Quadrennial Technology Review 2015

Chapter 3: Enabling Modernization of the Electric Power System

Technology Assessments

U.S. DEPARTMENT OF ENERGY

Quadrennial Technology Review 2015

Designs, Architectures, and Concepts

Chapter 3: Technology Assessments

Introduction

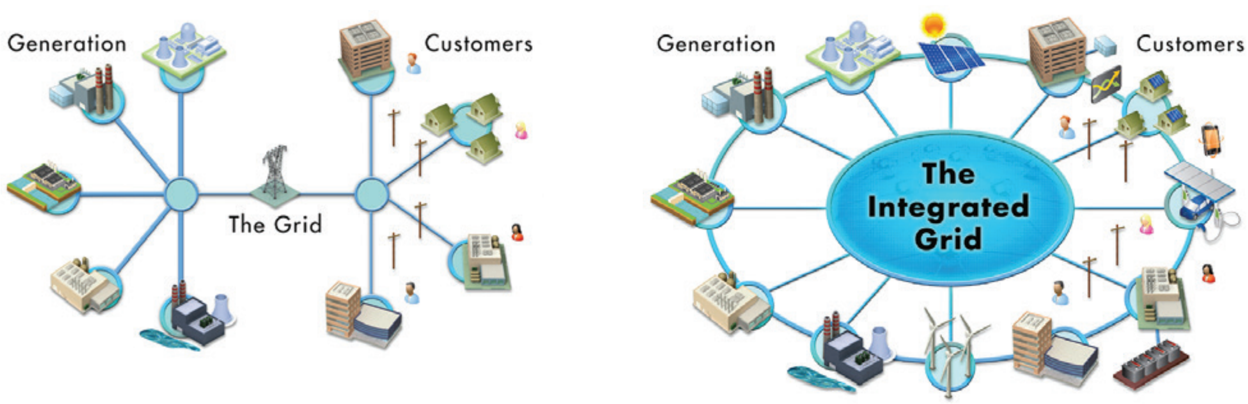
Society's growing dependence on the electric infrastructure, along with rapid changes in generation-side and demand-side technologies, is forcing a reconsideration of the fundamental design principles and operational concepts of the grid. Currently, the grid is characterized by monolithic central generation interconnected by high voltage transmission lines, with one-way power flows on distribution feeders, delivering electricity to meet predictable customer loads. The nation's reliance on electric power for commerce, connectivity, comfort, and transportation, and the desire for more personalized energy options creates the need for more resilient and modular designs as well as agile operational concepts.[1]

Dramatic reductions in the costs of communication, computation, data storage, sensors, and control technologies as well as improvements in algorithm efficiency are making such concepts possible. As more energy resources are deployed on distribution systems and customers begin to participate in energy markets, the boundary between transmission and distribution begins to blur. This trend is raising many questions regarding the design of the grid of the future, along with operating paradigms, resource options, stakeholder roles, business models, and regulatory constructs. The Electric Power Research Institute's (EPRI) model for the future grid is one where the transmission and distribution systems are integrated into a common platform where all energy resources, centralized and distributed, can participate to meet the needs of society and maximize value, as illustrated in Figure 3.B.1.

One example that highlights the need to transition to an integrated grid is the "Duck Curve," created by the California Independent System Operator (CAISO), illustrated in Figure 3.B.2. Simulations through 2020 show the anticipated challenges with the established design and operating principles of the grid. The net load curve[3]

Figure 3.B.1 Transition from the Current Grid to a Future Integrated Grid [2]

Credit: Electric Power Research Institute

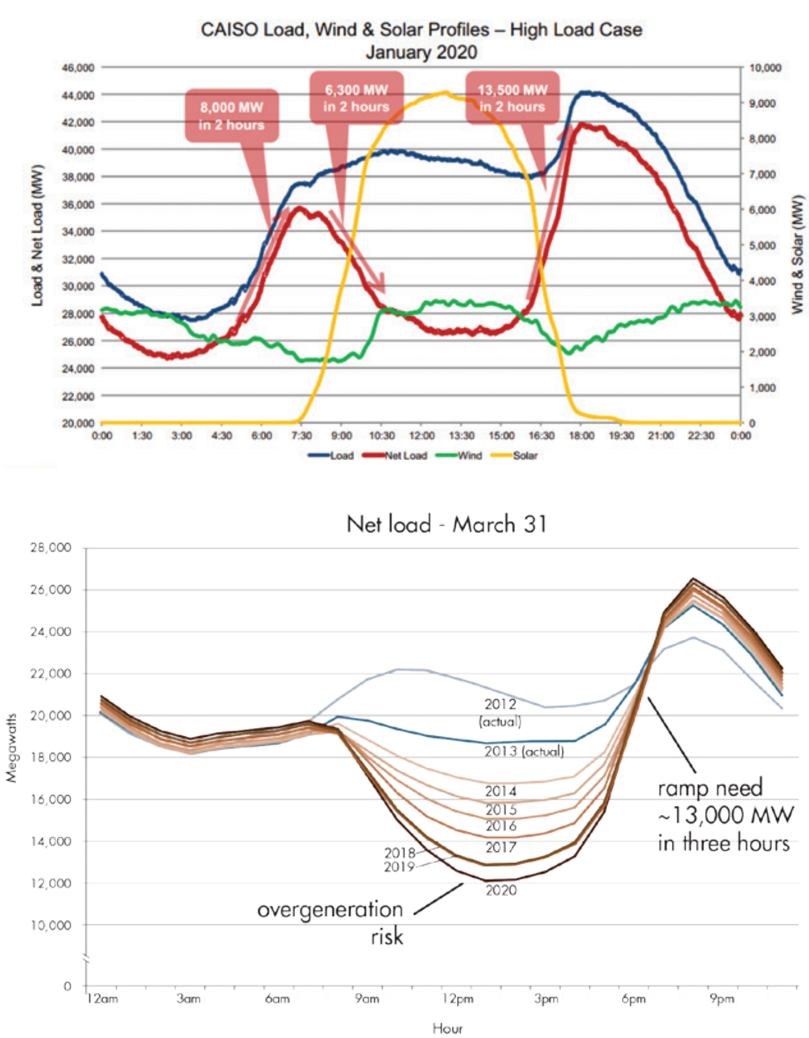


is a composite of load and non-dispatchable centralized and distributed generation (e.g., wind and solar). The penetration of variable energy resources is changing the balance issue in California from managing peak to managing ramp. While the steep ramps[4] in the evening and "overgeneration"[5] in the afternoon present tremendous challenges at the system operator level, they also present thousands of new challenges at the distribution level. As rooftop solar photovoltaics kick in and residential loads drop, unintentional islanding and reverse power flows create control, protection, low-voltage ride through (LVRT), fault ride through (FRT),[6] and safety challenges. Critical non-technical challenges include understanding how the industry, markets, and regulations interact to ensure reliable and economical operation under these emerging trends.

