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SMART GRID
RESEARCH**

**IEEE SMART GRID VISION FOR
COMPUTING: 2030 AND BEYOND**



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IEEE Smart Grid Vision for Computing: 2030 and Beyond



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Dedication

This report is dedicated to the computing and power grid professionals in industry, academia, and the government who work tirelessly to deliver reliable electricity.

Dan McCaugherty

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Executive Summary

This document provides the results of the IEEE Computer Society Smart Grid Vision Project (CS-SGVP), which is chartered to develop Smart Grid visions looking forward as far as 30 years into the future. The CS-SGVP team emphasized creative thought leadership and “blue sky” thinking to identify future Smart Grid operational visions and the role of computing to achieve these visions. The visions in this document were not bounded by the current understanding of technologies, today’s regulatory or business environments, or today’s activities to establish Smart Grid operational concepts, architectures, standards, and interoperability. In some cases, the visions are complementary, and in other cases, they are mutually exclusive or even contradictory. The CS-SGVP team did not drive visions toward a common end-concept solution. The Smart Grid scope, societal needs, infrastructure topologies, and the evolution of enabling technologies are manifold, leaving any single vision likely inappropriate for too many Smart Grid stakeholders. Therefore, this document does not contain a single end-state vision for computing within the Smart Grid, but rather examines numerous potential branches for the evolution of both Smart Grid operational concepts and computing technologies.

The CS-SGVP team developed its visions using a three-tiered approach. From top to bottom, these three tiers include architectural concepts, functional concepts, and technological concepts. Architectural concepts describe Smart Grid goals and characteristics, general grid types, as well as computing concepts considered common across grid types. Functional concepts describe how the grid will operate. Technological concepts describe the roles of certain technologies within the Smart Grid. The team considered multiple Smart Grid variants—from bulk generation (as is typical in developed regions) to islanded grids (more common in developing regions). Scenarios cover stakeholders from electric utilities, emergency responders, and energy brokers, as well as industrial power users and homeowners. Computing technology visions include modeling and simulation, cyber security, verification and validation, high-performance computing, and other topics. The CS-SGVP team recognizes that an endless number of branches of functional scenarios and computing technologies be included in this document, and that some are more represented than others. The team also expects that over the course of many years, various visions will come to fruition while others will be deprecated by unforeseen or disruptive new technologies, all motivating a periodic update to this document.

This document intends to stimulate research and development, education, training, and the development of standards. The computing technologies described in this document will progress at different rates, some stimulated by a myriad of socio-economic drivers and others by Smart Grid-specific needs. The following computing disciplines play key roles in realizing the visions described in this document:

- Computational intelligence
- Cyber security and resilience
- Data analytics and databases
- Distributed multiple-agent architecture
- High-performance computing
- Messaging-oriented middleware
- Modeling and simulation
- Self-integrating systems

- Software verification and validation
- Virtual computing
- Visualization

Chapter 1 introduces the reader to the content and structure of this document. Chapter 2 provides Smart Grid architectural concepts. Chapter 3 provides functional concepts. Chapter 4 provides technological concepts that describe the roles of certain computer science-related technologies that enable Smart Grid functions. Annex A provides mappings between functional concepts and technological concepts.

Acronyms and Abbreviations

AI	artificial intelligence
AMI	advanced metering infrastructure
API	application programming interface
C³	command, control, and communications
CIM	Common Information Model
CDM	Canonical Data Model
CM	condition monitoring
COMSEC	communications security
COTS	commercial off-the-shelf
DAP	distribution access point
DER	distributed energy resource
DG	distributed generation
DMS	demand management system <i>or</i> distributed management system
DNO	distributed network operator
DR	demand response
DSM	demand-side management
DSO	distributed system operator
DSP	digital signal processing
EDIG	entity data integrity gateway
EMS	energy management systems
ESB	enterprise service buses
ESCO	energy service company
FACTS	flexible AC transmission systems
FDD	fault detection and diagnosis
FERC	Federal Energy Regulatory Commission
FPGA	field-programmable gate array
GIS	geographic information system
GPU	graphics processing unit
HPC	high-performance computing
HVDC	high-voltage direct current
ICT	information and communications technology

Acronyms and Abbreviations

IED	intelligent electronic device
IP	Internet Protocol
ISO	independent system operator
IT	information technology
LOLP	loss of load probability
M&S	modeling and simulation
MCS	monitoring and control systems
MFD	multiple-feature detector
MOM	messaging-oriented middleware
NETL	National Energy Technology Laboratory
NIST	National Institute of Standards and Technology
OPF	optimal power flow
OWL	Web Ontology Language
PAM	prognostics and asset management
PCT	programmable communicating thermostat
PEV	plug-in electric vehicle
PLC	programmable logic controllers
PMU	phasor measurement unit
PV	photovoltaics
RES	renewable energy storage
RTO	regional transmission organization
SCADA	supervisory control and data acquisition
SOA	service-oriented architecture
SP	signal processing
TOU	time-of-use
V2G	vehicle-to-grid
V&V	verification and validation
VLSI	very-large-scale integration
WSDL	Web Service Definition Language
XML	eXtensible Markup Language

1.1 Purpose and scope

The purpose of this document is to stimulate investments in computing technologies (including research and development, standards, and education) that will enable achievement of Smart Grid visions and improve the performance and capability of electric power systems, to make them more efficient, faster, reliable, resilient, and so on.

