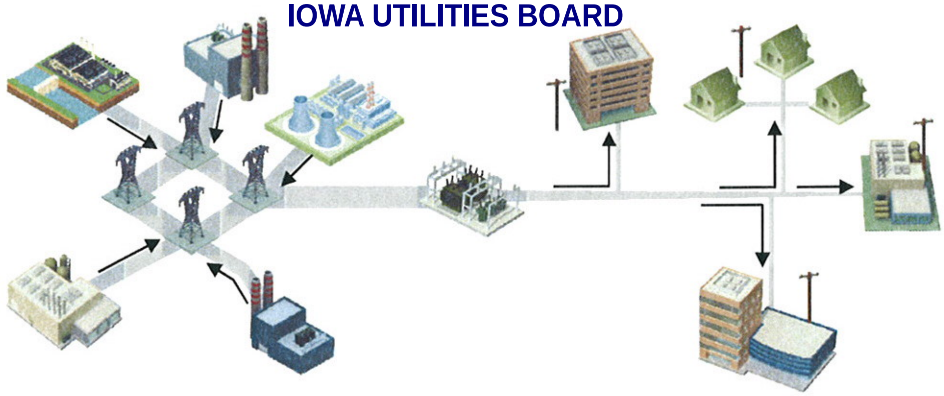


Figure 1-1
Today's Power System

Figure 1-2 illustrates the elements which will be part of a fully functional Smart Grid. The Smart Grid still depends on the support of large central-station generation, but it includes a substantial number of installations of electric energy storage and of renewable energy generation facilities, both at the bulk power system level and distributed throughout. In addition, the Smart Grid has greatly enhanced sensory and control capability configured to accommodate these distributed resources as well as electric vehicles, direct consumer participation in energy management and efficient communicating appliances. This Smart Grid is hardened against cyber security while assuring long-term operations of an extremely complex system of millions of nodes.

Figure 1-2
Tomorrow's Power System: A Smart Grid

As a result, there is a national imperative to modernize and enhance the power delivery system. The Smart Grid is envisioned to provide the enhancements to ensure high levels of security, quality, reliability, and availability (SQRA) of electric power; to improve economic productivity and quality of life; and to minimize environmental impact while maximizing safety and sustainability. The Smart Grid will be characterized by pervasively collaborative distributed intelligence, including flexible wide band gap communication, dynamic sharing of all intelligent electronic devices and distributed command and control. Achieving this vision will require careful policy formulation, accelerated infrastructure investment, and greater commitment to public/private research, development, and demonstration (RD&D) to overcome barriers and vulnerabilities.

Previous Studies

Previous EPRI studies have estimated both the costs and benefits of a Smart Grid. According to an earlier study, "The Power Delivery System of the Future," the Smart Grid would require $165 billion in net investment (over and above investment for load growth and that needed to maintain reliability), and lead to a benefit-to-cost ratio of 4:1 (EPRI 1011001).

The Smart Grid, combined with a portfolio of generation and end-use options, could reduce 2030 overall CO_2 emissions from the electric sector by 58% relative to 2005 emissions (EPRI 1020389). A Smart Grid would be capable of providing a significant contribution to the national goals of energy and carbon savings. One EPRI report (EPRI 1016905) estimated the emissions reduction impact of a Smart Grid at 60 to 211 million metric tons of CO_2 per year in 2030.

Other EPRI studies have estimated the cost of power disturbances across all business sectors in the U.S. at between $104 billion and $164 billion a year as a result of outages and another $15 billion to $24 billion due to power quality (PQ) phenomena (EPRI 1006274). The cost of a massive blackout is estimated to be about $10 billion per event as described in EPRI's "Final Report on the August 14, 2003 Blackout in the United States and Canada."

Purpose and Scope

The purpose of this study is to inform the public debate on the investment needed to create a fully functioning Smart Grid. For each key portion of the overall task, the project team selected methods based on the availability of credible information and the need to conduct a cost-effective and time-efficient study. The resulting estimates of costs remain highly uncertain and open to debate. This report is viewed as a starting point for discussion of possible levels of investment to bring the current power delivery system to the higher performance levels required for a Smart Grid.

In addition to welcoming and encouraging comments on this report, EPRI invites the participation of energy companies, universities, government and regulatory agencies, technology companies, associations, public advocacy organizations, and other interested parties throughout the world in refining the vision for the Smart Grid. Only through collaboration can the resources and commitment be marshaled to achieve the vision.

Summary of Results

Over and above the investment to meet electric load growth, Table 1-1 shows that the estimated *net* investment needed to realize the envisioned power delivery system (PDS) of the future is between $338 and $476 billion. The total value estimate range of between $1,294 and $2,028 billion; and when compared to the Future PDS cost estimate results in a benefit-to-cost ratio range of 2.8 to 6.0. Thus, based on the underlying assumptions, this comparison shows that the benefits of the envisioned Future PDS significantly outweigh the costs. At first glance, it may appear the most obvious change from the 2004 report (EPRI 1011001) is the significant increase in projected costs associated with building the smart grid. In actuality, the increased costs are a reflection of a newer, more advanced vision for the smart grid. The concept of the base requirements for the smart grid is significantly more expansive today than it was seven years ago, and those changes are reflected in this report. The project team has made every effort to capture a reasonable send-state of the Smart Grid in this report, rather than creating a snap shot that will change in another six or seven years.

Table 1-1
Summary of Estimated Cost and Benefits of the Smart Grid

	20-Year Total ($billion)
Net Investment Required	338 – 476
Net Benefit	1,294 – 2,028
Benefit-to-Cost Ratio	2.8 – 6.0

This indicates an investment level of between $17 and $24 billion per year will be required over the next 20 years. The costs cover a wide variety of enhancements to bring the power delivery system to the performance levels required for a Smart Grid. The costs include the infrastructure to integrate distributed energy resources (DER) and to achieve full customer connectivity, but exclude the cost of generation, the cost of transmission expansion to add renewables and to meet load growth, and a category of customer costs for smart-grid ready appliances and devices. Table 1-2 lists major components of the total cost. As highlighted in the body of the report, the wide range in these estimates reflects the uncertainty the industry currently faces in estimating these costs and the possible reductions which may or may not occur over time.

Smart Grid Costs

Included in the estimates of the investment needed to realize the Smart Grid, there are estimated expenditures needed to meet load growth and to enable large-scale renewable power production. As part of these expenditures, the components of the expanded power system will need to be compatible with the Smart Grid.

Table 1-2
Total Smart Grid Costs

Costs to Enable a Fully Functioning Smart Grid ($M)		
	Low	**High**
Transmission and substations	82,046	90,413
Distribution	231,960	339,409
Consumer	23,672	46,368
Total	**337,678**	**476,190**

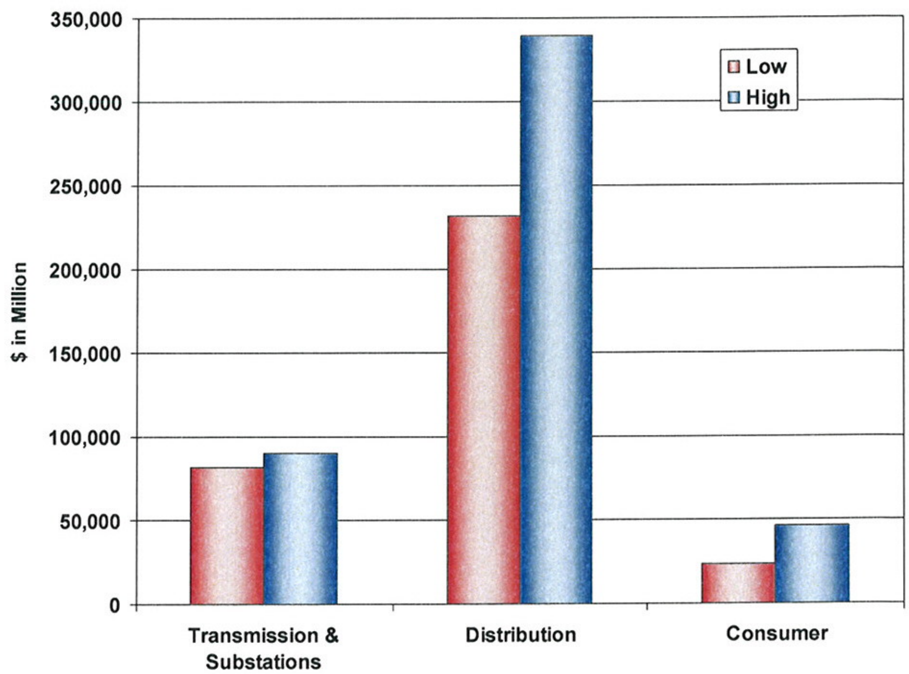


Figure 1-3
Total Smart Grid Costs

Table 1-3 summarizes one attempt to portray the consumer implications of the EPRI estimate of Smart Grid costs.

In this table, the Smart Grid costs are allocated to classes by energy (which are often what a regulatory body would mandate in the case of a regulated utility) and then calculated in several ways: (1) total Smart Grid cost divided by the number of customers for each class (a one-time payment proxy); (2) total cost per customer per year by class for 10 years for a 10-year amortization of the Smart Grid cost (in nominal, not present value, terms); and (3) the monthly equivalent of the annual amortized cost. Finally, for the last value, the EPRI team calculated the corresponding percentage increase in the average customer monthly bill.

In practice, more complex cost allocation methods might well be applied that would shift cost among the class. This calculation assumes that the Smart Grid costs are equalized over customers across the country. However, the Smart Grid cost per costumer is likely to vary considerably, and therefore, the total estimated Smart Grid cost may be more concentrated in some areas, which would raise their cost per customer in those areas and reduce it elsewhere. These costs are modest when compared to the benefits the Smart Grid will yield. However, the challenge for all of those in the electricity sector will be communicating that the Smart Grid is indeed a good investment.

Table 1-3
Possible Consumer Implications of the EPRI Estimate of Smart Grid Costs

Smart Grid Cost to Consumers – Allocated by Annual kWh (a)								
Class	**$/Customer Total Cost (b)**		**$/Customer-Year, 10-Yr Amortization (c)**		**$/Customer-Month, 10-Yr Amortization (d)**		**% Increase in Monthly Bill, 10-Yr Amort (e)**	
	Low	**High**	**Low**	**High**	**Low**	**High**		
	$/Customer	**$/Customer**	**$/Cust/yr**	**$/Cust/yr**	**$/Cust/ Month**	**$/Cust/ Month**	**Low**	**High**
Residential	$1,033	$1,455	$103	$145	$9	$12	**8.4%**	**11.8%**
Commercial	$7,146	$10,064	$715	$1,006	$60	$84	**9.1%**	**12.8%**
Industrial	$107,845	$151,877	$10,785	$15,188	$899	$1,266	**0.01%**	**1.6%**

(a) LOW refers to EPRI low estimate of $ total SG costs; HIGH is the other SG cost. Customer numbers by class (residential, commercial industrial) are for 2009 from EIA. SG costs are allocated to customer classes based on 2009 kWh sales (38 %residential; 37% Commercial; 25% industrial).

(b) Total SG cost divided by customers for each segment (residential +commercial+ industrial).

(c) Annual cost per customer per year for total SG cost spread out (amortized) equally over 10 years (nominal values).

(d) Annual cost per customer per month for total SG cost spread out (amortized) equally over 10 years (nominal values).

(e) Annual increase in monthly bill for based on (d).

Smart Grid Benefits

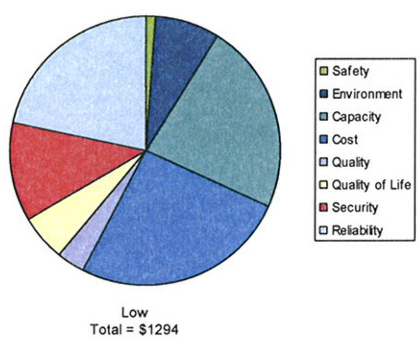
The benefits of the Smart Grid are numerous and stem from a variety of functional elements which include cost reduction, enhanced reliability, improved power quality, increased national productivity and enhanced electricity service, among others. Table 1-4 and Figure 1-4 summarize these benefits. In general terms, the Smart Grid will assure that consumers are provided with reliable, high quality digital-grade power, increased electricity-related services and an improved environment. The Smart Grid will allow the benefits resulting from the rapid growth of renewable power generation and storage as well as the increased use of electric vehicles to become available to consumers. Without the development of the Smart Grid, the full value of a lot of individual technologies like Electric Vehicles, Electric Energy Storage, Demand Response, Distributed Resources, and large central station Renewables such as wind and solar will not be fully realized.

As detailed in Chapter 2, the benefits of the Smart Grid include:

- **Allows Direct Participation by Consumers.** The smart grid consumer is informed, modifying the way they use and purchase electricity. They have choices, incentives, and disincentives.
- **Accommodates all Generation and Storage Options.** The Smart Grid accommodates all generation and storage options.
- **Enables New Products, Services, and Markets.** The Smart Grid enables a market system that provides cost-benefit tradeoffs to consumers by creating opportunities to bid for competing services.
- **Provides Power Quality for the Digital Economy.** The Smart Grid provides reliable power that is relatively interruption-free.
- **Optimizes Asset Utilization and Operational Efficiently.** The Smart Grid optimizes assets and operates efficiently.
- **Anticipates and Responds to System Disturbances (Self-heal).** The Smart Grid independently identifies and reacts to system disturbances and performs mitigation efforts to correct them.
- **Operates Resiliently against Attack and Natural Disaster.** The Smart Grid resists attacks on both the physical infrastructure (substations, poles, transformers, etc.) and the cyber-structure (markets, systems, software, communications).