While these changes may be addressed through taking principles and technologies used in the transmission system and applying them to distribution systems, it is by no means a duplicative solution. The scale, designs, topologies, business models, and regulatory factors change the requirements of technological solutions. There is no silver-bullet solution presented by a single technology because there are many options to choose from that are suited for different regional needs. In addition to the challenges associated with integrating transmission and distribution operations, there is a need to integrate and optimize use of distribution and customer resources by taking into account the differing value of reliability and other services to different customers.[8,9]

Figure 3.B.2 CAISO Projected Load Curves and Overgeneration Risk[7]

Credit: California Independent System Operator Corporation



An optimal transition to the grid of the future will require fundamental advances in "system-level" understanding, enhanced capabilities for analysis, and exploration of the design option space. Recent issues in Hawaii with high solar penetration, contention with net-metering policies in many states, and the launch of the New York Reforming the Energy Vision[10] initiative highlight the challenges with making long-lived energy investment decisions and the need to ensure they are in the best interest of the numerous stakeholders. Developing tools and capabilities that can help assess various portfolios and options on a level playing field, increase interoperability, and structure discussions among stakeholders will increase the likelihood of finding "noregrets" decision paths that are more cost-effective. The U.S. Department of Energy (DOE) has worked on the development of tools to support consideration of alternative regulatory models.[11]

Some of the key technical accomplishments needed to transition to the integrated grid of the future are as follows:

- Combining and integrating distribution and transmission level control architectures
- Coordinating the management of distribution resources and other distributed energy technologies to provide grid services, such as volt/VAR optimization
- Maintaining frequency and phase balance throughout each distribution circuit with limited ability to rely on generator inertia
- Managing the two-way power flows on distribution systems due to increased distributed generation
- Accurate forecasting of load and resources at the distribution level
- Integrating autonomous operation of devices both on the load and distribution side and determining how and to what extent the power system can rely on such autonomous devices in system operations
- Integrating transmission and distribution state estimation and developing sufficiently flexible and transparent distribution network models

Research and development (R&D) efforts and activities that address these challenges, support decision making, and help manage the transition to the grid of the future will be extremely valuable.

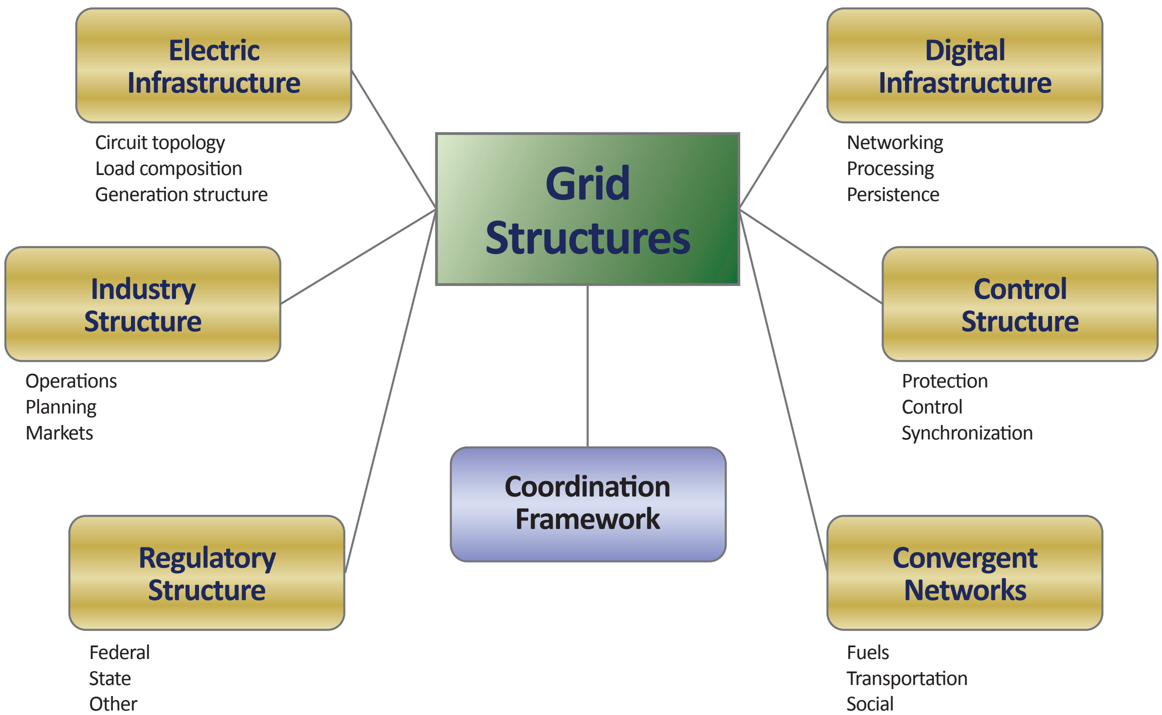
System Architecture and Interoperability

The current grid evolved from the gradual interconnection of independent vertically integrated utilities, followed by the introduction of competitive markets, and is now interspersed with a slew of technological innovation and third-party products. As the grid becomes more connected and more complex, a method of understanding how the various pieces and players function, come together, and interact is needed to ensure secure, reliable, and cost-effective system operations. A formalized abstraction to help identify and map system functions to desired metrics and system characteristics supports innovation and is necessary to ensure interoperability. Given the numerous stakeholders involved in the electric power system, common concepts and ways of looking at the various facets of the system can be used to align directions and facilitate the development of appropriate standards.

System architecture is a broad and expansive concept and includes electrical connectivity, physical topologies, data organizational structures, communications protocols, computational processes for modeling and simulation, control constructs, and even market rules and institutional relationships. Because of the growing interconnectivity and interdependency of the grid, changes made to the system may result in unintended consequences if the relationships and functions are not well understood and actions are not properly coordinated. Naturally, the development and use of system architecture to compare designs and practices will require an in-depth understanding of the current paradigms as well as proposed modernizations. Some of the possible performance drivers behind improvements in system designs include greater grid security, efficiency, and reliability. Fundamentally, these performance drivers relate to the overall resiliency of the power system.

Grid architecture design provides the structure of the grid and thereby determines the essential bounds of what can and cannot be done within that framework. It is essential to recognize what these bounds are, to change them where necessary, and to understand the interactions and consequences of the various grid structures. The discipline of grid architecture provides a modern set of methods to assist in thinking about grid complexities, to aid in understanding interactions and technical gaps, to enable new capabilities and remove old unnecessary limits, and to support communication among stakeholders. Actions to develop this modern grid architecture include the coordinated advancement of standards across the electric power system, including device characteristics, communications requirements, security, and other system aspects. Figure 3.B.3 outlines the various structures that the grid needs to consider and harmonize in order to provide the maximum flexibility to satisfy the required performance expectations.