The scope of this document focuses on computing technologies and the role they will play in the future electric grid. The computing technologies identified by the Computer Society Smart Grid Vision Project (CS-SGVP) team span many computing disciplines and do not necessarily represent all technologies that will shape the Smart Grid. Various projections of how Smart Grid concepts will influence power systems were considered. These projections span bulk transmission systems to isolated islands of local generation, as well as different demand-side participation concepts.

1.2 CS-SGVP approach

As shown in Figure 1.1, the vision is expressed through a three-tiered approach. At the top-level projection are high-level *Tier 1 architectural concepts* of power grid configurations and operations. Many of the concepts in these grid projections can exist concurrently and even involve the same interacting organizations. No one projection is likely to dominate the operational landscape; however, some concepts might be more fully realized and attain larger market share, while others might be overcome by events and achieve less influence. As described later in this section, a user of this vision report can construct a variety of vision scenarios. Each could be valid, at least from a technology standpoint. Additionally, each scenario can evolve as natural feedback mechanisms as shown in Figure 1.1 are activated.

These grid projections might be supported by a combination of *Tier 2 functional concepts*. A large number of functional concepts are required to support any Smart Grid vision. Many are in operation today and are not intended to be the focus of this document. Many ideas are emerging from various stages of research and development that could have some grounding in science and engineering, though not commonly deployed today. In addition, some functional concepts represent an envisioned capability with little idea of how such a capability will be achieved. The emerging and the imaginative functional concepts are topics for this document. These Tier 2

functional concepts cover high-level power system infrastructure functions as well as functions at end-user portions of the system, including end-use devices and systems.

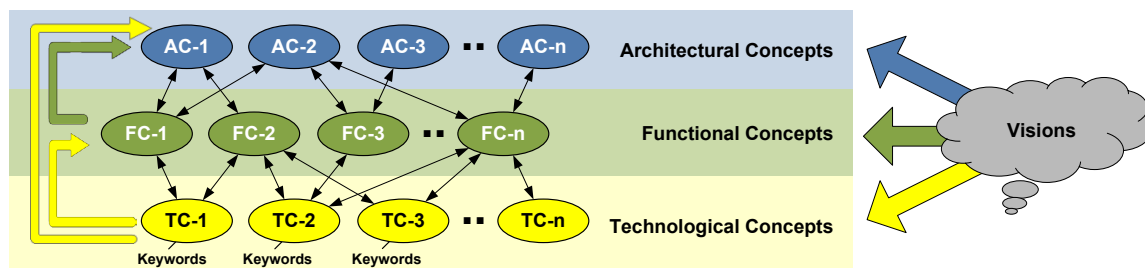


Figure 1.1 – CS-SGVP tiered approach

The functional concepts are enabled, in turn, by an aggregation of *Tier 3 technological concepts*. Technological concepts capture advancements in computational hardware and software technologies including information systems, interaction protocols, networks, frameworks, middleware, resource management, operating systems, etc. As with Tier 2 functional concepts, this vision document focuses on the emerging and imaginative technological concepts that will support game-changing functional concepts of Tier 2 and assumes that many more routine technology insertion trajectories will occur in parallel.

In this approach, Tier 1 provides overarching architectural concepts along supply, delivery, end-use, and complex system-of systems perspectives. These viewpoints provide context for the Tier 2 functional concepts. Tier 2 organizes clusters of functional concepts in a way that satisfies specific sets of future needs by describing desired outcomes to specific Smart Grid goals. A Tier 2 functional concept might contribute to multiple Tier 1 architectural concepts. In its intermediary role, the functional concepts in Tier 2 also provide areas of application for the technological concepts in Tier 3. The Tier 3 technological concepts might contribute to enabling the realization of multiple Tier 2 functional concepts, and multiple Tier 2 functional concepts can be supported by the same technological concept.

Although the information in each tier is grouped, there is no intent to constrain or imply a parent-child structure within a tier or between tiers as might be found in a systems engineering specification structure. This approach is meant merely to facilitate the communication of concepts and ideas. The end of Chapter 3 attempts to relate functions to specific technologies; however, this effort is meant to help visualize the tier approach and not a necessary or complete set of relationships. This document does not attempt to drive visions to a single end solution or set of solutions. There are too many variables and paths for Smart Grid evolution, and reality will likely reveal something closer to an ad hoc aggregation of various Smart Grid projections.

Additionally, no attempt is made to reconcile visions that might appear contradictory, or to choose among competing visions. In some cases, similar visions were consolidated to avoid redundancy. If functional concepts proved useful in realizing Smart Grid goals and concepts, they were included. If technological concepts played a role in functional concepts, they were included. In some cases, a bottom-up approach was applied, whereby potential future computing technologies were examined for their ability to contribute to a Smart Grid goal that resulted in the development of a functional concept previously unspecified. In some cases, Tier 2 functional

concepts necessitated the development or refinement of a Tier 1 architectural concept. Finally, the process of assembling this document confronted a relatively high degree of redundancy within any tier, demonstrating that the Smart Grid is replete with co-dependencies, thus challenging attempts to weave a story in an optimal sequence.

A reader this vision might question the absence of a clear, singular vision representing Smart Grid customers and their role in the realization of the Smart Grid promises. This lack is not an oversight; it is a realization. We feel that within the next 30 years, the customer is, and will grow to become more of, a vital player in any Smart Grid scenario. Consequently, the reader will find many fulfilling visions that significantly depend on the customer. The following list is given to help find more about the customer and the Smart Grid:

- Customer as foundation of smart grid (Section 2.2)
- Customer privacy and information exchange (Section 2.4)
- Customers as social nodes and providing functionality (Section 3.4)
- Customers and interfacing with smart grid (Section 3.5)
- Business cases and customer integration (Section 4.6)

1.3 Report organization and use

This document is structured to assist users with varying interests and perspectives. For example, a functional user or policy maker might take interest in a specific Tier 2 functional concept and use the table in Annex A to identify enabling technologies. Likewise, using this same information, a technologist might identify where their technology might support functions within one or many grid projections. This bi-directional model stimulates the connection between technology providers and organizations with functional needs.