Table 1-4
Estimated Benefits of the Smart Grid

Attribute	Net Present Worth (2010) $B	
	Low	High
Productivity	1	1
Safety	13	13
Environment	102	390
Capacity	299	393
Cost	330	475
Quality	42	86
Quality of Life	74	74
Security	152	152
Reliability	281	444
Total	**1294**	**2028**



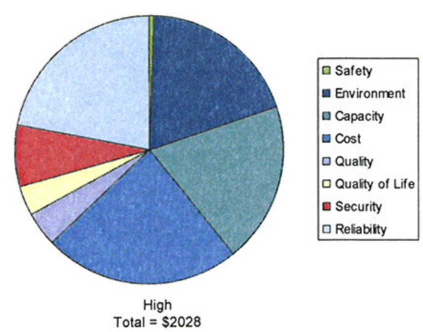


Figure 1-4
Estimated Benefits of the Smart Grid ($ in billions)

Cyber Security

Concern has arisen recently regarding the security of an information technology regime which would be integral with tomorrow's grid. Electric utilities have been incorporating cyber security features into their operations since the early 2000s. In recent years as the Smart Grid became increasingly popular, cyber security concerns have increased significantly. While there have to date been few reliable reports of cyber attacks on power systems, there is a great deal of concern that as the grid becomes smarter and more interactive, disruption of the reliability of U.S. electricity supply will become easier.

Cyber security is an essential element of the Smart Grid. It involves the protection needed to ensure the confidentiality and integrity of the digital overlay which is part of the Smart Grid.

The project team estimates for proper cyber security protection are included in the preceding estimates. An investment of approximately $3,729 million will be needed for the Smart Grid in addition to a related investment in information technology of approximately $32,258 million.

Section 2: Introduction

Smart Grid Vision

This section contains a definition of Smart Grid, an outline of benefits, Smart Grid characteristics, and challenges as contained in EPRI's report to the National Institute of Science and Technology (NIST). The vision is presented as it appeared in EPRI's report to NIST (EPRI, 2009).

What is the Smart Grid?

The Smart Grid definition is based upon the description found in the Energy Independence and Security Act of 2007. The term "Smart Grid" refers to a modernization of the electricity delivery system so it monitors, protects and automatically optimizes the operation of its interconnected elements – from the central and distributed generator through the high-voltage network and distribution system, to industrial users and building automation systems, to energy storage installations and to end-use consumers including their thermostats, electric vehicles, appliances and other household devices.

The Smart Grid will be characterized by a two-way flow of electricity and information to create an automated, widely distributed energy delivery network. It incorporates into the grid the benefits of distributed computing and communications to deliver real-time information and to enable the near-instantaneous balance of supply and demand at the device level.

Smart Grid Characteristics: Drivers and Opportunities

The definition of the Smart Grid builds on the work done in EPRI's IntelliGrid Program (intelligrid.epri.com), in the Modern Grid Initiative (MGI) (NETL, 2007), and in the GridWise Architectural Council (GWAC) (gridwise.org). These considerable efforts have developed and articulated the vision statements, architectural principles, barriers, benefits, technologies and applications, policies, and the frameworks that help define the Smart Grid.

Smart Grid Benefits

Smart Grid benefits can be categorized into 5 types:

- **Power reliability and power quality**. The Smart Grid provides a reliable power supply with fewer and briefer outages, "cleaner" power, and self-healing power systems, through the use of digital information, automated control, and autonomous systems.

- **Safety and cyber security benefits.** The Smart Grid continuously monitors itself to detect unsafe or insecure situations that could detract from its high reliability and safe operation. Higher cyber security is built in to all systems and operations including physical plant monitoring, cyber security, and privacy protection of all users and customers.
- **Energy efficiency benefits.** The Smart Grid is more efficient, providing reduced total energy use, reduced peak demand, reduced energy losses, and the ability to induce end-users to reduce electricity use instead of relying upon new generation.
- **Environmental and conservation benefits.** The Smart Grid facilitates an improved environment. It helps reduce greenhouse gases (GHG) and other pollutants by reducing generation from inefficient energy sources, supports renewable energy sources, and enables the replacement of gasoline-powered vehicles with plug-in electric vehicles.
- **Direct financial benefits.** The Smart Grid offers direct economic benefits. Operations costs are reduced or avoided. Customers have pricing choices and access to energy information. Entrepreneurs accelerate technology introduction into the generation, distribution, storage, and coordination of energy.

Stakeholder Benefits

The benefits from the Smart Grid can be categorized by the three primary stakeholder groups:

- **Consumers.** Consumers can balance their energy consumption with the real-time supply of energy. Variable pricing will provide consumer incentives to install their own infrastructure that supports the Smart Grid. Smart grid information infrastructure will support additional services not available today.
- **Utilities.** Utilities can provide more reliable energy, particularly during challenging emergency conditions, while managing their costs more effectively through efficiency and information.
- **Society.** Society benefits from more reliable power for governmental services, businesses, and consumers sensitive to power outage. Renewable energy, increased efficiencies, and Plug-In Electric Vehicle (PEV) support will reduce environmental costs, including carbon footprint.

A benefit to any one of these stakeholders can in turn benefit the others. Those benefits that reduce costs for utilities lower prices, or prevent price increases, to customers. Lower costs and decreased infrastructure requirements enhance the value of electricity to consumers. Reduced costs increase economic activity which benefits society. Societal benefits of the Smart Grid can be indirect and hard to quantify, but cannot be overlooked.

Other stakeholders also benefit from the Smart Grid. Regulators can benefit from the transparency and audit-ability of Smart Grid information. Vendors and integrators benefit from business and product opportunities around Smart Grid components and systems.

Modern Grid Initiative Smart Grid Characteristics

For the context of this section, characteristics are defined as prominent attributes, behaviors, or features that help distinguish the grid as "smart". The MGI developed a list of seven behaviors that define the Smart Grid. Those working in each area of the Smart Grid can evaluate their work by reference to these behaviors. These behaviors match those defined by similar initiatives and workgroups.

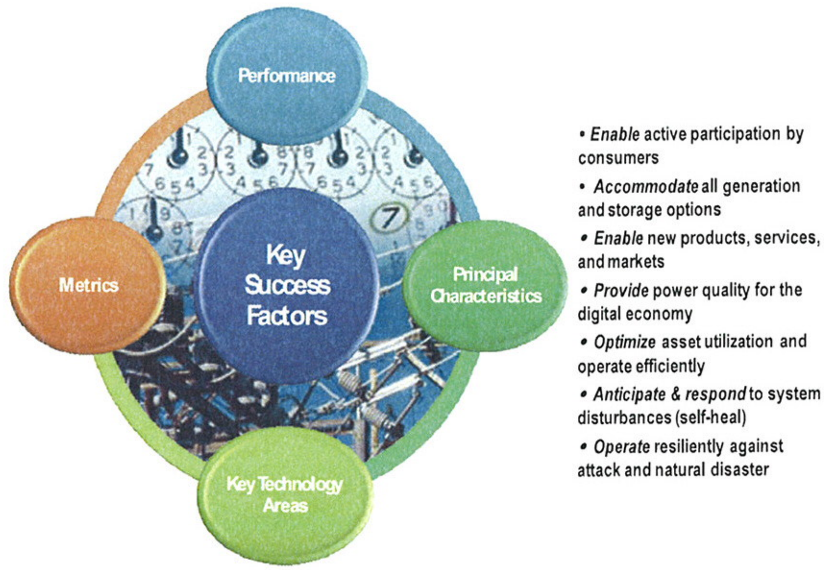


Figure 2-1
MGI's Principle Characteristics are Part of Their Smart Grid System Vision for Measuring Success (Source: EPRI Report to NIST, 2009)

The behaviors of the Smart Grid as defined by MGI are:

- **Enable Active Participation by Consumers.** The Smart Grid motivates and includes customers, who are an integral part of the electric power system. The smart grid consumer is informed, modifying the way they use and purchase electricity. They have choices, incentives, and disincentives to modify their purchasing patterns and behavior. These choices help drive new technologies and markets.
- **Accommodate All Generation and Storage Options.** The Smart Grid accommodates all generation and storage options. It supports large, centralized power plants as well as Distributed Energy Resources (DER). DER may include system aggregators with an array of generation systems or

a farmer with a windmill and some solar panels. The same is true of storage, and as storage technologies mature, they will be an integral part of the overall Smart Grid solution set.

- **Enable New Products, Services, and Markets.** The Smart Grid enables a market system that provides cost-benefit tradeoffs to consumers by creating opportunities to bid for competing services. As much as possible, regulators, aggregators and operators, and consumers can modify the rules of business to create opportunity against market conditions. A flexible, rugged market infrastructure exists to ensure continuous electric service and reliability, while also providing revenue or cost reduction opportunities for market participants. Innovative products and services provide 3rd party vendors opportunities to create market penetration opportunities and consumers with choices and clever tools for managing their electricity costs and usage.
- **Provide Power Quality for the Digital Economy.** The Smart Grid provides reliable power that is relatively interruption-free. The power is "clean" and disturbances are minimal. Our global competitiveness demands relatively fault-free operation of the digital devices that power the productivity of our 21st century economy.
- **Optimize Asset Utilization and Operate Efficiently.** The Smart Grid optimizes assets and operates efficiently. It applies current technologies to ensure the best use of assets. Assets operate and integrate well with other assets to maximize operational efficiency and reduce costs. Routine maintenance and self-health regulating abilities allow assets to operate longer with less human interaction.
- **Anticipate and Respond to System Disturbances [Autonomously] (Self-heal).** The Smart Grid independently identifies and reacts to system disturbances and performs mitigation efforts to correct them. It incorporates an engineering design that enables problems to be isolated, analyzed, and restored with little or no human interaction. It performs continuous predictive analysis to detect existing and future problems and initiate corrective actions. It will react quickly to electricity losses and optimize restoration exercises.
- **Operate Resiliently against Attack and Natural Disaster.** The Smart Grid resists attacks on both the physical infrastructure (substations, poles, transformers, etc.) and the cyber-structure (markets, systems, software, communications). Sensors, cameras, automated switches, and intelligence are built into the infrastructure to observe, react, and alert when threats are recognized within the system. The system is resilient and incorporates self-healing technologies to resist and react to natural disasters. Constant monitoring and self-testing are conducted against the system to mitigate malware and hackers.

Smart Grid Challenges

The Smart Grid poses many procedural and technical challenges as we migrate from the current grid with its one-way power flows from central generation to dispersed loads, toward a new grid with two-way power flows, two-way and peer-to-peer customer interactions, distributed generation, distributed intelligence, command and control. These challenges cannot be taken lightly; the Smart Grid will entail a fundamentally different paradigm for energy generation, delivery, and use.

Procedural Challenges

It the short term it will be useful to prioritize the challenges that the Smart Grid needs to overcome first as a foundation for what is to come. The industry should collaborate to segregate the challenges into buckets to test a hypothesis under which to move forward or so that addressing these challenges becomes more manageable. To address this problem, EPRI is working with several members to develop roadmaps for achieving the promise of the Smart Grid including the necessary decision trees, off ramps and schedules. These are expected to become available during 2011. The procedural challenges to the migration to a smart grid are enormous, and all need to be met as the Smart Grid evolves:

- **Broad Set of Stakeholders.** The Smart Grid will affect every person and every business in the United States. Although not every person will participate directly in the development of the Smart Grid, the need to understand and address the requirements of all these stakeholders will require significant efforts by utilities, system operators, third party electricity service providers and consumers themselves.
- **Complexity of the Smart Grid.** The Smart Grid is a vastly complex machine, with some parts racing at the speed of light. Some aspects of the Smart Grid will be sensitive to human response and interaction, while others need instantaneous, intelligent and automated responses. The smart grid will be driven by forces ranging from financial pressures to environmental requirements.
- **Transition to Smart Grid.** The transition to the Smart Grid will be lengthy. It is impossible (and unwise) to advocate that all the existing equipment and systems to be ripped out and replaced at once. The smart grid supports gradual transition and long coexistence of diverse technologies, not only as we transition from the legacy systems and equipment of today, but as we move to those of tomorrow. We must design to avoid unnecessary expenses and unwarranted decreases in reliability, safety, or cyber security.
- **Ensuring Cyber Security of Systems.** Every aspect of the Smart Grid must be secure. Cyber security technologies and compliance with standards alone are not enough to achieve secure operations without policies, on-going risk assessment, and training. The development of these human-focused procedures takes time—and needs to take time—to ensure that they are done correctly.
- **Consensus on Standards.** Standards are built on the consensus of many stakeholders over time; mandating technologies can appear to be an adequate short cut. Consensus-based standards deliver better results over.
- **Development and Support of Standards.** The open process of developing a standard benefits from the expertise and insights of a broad constituency.

The work is challenging and time consuming but yields results more reflective of a broad group of stakeholders, rather than the narrow interests of a particular stakeholder group. Ongoing engagement by user groups and other organizations enables standards to meet broader evolving needs beyond those of industry stakeholders. Both activities are essential to the development of strong standards.

- **Research and Development.** The smart grid is an evolving goal; we cannot know all that the Smart Grid is or can do. The smart grid will demand continuing R&D to assess the evolving benefits and costs, and to anticipate the evolving requirements.
- **Having a Critical Mass.** It is unclear to the EPRI project team if the Smart Grid implementation is subject to considerations like those of critical mass needed, tipping points and penetration of implementation. There is some concern that early efforts must yield benefits in order to gather support for the development. That support may not accrue until a critical number of consumers are on board with the concepts. If everything the industry does in building the Smart Grid is amenable to a slow diffusion model for evolution as opposed to undertaking some elements in a concentrated way, those benefits may not be revealed quickly enough.

Technical Challenges to Achieving the Smart Grid

Technical challenges include the following:

- **Smart Equipment.** Smart equipment refers to all field equipment which is computer-based or microprocessor-based, including controllers, remote terminal units (RTUs), and intelligent electronic devices (IEDs). It includes the actual power equipment, such as switches, capacitor banks, or breakers. It also refers to the equipment inside homes, buildings and industrial facilities. This embedded computing equipment must be robust to handle future applications for many years without being replaced.
- **Communication Systems.** Communication systems refer to the media and to the developing communication protocols. These technologies are in various stages of maturity. The smart grid must be robust enough to accommodate new media as they emerge from the communications industries, while preserving interoperable, secured systems.
- **Data Management.** Data management refers to all aspects of collecting, analyzing, storing, and providing data to users and applications, including the issues of data identification, validation, accuracy, updating, time-tagging, consistency across databases, etc. Data management methods which work well for small amounts of data often fail or become too burdensome for large amounts of data—and distribution automation and customer information generate lots of data. Data management is among the most time-consuming and difficult task in many of the functions and must be addressed in a way that can scale to immense size.
- **Cyber Security.** Cyber security addresses the prevention of damage to, unauthorized use of, exploitation of, and, if needed, the restoration of

electronic information and communications systems and services (and the information contained therein) to ensure confidentiality, integrity, and availability.