Figure 3.B.3 Grid Architecture Structure Types

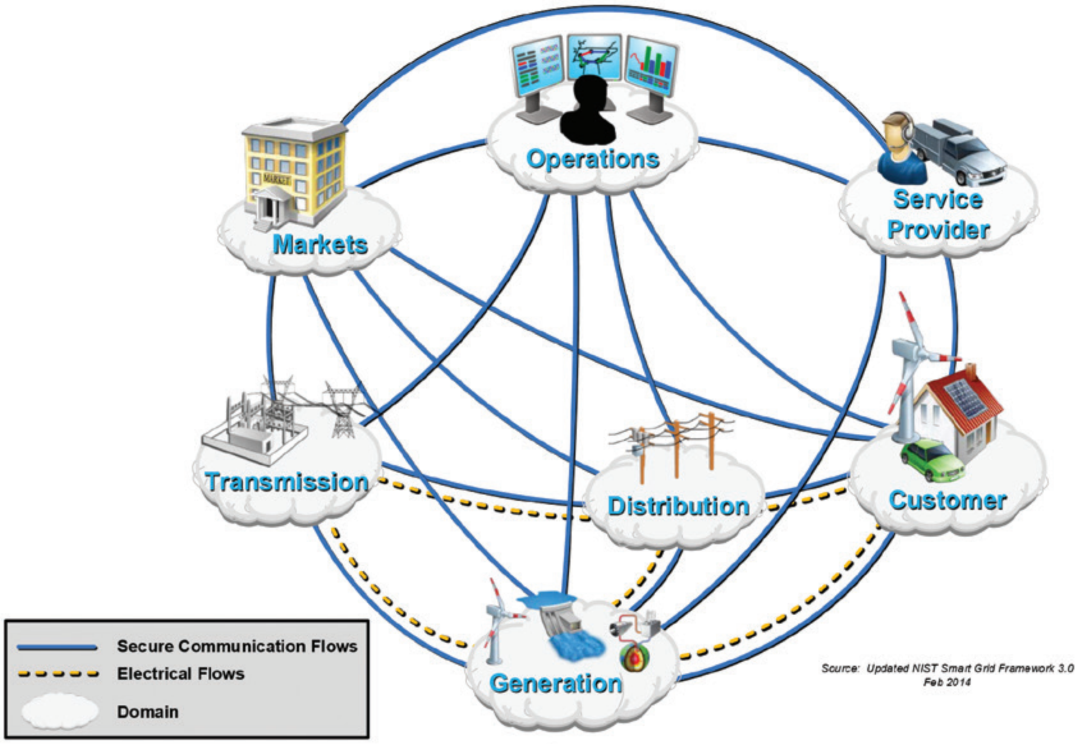


The structure of the grid is already changing, requiring broader changes across the entire system. The trend toward consumer participation in electricity production and management ("prosumers") is a significant shift. The associated interactions with the grid, especially in commercial buildings, are leading to issues with managing reliability at the distribution level and coordinating large numbers of devices and systems outside of the utility's domain. Consequently, definitions for the roles and responsibilities at the distribution level are changing, leading to both regulatory and industry changes. These changes will affect the design of key technologies such as protection and control systems and information and communications technology systems. At the same time, in parts of the country, electric power systems are converging with natural gas systems, electric transportation systems, and social networks, all of which impact grid control and communication. Significant changes are needed in the structure of controls systems, coordination frameworks, communications, and overall industry structure. It is critical that these changes be viewed, understood, re-architected, and managed simultaneously, because these systems are deeply interconnected.

Grid architecture must also address data fusion and exchange and not just communications between applications. One possible research area is that of shared data architecture for the future grid. The grid integration work to date is almost exclusively about applications exchanging information with each other as autonomous entities. In simpler terms, one application sends information to another, either through messaging or through a shared data store. This has led to a proliferation of applications with inconsistent data stores. Inconsistencies occur due to data transfer corruption, differences in algorithm estimation, incorrect mapping among different models, temporal synchronization, or other factors. The advantage of shared data architecture

Figure 3.B.4 The SGIP Conceptual Model[12]

Credit: National Institute of Standards and Technology



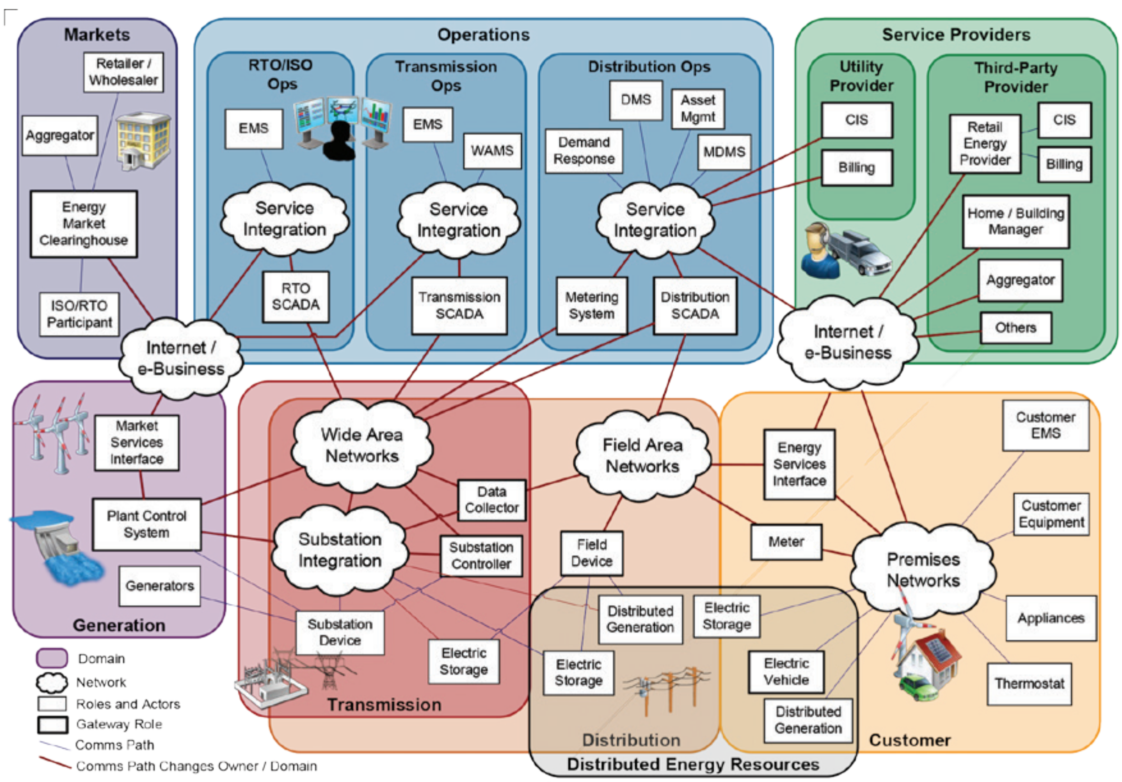
is that it allows applications to work from the same data and, thereby, to reduce the cost of innovation by allowing application developers to build on an existing data collection and management infrastructure.

Architectural frameworks are useful tools to establish a conceptual basis of definitions and structures from which complex landscapes can be mapped and discussed. For example, Figure 3.B.4 shows a model of the electric power system developed and maintained by the Smart Grid Interoperability Panel (SGIP). This model depicts various domains involved in the system and shows cyber and physical connections. On a macro level, these connections are where integration will need to take place and defines the interfaces for interoperability. A more detailed look at how the framework can be expanded to explore the communication connections between some of the actors, their roles, and the information networks used is shown in Figure 3.B.5. These models can help grid stakeholders see where their business concerns may align with those of other participants, thereby facilitating dialogue and identifying areas where coordination is needed.

Architectural frameworks are also helpful in examining areas where agreements and understanding outside the technical realm are needed to make the various systems (e.g., electrical, communications, business, and regulatory) interoperate. The GridWise® Architecture Council (GWAC) engaged stakeholders in the formation of a GridWise Interoperability Context-Setting Framework, as shown in Figure 3.B.6. This framework helps to organize and understand the different categories of interoperability and identifies a set of crosscutting issues that need to be addressed to improve interoperability. This framework was further extended by the European Union Smart Grid Coordination Group, which developed the three-dimensional Smart Grid Architecture Model as a tool to map smart grid use cases and system standards, as illustrated in Figure 3.B.7. This tool helps compartmentalize the complexity of the grid, separating various interoperability requirements into discrete layers (e.g., component, communication, information, function, and business).

Figure 3.B.5 System Components for Smart Grid Information Networks[13]

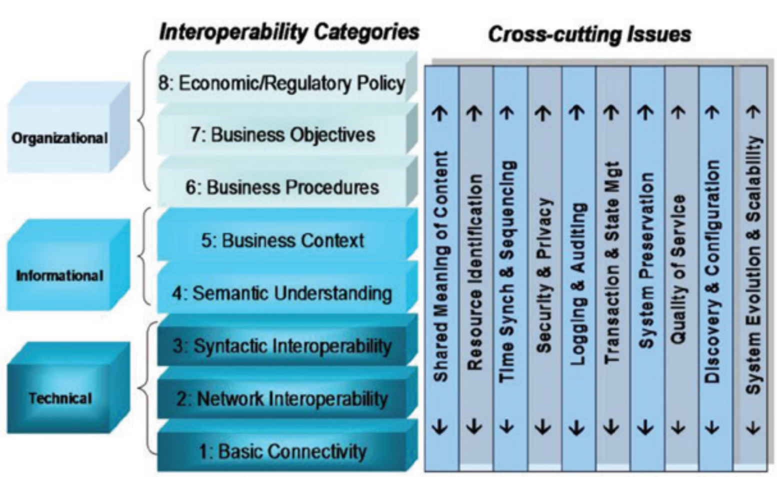
Credit: National Institute of Standards and Technology