There are many authors of this vision. To enhance its readability, the document avoids self-citation by the contributing authors and instead includes a list of references at the end of each chapter. Where a citation is not from an author, it is cited in the reference list. The reference list also includes references to other useful Smart Grid information.

1.3.1 Overview of Chapter 2, “Architectural Concepts”

This chapter describes Smart Grid architectural concepts, goals and objectives, various supply-side and demand-side Smart Grid concepts, and system concepts that apply to our vision. This chapter introduces important concepts in the following areas:

- Evolution of energy supply mix
- Transmission grid enhancement
- Coexistence of many grid configurations
- End use as an active component
- Advancement of enabling technologies
- Control methodologies

This chapter then provides discussions on these topics, including a narrative of the challenges and problem space, grid preconditions, a vision for how the grid will evolve, and outcomes of a smarter grid. Topics covered in these discussions include supply side, demand side, and system concepts.

Supply side

On the supply side, a driving factor is the increased penetration of renewable energy resources, which will have a significant impact on how the future grid will be configured.

Higher penetration of renewable resources

Increasingly, new power generation coming online is based on renewable resources, which currently consists mostly of wind turbines. Installation of solar photovoltaics (PV) is projected to pick up substantially. These non-CO₂-emitting distributed resources will create new paradigms for energy supply management. The ability to cope with the variability of renewable resources will be a challenge to widespread adoption because of the need for voltage and frequency support. This need will necessitate advanced monitoring and control coupled to a mix of energy storage resources such as pumped hydro turbines, as well as fast-start gas-turbine plants.

Energy storage and balancing

Wind and insolation are weather dependent and hence cannot be forecasted with perfect certainty. A power system with high renewable penetration creates opportunities for energy storage to balance system frequency in a fast time scale and energy in a slow time scale. The development of electric energy storage devices will be multifaceted. Choices of future storage systems include advanced battery systems, flywheels, superconducting magnetic energy storage, and ultra-capacitors. Some storage systems are multifunctional, such as batteries for electric vehicles, which can be used for propulsion as well as supplying power back to the grid.

Integrated zones of renewable energy grids

A future grid could have a distributed architecture, consisting of many zones with energy supply from various renewable sources serving their load demand through a regional transmission grid. A distributed architecture will allow greater autonomy of decision-making in each zone. These zones are still connected to the main transmission grid, but they can operate in an isolated manner if necessary.

Isolated islands

A grid configuration that is particularly attractive to developing economies and remote regions is one in which the grid consists mainly of isolated islands. Each island is a minigrid or microgrid with its own electricity generation, distribution, and consumption network. The generation in such an islanded microgrid might come from fuel that is locally available (biomass, coal, wind, solar, hydro, geothermal, etc.), or fuel that is transported in bulk to the island (natural gas, oil, etc.). The fuel can then be used for generating electricity and other purposes such as steam and heating.

Demand side

The main drivers in demand side management include a high level of demand response, loads with self-supplied energy, and the emergence of electric transportation.

Utility control demand response

A critical characteristic of the Smart Grid is the active participation of the consumers in the operation of the grid. Such demand response activities could be direct if an energy service

company directly controls the appliances, or indirect if the decisions are responses to price signals or negotiation. Active demand control can provide several services to the system such as congestion management, peak load shaving, or renewable energy storage production support.

Aggregated local energy

In a Smart Grid, a large number of customers could dynamically participate in bi-directional exchange of power and information with the distribution system and energy service providers. These customers range from small residential homes to large commercial and industrial facilities, providing both generation and demand. Such aggregated local energy will lead to emergent dynamic behavior due to increased real-time network and market connectivity and coupling. The impact of this emergent behavior on the stability and reliability of the electric system might be significant.

Self-owned base energy

In this vision, the management of electricity—both production and use—is done at the end nodes of the electric power system. The generation might come from variable renewable resources, natural gas, or other fuels. Energy can be stored locally at economically convenient times or when variable resources exceed immediate needs. The stored energy can be used to supplement production during high usage, less economic, or low variable-resource generation periods. Although islanded operation is supported, the linkages to energy sources mean that the facility can buy energy at convenient times as well as sell energy to others when production and economics make sense.

Electric transportation

The future path for transportation is uncertain, but electric drives are dominating boats and trains, and will likely have an increased role in road-based passenger vehicles and trucks. One compelling vision is that automation and cyber-based intelligence will link vehicle controls with traffic flow controls and passenger preferences to move the operator to a more supervisory role. These systems will also link electric drives to coordinate with energy sources.

System concepts

To support the advancement and organization of a Smart Grid and its interactions with other systems, several system concepts are formulated and discussed.

Coherent system operations

The vision of a smarter electric system includes widespread use of sensors to make its devices and systems self-aware of their current configurations. Other domains, such as manufacturing and transportation, will influence and be influenced by the evolving electric system. The emerging discipline of intelligent systems engineering will help support the integration of increasingly smarter electricity-related nodes into an intelligent system that operates within an interconnected system-of-systems with other sectors of the critical infrastructure. These concepts will lead to a decentralized, self-organizing control model for the Smart Grid.

