grid, like much American infrastructure is aging, compounding the difficulty of converting to new systems. Also an opportunity to introduce IoT infrastructure when necessary upgrades are made. • Increasing more complex grid controls requires a more skilled workforce. • How to upgrade firmware in existing devices to support new features such as the ability of advanced inverters to control voltage and frequency. | Concerns related to continuous, effective operation of grid components. | <ul style="list-style-type: none"> • 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. |

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