These frameworks are examples that have been used to engage stakeholders to identify areas where new standards are needed or where existing standards can be improved. Developing these tools is not an easy task because they require the buy-in of the various stakeholders that will be using them. DOE has been a key supporter in the development of these tools and processes, having funded the assembly of the GWAC[16] since 2004 and working with the National Institute of Standards and Technology (NIST) and the SGIP[17] since 2008. DOE continues to support these efforts, with the goal of enabling the integration and interoperability of various new technologies, such as distributed energy resources.[18]

Figure 3.B.6 GWAC Smart Grid Interoperability Context-Setting Framework[14]

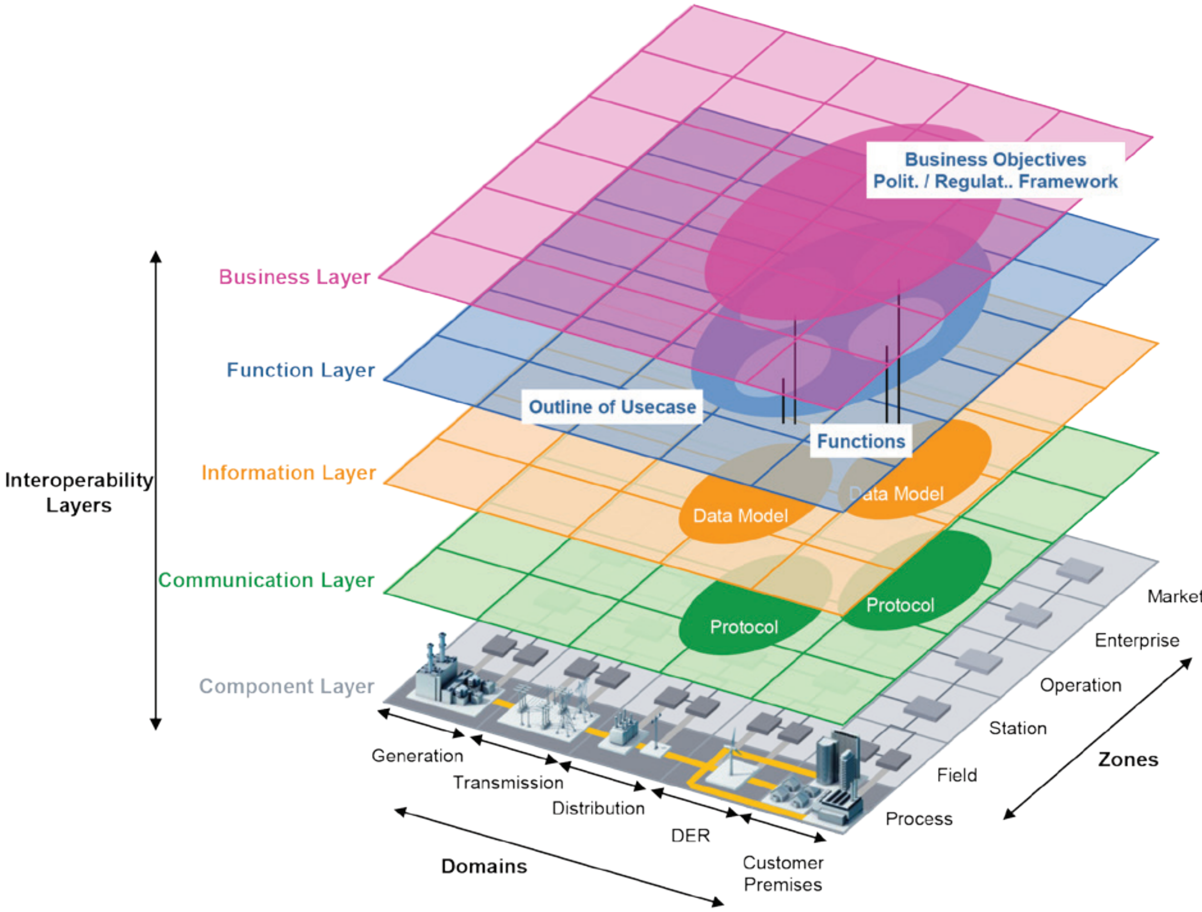
Credit: The GridWise Transactive Energy Framework is a work of the GridWise Architecture Council



Within the context of an established architecture, standards are needed to facilitate

Figure 3.B.7 European Union Smart Grid Architecture Model[15]

Credit: © CEN, reproduced with permission © CENELEC, reproduced with permission

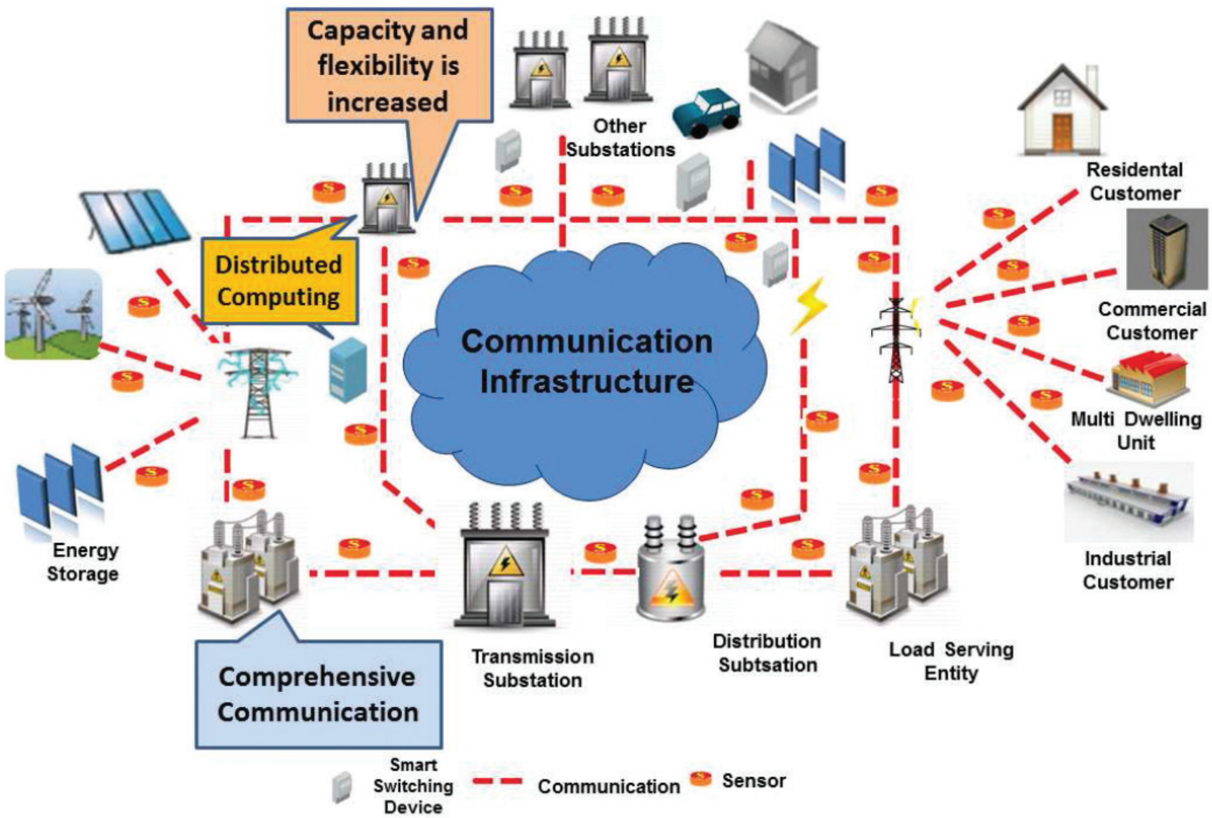


the consistent embodiment of new technologies and to achieve true interoperability. A modernized grid that exchanges data at an unprecedented scale cannot subsist on legacy data quality standards or with interoperability being a forced outcome. For example, standards are needed to define how data gathered at various sensors in a smart grid network will be structured, aggregated, and transmitted within the limits of the communication infrastructure as depicted in Figure 3.B.8. Through distributed computing, local data can be used for local applications and be distilled for regional applications, such as increasing capacity and system flexibility. There is also a need to develop standards and protocols for consumer devices (e.g., electric vehicle chargers, appliances, and demand-responsive devices) to facilitate communications between each other and with the utility. Because information and data will inevitably cross more operational boundaries than fewer, standards must evolve to pass data more efficiently and securely and to ensure that the value of such data is preserved. Standards for flexible data requirements would also help to address the changes associated with grid modernization.