- **Information/Data Privacy.** The protection and stewardship of privacy is a significant concern in a widely interconnected system of systems that is represented by the Smart Grid. Additionally, care must be taken to ensure that access to information is not an all or nothing at all choice since various stakeholders will have differing rights to information from the Smart Grid.
- **Software Applications**. Software applications refer to programs, algorithms, calculations, and data analysis. Applications range from low level control algorithms to massive transaction processing. Application requirements are becoming more sophisticated to solve increasingly complex problems, are demanding ever more accurate and timely data, and must deliver results more quickly and accurately. Software engineering at this scale and rigor is still emerging as a discipline. Software applications are at the core of every function and node of the Smart Grid.

Smart Grid Networking

The Smart Grid is a network of networks, including power, communications and intelligence. That is, many networks with various traditional ownership and management boundaries are interconnected to provide end-to-end services between stakeholders and in and among intelligent electronic devices (IEDs).

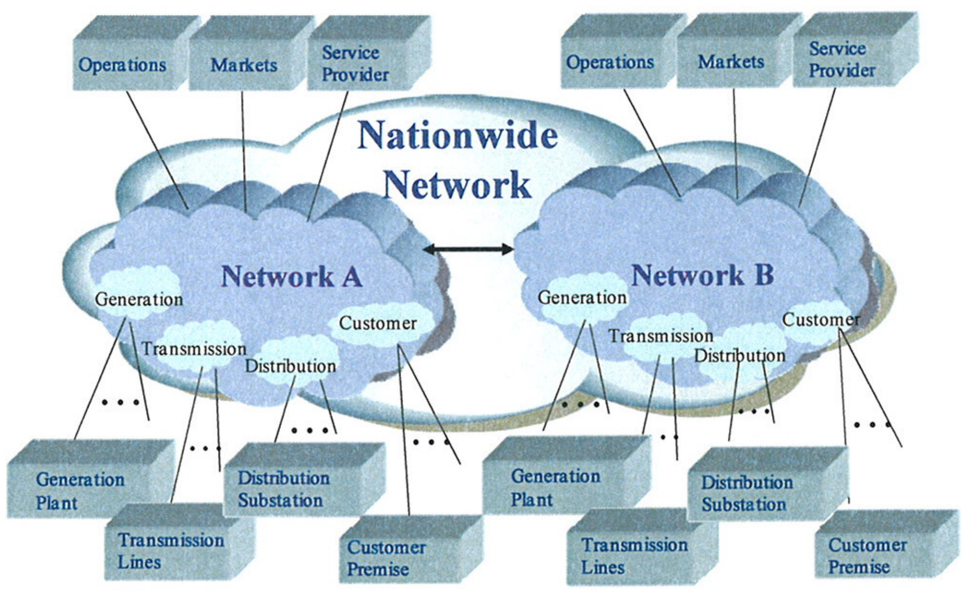


Figure 2-2
Smart Grid Networks for Information Exchange (Source: EPRI Report to NIST, 2009)

Figure 2-2 is a high level view of the information network for the Smart Grid. It handles the two-way communication between the network end points residing in their respective domains. By domain, we mean the unique distributed computing environments in which communicating end points can be found (see next section). Thus, any domain application could communicate with any other domain application via the information network, subject to the necessary network access restrictions and quality of service requirements.

The applications in each domain are the end points of the network as shown on the top and bottom of Figure 2-2. For example, an application in the Customer domain could be a smart meter at the customer premise; an application in the Transmission domain could be a phasor measurement unit (PMU) unit on a transmission line or in a Distribution domain at a substation; an application in the Operation domain could be a computer or display system at the operation center. Each of these applications has a physical communication link with the network. The smaller clouds within the network represent sub-networks that may be implementing unique functionality. The networking function in the Operations, Market, Service Provider domains may not be easily differentiated from normal information processing networks; therefore no unique clouds are illustrated.

This information network may consist of multiple interconnected networks as shown in Figure 2-2, where two backbone networks, A and B are illustrated. The physical links within these two networks and between the network and the network end points could utilize any appropriate communication technology currently available or yet to be developed.

Additional requirements for the information network are as follows:

- Management functionality for network status monitoring, fault detection, isolation, and recovery,
- Secure protocols to protect Smart Grid information in transit and authenticate infrastructure components,
- Cyber security countermeasures,
- Addressing capability to entities in the network and devices attached to it,
- Routing capability to all network end points,
- Quality of service support for a wide range of applications with different latency and loss requirements.

The Smart Grid Conceptual Model

The Smart Grid Conceptual Model is a diagram and description that are the basis for discussing the characteristics, uses, behavior, interfaces, requirements and standards of the Smart Grid. This does not represent the final *architecture* of the Smart Grid; rather it is a tool for describing, discussing, and developing that architecture. The conceptual model provides a context for analysis of interoperation and standards, both for the rest of this document, and for the development of the architectures of the Smart Grid. The top level of the conceptual model is shown in Figure 2-3.

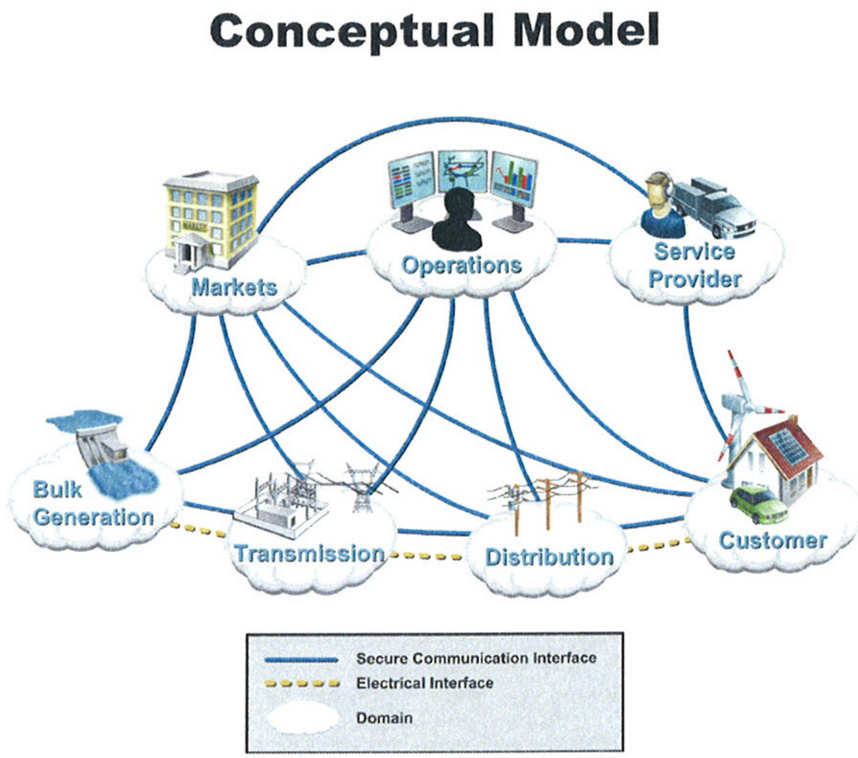


Figure 2-3
Smart Grid Conceptual Model – Top Level (Source: EPRI Report to NIST, 2009)

The conceptual model consists of several *domains*, each of which contains many *applications* and *actors* that are connected by *associations*, which have *interfaces* at each end:

- **Actors** may be devices, computer systems or software programs and/or the organizations that own them. Actors have the capability to make decisions and exchange information with other actors through interfaces.
- **Applications** are the tasks performed by the actors within the domains. Some applications are performed by a single actor, others by several actors working together.
- **Domains** group actors to discover the commonalities that will define the interfaces. In general, actors in the same domain have similar objectives. Communications within the same domain may have similar characteristics and requirements. Domains may contain other domains.
- **Associations** are logical connections between actors that establish bilateral relationships. At each end of an association is an *interface* to an *actor*.
- **Interfaces** show either electrical connections or communications connections. In the diagram, electrical interfaces are shown as yellow lines and the communications interfaces are shown in blue. Each of these interfaces may be bi-directional. Communications interfaces represent an information exchange between two domains and the actors within; they do not represent

physical connections. They represent logical connections in the smart grid information network interconnecting various domains (as shown in Figure 2-2).

The domains of the Smart Grid are listed briefly in Table 2-1 and discussed in more detail in the sections that follow. In Figure 2-3, domains are shown as clouds.

Table 2-1
Domains in the Smart Grid Conceptual Model

Domain	Actors in the Domain
Customers	The end users of electricity. May also generate, store, and manage the use of energy. Traditionally, three customer types are discussed, each with its own domain: home, commercial/building, and industrial.
Markets	The operators and participants in electricity markets
Service Providers	The organizations providing services to electrical customers and utilities
Operations	The managers of the movement of electricity
Bulk Generation	The generators of electricity in bulk quantities. May also store energy for later distribution.
Transmission	The carriers of bulk electricity over long distances. May also store and generate electricity.
Distribution	The distributors of electricity to and from customers. May also store and generate electricity.

It is important to note that domains are NOT organizations. For instance, an ISO or RTO may have actors in both the Markets and Operations domains. Similarly, a distribution utility is not entirely contained within the Distribution domain – it is likely to also contain actors in the Operations domain, such as a Distribution Management System, and in the Customer domain, such as meters

Additional Challenges

Work Force Issues

The utility work force is undergoing a significant challenge. One-half of the 500,000 to 600,000 utility workers will be eligible to retire in the next five years. They need to be replaced with a trained and motivated work force. Introducing Smart Grid technologies requires employees with different skills to support the implementation, maintenance, and operation of the systems with digital components. Accomplishing this when it is already difficult to get highly skilled employees with technical experience will be challenging. In addition, these staffing requirements must be met at the same time as utilities reduce their work forces in order to hold the line on costs (Lave, 2007.) This report includes the labor costs associated with installation of Smart Grid devices and software as well as the differential maintenance. However, it does not include costs for a workforce which generally has different skills involving more expertise in digital devices and communications.

Outage management systems can be used to save costs associated with incorrect outage reports by verifying power outages at customer facilities. (PECO estimates that it avoided 7,500 crew dispatches in 2005 because it was able to see that the customer-reported outage was inaccurate (PECO, 2006).

Regulatory Challenges to Achieving the Smart Grid

Smart Grid technologies offer unprecedented challenges to regulators in encouraging and adjudicating decisions regarding Smart Grid investments. Power systems have largely operated without "smart" technology for decades. In fact, many power systems operate at 99.999% reliability at the bulk transmission level. As long as reliability levels have been maintained (the lights were still on) and costs were low (rates have been essentially flat for decades), it is conceptually difficult to understand how a basket of digital-based technologies can improve the current value of today's power system.

New regulatory and business models are being considered which would offer a greater incentive for utilities to engage in energy efficiency. In some cases, they may be faced with reducing rates as part of seeking approval for Smart Grid investments and, subsequently, losing revenue. Regulated utilities are increasingly embracing energy-efficiency measures on the distribution system or those involving end-use customers.

An additional regulatory challenge is to understand the incremental value of Smart Grid investments. Often, for logical reasons, Smart Grid technologies are implemented in stages, with each stage requiring a business plan for regulators to approve. However, the benefits of many of the Smart Grid efforts come from the synergistic applications of a portfolio of Smart Grid technologies.

This issue was summarized nicely by the Illinois Commerce Commission in a recent report (ISSGC, 2010):

> "The issue of smart grid cost recovery has been a matter of controversy and litigation for several years. Disagreements exist about whether recovery of a utility's smart grid costs should be restricted to the 'traditional' rate-base method, or whether a 'non-traditional' method (e.g., 'rider' recovery) should be used.
>
> Some stakeholders are concerned that utility proposals for cost recovery of smart grid investments would lead to significantly higher monthly bills and a shift in the risk of investment from utilities to ratepayers. Others believe that non-traditional cost recovery would be essential to accelerate deployment of smart grid technologies."

Finally, regulators and utilities are accustomed to utility asset life in the range of 30 to 50 years and business plans and rate cases for regulated utilities are typically based on that supposition. When digital equipment is involved – particularly at the early stages of evolution – the depreciation rates for a significant amount of capital investment may be 5 to 15 years. Appropriate depreciation rates must be allowed in order to pay for asset renewal without increasing costs more than necessary.

In short, a forward view of technology must be embraced by utilities and regulators in order for the Smart Grid to be successful.

Drivers of Smart Grid Investment

A wide variety of policies and economic trends have begun to stimulate and drive U.S. investment in Smart Grid technology, including:

- **The Energy Independence and Security Act (EISA) of 2007** established national policy for grid modernization, created new federal committees, defined their roles and responsibilities, and provided incentives for investment.
- **The American Recovery and Reinvestment Act of 2009** provided more than $3.4 billion in stimulus funding for Smart Grid technology development and demonstration, plus $615 for Smart Grid storage. In October, 2009, 100 Smart Grid Investment Grants were awarded. These were 50/50 matching grants over a three-year period leading to an infusion of $7 to $8 billion in Smart Grid investments that are specifically targeted at projects that can be emulated by others.
- **Renewable portfolio standards** have been established in 30 states plus the District of Columbia stimulating rapid expansion of renewable technology and accelerating the need for Smart Grid technology for grid integration. EPRI's Prism analysis anticipates 135 GW of renewables by 2030 (EPRI 1020389). A number of states have also enacted policies to address specific environmental concerns.
- **Smart Grid interoperability standards,** called for by the EISA, moved forward with NIST's release in September, 2009, of a roadmap for interoperability standards. NIST's efforts were aided by EPRI's draft interim roadmap report released in August, 2009. While not a driver of Smart Grid investment of itself, these recommended standards facilitate Smart Grid deployment.
- **Critical Infrastructure Protection (CIP) Cyber Security Standards,** maintained by the North American Electric Reliability Corporation (NERC) and approved by the Federal Energy Regulatory Commission (FERC) in 2006, are intended to ensure the protection of the critical cyber assets that control or effect the reliability of North America's bulk electric systems. The CIP Cyber Security Standards are mandatory and enforceable across all users, owners, and operators of the bulk power system (LogRhythm, 2009).