Complex autonomous adaptive systems

The complexity in a Smart Grid must be well managed, with performance enhanced by existing and new technologies for computing, data analytics, and control. One such concept on performance is a complex autonomous adaptive system, enabled by computational intelligence with ubiquitous connectivity and autonomous self-adaptation. The types of autonomous self-adaptive behaviors will provide capabilities to self-configure, self-heal, self-optimize, and self-protect to maintain the health of the grid. These capabilities are particularly important to address

the rare but occasional failure events that characterize complex systems with their long-tail probabilities, where the risk of substantial failure never fully vanishes.

Cyber security

A cyber security infrastructure needs to be implemented for the Smart Grid for it to be secure from cyber attacks to the extent practical, and resilient to those attacks that do partially succeed. As a result, the power system infrastructure depends on the health of an underlying computing and communication network infrastructure that is at risk from both malicious cyber attacks and accidental failures. Industry studies suggest that the risk of future cyber attacks on the electric power grid cyber infrastructure is significant. Clearly, work is needed to enable the design of a next-generation cyber infrastructure for the Smart Grid that can tolerate malicious cyber attacks and keep up with the ever-changing operating constraints of the power system.

1.3.2 Overview of Chapter 3, “Functional Concepts”

1.3.2.1 Introduction

Due to the multiple-domain complexity of large sustainable energy systems, society’s understanding of such systems’ likely performance in practice is limited. Despite the enormous importance of the Smart Grid and its support of sustainable energy systems to the global economy and energy security, developing the basic functions required for understanding and operating the power system, which includes optimizing and securing its performance, will be a daunting functional challenge. Currently, there are serious challenges in safety and security, communications, autonomy, and enterprise business solutions. The solutions must span previously unconsidered interactions with other devices and systems, which include uncertainties related to cyber security as well as social, economic, and environmental co-dependencies that are increasingly dominant in any discussion. Therefore, the need for theoretical and applied computer science is significant.

This chapter presents several visionary Smart Grid functional concepts that will enable the future electric system. This set of concepts is not meant to be complete and will be supported by many more new and old functions. We have tried here to capture a very high level of function, with the expectation that every few years this vision can evolve and grow as society and businesses better understand the interdependencies and needs of a Smart Grid. To support this evolution, many solutions and analytical tools will need to emerge that can evaluate a Smart Grid system at significant scale (particularly a scale that depends on the spatial and temporal co-dependencies of engineered systems, economic systems, environmental systems, and human behaviors) to provide functionality, communication, security, and decision support to make the Smart Grid robust and profitable. It is hoped that these functional concepts will help all stakeholders determine which Smart Grid investments will accelerate the pace to a sustainable energy system.

1.3.2.2 Overview and structure

The Smart Grid architectural concepts discussed in Chapter 2 depend on a number of new functionalities that will be supported by future computer science technologies that span a spectrum of computer science disciplines. To facilitate conveying the future directions of these relevant topics, Chapter 3 arranges the functional concepts according to the major topics and subtopics explained in the rest of this section and relates them to technological concepts that are discussed in Chapter 4.

This chapter does not offer a singular conclusion; nor does it provide a plan that might fully forms all architectural concepts or functional concepts, by linking their assumptions, precursors, and triggers into sequences of events and milestones. Instead, the concepts are presented as functions that might not be aggregated to achieve the architectural concepts presented in Chapter 2.

Systemic functions

Systemic functions and technologies permeate the structure of a Smart Grid. The functions and technologies that fall within this area apply throughout the electric grid. They often take abstract forms in their conceptualization and can relate strongly to processes as compared with tangible characteristics. The implementation of systemic functions and technologies are results-oriented, with measurement often related to the quality of the end product, such as adequacy to scope, schedule, cost, and reliability.

Cyber security

This subtopic refers to the security of information and computing assets such as system control data, personal data, networks, grid control devices, or control centers. As Smart Grid concepts require computers and communications, the processes and mechanisms to protect the proper exchange and use of information permeate the development, operation, and maintenance of Smart Grid deployments.

Systems engineering

The electric grid is a complex system of independent components and subsystems that interact at many levels and time scales to orchestrate a sustained making, moving, and consuming of electricity. Systems engineering is the broad discipline related to conceptual modeling, architecture, and design of complex systems. It encompasses the life cycle issues associated with managing the components and subsystems, their maintenance, and their evolution over time. Systems engineering tools might be applied with high fidelity in detailed areas of the system, or at conceptual levels of the management of Smart Grid systems through more abstract policies and procedures. While cyber security could be considered under the systems engineering umbrella, it is addressed separately due to the nefarious nature of threats to the system.

Enabling functions

Enabling functions relate technologies, methodologies, and tools that support Smart Grid capabilities, but do not represent Smart Grid functions directly. Enabling topics generally apply to a wide array of business domains. In general, enabling functions depend on enabling information and communications technology hardware and software infrastructure and tools.

Communications networks

This subtopic addresses all forms of communications relevant to the effective integration of smart devices and systems.

Visualization and data management

This subtopic addresses the hardware and software tools that support the analysis, management, and rendering of data that enable its transformation to information for human interaction.

Markets and economics

The depth of penetration of Smart Grid capabilities into an interconnected electric system will be determined in large part by concerns such as profitability, macroeconomics, microeconomics,

incentives, behaviors and choice. New tools and the integration of these tools into the day-to-day operation of the grid will become increasingly necessary to maximize a return on investment.