Benefits of interoperability standards include improved electricity market connectivity using established information and communications technologies and easier integration of demand response, distributed generation, variable generation, energy storage, electric vehicles, and other new technologies. Additionally, some residential consumers are now able to obtain their energy usage information from their utilities and share it with third-party service providers for use in innovative applications. The diversity of entities involved in these multi-stakeholder processes—from the federal government and the private sector to non-profits and standards development

Figure 3.B.8 Smart Grid Architecture Increases Capacity and Flexibility[19]

Credit: G. Shafiullah, A. Oo, A. Ali and P. Wolfs, "Smart Grid for a Sustainable Future," *Smart Grid and Renewable Energy*4 (2013), 23-34, doi: 10.4236/sgre.2013.41004.



organizations (SDOs)—indicates that coordination must increase. It will be important to leverage established cross-SDO groups, such as the SGIP and the OpenADR initiative, to accelerate efforts on standards and interoperability.

To achieve the vision of an integrated grid, many more interoperability issues must be resolved. For example, ensuring that the appropriate level of cybersecurity is in place for data exchanges will also require clear designation of who must provide this protection. However, these challenges are not unique to the electric industry but are shared with manufacturing, finance, health care, transportation, and other industries. Open data frameworks, machine-to-machine standards, business-to-business standards, and semantic technologies are contributing to the "Internet of Things" (IoT) concept being promulgated.[20] One of the challenges introduced by IoT convergence with the grid is the additional layer of cyber-security risk that has to be addressed; the addition of critical infrastructure to the Internet greatly expands the threat surface. Maintaining awareness of these advancements and how they can be applied in a safe and cyber-secure manner to allow for a continually evolving set of electric power system applications is a great challenge and opportunity that lies ahead.

Control Concepts

As electricity generation shifts from centralized plants to more distributed resources and from dispatchable units to variable and intermittent renewables, maintaining the generation-load balance will become increasingly difficult. Operating the grid to continue powering society reliably will require a vast supply of flexible resources.

Currently, available technological options—such as responsive loads, distributed electrical and thermal storage, smart inverters on solar photovoltaic systems, and electric vehicles—can augment the flexibility in conventional thermal generators to meet this growing requirement. However, coordinating all of these resources in an optimal manner is fundamentally different from the control methodologies of today, requiring the development of new control concepts.[21]

In the near future, operators will no longer be constrained to thermal generators, including automatic governor controls and economic dispatch, as a primary means to balance the broader power system. Connectivity to the distribution network as well as to consumers through smart appliances and demand response programs will expand the options available to achieve system objectives. This new operating paradigm will require improvements in control methodologies that can span the entire system and can handle the probabilistic and stochastic nature of variable and distributed resources within the emerging operating environment.

Utilizing a centralized control solution under the current paradigm—adding more distribution assets and centrally controlling them with higher bandwidth and lower latency communications—becomes increasingly less feasible and prohibitively expensive. System designs and architecture that relies more on local intelligence and distributed controls, which can accommodate two-way power flows within distribution systems and facilitate information sharing for better coordination, must emerge. These requirements call for a combination of centralized and distributed control paradigms, a hybrid approach, to manage the integrated grid of the future.

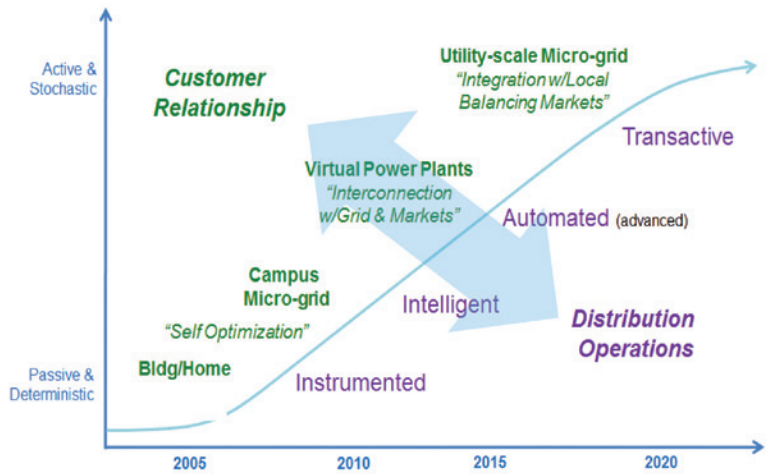
For future control architectures and solutions, the distinct challenge is to develop technologies that are inherently secure and resilient. Some of the promising research efforts in this field involve grid systems that can autonomously defend themselves from cyber-attack and systems that can seamlessly recover from failures to maintain grid operation.[22,23] R&D on new control architectures and approaches involving distributed energy technologies, microgrids, smart end-use technologies, dynamic distribution topologies, modern power electronics, advances in distribution automation, improvements in cyber security, and enhanced data analytics is needed.

Connectivity initiatives, spawned by the growth of the Internet, are offering new opportunities for the integration of distributed energy resources. A fundamental requirement for resources used in grid operations is the ability to provide a smooth, stable, and predictable response. One challenge with distributed energy resources is the significant growth in control points that will need to be coordinated to provide this response. Moving from thousands of centrally controlled power plants today to the potentially hundreds of millions of plug-in electric vehicles, smart thermostats, and other consumer-owned assets is a significant shift. Another challenge is consumer privacy concerns (reluctance to share information with the operator), which may make centralized coordination and control untenable because good controls require good visibility and access to accurate information. Even if information is shared willingly, communication bandwidth limitations and the latency of information (from large amounts of data traveling long distances) may render centralized operational paradigms impractical. Additionally, since most of these assets are owned by consumers and third-party service providers, coordination with grid operations needs to appeal to the owners' self-interest (e.g., rewards for their participation). New coordination and control concepts are needed to achieve optimization over multiple-actor objectives, which can be synergistic or competing, and must meet both local and system requirements.

"Transactive" energy is a concept that could potentially contribute to the optimal balancing of supply and demand at all levels of the grid. It is defined as a set of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter.[24] A large share of electric demand is potentially responsive to price forecasts and grid conditions. If properly managed, this adaptive response can be used to significantly improve grid efficiency and reliability. Through the use of economic signals, customer and third-party assets can compete in the provision of grid services and coordinate with grid operations. Transactive control solutions emphasize a decentralized approach, where discretion of the asset owner is maintained and decision making is kept local and private, yet

Figure 3.B.9 Stages of Adoption of Transactive Operations for Industry

Credit: The GridWise Transactive Energy Framework is a work of the GridWise Architecture Council



the coordinated assets are able to provide the smooth, stable, predictable response required for operations. Transactive approaches can be incorporated into many different structures and mechanisms that allow them to coexist with present operational approaches. The evolution of this control concept is shown in Figure 3.B.9.[25] Customers begin with self-optimization and intelligent coordination with the distribution operator. As participation becomes more numerous, active, and geographically disperse, automation and fully transactive distribution operations will be needed to maintain cost-effective and optimal grid controls.