- **Demand response programs** have accelerated. The Federal Energy Regulatory Commission's (FERC's) 2008 Demand Response (DR) and Automated Metering Infrastructure (AMI) Survey indicated that advanced metering penetration reached 4.7% of total meters, up from less than 1% in 2006, and that 8% of U.S. customers were currently involved in DR programs. DR continues to gain ground through state legislative initiatives and utility regulation. FERC's "A National Assessment of Demand Response Potential – Staff Report" in June 2009 and FERC's staff report "National Action Plan on Demand Response" in June 2010 highlight the potential (FERC, 2009 and 2010).
- **Market demand** for Smart Grid technologies has drawn the interest of many major information technology companies, from Cisco and Intel, to Google, IBM, and Microsoft which want to participate in one of the most attractive business opportunities of the future. The Smart Grid is viewed as the market equivalent of the Internet in terms of its trillion-dollar potential worldwide. It is the enabling infrastructure for the accelerated deployment of electric vehicles and plug-in hybrid electric vehicles. In addition, consumers will a driving force in shaping the nature of tomorrow's Smart Grid technologies as they respond to evolving offerings by equipment providers.
- **Venture capital** is also entering the Smart Grid domain in a large way, promising to bring faster and more concentrated technical innovation in the areas of Automated Metering Infrastructure (AMI), communications and network technologies. More than $1 billion in VC funding has been extended to key startups, typified by GridPoint and Silver Spring Networks (Green tech media, 2010).
- **Smart Grid roadmaps** are being developed by many electric utilities to optimize their investment strategy going forward. Objectives and starting points vary from company to company, and the optimal pathway difficult to assess. EPRI has been working with SCE, FirstEnergy, and SRP, among others, to create roadmaps for Smart Grid investment. What is critical today is reliable data on benefits from Smart Grid demonstrations. Every effort must be made to measure the actual benefits realized through Smart Grid demonstrations as projects are deployed.
- **National transmission corridors** have been identified. The Energy Policy Act of 2005 authorized the DOE to conduct national electric transmission congestion studies and to designate National Corridors if appropriate. In 2007, DOE designated a Mid-Atlantic National Corridor and a Southwest Area National Corridor (DOE, 2007).
- **Outage prevention** becomes increasingly important in an information-service-based economy. There have been five major blackouts in the last 40 years, three of which occurred in the last decade. The Northeast blackout of 2003 resulted in an estimated $7 to $10 billion in losses to the region. Less disruptive but more pervasive power quality problems are estimated to now cost the U.S. $119 to $188 billion per year (EPRI 1006274).

Previous Studies by EPRI

EPRI has been involved in collaborative, electricity-based innovation in what is now called the Smart Grid since the mid-1980s. EPRI has acted as the catalyst for a process of engagement and consensus building among diverse parties within and outside the electricity enterprise. This effort continues.

Previous EPRI studies have estimated both the costs and benefits of a Smart Grid.

- According to a 2004 study, "The Power Delivery System of the Future" will require $165 billion in net investment (over and above investment for load growth and correcting deficiencies), and lead to a benefit-to-cost ratio of 4:1. Benefits accrue from:
  - Reduced energy losses and more efficient electrical generation.
  - Reduced transmission congestion.
  - Improved power quality.
  - Reduced environmental impact.
  - Improved U.S. competitiveness, resulting in lower prices for all U.S. products and greater U.S. job creation.
  - Fuller utilization of grid assets.
  - More targeted and efficient grid maintenance programs.
  - Fewer equipment failures.
  - Increased security through deterrence of organized attacks on the grid.
  - Improved tolerance to natural disasters.
  - Improved public and worker safety.
- EPRI studies show the annual cost of power disturbances to the U.S. economy ranges between $119 and $188 billion per year (EPRI 1006274). The societal cost of a massive blackout is estimated to be in the order of $10 billion per event as described in a report published by the North American Electric Reliability Corporation titled "Final Report on the August 14, 2003 Blackout in the United States and Canada" (NERC, 2004)
- The Smart Grid is capable of providing a significant contribution to the national goals of energy and carbon savings, as documented in two recent reports.
  - One report by EPRI states that the emissions reduction impact of a Smart Grid is estimated at 60 to 211 million metric tons of CO2 per year in 2030.
  - Another report by Pacific Northwest National Laboratory (PNNL) states that full implementation of Smart Grid technologies is expected to achieve a 12% reduction in electricity consumption and CO2 emissions in 2030.
- And in another report, EPRI estimated that the Smart Grid, combined with a portfolio of generation and end-use options, could reduce 2030 annual CO_2 emissions from the electric sector by 58% relative to 2005 emissions (EPRI 100389).

EPRI Demonstrations

EPRI's Smart Grid Demonstration initiative involves a number of ongoing projects to demonstrate the potential for integrating distributed power generation, storage, and demand response technology into "virtual power plants." Demonstrations include both utility side and customer side technologies, and are intended to address the challenges of integrating distributed Energy resources (DER) in grid and market operations, as well as in system planning. The program addresses key industry challenges, such as:

- Demonstrating effective ways of integrating different forms of distributed resources.
- Demonstrating multiple levels of integration and interoperability among various components.
- Exploring existing and emerging information and communication technologies.

The demonstrations are taking place at a number of U.S. locations and will include a variety of feeder constructions, climate zones, and technologies. Individual demonstrations are focused on the integration of specific feeder types used in residential neighborhoods, in a mixture of residential and commercial customers, and in areas with mostly commercial customers.

Purpose of this Report

The primary purpose of this report is to initiate a discussion and debate of the investment needed to create a viable Smart Grid. To meet this objective, this report documents the methodology, key assumptions, and results of a preliminary quantitative estimate of the needed investment (cost). The report is a starting point intended to encourage further stakeholder discussion of this topic.

The complexity of the power delivery system and the wide range of potential technology applications and configurations to enhance its performance complicate the process of quantitatively estimating the needed investment. In addition, due to the various types of information available, complexity of subparts of the analysis, and uncertainties associated with estimating techniques, no single approach can be applied to all portions of the evaluation. Nevertheless, the debate over the appropriate level of power delivery system investment cannot be advanced without some preliminary estimate of costs. Hence, for each key portion of the overall task, the project team selected methods based on the availability of credible information and the need to conduct a cost-effective and time-efficient study. The resulting estimates of costs are highly uncertain and open to debate.

In this report, EPRI will only address the aggregate cost of the Smart Grid. A separate study has been launched to thoroughly assess the benefits. However, a preliminary update of benefits is included in Section 4.

Why Did the Smart Grid Cost Estimates Change?

There are a number of reasons these estimates changed so dramatically since EPRI last estimated the potential costs of the Smart Gird. First, these changes are due in part to inflation and increasing component costs. Second, they are due to a considerable expansion in the functionality now envisioned in tomorrow's Smart Grid. Table 2-2 highlights these changes.

Table 2-2
Major Elements of Functionality Added to the Smart Grid

Element	Previously Included	Added Benefits
Demand Response	None	Reduced need for generation capacity. Reduced demand for electricity.
Facilitating Renewables	None	Reduced environmental impact of electricity generation.
Plug-In Electric Vehicles or Plug-In Hybrid Electric Vehicles (PEVs)	None	Reduced environment impact from displaced fossil fuels. Grid support (increased system flexibility/ancillary services).
Energy Efficiency	Cost reduction. Reduced need for T&D. Reduced environmental impact.	Reduced need for generation capacity.
Enhanced Energy Efficiency* (additional energy efficiency)	None	Reduced costs. Reduced environmental impact.
AMI	None	AMI-related cost reductions.
Distributed Generation	None	Reduced need for central generating capacity.
Storage	None	Capacity. Reliability and power quality. O&M. Congestion management.

*Enhanced Energy Efficiency includes:

- Continuous Commissioning of Large Commercial Buildings
- Direct Feedback on Energy Usage
- Energy Savings Corresponding to Peak Load Management
- Energy Savings Corresponding to Enhanced M&V Capability

Section 3: Approach

The project team separated the power delivery system into distinct functional areas, and made a number of assumptions about technology development, deployment, and cost over the study period (2010-2030). These assumptions are covered at a high level in this section, and then covered in greater detail for each of the 25 cost components of the four main technology sections of the report – transmission, substations, distribution and customers.

What Constitutes the Power Delivery System?

The power delivery system includes the busbar located at the generating plant (where the power delivery system begins) and extends to the energy-consuming device or appliance at the end user. This means that the power delivery system encompasses generation step-up transformers; the generation switchyard; transmission substations, lines, and equipment; distribution substations, lines, and equipment; intelligent electronic devices; communications; distributed energy resources located at end users; power quality mitigation devices and uninterruptible power supplies; sensors; energy storage devices; and other equipment.

Inadequacies in the power delivery system are manifested in the form of poor reliability, excessive occurrences of degraded power quality, vulnerability to mischief or terrorist attack, the inability to integrate renewables, and the inability to provide enhanced services to consumers.

What Differentiates Smart Grid Enhancement?

Meeting the energy requirements of society will require the application across the entire power delivery system of a combination of current and advanced technologies, including but not limited to the following:

- Automation: the heart of a "smart power delivery system."
- Communication architecture: the foundation of the power delivery system of the future and the enabler of Smart Grid integration.
- Distributed energy resources and storage development and integration.
- Power electronics-based controllers and widely dispersed sensors throughout the delivery system.
- An advanced metering infrastructure.

- A consumer portal that connects consumers and their equipment with energy services and communications entities.
- Power market tools – information systems which enable fluid wholesale power markets.
- Technology innovation in electricity use.
- Appliances and devices which are demand-response ready.

Developing an optimal combination of these technologies will require a significant, sustained RD&D investment. Making such an investment in a critical industry like the U.S. electric power industry is not unprecedented.

Study Steps

To conduct a preliminary quantitative estimate of the level of investment needed over the next 20 years, the project team first separated the core technologies into four broad areas: transmission, substations, distribution and the customer interface. Next, the team subdivided the estimating process into the following segments:

- **Meeting load growth and correcting deficiencies** via equipment installation, upgrading, and replacement to accommodate new customers (new connects), to meet the increasing energy needs of existing customers as their load grows, and to correct deficiencies (e.g., correct power flow bottlenecks and limit high-fault currents that damage critical grid equipment).
- **The Smart Grid:** The project team estimated the investment needed to develop and deploy advanced technologies needed to enhance the functionality of the power delivery system to achieve the level of a Smart Grid.

The first segment represents investments required to maintain adequate capacity and functioning of the existing power delivery system, while the second segment is the additional cost to elevate this system to that of a Smart Grid.

Key Assumptions

The cost estimate was built upon a number of key assumptions:

- Incorporate technologies that not only make the electricity delivery system smarter, but also stronger, more resilient, adaptive, and self-healing.
- Include every reasonable and cost-effective enhancement to accommodate regulatory mandates:
  - Consistent with the functionality requirements of the Energy Independence and Security Act (EISA) of 2007.
  - Meets reasonable cost-benefit assessment.

- Meets North American Electric Reliability Corporation (NERC) reliability standards, maintaining or enhancing today's reliability levels (1 day in 10 years loss of load probability or LOLP).
- Meets System Average Duration Interruption and System Average Interruption Frequency (SADI/SAFI) state guidelines normally suggest 100 minutes SADI/SAFI and power quality (PQ) events to remain at today's levels or to improve.
- Meets performance rate-making targets.
- Meets requirements of future renewable portfolio standards (RPS).

- Incorporate technology and policies that enhance Smart Grid functionality while meeting load growth, expanding and modernizing the power delivery system.
  - Enable a fully functional power delivery system
  - Enable consumer connectivity and service enhancement
  - Enable integration of distributed energy resources
- Accommodate expansion of renewable energy resources consistent with PRISM and other EPRI scenarios, and affords the possibility of meeting DOE targets for wind.
  - EPRI Prism estimates 135GW of renewables by 2030
  - DOE's aggressive target for wind–20% by 2030 seems increasingly plausible.
- The Energy Information Agency's Annual Energy Outlook 2010 projects that the annual growth rate in electricity for the period 2008 to 2035 is projected to be 1.0%. This is as a result of "structural changes in economy – higher prices – standards – improved efficiency" (EIA, 2009). EPRI estimates that the programs and activities which are part of the Smart Grid as envisioned in this report have the potential to reduce this growth rate to 0.68% per year. In addition, EPRI estimates that peak demand's growth rate will be 0.53% per year (EPRI 1016987). These growth rates were used in assumptions about the increasing needs for assets to serve consumers.
- Assume simultaneous deployment of Smart Grid functionality. While deployments will realistically be made along parallel paths and in discrete steps, this study assumes they will occur simultaneously and continuously.
- Assume steady rate of deployment. Deployments are assumed to begin in 2010. Deployment of most technologies will be made at a rate of 1/20th of the maximum assumed penetration each year over the 20-year period. Enhancement and modernization will continue after 2030.
  - The Smart Grid will never be finished. It will continue to evolve organically, not as a step function and not as a "revolution," but as new technology becomes available, practicable and reliable.

- The investigators recognize that investments in Smart Grid will not be made linearly over 20 years, or necessarily even within 20, and will not be uniformly distributed around the country.