Performance functions

Performance functions address the capability of an electric system to meet its dynamic and static physical requirements. They are highly dependent on Smart Grid devices and systems. These functional aspects of the electric system can be measured to performance expectations, such as efficiency, quality of service, and reliability.

Operations, monitoring, and control

This subtopic addresses the moment-by-moment operations of the system, including the measurement of device, and system characteristics and their control. The time frame for this area ranges from a few minutes to instantaneous operations.

Planning, analysis, and simulation

This subtopic addresses the disciplines associated with situating the system for effective operation. The time frames can extend to years (for large generation and transmission projects) to near real time, as decisions are made to align plans with operational necessities. Simulations are often used, which model potential operating scenarios, forecast behavior, and provide information for analysis and decision-making that align resources for operations.

1.3.3 Overview of Chapter 4, “Technological Concepts”

The technological concepts provide expert viewpoints on the future of computing technology and its application to enable the functional concepts described in Chapter 3. As computing technology continues to contribute to the advancement of all areas of the economy (industry, commerce, finance, health, agriculture, as well as infrastructure), the Smart Grid will evolve along abstract notions of methodology and tools that will be applied to realize new capabilities in all these areas. An important Smart Grid principle is that advances in computer science will be used across the economy, resulting in affordable value propositions for applying this technology to deliver a more efficient and secure electric system. Because of this, the technological concepts explore computer science disciplines and capabilities that can sound more general than the grounded functional concepts in Chapter 3. Nevertheless, the technology must consider specific Smart Grid functional requirements, and key aspects of these requirements are highlighted throughout the chapter.

The intent of the document is for each technological concept to be able stand on its own. In this way, the technology ideas can be considered for supporting multiple functional concepts, and functional concepts can be supported by assembling the capabilities expressed in multiple technological concepts. Each technological concept description provides the reader with a short overview of the concept, some background information that might introduces the current state of the technology and the challenges being confronted, and a future vision for the technology. The future vision discusses the technology’s anticipated advanced state and its relevance for enabling Smart Grid capabilities. The description might contain a statement of evolutionary steps to advance the technology; however, it avoids being prescriptive. This choice makes descriptions more succinct, arguably avoids some controversy, and invites future efforts to explore the potential directions that these important technologies should take in their realization. The technology description concludes with a list of computer science keywords to help relate topics to recognized terminology, and a list of references.

While each technology can stand on its own, the contributions are grouped according to four themes. This organization assists the reader in locating areas of interest, and once in a theme, a synergy between concepts and terminology hopefully enhances the document's ability to communicate. The themes cover the following areas:

- **Distributed systems architecture.** Technological concepts that support the evolving connected world of people, devices, and systems. Ideas behind self-integrating systems, multi-agent systems, virtual computing architectures, and messaging-oriented middle are covered here.
- **Computer applications.** Computer software and systems that address Smart Grid application areas. With more direct ties to Smart Grid functionality, this area looks at market-inspired controls, tools for monitoring and control as well as modeling and simulation, signal processing, protection, and performance monitoring, state estimation, contingency analysis, stochastic analysis, and prognostics and asset management.
- **Information science.** Visualization, artificial intelligence, data analytics, high-performance computing, Internet for real-time systems, and other computer science advancements that support Smart Grid applications. This section also includes methodologies and tools, such as software validation and verification that enable the development and reliable deployment of complex systems.
- **Cyber security.** Technology and methodology to thwart cyber attacks, mitigate the damage from such attacks, increase resiliency, and protect the integrity and privacy of information. Technologies include trusted component validation, portable identity, hierarchical sense-making, massive parallel pattern detection, agile self-organizing security, and signal security technology.

These technological concepts represent a reasonable starting point for reviewing important areas for Smart Grid investments in research and development and education; however, it is not a comprehensive list. Several other technologies have been identified for inclusion should there be opportunities for experts to contribute to this body of work. In addition, to keep the main document a reasonable size and not overwhelm most readers, the length of each technological concept contribution was reduced.

2.1 Introduction

This chapter provides Tier 1 architectural concepts that serve as a foundation for development of Smart Grid Tier 2 functional concepts and Tier 3 technological concepts. Tier 1 architectural concepts are not necessarily repeated as assumptions in Tier 2 functional concepts or Tier 3 technological concepts.

2.2 Smart Grid characteristics

The Energy Independence and Security Act of 2007 (originally named the Clean Energy Act of 2007 and often referred to as EISA) states that the creation of a Smart Grid is a national priority, and defines the following distinguishing characteristics of a Smart Grid [5]:

1. Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid
2. Dynamic optimization of grid operations and resources, with full cyber security
3. Deployment and integration of distributed resources and generation, including renewable resources
4. Development and incorporation of demand response, demand side resources, and energy-efficiency resources
5. Deployment of *smart* technologies for metering, communications concerning grid operations and status, and distribution automation
6. Integration of *smart* appliances and consumer devices
7. Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in electric and hybrid electric vehicles, and thermal-storage air conditioning
8. Provision to consumers of timely information and control options
9. Development of standards for communication and interoperability of appliances and equipment connected to the electric grid, including the infrastructure serving the grid
10. Identification and lowering of unreasonable or unnecessary barriers to adoption of Smart Grid technologies, practices, and services

These characteristics and priorities form the foundation for increased customer participation in the electric power system as both generators and consumers of electrical energy. Enabling customers to integrate into the system requires a coordination of activities from various stakeholders:

1. Policies and regulations enable customer energy assets, both supply and demand, to be intelligently and securely integrated into the distribution system.
2. Markets and technology provide economically viable exchange of energy and information.
3. Energy service provider business objectives, models, policies, and procedures intelligently incorporate customer energy assets while preserving customer choice and innovation.
4. Distribution systems operate safely and reliably to both import and export energy.
5. Interoperability standards have been developed and integrated into products.
6. Reference models and architectures have been created that provide the scaffolding for systems of systems.