For this concept to work, the economic signals must be transparent and reflect the true value of the assets contribution at all levels of the grid for all relevant value streams at different moments in time. This will allow distributed energy resources to compete equitably with all other types of resources on a level playing field, including traditional generation and new technologies, so that an optimal mix can be used to achieve each operational objective. Additionally, these signals must be communicated to the various distributed assets in near real-time or in advance, the assets must have local intelligence and control capabilities to respond to the opportunities presented by these signals, and the assets must be capable of negotiating and transacting a range of market-driven energy services with the grid and each other. Transactive controls may also require system operators to provide an indicative forecast of future prices for various grid services. While it may be possible to have real-time, two-way interactions with individual devices and a central clearing server, the cost of scaling this model remains in question.

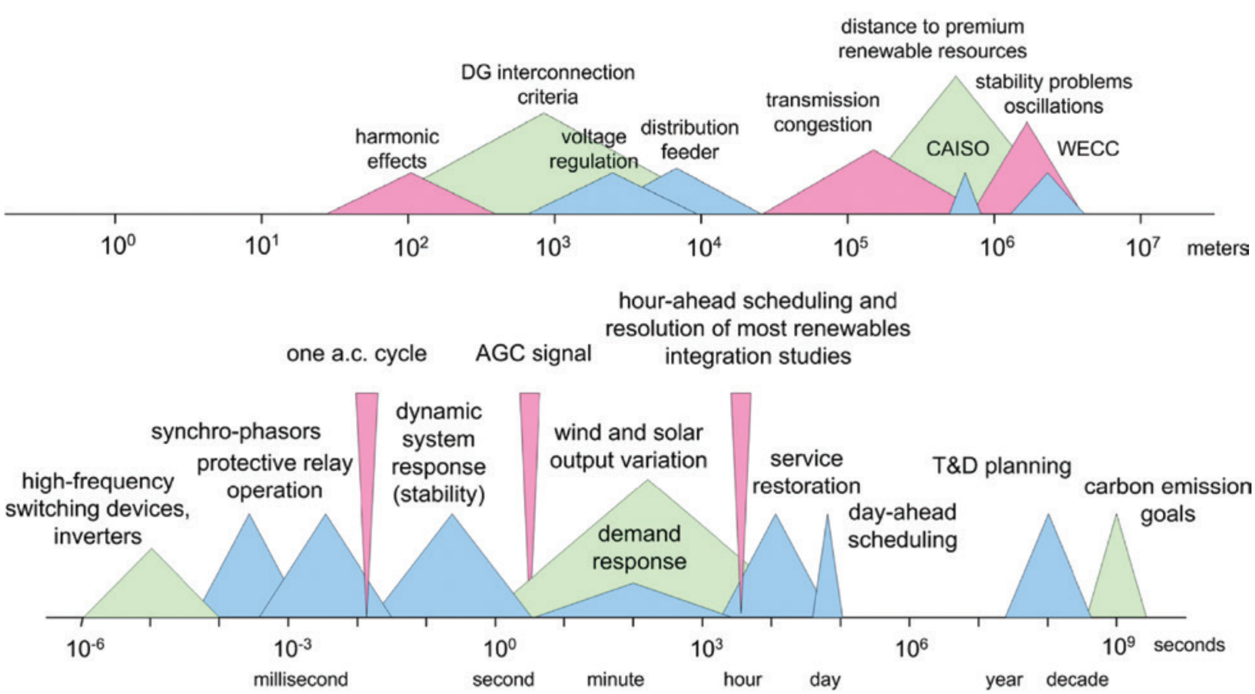
DOE has supported the development of transactive controls in three pilot demonstrations: the Olympic Peninsula Demonstration (2006–2007), AEP Ohio's gridSMART® Demonstration Project (2010–2013), and the Pacific Northwest Smart Grid Demonstration Project. While these projects established the fundamental viability and functionality of such concepts, a more systematic approach is needed to refine transactive concepts and prove their efficacy in the full range of regulatory environments and operational conditions. In particular, advancing the theoretical foundation of combining economics with physical system controls is needed to ensure the robustness and stability of using such techniques. Another challenge is the need to quantify the various value streams that can be realized (e.g., voltage control, reliability, and resilience) and translate them into the proper economic signals. More advanced transaction systems could conceivably have market systems where participants are incentivized to make decisions that are not in their immediate self-interest but still have long-term overall societal benefits.

Other than transactive energy, there are many aspects of control concepts that require investigation in light of new technical capabilities and system changes. With the expected greater deployment of power electronic-based systems (e.g., flexible alternating current transmission system [FACTS] devices, HVDC converters, and electrical energy storage) in the future grid, development of controls for increased power flow control, faster system dynamics, and less system inertia (due to retiring thermal units) could be valuable. New control concepts that can achieve multi-objective and multi-stakeholder optimization, in addition to balancing between local and global objectives, will be needed for micro-grids, virtual power plants, and hybrid systems. Additionally, with growing interdependencies (e.g., electric-gas or energy-water) and concerns with cyber-attacks, physical attacks, and extreme weather events, new control concepts for robust operations, graceful failures (segmentation), and autonomous recovery (reconstitution) are other areas worth exploring. Studying the impact of communication latencies on controls, adaptive controls based on sensor measurements, and stochastic controls to manage uncertainty are other areas under control concepts that require further development. Finally, the applicability of hierarchical distributed controls to bridge between transmission and distribution systems is another critical area of R&D. Some possible opportunities for improving control concepts with respect to improved security and resilience are listed below:

- Developing an infrastructure degradation assessment and proactive control framework that can maintain critical operations under threat
- Developing a role-based, cyber-physical state awareness framework
- Developing an intelligent cyber detection and feedback mechanism for recognition and autonomous response to attack
- Developing an adaptive and agile control architecture for optimizing efficiencies of operation along with autonomous and human response in an all-hazards environment

Figure 3.B.10 Temporal and Spatial Scales Associated with Power System Planning and Operations[26]

Credit: Alexandra von Meier, "Challenges to the Integration of Renewable Resources at High System Penetration," California Institute for Energy and Environment (2014). http://uc-ciee.org/all-documents/a/441/113/nested



Key: **CAISO** = California Independent System Operator; **WECC** = Western Electricity Coordinating Council; **DG** = Distributed Generation; **AGC** = Automatic Governor Control; **T&D** = Transmission and Distribution

Planning Tools and Simulators

Due to the overall size and complexity of the electric power system, planning tools and simulators were developed to help answer specific questions and support decision making. From transmission expansion and production costs to component designs and protection schemes, planning tools and simulators are used regularly to study various aspects of the grid, assessing the trade-offs between choices. While the accuracy of any modeling or simulated result is limited by many factors—such as the availability and accuracy of data sets, the accuracy and precision of models, simplifying assumptions, computational capabilities, and run times—the results can still be used to improve understanding of general trends and for exploring possibilities.

As we transition to a future grid, planning tools and simulators will become even more important to making well-informed decisions regarding potential changes. Figure 3.B.10 depicts the spatial scale (from an individual solar panel sitting on a rooftop to the entire North American continent) and the temporal scale (from microseconds to decades) over which planning tools are needed to support decisions that have significant implications. For example, planning tools help determine operating limits and the amount of reserves needed for a particular region. Inaccuracies can lead to conservative limits that raise system operating costs or improper settings for protection schemes that could result in wide-area disturbances. There is no single tool that has the capability to answer the range of questions; a variety of tools will be required.

The growing interconnectivity, interdependencies, and complexity of the electric power system are demanding tools with enhanced capabilities to answer new questions. Many recent innovations can be leveraged to improve existing tools, such as using high-quality sensor data (e.g., phasor measurement units [PMUs]) to validate models, using advanced computational platforms (e.g., parallel processing) to accelerate run times, and facilitating seamless connectivity among different tools to increase the precision of results. Improvements in planning tools and simulators will help ensure the safe, reliable, secure, and cost-effective delivery of electric power by evaluating the merits of new architectures, assessing the consequences of policies implemented, simulating the efficacy of new control concepts, and understanding the impacts of new technology solutions.