- Total power delivery investment costs will exceed Smart Grid investments. They will include investments to meet load growth and to maintain reliability.
- Technology costs are likely to decrease while performance levels increase in unforeseen, and possibly dramatic, ways over the next 20 years. Reasonable estimates have been made, but they are likely to prove conservative given the rapid pace of technological advances. Historically, massive technology advances such as implied by the Smart Grid are invariably driven by a single breakthrough innovation. Smart Grids don't have just one; instead they have a wide range of ideas – some at the pilot or even experimental stage. In some sense, communications, control, and computational ability is one such set of breakthroughs. However, other advances in storage, power electronics, and sensors are still needed to complete the mosaic this report paints.
- Appropriately consider operating and maintenance (O&M) costs associated with running utilities which deploy Smart Grid technologies. O&M expenses are a substantial part of total costs and are built into rates at estimated levels. The IT and technology O&M aspects of the Smart Grid need to be included in cost estimates.
- As the smart grid evolves communications networks will become more ubiquitous and multi-purpose. Utilities may use commercial carriers to provide these networks or they may build out their own networks using dedicated spectrum, share spectrum dedicated to public safety or use unlicensed spectrum. Cost varies significantly for each approach. For this study we have assessed the overall cost for communications networks and have allocated it to the various domains and smart grid applications.

Smart Grid Costs are Particularly Hard to Estimate

Smart Grids are by their nature difficult to estimate for several reasons:

- They frequently involve the integration of digital technology – Sometimes virtually embedded transmission and distribution assets have different failure rates and life expectancy than the majority of today's grid technologies. These failures and resultant replacement rates must be estimated. Utilizing a reliable component, like a substation transformer, with a 40-year design life and incorporating an information technology with 10, 15 or 20 life forces careful consideration of the costs to upgrade the embedded components.
- The obsolescence of digital technology is rapid. Increasingly complex and expanding communications and computational ability makes it possible to render Smart Grid components obsolete or inoperable with respect to the rest of the information and communications technology (ICT) system well before the end of their life. Therefore, reasonable replacement costs must be estimated.

- The improvement in Smart Grid technologies and projected decreases in their costs will occur at a greater rate than "conventional" technology.
- Uncertainty in performance – Many Smart Grid technologies are relatively new and unproven. If their performance is marginal or degrades unexpectedly over time, the entire business plan for the technology could be undermined.
- Smart Grid component costs are declining rapidly. As these technologies mature and as production volumes increase, the marginal costs of Smart Grid technologies have the potential to decline rapidly.

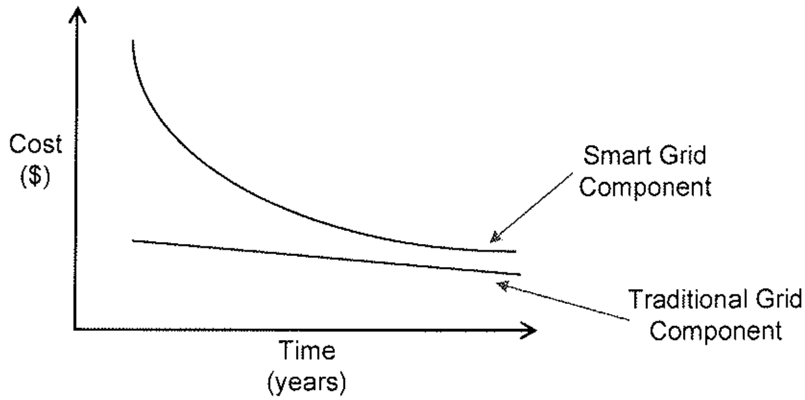


Figure 3-1
Grid Component Costs (Illustrative)

Technology Assessment: What's In and What's Not In?

Table 3-1 summarizes what has been included in the cost analysis and what has not been included. For the most part, T&D line expansion to meet load growth has been excluded.

Figure 3-2 illustrates the scope of the cost estimates included in this report. Investments traditionally made by customers, such as appliances and hybrid vehicles, have been excluded. However, infrastructure integration costs are included.

Table 3-1
Technologies Included and Excluded in the Cost Estimates

Technologies	Costs Included in This Analysis	Costs Excluded
1. Increased use of digital information and controls technology to improve reliability, security, and efficiency of the electric grid.	Sensors, communications and computational ability	None
2. Dynamic optimization of grid operations and resources, with full cyber-security.	All grid-related	None
3. Deployment and integration of distributed resources: storage and generation, including renewable resources.	All integration costs	New transmission lines including those to integrate renewables; and costs of renewable power generation technology*
4. Development and incorporation of demand response, demand-side resources, and energy-efficiency resources	All integration costs	The cost of energy-efficient devices
6. Integration of "smart" appliances and consumer devices.	All integration costs (see above)	Consumer appliances and devices
7. Deployment and integration of advanced electricity storage and peak-shaving technologies, including plug-in and hybrid-electric vehicles, and thermal-storage air conditioning.	Bulk power storage devices and high-value distributed storage – such as bulk storage for wind penetration; distributed storage for grid support; customer-side-of-the-meter storage for end-use energy management	Low-value distributed storage
8. Provision to consumers of timely information and control options to enable consumer engagement.	All enabling costs including cost of consumer display devices	None

Table 3-1 (continued)
Technologies Included and Excluded in the Cost Estimates

Technologies	Costs Included in This Analysis	Costs Excluded
10. Identification and lowering of unreasonable or unnecessary barriers to adoption of Smart Grid technologies, practices, and services.	All	None
11. Costs to implement NERC's Critical Infrastructure Protection (CIP) Standards	None	CIP requirements applied to the Distribution System SCADA would incur substantial costs and are excluded here

*It should be noted that some reviewers felt that the cost of new transmission needed to integrate renewables should ultimately be included in estimating the cost of tomorrow's power delivery system.

One additional cost which could be imposed on some utilities involves conversion to the International Electrotechnology Commission's (IEC) standard for substations communication called IEC 61850. If conversion to IEC 61850 were mandated, legacy systems now utilized by some for both distribution SCADA and communications on the power system would become obsolete. These utilities used a form of Multi-Agent Systems or MAS as a simple format for the exchange of digital information on their power system. For some of these utilities, a mandate to convert to implement IEC 61850 would necessitate replacing their MAS infrastructure, all remote MAS radios and Remote Terminal Units (RTUs) in order to provide the increased bandwidth necessary to support IEC 61850.

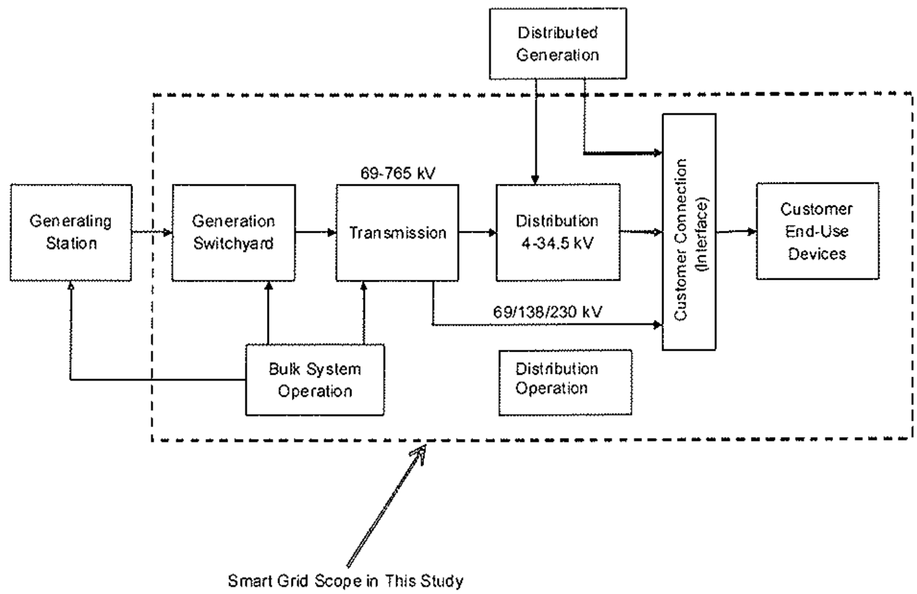


Figure 3-2
Smart Grid Diagram

To conduct a preliminary quantitative estimate of the level of investment needed over the next 20 years to enable the envisioned power delivery system, the project team first decided to treat transmission, distribution, and customer-related costs separately. This is due to fundamental differences in the nature of the transmission and distribution portions of the power delivery system; and uncertainty whether the costs categorized as consumer costs would be borne by utilities, consumers, or third-party service providers. It should be noted that there are, however, substantial areas in which distribution technology enhancements will greatly affect the operation and potentially the configuration of the transmission system. These interactions were not considered in this evaluation. The team also decided to further subdivide the estimating process for transmission and distribution into the following two segments:

- **Load Growth.** Via equipment installation, upgrading, and replacement, transmission and distribution system owners invest in the power delivery system to accommodate new customers (so-called "new connects") and to meet the increasing energy needs of existing customers as their load grows.
- **Power Delivery System of the Future ("Future PDS").** The project team estimated the investment needed to develop and deploy advanced technologies needed to realize the vision of the power delivery system (both transmission and distribution) described above.

Modernizing an Aging Infrastructure

All components of any infrastructure have limited lives regardless if they are roads, bridges, natural gas transmission, water pipelines or telecommunications. From the moment any given infrastructure is installed or renovated, aging begins.

Accelerated aging resulting in premature or unexpected failure is important to avoid in any of the infrastructures which provide society essential services Electricity is no exception as failures of components can lead to poor power quality, interruptions or wide-scale blackouts.

In the case of electric power delivery systems, substantial efforts are made to undertake the investments necessary to maintain reliability. Those investments are not included in estimating the cost of the Smart Grid in this study. Transmission and distribution utilities often spend an amount equal to 1 to 2% of their depreciated plant in service on refurbishment so as to maintain reliability. In conducting business as usual, necessary expenditures to accommodate load growth and to maintain reliability will naturally be made with equipment that is compatible with the power delivery system of the future.

Figure 3-3 illustrates how these three cost elements might combine to build the power delivery system of the future. The figure highlights the fact that as utilities make investments to maintain reliability sufficient to accommodate load growth, they are making investments which help build part of the power delivery system of the future.

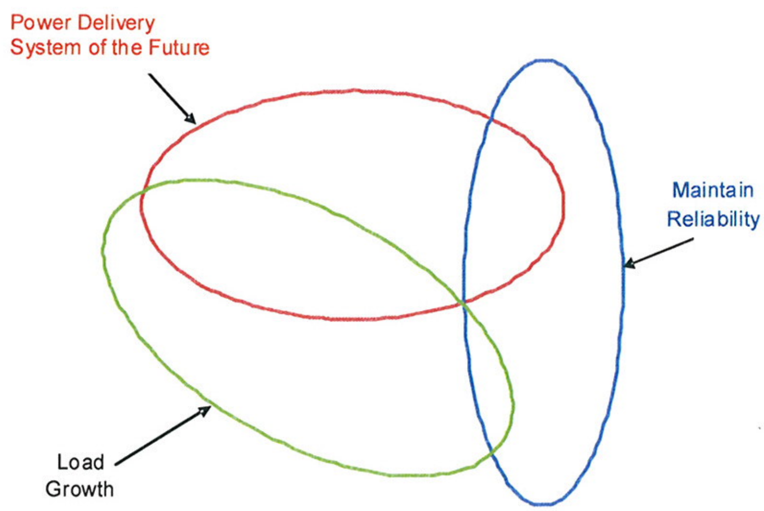


Figure 3-3
Illustration of Synergies in the Three Categories of Needed Transmission and Distribution Investment

Evolving the Smart Grid will mitigate declining reliability caused by aging components on the power delivery system. As Smart Grid components are added to the power delivery system, highlighted as Power Delivery System of the Future in Figure 3-3, and as Load Growth is accommodated as illustrated, the power delivery infrastructure will be strengthened and reliability enhanced. By its nature, the enhanced functionality which the Smart Grid's sensors, communications and computational ability enable will improve O&M, increase reliability and assure that the investments made to maintain reliability are appropriately targeted at infrastructure components which have the greatest risk of failure. In this study, the project team separated the expenditures necessary to accommodate load growth from the expenditures directly related to the power delivery system of the future, in order to elucidate the true cost of the Future PDS.

Section 4: Power Delivery System of the Future: Benefits (The Benefits of the Smart Grid)

Previous EPRI Study

There have been a number of studies which have estimated some of the benefits of a Smart Grid. Each varies somewhat in their approach and the attributes of the Smart Grid they include. None provides a comprehensive and rigorous analysis of the possible benefits of a fully functional Smart Grid. EPRI intends to conduct such a study, but it is outside the scope of the effort presented in this report.

In 2004, EPRI undertook a study to estimate the cost and value (benefits) of the power delivery system of the future. To do so, it developed a flexible framework.

The fundamental approach that was used in the 2004 study involved the identification of *attributes* of the power system (e.g., cost of energy, capacity, security, quality, reliability, environment, safety, quality of life, and productivity). EPRI then developed the framework to quantitatively estimate the dollar value of improving each of these attributes by a defined amount (i.e., percentage improvement).

Existing, documented data sources were used for this estimation process for each attribute. These sources included the U.S. Energy Information Administration, the U.S. Department of Energy's Policy Office Electricity Modeling System, the Federal Energy Regulatory Commission's transmission constraint study, the U.S. Labor Department's Bureau of Labor Statistics, and many more.

Attributes

Table 4-1 shows the various types of improvements that correspond to each of the attribute types used in the root study. A key aspect of the value estimation process in general is its consideration of improvements to the power delivery system (see the left column of Table 4-1), as well as improvements that consumers directly realize (see the right column of Table 4-1). This was done to ensure that emerging and foreseen benefits to consumers in the form of a broad range of value-added services addressed in the estimation of value.