The remainder of this chapter discusses several Smart Grid concepts at a high level and how the Smart Grid 30 years henceforth will be different from the power and energy grid as we know it today.

2.3 Smart Grid architectural concepts

A Smart Grid vision is a seamless integration of the participants or players in the Smart Grid. These participants are shown in the current National Institute of Standards and Technology (NIST) conceptual model of the Smart Grid by the roles they play within the grid (Figure 2.1).

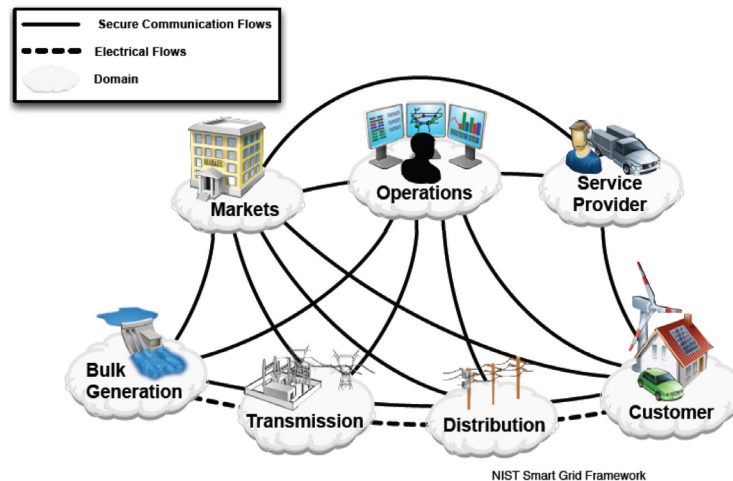


Figure 2.1 – NIST Smart Grid Model [16]

In a Smart Grid, it is expected that all current and future components of an electric power grid will interact with each other, sometimes in a complex way, and be used intelligently for maximum benefit and at acceptable costs. There will be significant competition between technologies for various levels of services and choices of grid configurations.

For the purpose of this document, we state several Smart Grid concepts that will be discussed further and reinforced with functional scenarios in Chapter 3 and technology visions in Chapter 4.

1. **Evolution of energy supply mix.** The trend to reduce the environmental impact from the generation of power, such as from coal-fired power plants, will continue. Renewable resources are an attractive replacement, except that displacing 100 megawatt-hour (MWh) of energy from a coal plant will require the installation of 333 to 400 MW of wind farms, as the capacity factors of wind farms average about 0.25 to 0.30. Recently, the falling price of natural gas in the U.S. (which emits only about half of the amount of CO₂ and much less other toxic gases compared to coal) has cut significantly into the energy supplied by coal plants and delayed new renewable energy projects. Although clean energy is the future, the pathway to get there will be neither direct nor without interruption. Each combination of fuel (including wind and solar) mix used for generation will present its own challenges to the system operators. However, in a Smart Grid, an appropriate mix of renewable and traditional generators will provide reliable electricity supply to the loads at any time.
2. **Transmission grid enhancement.** In some areas, renewable resources are abundant in remote and less populated locations. To harness these resources to supply ever-growing load centers, new long-distance transmission lines will be needed. Most likely, these new lines might be high-voltage direct current (HVDC) transmission systems owned by companies separate from the traditional utilities. In addition, new power electronics-based controllers such as the Flexible AC Transmission Systems (FACTS) will be installed for improving power transfer and providing voltage support, which are key factors for reliable operations. Thus, the transmission system in a future Smart Grid will be much more controllable, and the benefits of HVDC systems and FACTS controllers will be maximized.
3. **Coexistence of many grid configurations.** The prevalent electricity supply model in developed countries is the central-generating-station paradigm—that is, loads are competitively supplied from large fossil fuel and nuclear generating stations through the transmission and distribution grid. In a Smart Grid, with the advent of renewables and distributed generation, other types of grids might become competitive. For example, a minigrid with several megawatts of self-energy supply might serve a small town or a large subdivision. A microgrid could consist of several solar photovoltaic (PV) panels with battery storage that might provide a few hours of electricity service to a small village in a developing country, which nonetheless would elevate significantly the quality of life. These trends encourage new ideas about more reliable electricity service. By enabling distributed resources, reliable power has the potential to be supported at different service levels with the expense distributed accordingly. A Smart Grid will encompass all these new grid configurations, even allowing them to coexist in the same geographical region.
4. **Loads as an active component.** Generation is traditionally dispatched to meet a forecasted daily load profile. Electricity market restructuring in the last 10 years in the

U.S. has led to the engagement of large loads to shape the daily load profile as a means to reduce power consumption and lower high-energy prices during peak hours. Recent engagement of medium-sized and commercial loads as a means to reduce peak energy prices and improve system performance will expand in the Smart Grid with penetration to lower power levels, such as several kilowatts. The key driver is the empowerment of kilowatt-hour (kWh)-range consumers, with both ready access to real-time information on power system operating conditions and energy prices, and remotely/automatically controlled loads, such as lighting, appliances, refrigeration, and building climate control (HVAC). An important part of the future demand-side situation is electric vehicles. Scheduling the charging (grid-to-vehicle) and the regeneration (vehicle-to-grid) will be an integral component in a Smart Grid.