Commercial software tools[27] are not advancing quickly enough to answer key questions about technologies that are on the near-term or not-too-distant horizons.[28] Various new planning tools and simulators are already being demonstrated in the field but there is significant room for improvement. Next-generation software tools will need to be able to do the following:

- Incorporate distributed energy resources and new technologies (e.g., batteries, electric vehicles, microgrids, virtual power plants, smart inverters, virtual inertia, demand response, smart buildings, HVDC, and FACTS devices) along with their function, control, and protection
- Include the stochastic nature of consumer behaviors, non-dispatchable loads, variable renewable generation, moving electric vehicles, and other new system dynamics
- Allow exploration of new market and customer pricing mechanisms to coordinate resources with the grid, such as transactive energy, and linking with real-time operations and control
- Provide better real-time simulations, especially for real-time operation and control purposes
- Enable simulation of extreme events, such as electromagnetic pulse and geomagnetic disturbance, weather events, physical/cyber-attack and many other nationwide threats
- Investigate and quantify the value of new energy products, such as retail ancillary services, differential reliability, volt/VAR control, or flexibility services
- Explore new resiliency mechanisms, such as microgrids or dynamic reconfiguration
- Enable dynamic security assessments and update of defense plans and restoration plans in response to variations in power system operating conditions
- Examine the convergence of new and legacy operational approaches and technologies

- Integrate multiple system domains, such as transmission, distribution, generation, markets, communications, buildings, natural gas, water, transportation, and environment
- Enable more holistic decision making and better quantification of life-cycle costs, including the correlation between temporal and spatial data and scales
- Support the analysis of existing and innovative business models and policies
- Validate observations achieved through testing and demonstrations

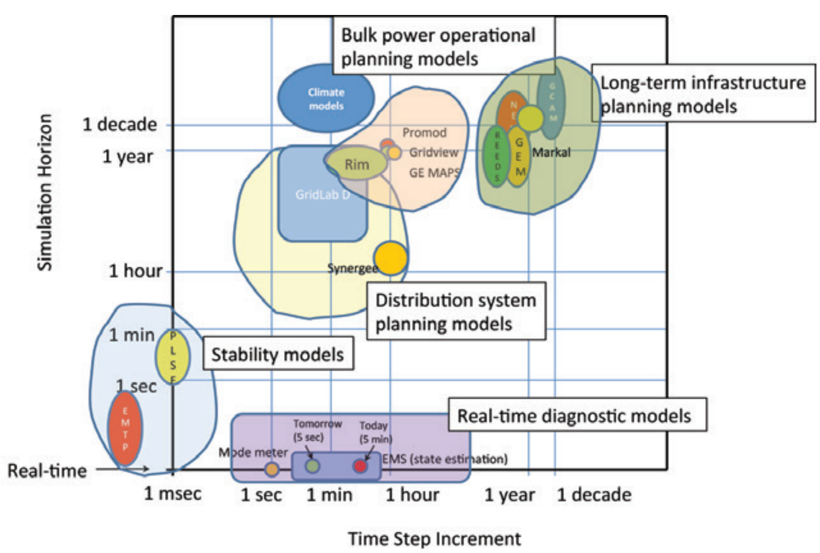
The challenges for planning and simulation tools can be summarized under two broad categories.[29] The ability to transition advancements to operational systems that can run in real-time based on real-time data feeds to support control and coordination is the larger challenge. As the grid transitions to one that is analytically driven and controlled, foundational improvements in operational models and simulators become even more critical. Validation of reduced-order models using real world data and established use cases is needed before automation and model-based control can be fully trusted. Additionally, significant amounts of information will need to be rapidly processed and fed into these models and simulators. The second category of challenges includes developing planning and simulation tools that are easy to use, accessible and accurate, and transparent to all power sector stakeholders.

DOE has been supporting the development of high-fidelity modeling and simulation tools to improve grid planning, operation, and policy decision making. GridLAB-D™ (DOE funded) and OpenDSS (EPRI funded) are examples of open-source simulators that address some of the needs in distribution-level analysis. The availability of these tools has pushed commercial vendors to modernize their software packages and incorporate high-fidelity modeling of distributed energy resources.[30,31] While GridLAB-D and OpenDSS are research focused, they are making inroads into the utility industry as users (both researchers and utility planners) begin to ask questions about the future of the distribution utility.

As mentioned earlier, there is currently a range of planning and simulation tools that are utilized by the industry with varying capabilities as highlighted in Figure 3.B.11. DOE has supported initial work to integrate tools across multiple domains.[32] The work involved integrating GridLAB-D (distribution) with NS-3 (communications), PowerWorld Simulator (transmission), PowerLab™ (markets), Distributed Energy Resources Customer Adoption Model (DER-CAM) (microgrids), and Technology Management Optimization (TMO). In the process, the value of circumventing the cost and complexity of constructing modeling and simulation tools with ever-expanding scope and capabilities has become clear. A common, systematic approach in which existing tools from disparate technical domains converge on mutual boundary conditions is needed. A prototype environment with this approach has been created by DOE, GridOptics™ Framework for Network Co-Simulation, which employs

Figure 3.B.11 Landscape of Infrastructure Models and Tools Used by the Electric Power Industry

Credit: Michael Kintner-Meyer," "Landscape of Electricity Infrastructure Models," Pacific Northwest National Laboratory



co-simulation techniques for integrating transmission, distribution, communication, and markets. The National Rural Electric Cooperative Association (NRECA) is also developing an open modeling framework based on Pacific Northwest National Laboratory's (PNNL) GridLAB-D. However, more is needed to accelerate the development and application of this environment to keep pace with the needs of the future grid.

Another important aspect of tool interoperability is the development of accurate, comprehensive, and harmonized data sets that can be broadly used. Modeling and simulations are only as good as the data used, and there is a wide variety of data sources that are needed for accurate analyses. Information that should be collected and harmonized includes data on weather, load profiles (including composition), device models, grid asset location and specifications, generator location and performance, storm history, communications, geographic attributes, and water availability, among others. One major challenge in gathering and assembling data is the inconsistent naming conventions used for the same grid assets among different data sets. These discrepancies can lead to errors and limitations in modeling results. Another challenge is the costs (e.g., labor and time) associated with the collection, scrubbing, and organization of data. Mechanisms to connect off-line data sets with sources from an operational environment would greatly facilitate the process.

Many of the advances made in planning and simulator tools can be utilized to improve the tools used in an operation environment. While operational models are focused on speed and accuracy, they can benefit from reduced-order models that are developed and validated for off-line planning tools and simulators. Additionally, the development of dynamic and adaptive models can be integrated with data streams to enable new capabilities for operations. Current grid models typically have a regional, control area, power pool, or utility-level focus. There is a lack of simulation capabilities and modeling tools at a national level. A national power grid simulator could be highly beneficial to the power sector and broader society.[33] Such a simulator would also be expected to model the interconnections to and interdependencies with related critical infrastructures such as transportation, oil and natural gas, and communications. A national grid simulator would provide a state-of-the-art capability for a wide range of independently funded research projects in academia, utility industry, reliability organizations, and national laboratories.

Technical Analyses and Decision-Making Tools

While the development of next-generation planning tools and simulators provides tremendous analytical capabilities for answering complex questions, the majority of grid stakeholders do not have the technical expertise to use these tools or have limited access to the required advanced computational capabilities. This section addresses the need to develop software tools that are user friendly and accessible so they can be implemented by stakeholders other than the developer. For these tools to derive the most value in shaping the grid of the future, they must be used to answer key questions with transparent results that are distilled into technically sound and unbiased analyses. While technical analyses are limited by the assumptions used, they provide valuable insights into future scenarios.