Table 4-1
Attributes and Types of Improvements Assumed in the Value Estimation of the Future Power Delivery System (Left: Power Delivery System Improvements; Right: Improvements That Consumers Realize)

Power Delivery (Improvements/ Benefits) 	Attributes ⟷	 Consumer (Improvements/ Benefits)
O&M Cost Capital Cost of Asset T&D Losses	*Cost of Energy (Net delivered life-cycle cost of energy service)*	End Use Energy Efficiency Capital cost, end user infrastructure O&M, End User Infrastructure Control/Manage Use
Increased Power Flow New Infrastructure Demand Responsive Load	*Capacity*	Improved power factor. Lower End User Infrastructure cost through economies of scale and system streamlining, expand opportunity for growth
Enhanced Security Self Healing Grid for Quick Recovery	*Security*	Enhanced Security and ability to continue conducting business and every day functions
Improve Power Quality and enhance equipment operating window	*Quality*	Improve Power Quality and enhance equipment operating window
Reduce frequency and duration of outages	*Reliability & Availability*	Enhanced Security Self Healing Grid for Quick Recovery Availability Included
EMF Management Reduction in SF6 (sulfur hexafluoride) emissions Reduction in cleanup costs Reduction in power plant emissions	*Environment*	Improved Esthetic Value Reduced EMF Industrial Ecology
Safer work environment for utility employees	*Safety*	Safer work environment for end-use electrical facilities
Value added electric related services	*Quality of Life*	Comfort Convenience Accessibility
Increase productivity due to efficient operation of the power delivery infrastructure Real GDP	*Productivity*	Improved consumer productivity Real GDP

The "cost of energy" attribute is the total cost to deliver electricity to customers, including capital costs, O&M costs, and the cost of line losses on the system. Therefore the value of this attribute derives from any system improvement that lowers the direct cost of supplying this electricity. "SQRA" is the sum of the power security, quality, and reliability attributes, because the availability part of SQRA is embedded in the power quality and reliability attributes. The quality of life attribute refers to the integration of access to multiple services, including electricity, the Internet, telephone, cable, and natural gas. This involves integration of the power delivery and knowledge networks into a single intelligent electric power/communications system, which sets the stage for a growing variety of products and services designed around energy and communications.

To quantify the benefit of these improvements for various attributes, the project team developed various "benefit calculator tools." Figure 4-1 shows the relationship of these benefit calculator tools, the attributes, and the overall value. Note that science and technology drivers feed generally into the process.

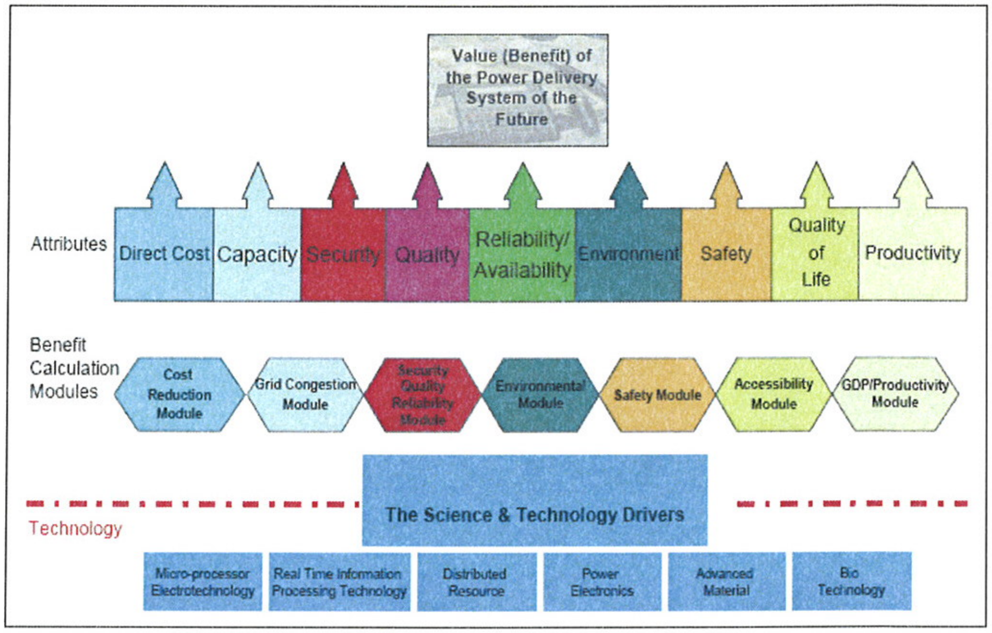


Figure 4-1
Relationship Between Value, Attributes, and Benefit Calculator Tools in the Value Estimation Process

Table 4-2 and Figure 4-1 illustrate the attributes considered in the original estimates of value published in 2004. Table 4-3 summarizes these estimates and escalates them using a chained GDP sequence to 2010 dollars. Table 4-4 lists the major attributes and benefits not included in the original EPRI study.

The increase of benefits using the chained GDP sequence masks the fact that the majority of the overall increase in benefits is from a change in scope of the Smart Grid from a system that can "almost" instantaneously balance supply and demand when the predictability of supply is decreased with the addition of increased amounts of variable renewable resources and the predictability of demand is aggravated with the addition of Plug-in Electric Vehicles, distributed photovoltaics and storage. To rectify this EPRI team analyzed the benefits from Demand Response, PEVs, AMI, Distributed Generation and Storage as shown in Table 2-2. Including these elements has increased the focus of the Smart Grid from operational efficiencies so as to include economic, societal, and energy policy benefits.

The electric power industry is the last industry in the western world to modernize itself through the use of sensors, communications, and computational ability. The combination of these functions allow for a truly interactive power system which can integrate consumer demand with supply interactively.

In addition to the obvious benefits achieved by this enhanced functionality – namely, improved asset utilization, reduced electricity cost, and improved reliability, it is now obvious that other substantive benefits will accrue once the Smart Grid is implemented. Chief among these is the reduction of peak demand, the adoption of electric vehicles, the use of storage, and the increased use of renewable power production.

Table 4-2
Summary of Benefit Calculations Included in Original EPRI Study

Benefit Calculations	Attributes
T&D Cost Reduction	Energy efficiency and T&D losses impact on: • Capital cost • O&M Cost • Administrative and general cost
Congestion	• Transmission congestion cost
Security	• Self-healing infrastructure • Mitigating major outages
Power Quality & Reliability/ Availability	• Reliability • Power Quality
Environmental Impact	• SO_2 • CO_2 • NOx
Safety	• Accidental electrocutions • Building fires caused by electrical infrastructure
Quality of Life	• Access to competing suppliers
GDP/Productivity	• Increase GDP from reduced electricity cost

Table 4-3
Benefit Estimates in 2004 EPRI Study Escalated to 2010 Values

Attribute	Net Present Worth (2004) $B		Net Present Worth (2010) $B	
	Low	High	Low	High
Productivity	1	1	1.14	1.14
Safety	11	11	12.54	12.54
Environment	48	48	54.72	54.72
Capacity	49	49	55.86	55.86
Cost	50	50	57	57
Quality	35	57	41.04	64.98
Quality of Life	65	65	74.1	74.1
Security	133	133	151.62	151.62
Reliability	247	390	281.58	444.6
Total	**640**	**804**	**729.6**	**916.56**

Table 4-4 lists the major attributes and benefits not included in the original EPRI study. Hence, the value of the Smart Grid, even with escalation applied, is substantially understated in Table 4-3.

In order to provide a preliminary estimate of at least the major benefits of a fully functional power delivery system, EPRI has attempted to provide estimates for most of the remaining benefits. These are depicted in Table 4-5 using a framework developed by the U.S. Department of Energy (USDOE) and EPRI (EPRI 1020342). The table includes the attributes and benefits explicitly included in the DOE/EPRI framework as well as other attributes not included.

As summarized in the table, the total benefit of all attributes for the Smart Grid is estimated to be between $1,294 billion and $2,028 billion for the period 2010 to 2030. EPRI believes that once all of the attributes and benefits of a Smart Grid are identified and analyzed, estimates of the total benefit will increase even more.

Table 4-4
Major Attributes and Benefits Not Included in Original EPRI Study

Attributes	Benefits
Demand Response	• Reduced need for generation capacity • Reduced demand for electricity
Facilitating Renewables	• Reduced environmental impact of electricity generation
PEVs	• Reduced environmental impact from displaced fossil fuels • Increased system flexibility/ancillary services
Work Force	• Improved utilization of work force
Energy Efficiency	• Generation Capacity deferrals
Enhanced Energy Efficiency (additional energy efficiency)	• Reduced Environmental Impacts
AMI	• AMI-related cost reductions
Distributed Generation	• Facilitating distributed generation
Value-Added Electricity Services	• Comfort and convenience
Synergistic Effects Between Elements	• Compounding between multiple attributes
Storage (various benefits)	• Capacity • O&M • Congestion
Safety	• Personal safety
Transmission O&M	• Ancillary services

Table 4-5
List of Smart Grid Benefits: Based on EPRI/DOE Framework (EPRI 1020342)

Benefit Category	Benefit Sub-Category	Benefit	Included in Original Estimate?	Estimated Value 2010-2030 $Billion Low	High	Reference
		Optimized Generator Operation		–	–	not included
		Deferred Generation Capacity Investments	→			Appendix A
		Reduced Ancillary Service Cost	X →			included below
		Distributed Generation		–	–	not included
	Improved Asset Utilization	Storage		48	89	Appendix A
		PEVs as Storage & Load Control		11	11	Appendix A
		Energy Efficiency	X →			included below
		Demand Response		–	–	not included
		Enhanced Energy Efficiency*		–	–	not included
Economic		Reduced Ancillary Service Cost		–	–	not included
		Reduced Congestion Cost	X →			included below
		Distributed Generation		27	27	Appendix A
		Storage		23	65	Appendix A
		Demand Response		192	242	not included
	T&D Capital Savings	Energy Efficiency	X →			included below
		Enhanced Energy Efficiency*		1	3	Appendix A
		Deferred Transmission Capacity Investment	X →			included below
		Deferred Distribution Capacity Investment	X →			included below
		Reduced Equipment Failures	X →			included below

Table 4-5 (continued)
List of Smart Grid Benefits: Based on EPRI/DOE Framework (EPRI 1020342)

Benefit Category	Benefit Sub-Category	Benefit	Included in Original Estimate?	Estimated Value 2010-2030 $Billion Low	High	Reference
Economic	T&D O&M Savings	More Effective Use of Personnel		–	–	not included
		Economic Benefit of Added Personnel		–	–	not included
		Operations Savings from AMI		4	4	Appendix A
		T&D Efficiency	X →			included below
		Reduced Distribution Equipment Maintenance Cost	X →			included below
		Reduced Distribution Operations Cost	X →			included below
	Theft Reduction	Reduced Electricity Theft		–	–	Not included
	Energy Efficiency	Enhanced Energy Efficiency*		0	2	Appendix A
		Electrification (Net Reduced Energy Use)		–	–	Appendix A
		Reduced Electricity Losses	X →			included below
		Productivity Increase	X →			included below
		Reduced Electricity Cost	X →			Included below
	Electricity Cost Savings	Automatic Meter Reading		91	91	Appendix A
		Customer Service Costs (Call Center)		2	2	Appendix A
		Storage		115	199	Appendix A
		Enhanced National Productivity	X →			included below
		Reduced Restoration Cost	X →			included below
		Speed of Restoration		–	–	not included

Table 4-5 (continued)
List of Smart Grid Benefits: Based on EPRI/DOE Framework (EPRI 1020342)

Benefit Category	Benefit Sub-Category	Benefit	Included in Original Estimate?	Estimated Value 2010-2030 $Billion Low	High	Reference
		Storage		2	20	Appendix A
		Reduced Sustained Outages	X →			included below
		Reduced Major Outages	X →			included below
		Accessibility	X →			included below
		Reduced Momentary Outages	X →			included below
	Power Quality	Reduced Sags and Swells	X →			included below
		Storage		1	21	Appendix A
		Electrification		21	21	Appendix A
		PEVs		5	123	Appendix A
		Enhanced Energy Efficiency*		1	4	Appendix A
Environmental	Air Emissions	Storage		10	15	Appendix A
		Facilitate Renewables		10	172	Appendix A
		Reduced CO_2 Emissions	X →			included below
		Reduced SOx, NOx and PM-10 Emissions	X →			included below

Table 4-5 (continued)
List of Smart Grid Benefits: Based on EPRI/DOE Framework (EPRI 1020342)

Benefit Category	Benefit Sub-Category	Benefit	Included in Original Estimate?	Estimated Value 2010-2030 $Billion Low	High	Reference
Security	Energy Security	Reduced Imported Oil Usage		–	–	not included
		Personal Security		–	–	not included
		National Security		–	–	not included
		Reduced Wide-Scale Blackouts	X →			included below
		Safety	X →			included below
Previous EPRI Estimates – All included in original estimate			X	730	917	
Not included in original estimate				564	1,111	
Total				1,294	2,028	

*Enhanced Energy Efficiency includes:
Continuous Commissioning of Large Commercial Buildings
Direct Feedback on Energy Usage
Energy Savings Corresponding to Peak Load Management
Energy Savings Corresponding to Enhanced M&V Capability

Section 5: Transmission Systems and Substations

The high-voltage transmission system is the "backbone" of the power delivery system. It transmits very large amounts of electric energy between regions and sub-regions. Transmission system equipment fails and causes power outages much less frequently than distribution equipment. But when transmission equipment fails, many more customers are affected, and outage costs can be much higher, compared to the impact of a distribution equipment-related outage. This fact, combined with the high cost per mile or per piece of transmission equipment, has historically led to greater attention to transmission system reliability. However, in the last several decades, a variety of factors has led to a significant decrease in investment in transmission system expansion.

Introduction

To estimate the investment needed in the transmission system, a top-down approach was used for the load-growth and correct-deficiencies segments of investment, while a bottom-up approach was used for estimating the elements needed to create a Smart Grid. In the U.S., according to EEI, there are now more than 200,000 miles of high-voltage transmission lines greater than 230 kV. An earlier study by DOE, entitled the *National Transmission Grid Study, 2002*, showed a total of 187,000 miles, broken down by the voltage levels shown in Table 5-1.

The total cost for enhancing transmission system and substation performance to the level of a Smart Grid is estimated between $56 and $64 billion, as summarized in this section. The cost includes several categories of technology whose functionality overlaps significantly between the transmission system and substations as well as some elements of the distribution system described later, as well as enterprise level functions, such as cyber security and back office systems.