5. **Advancement of enabling technologies.** The Smart Grid will be built on advanced computing and communication technologies. Computing technologies will be used, for example, in more complex dispatches to include finer resolution models of loads and variable renewable generations, in faster-than-real-time simulation of power systems to study the viability of operating conditions, and in large data set analysis using advanced computational intelligence and data-analytics methods. A reliable and secure cyber network communication system must also be built to handle the data exchange needs for intelligent devices at all voltage levels. These networks will likely be multipurpose, so that energy decisions can interact with other decisions in businesses and the well-being of end users.
6. **Control methodologies.** A Smart Grid will encompass many different control methodologies, from centralized to hierarchical to distributed approaches applied as appropriate to power systems of different sizes. Distributed sensors and actuators, connected by communication links, will be critical to the deployment of advanced wide-area controls. New methodologies for system frequency regulation, voltage control, and inter-area damping will be developed. Plug-and-play capability will reduce the effort to add new control components to the system.

2.4 Smart Grid architectural concept visions

This section provides several Smart Grid concepts that elaborate a Smart Grid vision. This section is organized into three subsections:

1. **Supply side concepts (Section 2.4.1).** These concepts concern the increased penetration of renewable resources, energy storage and balancing, and grid sizing.
2. **Demand side concepts (Section 2.4.2).** Demand response, load aggregation, self-supply, and electric transportation.
3. **Smart Grid system concepts (Section 2.4.3).** System engineering and complex adaptive systems.

2.4.1 Supply-side concepts

2.4.1.1 Architectural Concept 1: Higher penetration of renewable resources

The traditional approach of building large fossil fuel thermal plants to meet new load demand is not a sustainable strategy. Advances in technology to capture wind and solar energy enable the building of smaller but sustainable power generators. Although the investment per kilowatt-hour is still more expensive than traditional thermal plants, the price gap is narrowing. In addition, it might be possible to build solar PV facilities closer to consumption areas, thus reducing the need for new transmission facilities.

The non-CO₂-emitting distributed resources will create new paradigms for energy supply management. Most of the loads (such as large cities) will still be connected to central generation, which will get energy from traditional non-CO₂-emitting base-loaded units such as nuclear generating stations, and large renewable installations such as wind farms. Some of the loads (most likely rural co-ops) might organize into semi-self-sufficient Smart Grids with a high proportion of renewables. They will still maintain some connections to a large power grid to make up for any shortfall in generation. In some more remote areas, a community might form a Smart Grid entirely based on renewables (wind, solar, and small hydro generators), with no connections to other sources of power. This scenario is more likely in developing countries.

This paradigm shift will take years to fully evolve. The rate of development could depend on government policies on renewable energy. Other factors would simply be a different approach to energy accounting due to the variability of renewable resources. For example, a system operator could assess the energy output of a land-based wind turbine at 20% of its maximum rated power. Thus, statistically a community grid wanting to fully supply its own demands would need wind turbines totaling five times its energy demand. Such an implementation requires some shift in consumer attitude as well as efforts to make loads more efficient and controllable, such as switching to LED lights.

At all levels, the ability to cope with the variability of renewable resources such as wind and solar will be a challenge to adoption due to the need for voltage and frequency support. This requirement will necessitate advanced monitoring and control coupled to a mix of energy storage resources such as pumped hydro turbines, as well as fast-start gas-turbine plants. Fast and intelligent demand response would also be very helpful and most likely will have a shorter implementation timeline. Investment in distributed systems, such as substation automation, will help the integration of renewable resources and load management.

Grid preconditions

1. **Technology advancement.** Continual advancement in renewable resource capture technologies, storage technology, smart meters, and smart appliances will form the basis of a more renewable energy world. Most components will be equipped with plug-and-play technologies to ease the deployment cost.
2. **Economics.** Renewable energy costs will become more competitive with fossil fuel costs. Government incentives can be helpful in accelerating investments in renewables.
3. **Behavior changes.** Successful renewable deployment depends largely on public acceptance of renewable resources, such as large wind turbines close to population areas,

which is already happening in many European countries. In addition, demand response needs to be widely practiced.

4. **Infrastructure investment.** Investments are required in: 1) new transmission systems to bring remote wind and solar generation to urban areas, 2) communication systems for handling large amount of data transfer for system operation, and 3) advanced control methodology to properly manage the variability of renewable resources.

Grid evolution

Grid evolution is envisioned to follow the following phases:

1. In the initial state, nonhydro-renewable generation, mostly from wind turbines, in most developed countries is significant less than 10%. Solar PV installation is particularly low. Most wind sites are located in regions with ready transmission access without having to add significant new transmission.
2. Additional wind and solar PV farms will be installed over a period of time, of which the implementation rate will be influenced by many factors such as natural gas prices and government policy.
3. Other non-hydro renewable generation technology will be gradually developed.
4. New transmission systems will be built to facilitate long-distance power transfer from remote wind sites.
5. New energy storage devices will be built (also see discussions in Section 2.4.1.2).
6. New control systems and architectures will be built to control the power grid with high renewable penetration.
7. Significant reduction in the consumption of fossil fuel and the emission of greenhouse gases will be achieved.

2.4.1.2 Architectural Concept 2: Energy storage and balancing

Electricity energy storage, such as pumped-hydro units, is traditionally used for peak shaving when generating capacities are scarce and energy prices are high. That is, the energy storage charges during early morning hours when the load and energy prices are low, and discharges during peak hours. The application of electricity energy storage will expand with higher penetration of renewable generation and the requirement for uninterrupted power supply for the modern interconnection era, such as data center applications [10].