DOE has sponsored numerous technical analyses and studies, leveraging the modeling and simulation tools available, that have made an impact on industry. The Western Wind and Solar Integration Study series[34] has explored renewable integration operational impacts, including cost and benefits and the impacts of ramping on thermal units, and is currently looking at frequency issues. The Eastern Wind Integration and Transmission Study[35] helped to understand system issues in the Eastern Interconnection and the result of the current Eastern Renewable Grid Integration Study[36] is highly anticipated. The Renewable Energy Futures[37] study demonstrated interesting results, combining a capacity expansion model with a production cost model to simulate what could be feasible in a high renewable future. While these examples were highly publicized, there are numerous other analyses that answer specific technological questions, such as optimal siting of energy storage or trade-offs between renewable resources and grid upgrades.

Accurate analysis and assessment of scenarios with different combinations of grid technologies, bulk generation, and distributed energy resources can both inform stakeholders and support continued delivery of reliable and cost-effective electricity. These analyses can be used to explore options and balance between various objectives, such as local versus national goals and near-term versus long-term. Co-optimization of electric power transmission with other resources such as generation, demand-side resources, and natural gas infrastructure is another area of analysis. The benefits of co-optimization were demonstrated for planning activities by the Eastern Interconnection States' Planning Council (EISPC).[38,39] National-level studies employing co-optimization approaches could guide policy formulation as well as provide inputs for integrated system design.

Potential areas that require further analysis include the following:

- Exploring the role of off-shore wind
- Estimating the value of enhanced power flow control
- Evaluating the benefits of hybrid AC/DC circuits
- Assessing a national HVDC backbone
- Studying electric system interdependencies with other infrastructures (such as fuels)
- Studying the impacts of new markets and regulations
- Assessing the value proposition of microgrids towards resilience
- Studying the impacts of climate change

In addition to technical analyses, developing decision-making tools that are publicly accessible and user friendly can also support the transition to a future grid. "Dashboards" and Web-based desktop tools that are sufficiently accurate can help regulators, policy makers, energy developers, and other institutional entities quickly understand the impact of their choices. These tools can also help with economic decision making by establishing a common reference for answering often contentious questions around valuation, costs, and benefits of particular technologies or options. For example, the Interruption Cost Estimation (ICE) Calculator can help quantify avoided cost based on the number of outage hours avoided and understanding the makeup of the customer population where outage duration was reduced.[40]

DOE has invested in the development of advanced optimization and economic assessment tools, such as DER-CAM and TMO, which focuses on informing cost-effective deployment strategies for technologies. The Microgrid Design Tool helps interested parties consider trade-offs between different energy resources to meet their desired objectives. There is also a need to adapt decision-making tools to allow for recognition of resilience-related interdependencies among communications, control, human, and physical elements. Desired capabilities will help decompose the interdependencies of the various grid elements, reducing the potential for cascading failures and supporting the planning and placement of resilient monitoring and controls. Other than economic decision tools, DOE also supports software that improves access to information and helps inform policies. For example, the energy-water dashboard[41] helps stakeholders in the western United States evaluate competing policies and technology options relevant to the energy water nexus. Tools such as DSIRE[42] and the EZ Mapping Tool[43] help stakeholders understand where the opportunities are for developing clean energy.

Future opportunities include developing simple interfaces that can link with the more complex planning tools and simulator to blend ease of use and analytical rigor. With advances in cloud-based computing, it could be possible to permit broader access to advanced analytical capabilities. Additionally, future decision-making tools should be made to accommodate major uncertainties associated with the future grid. A regret-minimization[44] (as opposed to a risk- or cost-minimization) approach should be taken when considering grid investments. Random Regret Minimization asserts that a choice between alternatives is based on the desire to avoid situations where a non-chosen alternative turns out to be more attractive than the chosen one. With this approach, a decision would be made based on minimization of anticipated regret as opposed to maximizing utility.

Endnotes

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[3] Net load is the difference between forecasted load and electricity production from variable generation resources.

[4] The term "steep ramps" refers to the condition in which the independent system operator must bring on or shut down generation resources to meet an increasing or decreasing electricity demand quickly over a short period of time.

[5] The term overgeneration refers to the situation where electricity generated is more than what can be consumed at that particular instant of time.

[6] LVRT/FRT is the capability of electrical devices, especially wind generators, to operate through periods of lower grid voltage.

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[21] See also Measurements, Communications, and Control chapter for additional explanation on various control concepts.

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Glossary and Acronyms

California Independent System Operator (CAISO)	California Independent System Operator. ISOs are independent organizations that are responsible for managing a regional transmission grid.
Distributed Energy Resources Customer Adoption Model (DER-CAM)	An economic and environmental model of customer DER adoption. It is hosted by Lawrence Berkley National Laboratory.
DOE	U.S. Department of Energy
Electric Power Research Institute (EPRI)	A nonprofit organization that conducts research, development and demonstration (RD&D) relating to the electric power sector.
Electromagnetic pulse (EMP)	A short burst of natural or man-made electromagnetic energy that may occur in the form of a radiated, electric, or magnetic field or conducted electrical current depending on the source.
Eastern Renewable Grid Integration Study (ERGIS)	Eastern Renewable Grid Integration Study is a multi-year U.S. Department of Energy-funded research project designed to simulate operations of the largest power system in the world with high penetrations of wind and solar generation. The study will inform critical questions on how system operations could be impacted by various wind and solar deployment strategies and operational paradigms.
European Union Smart Grid Coordination Group (EU SG-CG)	The European Union Smart Grid Coordination Group was set up by the European Commission in 2009 to advise on issues related to smart grid deployment and development. It consists of five Expert Groups, including the SG-CG, who focus on specific areas. Their work helps shape EU smart grid policies.
Eastern Wind Integration and Transmission Study (EWITS)	The Eastern Wind Integration and Transmission Study is a multi-year U.S. Department of Energy-funded research project designed to simulate operations of the largest power system in the world with high penetrations of wind and solar generation.
Fault ride through (FRT)	See Low voltage ride through (LVRT)
Framework for Network Co-Simulation (FNCS)	A framework for integrating simulators across multiple domains.
Geomagnetic disturbance (GMD)	GMD occurs when solar storms on the sun's surface send electrically charged particles toward earth. This could potentially affect the power grid operations.
GridLAB-D	An open source power distribution system simulation and analysis tool.
GridWise Architecture Council (GWAC)	GWAC was formed by DOE to promote interoperability among the many entities that interact with the nation's electric power system.
Low voltage ride through (LVRT)	The capability of electrical devices to operate through periods of lower grid voltage, such as during faults.

Microgrid design tool (MDT)	Designed to aid microgrid planners and designers in quantitative analysis.
National Institute of Standards and Technology (NIST)	NIST is the federal technology agency that works with industry to develop and apply technology, measurements, and standards.
North American Reliability Corporation (NERC)	The North American Electric Reliability Corporation (NERC) is a not-for-profit international regulatory authority whose mission is to assure the reliability of the bulk power system in North America.
Open Automated Demand Response (OpenADR) Initiative	An open-source initiative, led by Lawrence Berkley National Laboratory, to develop the standards, protocols and infrastructure for automated demand response programs.
Open Distribution System Simulator (OpenDSS)	An open-source power systems simulation tool, primarily for the distribution systems. OpenDSS is hosted by EPRI.
Random regret minimization (RRM)	An optimization approach of minimizing the anticipated regret (i.e. deviation from the optimal/actual state) for a given set of outcomes/ scenarios.
Renewable Electricity Futures (REF)	A study by NREL on the implications of large-scale deployment of renewable resources in the continental United States.
Standards Development Organizations (SDO)	Standards Development Organizations
Smart Grid Architecture Model (SGAM)	The Smart Grid Architecture Model is a method whereby power supply companies and industry can display aspects of smart grid systems. The model can be used for the visualization, validation, and configuration of smart grid projects, and also for standardization within smart grids
Smart Grid Interoperability Panel (SGIP)	A global non-profit organization that aims to accelerate the implementation of interoperable smart grid devices and systems.