Table 5-1
Transmission Line Miles

Voltage (kV)	Miles
230 AC	85,048
345 AC	59,767
500 AC	32,870
765 AC	4,715
250-500 DC	3,307
Total Miles	**184,707**

In general, monitoring of transmission assets is more cost-effective and beneficial than any other asset class (EPRI 1016055). Although transmission lines are one of the critical core backbone elements of the power grid, thousands of miles are unattended and not monitored in any way. Transmission lines have seasonal ratings that need to be considered by operations and planning. For the most part, there is little if any real-time monitoring other than at substations that provide operators with loading information.

Transmission investment trended downward for more than two decades, declining from $4.8 billion in 1975 to $2.25 billion in 1997, then leveled off before beginning to climb again. It reached roughly $5 billion in 2000 and is expected to reach nearly $11 billion in 2010. Smart Grid functionality should help to increase the value of future transmission investment over and the expansion needed to meet load growth.

The number of substations is one of the basic metrics upon which investment costs were determined. There are an estimated 70,000 substations in the U.S. that reduce voltage between the bulk transmission system and the distribution feeder system, and serve as critical hubs in the control and protection of the electricity grid. This figure was derived from FERC data that shows investor-owned utilities (IOUs) operate a total of 40,619 substations at voltage levels ranging from just above 1 kV to 765 kV. Since IOUs represent roughly 70% of all U.S. customers, the number of existing substations was thus calculated to be 58,027 (40,619/.7 = 58,027).

As elucidated in Chapter 3, load was estimated in the study to grow at a rate of 0.68%/year. Compounded over the 20-year period of the study (2010-2030), this would imply an additional 8,423 substations will be required by 2030. Accordingly, the base figure used throughout this report for substations is 58,027 which could potentially be upgraded and 8,423 which will be new. In addition to this base, another 700 substations will be required by 2030 to handle renewable generation.

Other key benchmarks used in the analysis include an estimate of 8 feeders/substation serving lower-voltage customers downstream. Thus, there are 464,216 feeders that are eligible to be upgraded with intelligent electronic devices for a fully functioning Smart Grid. In addition, there are 67,384 new feeders to be added to accommodate load growth. Segments of the feeders that can be isolated electrically in case of faults and/or reconfiguration are called "pods," and for purposes of the Smart Grid, the analysis team used roughly 4 pods/feeder, yielding more than 2,260,000 isolatable pods for purposes of monitoring and control.

Table 5-2 lists these assumptions.

Table 5-2
Number of Substations and Feeders

Substations	Number
Existing substations	58,027
New substations to accommodate load growth (2030)	8,423
New substations to accommodate renewables (2030)	700
Distribution	
Number of existing feeders	464,216
New feeders to accommodate load growth (2030)	67,384

An underlying assumption in the report is that the digital devices to be deployed in the Smart Grid will comply with the International Electrotechnology Commission (IEC) Standard 61850 (IEC 61850). That standard applies to substation automation and protection, distribution automation, distributed energy resources, hydro generation, SCADA to field devices, and applies to protective relays, SCADA Master, DER, PQ meters, fault recorders and other applications.

Cost Components for the Smart Grid: Transmission Systems and Substations

The core components of cost for the transmission and substation portion of the Smart Grid are as follow:

- Transmission line sensors including dynamic thermal circuit rating
- Storage for bulk transmission wholesale services
- FACTS devices and HVDC terminals
- Short circuit current limiters
- Communications infrastructure to support transmission lines and substations
- Core substation infrastructure for IT
- Cyber-security
- Intelligent electronic devices (IEDs)
- Phasor measurement technology for wide area monitoring

- Enterprise back-office system, including GIS, outage management and distribution management
- Other system improvements assumed to evolve naturally include:
  - Faster than real-time simulation
  - Improved load modeling and forecasting tools
  - Probabilistic vulnerability assessment
  - Enhanced visualization

Substation upgrades will enable a number of new functions including, but not limited to:

- Improved emergency operations
- Substation automation
- Reliability-centered and predictive maintenance

Dynamic Thermal Circuit Rating (DTCR)

Dynamic rating and real-time monitoring of transmission lines are becoming important tools to maintain system reliability while optimizing power flows. Dynamic ratings can be considered a low-cost alternative for increased transmission capacity. Dynamic ratings are typically 5 to 15% higher than conventional static ratings. Application of dynamic ratings can benefit system operation in several ways, in particular by increasing power flow through the existing transmission corridors with minimal investments.

Dynamic rating increases the functionality of the Smart Grid because it involves the monitoring of real-time system data that can be used in various applications:

- Real-time monitors yield a continuous flow of data to system operations – line sag, tension or both, wind speed, conductor temperature, etc. – traditionally not available to operators.
- Monitored data can be processed to spot trends and patterns.
- Real-time monitored data may be turned into useful operator predictive intelligence (e.g., critical temperature and percent load reduction needed in real time).

The New York Power Authority (NYPA) has engaged with EPRI in a demonstration project that will evaluate the instrumentation and dynamic thermal ratings for overhead transmission lines. An area of possible application for DTCR is the growing penetration of wind generation; when turbines are operating, one expects higher dynamic ratings because of increased wind speed. The project will use EPRI's DTCR software, which uses real-time or historical weather and electrical load data to calculate dynamic ratings for overhead lines in real time based on actual load and weather conditions that generally are accessed through the utility's SCADA/EMS system.

The study team assumed that AC transmission lines rated 115 kV to 230 kV in the U.S. are most susceptible to being thermally limited. They considered lines rated 345 kV and above are more likely voltage-limited. Albeit, there may be a few lines rated at these higher voltages that are thermally limited – they would be an exception and not the rule. Furthermore, of the lines which are potentially thermally limited, only 50% actually are. There are 85,048 miles of lines at 230 kV. To dynamically rate all 85,048 miles would require one unit per 7.5 miles or 11,340 units. The cost of DTCR deployed in quantity is estimated to be $20,000 initially, declining to $10,000.

It should be noted that the above calculation does not include any transmission lines at voltages lower than 230 kV, e.g., 115, 138 and 161 kV. It is expected that these transmission lines will benefit from DTCR.

Table 5-3
Cost of Dynamic Thermal Circuit Rating

Technology	Total Units	Units	% Sat	Cost/ Unit Low $	Cost/ Unit High $	Total Cost Low–High $M
Dynamic-Thermal Circuit Rating	11,340	Units/7.5 miles DTCR line	100	10,000	20,000	113.4-226.8

Sensors and Intelligent Electronic Devices

The Smart Grid will require a more diverse and wider array of sensors and other Intelligent Electronic Devices (IEDs) throughout the power system to monitor conditions in real time. In particular, sensors in transmission corridors and in substations can address multiple applications:

- Safety: The application of sensors for transmission line or substation components will allow for the monitoring and communication of equipment conditions. Information that a transmission line or substation component is in imminent risk of failure will enable actions to be taken to address the safety of utility personnel.
- Workforce Deployment: If the condition of a component or system is known to be at risk, personnel can be deployed to prevent an outage.
- Condition-Based Maintenance: Knowledge of component condition enables maintenance actions to be initiated at appropriate times rather than relying on interval-based maintenance.
- Asset Management: Improved knowledge of the condition of equipment and stresses that they have been subjected to will allow managers to better manage the assets. Sensor data used together with historic performance

information, failure databases and operational data allows better allocation of resources.

- **Increased Asset Utilization:** The rating of transmission components is influenced by a range of factors such as ambient weather conditions, loading history and component configuration. In order to address this complexity, static ratings are usually based on conservative assumptions of these factors. Higher dynamic ratings can be achieved with more precise, real-time knowledge of the asset's condition.
- **Forensic and Diagnostic Analysis:** After an event occurs, there is limited information to understand the root cause. Sensors allow the capture of pertinent information in real time for a more rigorous analysis.
- **Probabilistic Risk Assessment:** Increased utilization of the grid is possible if contingency analyses are performed using a probabilistic, rather than deterministic, methods. To use probabilistic methods, knowledge of the condition of components and the risks they pose are needed

The transmission system of the future will utilize a synergistic concept for the instrumentation of electric power utility towers with sensor technology designed to increase the efficiency, reliability, safety, and security of electric power transmission. The system concept is fueled by a list of sensing needs illustrated in Figure 5-1 (EPRI 1016921). This system scope is limited to transmission line applications (i.e., 69 kV and above), not distribution, with the focus on steel lattice and pole structures, not wooden.

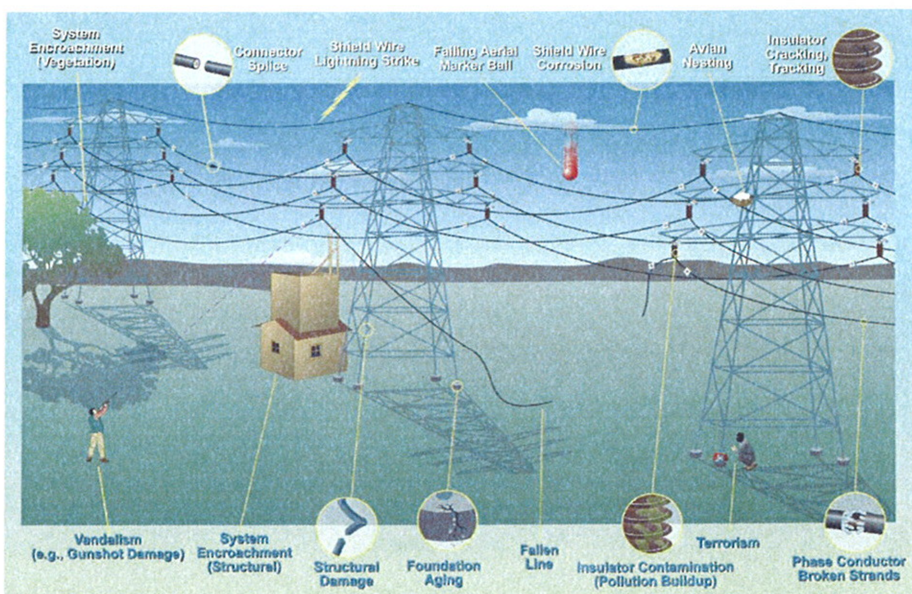


Figure 5-1
Illustration of Sensor Needs for Transmission Lines and Towers (EPRI 1016921)

In this concept, the addition of wiring to interconnect and/or power distributed sensors is not viable because of electromagnetic susceptibility concerns and labor intensive installation. Consequently, sensor concepts will rely on wireless and/or fiber optic technology.

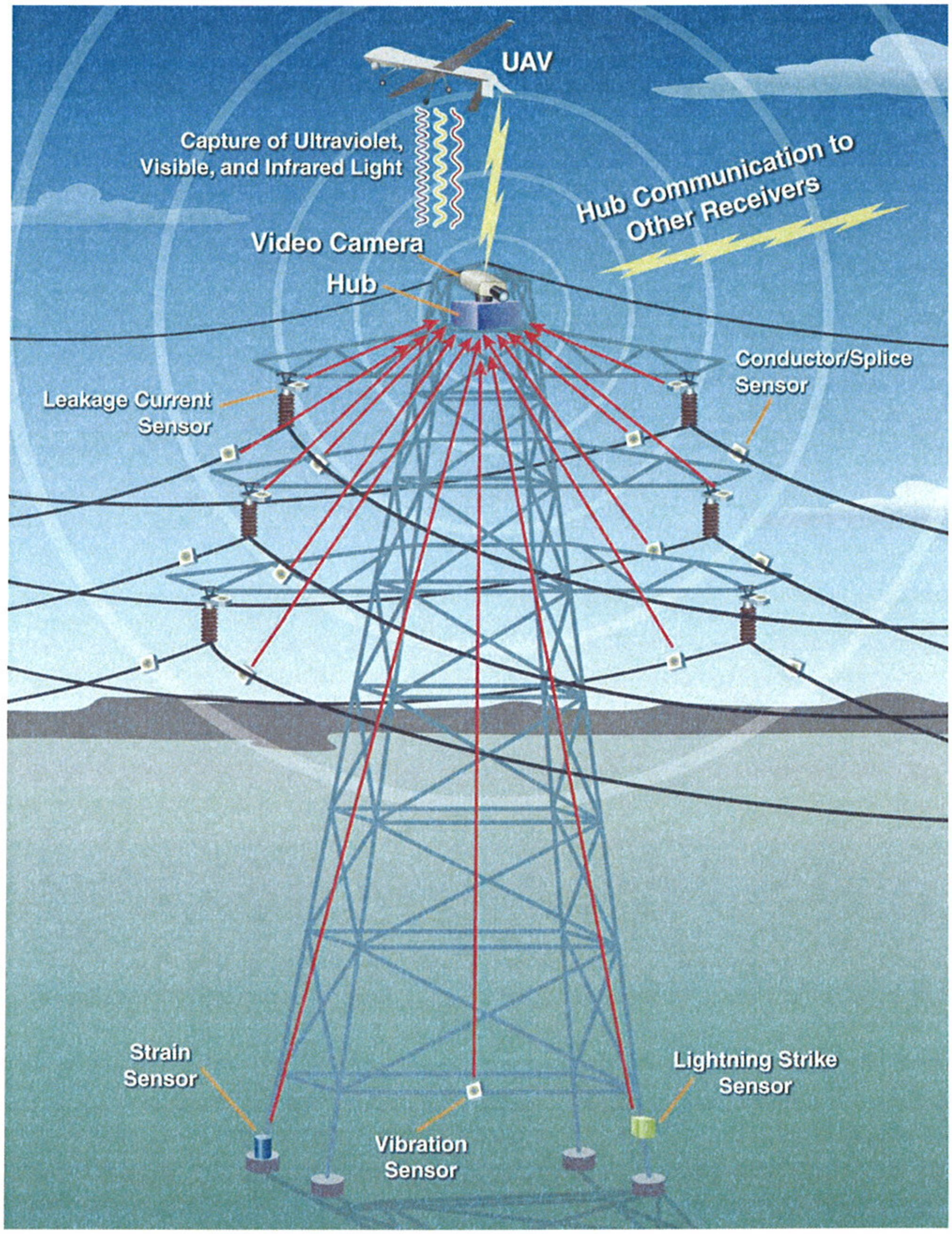


Figure 5-2
Image Showing a Single Structure Illustrating Some of the Concepts (EPRI 1016921)

Figures 5-1 and 5-2 depict some of the high-level concepts that are listed below:

- Sensors distributed on transmission structures and /or conductors.