A drawback of renewable generation is that wind and insolation are weather dependent and hence cannot be forecasted with perfect certainty. Thus, one cannot dispatch and schedule wind and solar PV generators like traditional fossil generating units. The variability of renewable generation in real time creates opportunities for energy storage for frequency balancing in a fast time scale and energy balancing in a slow time scale. Currently, data centers, aiming at instant access to computing power at any instant in time with a click on a keyboard anywhere in the world, use many diesel generators as backup power supplies. It is in the interest of such Internet-based information companies to use more environmentally friendly and lower cost power supply systems.

The development of electric energy storage devices is multifaceted. The traditional wisdom of using capacitors for short-term storage, batteries for intermediate storage, and diesel generator for longer-term storage might be blurred with advances in new storage technologies [18]. Choices of future storage systems include advanced battery systems (advanced lead-acid, sodium sulfur, nickel metal hydride, and lithium ion), flywheels [8], superconducting magnetic energy storage, and ultracapacitors [9]. Some storage systems are multifunctional, such as batteries for electric vehicles, which can be used for propulsion and supplying power back to the grid.

For longer-term energy supply, pumped hydro is a good option, except that its economics might not always be favorable. The fast-start gas turbine can be a strong contender if the price of natural gas stays low, as is the case in 2012. Fortunately, gas turbines have half the emissions of a coal-fired plant, and are very efficient. Incidentally, less expensive natural gas also makes fuel cells more competitive economically.

The coordination of traditional generation, renewable generation, energy storage, and forecasted load is a complex scheduling task requiring information on wind and solar forecasts, state of charge in individual energy storage units, response capabilities of fast-start units, and potentially many other considerations. Fast data communication and high-performance computing will be essential in ensuring an economic and reliable operation of an evolving power grid.

Grid preconditions

Several primary infrastructures are needed for successful deployment and integration of energy storage technologies into the Smart Grid:

1. **Advanced technology.** Development of advanced energy storage technologies, such as batteries and fuel cells, in one or more areas, thus reducing the cost disadvantage of energy storage equipment.
2. **Workforce training.** Programs for training a competent workforce to support manufacturing and maintenance of new energy storage equipment.
3. **Renewables.** Penetration of renewables above 15% to 20% of conventional generation.
4. **Infrastructure investments.** Development of capability (communication, computing, and control) to manage a large number of individual energy storage units.

Grid evolution

1. In the current state-of-the-art, most countries have less than 5% of renewable generation (not including hydro generating units), a small percentage of automobiles that are either hybrid (both gasoline and battery) or plugged-in electric, and sporadic development of storage units for specific power dispatch opportunities, such as dynamic reserves.
2. Although there are uncertainties about how fast electric vehicles will replace gasoline vehicles, electric vehicles will still likely be the largest initial market for energy storage. When the number of electric vehicles is substantial, one can consider powering the grid from electric vehicles, albeit only for brief intervals.
3. When the penetration of renewable energy is above 20%, energy storage devices, fast-start gas turbines, or both will be deployed alongside new renewable energy to ensure reliable grid operation.

4. Data centers will benefit by having energy storage units for backup power to replace diesel generators.
5. System operation will be more complex. One challenge is the processing of large volumes of data in real time and accurate modeling and implementation strategies for the power grid operation and financial transactions in the power markets. While distributed and parallel computing will define the core requirements to develop distributed complex market operation mechanisms under such a scenario, additional ideas of agent-based modeling, stochastic networks, combinatorial optimization, and information theory will form the fundamental tools for computing and data processing.
6. Research on such robust computational and communication architectures has already started evolving in the Smart Grid community, and the energy storage component will be yet another remarkable factor boosting this development.

2.4.1.3 Architectural Concept 3: Integrated zones of renewable energy grids

In a future grid consisting of high-penetration of renewable energy, the grid architecture could be distributed, consisting of many zones with energy supply from various renewable sources that serve the load demand in the zone through its regional transmission grid. A zone could range from tens of square kilometers with dense population to hundreds of square kilometers with sparse population. Zones are connected through a high-voltage, high-power transmission grid for additional reliability.

These zone configurations would emerge from several factors. A distributed architecture will evolve to allow greater autonomy of decision-making in each zone. These zones can still be connected to the main high-voltage transmission grid for added overall reliability. However, they can be operated in an isolated manner if there are disruptions in the main transmission grid.

Grid preconditions

1. Integrated grid will have high penetration of renewable energy resulting in increased variability in supply. Variability in wind or solar generation takes place on multiple time scales. Without highly controllable generation, volatility must be managed through storage and demand response. This type of system operation amounts to a stochastic control problem that is challenging for several reasons: 1) stochastic control is not as well understood as deterministic control, 2) the dimension of any natural stochastic state description is very large, and 3) the information structure is not standard, that is, it cannot be cast as a purely centralized control problem, nor is it purely distributed.
2. Demand response will come from all consumers. In particular, industrial users will expand upon their involvement. Highly automated manufacturing parks can be designed to operate in harmony with variability of energy supply.
3. Cooperation between supply and demand is needed to ensure that critical services remain reliable in every region. The challenges are not only rooted in engineering—demand response from residential consumers might require cultural shifts from consumers. For example, they might be willing to accept higher variability in temperature, given the right incentives and education. Contracts with consumers are needed that ensure some level of reliability to both the consumers and the grid operators.