- Sensors that may or may not communicate with the "hub" installed on the structure – either wireless or wired.
- Sensor information is collected, stored and analyzed in a "central database" which is part of the utility's current data management system. The data is collected /communicated from the sensors /hubs to the central database using one of the following methods:
  - Wirelessly back to the central database from the individual structure hub, e.g. RF directly, via satellite or cell phone network.
  - Collected using a vehicle traveling the length of the line. The data from the collection vehicle is transferred during or after the inspection. The following is a list of possible data collection vehicles:
    - Unmanned Airborne Vehicle (UAV)
    - Manned Aerial Vehicle
    - Line Crawler Robot
  - If the vehicle data collection approach is utilized:
    - The vehicle may collect the data wirelessly directly from the sensors (possibly excluding the need for a structure "hub").
    - The vehicle may also have sensors aboard recording data during the collection process, (e.g. video, UV, IR, still images)

These concepts are discussed in detail in the following sections.

There are a number of possible sensors to address each of these applications. Table 5-4 below elucidates the range of sensor needs. The study team assumed that by 2030 one-half of all substations would have installed an advanced sensors package on the transmission system, costing roughly $50,000-100,000/substation. The total Smart Grid investment for sensors approaches $1.5 to 2.9 billion. In addition, 100% of new substations built to accommodate load growth would incorporate a suite of sensors at a cost ranging between $421 to 842 million.

Table 5-4
Sensor Needs

	Item	Cause	Result	Update Interval	Probability	Consequence	Sensing Technologies
1	System Tampering	Terrorism	Tower/line down	Real-time	Low	High	Vibration, Acoustic, E-Field, Optical
2	System Encroachment	Man-made	Safety hazard, Less reliable	3-12 mo	High	Med	Optical, Satellite, Proximity, Vibration, E-Field
3	System Encroachment	Vegetation	Flashover, Fire	3 mo	High	High	Optical, Satellite, LIDAR, Line-of-Sight, Proximity
4	System Encroachment	Avian Nesting, Waste	Flashover	6-12 mo	High	High	Optical, Vibration, Leakage Current, Proximity, E-Field
5	Shield Wire	Corrosion	Flashover, Outage	3-6 years	Med	High	Optical, IR Spectroscopy, Eddy Current, MSS
6	Shield Wire	Lightning	Flashover, Outage	1 year	Med	High	Optical, IR Spectroscopy, Eddy Current, MSS, Lightning Detection, Vibration
7	Insulator (Polymer)	Age, Material Failure	Outage	6 years	Med	High	Optical, Vibration, RFI, UV, IR
8	Insulator (Ceramic)	Age, Material Failure	Outage	12 years	Low	High	Optical, Vibration, RFI, UV, IR
9	Insulator	Contamination	Flashover	3 mo	Med	Med	Optical, RFI, UV, IR, Leakage Current
10	Insulator	Gun Shot	Outage	Real-time, 3 mo	Med	High	Optical, Vibration, RFI, UV, IR, Acoustic

Table 5-4 (continued)
Sensor Needs

	Item	Cause	Result	Update Interval	Probability	Consequence	Sensing Technologies
11	Phase Conductor	External strands broke	Line Down, Fire	1 year	Low	High	Optical, Vibration, RFI, UV, IR
12	Phase Conductor	Internal strands broke	Line Down, Fire	1 year	Low	High	E-MAT, MSS, Electromagnetic
13	Phase Conductor	Corrosion of steel core	Line Down, Fire	1 year	Low	High	E-MAT, MSS, Electromagnetic, IR Spectroscopy, Optical
14	Connector Splice	Workmanship, thermal cycling, age	Line Down, Fire	1 year	Med	High	Direct Contact Temperature, IR Temperature, Ohmmeter, RFI, E-MAT, MSS
15	Hardware	Age	Line Down, Fire	6 years	Low	High	Optical, IR Spectroscopy
16	Phase Spacer	Age, galloping event	Line Down, Fire	6 years	Low	Med	Optical, UV, RFI
17	Aerial Marker Ball	Vibration Damage, Age	Safety concerns	1 year	Low	Med	Optical, UV, RFI
18	Structure (Steel Lattice)	Corrosion	Reliability Concerns	10 years	Med	Med	Optical, IR Spectroscopy
19	Structure (Steel Lattice)	Bent, damaged members	Reliability Concerns	1 year	Med	Med	Optical, Strain, Position, Tilt
20	Structure (Steel Pole)	Corrosion, age	Reliability Concerns	10 years	Med	Med	Optical, IR Spectroscopy

Table 5-4 (continued)
Sensor Needs

	Item	Cause	Result	Update Interval	Probability	Consequence	Sensing Technologies
21	Structure (Steel Pole)	Internal Deterioration	Reliability Concerns	1 year	Med	Med	Optical, MSS, Ultrasonics
22	Foundation (Grillage)	Age, corrosion	Reliability Concerns	10 years	High	High	Excavation, MSS, Radar, GPR Imaging, Half Cell, Voltage Potential
23	Foundation (Anchor Bolt)	Age, corrosion	Reliability Concerns	10 years	Low	High	Optical, Ultrasonics, E-MAT, Vibration
24	Foundation (Preform)	Age, corrosion	Reliability Concerns	10 years	Med	High	Optical, Ultrasonics, E-MAT, Vibration
25	Foundation (Stub Angles)	Age. Corrosion	Reliability Concerns	10 years	Low	High	Optical, Ultrasonics, E-MAT, Vibration
26	Foundation (Direct Embedment)	Age, corrosion	Reliability Concerns	10 years	High	High	Excavation, MSS, Half Cell, Voltage Potential
27	Foundation (Anchor Rods, Screw-In)	Age, corrosion	Reliability Concerns	10 years	High	High	Excavation, MSS, Half Cell, Voltage Potential, Ultrasonics
28	Grounding	Age, corrosion, tampering	Reliability, Lightning, Safety concerns	6 years	Med	Med	AC impedance, DC resistance, Impulse
29	TLSA (Transmission Line Surge Arrestor)	Lightning Strikes, age	Reliability, Lightning Concerns	1 year	Med	Med	Optical, IR, Leakage Current, Lightning Strike Counter

The sensor system architecture is comprised of sensors that acquire diagnostic data from components of interest and from communications hubs that collect the sensor data and relay it to a central repository. Sensors may be directly attached to the item being monitored, or may be remotely located such as in the case of a camera. Communications hubs may be mounted on or near towers or may be located on a wide variety of mobile platforms, such as manned airplanes or unmanned line crawlers or UAVs. Sensors and hubs may operate and be polled periodically (e.g., at intervals of minutes, hours, days) or continuously monitored (e.g., a real-time alarm) depending on the application. In any case, sensors communicate their results via hubs to a central repository. Figure 5-3 illustrates the architecture and flow of data.

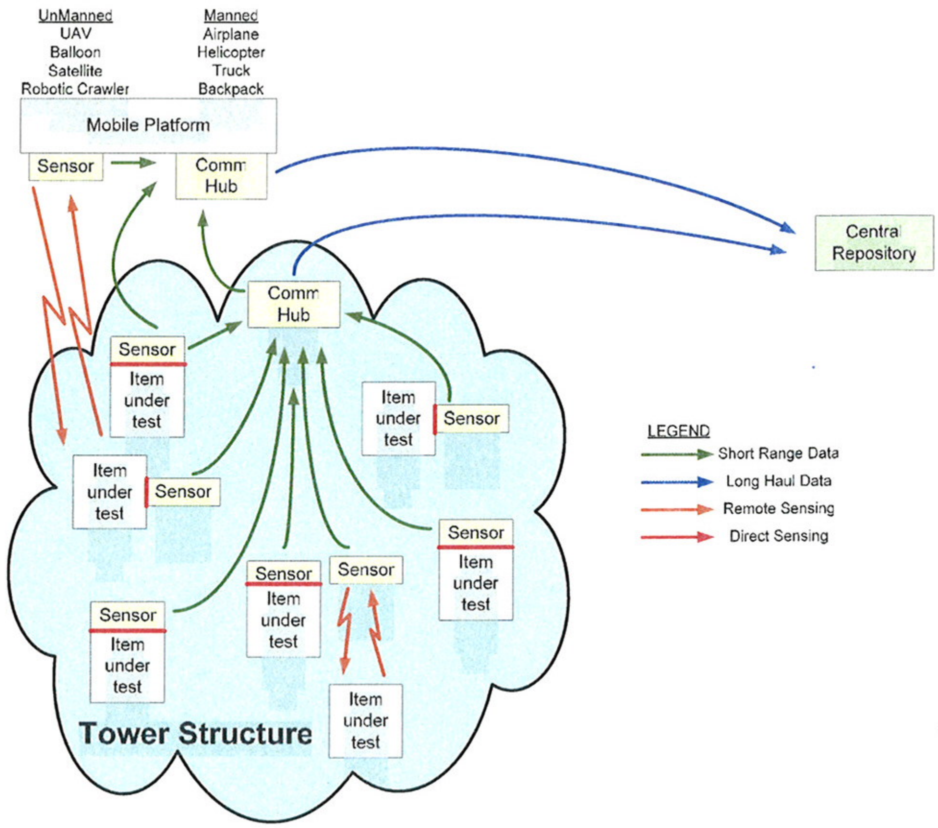


Figure 5-3
Sensor System Architecture (EPRI 1016921)

Table 5-5
Cost of Sensors

Technology	Total Units	Units	% Sat	Cost/ Unit Low $	Cost/ Unit High $	Total Cost Low–High $M
Transmission Line Sensors	58,027	Number of existing substations	50*	50,000	100,000	1,451-2,901
Transmission Line Sensors	8,423	Number of new substations	100	50,000	100,000	421-842

*Assumes 50% of substations will have sensors listed in Table 5-4 partially deployed.

Examples of Transmission Line Sensors

Figure 5-4
RF Conductor temperature and current sensor, offering power harvesting, live working install, and low cost. Cost is an order of magnitude lower than that of other available technologies.

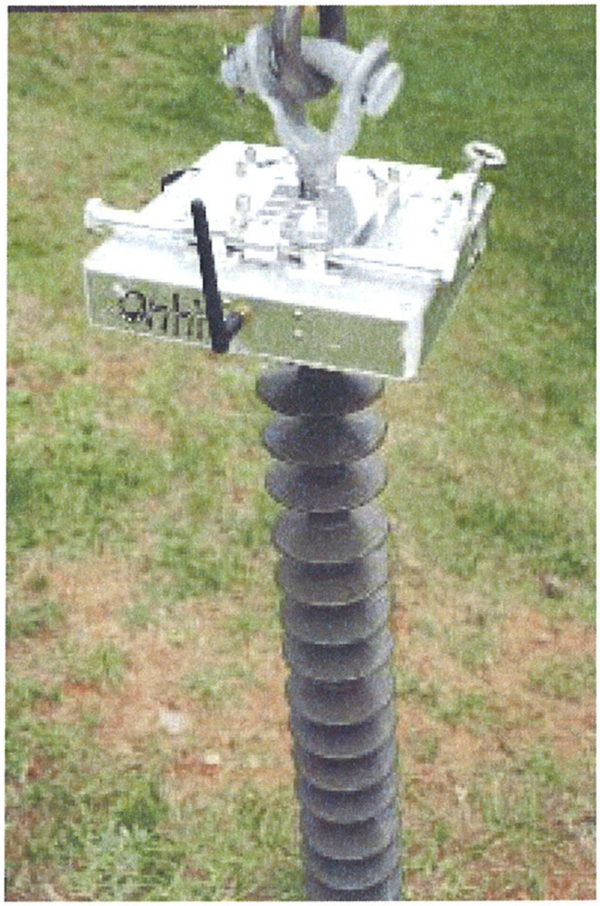


Figure 5-5
Clamp-on RF leakage current sensor for transmission line applications installed on a 115-kV composite insulator.

Figure 5-6
An RF leakage current sensor installed on a post insulator in a substation. It also shows dry band arcing (the discharge activity due to contamination and wetting that causes the leakage currents) captured during a contamination event. The sensor recorded the event

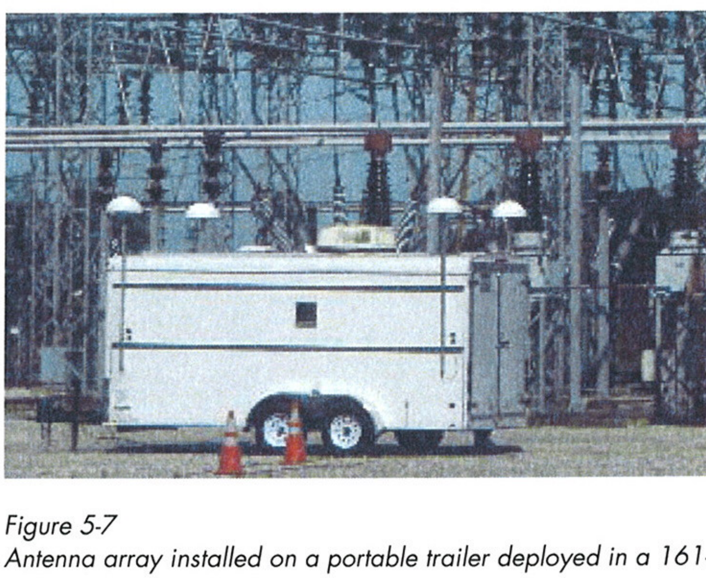


Figure 5-7
Antenna array installed on a portable trailer deployed in a 161-kV substation.