Smart Grid The Future of the Electric Energy System

Roger N. Anderson
Columbia University

Hamid Gharavi
National Institute of Science & Technology

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Roger N. Anderson[1], IEEE member, Reza Ghafurian[2], IEEE Fellow, Hamid Gharavi[3], IEEE Fellow

Abstract— This paper presents a discussion of the future of the electric energy system, addressing the entire spectrum from power generation, through substations, to distribution and the customer, and the feedback loops along the way necessary to provide the computational intelligence necessary to make the "Smart Grid". Both at the federal and state levels, governments have recognized a need for modernizing the electric energy system and establishing such Smart Grids around the world. We are at the point of a historic paradigm shift, with the opportunity to implement new, more intelligent methods for producing, distributing, delivering and using electricity in a much more sustainable manner. Whereas the current electric system is based on a one-way flow of energy and information from the sources to the end users, the future Smart Grid will provide multiple paths for the flow of electricity, and particularly information about that flow, throughout the system. This paper introduces this Special Issue by presenting a broad definition for the Smart Grid. We discuss the necessary attributes for such a system-of-systems, review the need for change, and identify the technical challenges facing successful deployment and implementation.

***Index Terms*—Smart Grid, Adaptive Stochastic Control, Distributed Generation and Storage, Demand Response.**

I. Introduction

Three dominant factors are impacting the future electric systems of the world; government policies, efficiency needs of the consumer, and the introduction of new intelligent computer and hardware technologies. In addition, environmental concerns have created governmental policies around the world, including at the federal and state levels, which are driving the entire energy system to efficiency, conservation, and renewable sources of electricity. These factors are the main drivers that are expanding the use of all sorts of new renewable energy and storage technologies on the one hand and new energy efficiency and conservation techniques on the other. Consumers are becoming more proactive and are being empowered to engage in the energy consumption decisions affecting their day-to-day lives. At the same time, they are expanding their energy needs. For example, consumer participation will ultimately include extensive use of electric vehicles (both cars and trucks), remote control of in-home appliances to promote energy conservation, ownership of distributed generation from ever more renewable energy sources, and management of electricity storage to locally match supply to demand. The availability of new technologies such as more abundant and aware SCADA sensors, secure 2-way communications, integrated data management, and intelligent, autonomous controllers has opened up opportunities that did not exist even a decade ago.

The electric energy system of the future needs to address all these needs and concerns by using advanced technologies to create a smarter, more efficient and sustainable grid. During recent years, there have been numerous articles and conferences about the Smart Grid, but much confusion remains among all constituencies about just what the term entails. Although many different definitions have been proposed for the Smart Grid, in most cases the users have chosen particularly focused definitions related to their specific applications and local needs. Below, we define the Smart Grid in its broadest global terms. We begin with a description of the make up of the present conventional electric energy system, and we then identify the areas that must change in order to provide the intelligence and control necessary to convert to the safe, secure, and efficient Smart Grid of the future. Papers that follow in this Special Issue give a cross-section through this vast new enterprise, and while not meant to be all-inclusive, are meant to be illustrative of the changes coming to the Smart Grid.

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[1] R. N. Anderson is with the Center for Computational Learning Systems, Columbia University, NY, NY 10027

[2] R. Ghafurian is with the Consolidated Edison Company of New York, NY, NY 10003

[3] H. Gharavi is with the National Institutes of Standards and Technologies, Washington, D.C.

II. The Conventional Electric Energy System

A general description of today's conventional electric delivery system is represented in figure 1. Traditionally the system is broken into mostly isolated components (silos): generation, transmission, substation, distribution, and the consumer. Key characteristics of this conventional system that will be most strongly impacted by the changes required to implement the Smart Grid are the following attributes:

1. centralized sources of power generation,
2. uni-directional flow of energy; from the source to the customers,
3. passive participation by the customers; consumer knowledge of electrical energy usage is limited to a monthly bill received, after the fact, at the end of the month,
4. real-time monitoring and control is mainly limited to generation and transmission, and only at some utilities, does it extend to the distribution system,
5. the system is not flexible so that it is difficult to either inject electricity from alternative sources at any point along the grid, or to efficiently and sustainably manage new services desired by the users of electricity.

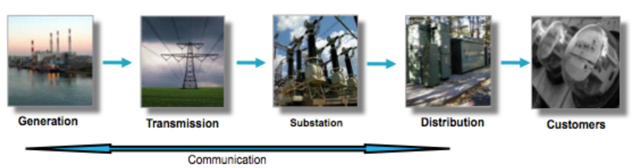


Figure 1. Conventional Electric Grid

These conventional attributes have adequately served the needs of electric utilities and their customers in the past. However, the new needs of more energy knowledgable, computer savvy, and environmentally conscious consumers, combined with regulatory changes that promote sustainability and energy independence from foreign sources, availability of more intelligent technologies, and ever greater demands for enough energy to drive the global economy, require an electric energy system of the future that is fundamentally different in all 5 areas listed above.

III. The Future Smart Electric Energy System

A general schematic of the future electric energy system, or Smart Grid, is presented in figure 2. The key requirements of this system will address the following transformational functionalities:

- Allow for the integration of renewable energy resources to address global climate change,
- Allow for active customer participation to enable far better energy conservation,
- Allow for cyber-secure communications systems to address system safety,
- Allow for better utilization of existing assets to address long term sustainability,
- Allow for optimized energy flow to reduce losses and lower the cost of energy,
- Allow for the integration of electric vehicles to reduce dependence on hydrocarbon fuels,
- Allow for the management of distributed generation and energy storage to eliminate or defer system expansion to reduce the overall cost of energy,
- Allow for the integration of communication and control across the energy system to promote interoperability and open systems and to increase safety and operational flexibility.

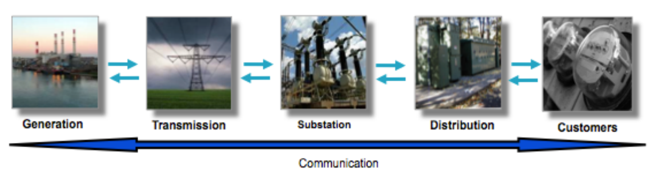


Figure 2. The Smart Grid

It should be noted that the Smart Grid, as characterized above, does not replace the existing electric system but rather builds on the available infrastructure to increase the utilization of existing assets and to empower the implementation of the new functionality. For example, centralized sources of generation will still play a major role in the Smart Grid, and large-scale wind and solar generation, wherever cost justified, will become major parts of the generation mix. Availability of a 2-way, cyber-secure, end-to-end communications system will provide consumers with the knowledge of their energy usage necessary to allow them to locally and/or remotely control their smart appliances and temperature settings. Monitoring and control of the electric system components will provide the utility with the real time status of the system. The use of this real time data, combined with integrated system modeling and powerful new diagnostic tools and techniques, will provide the detection of incipient failures in order to drive preventive maintenance and dynamic work management systems. Automatic reconfiguration of the system, powered by sophisticated, adaptive and autonomous optimization controllers will maintain the flow of energy without interruption when equipment failures do happen. Distributed generation and storage resources and remotely controlled equipment will also play an important role in the management of the Smart Grid energy system not only to address contingency needs but also to optimize power flow, eliminate load pockets, and minimize system losses. It should be noted that building the Smart Grid, as envisioned here, will be very costly and will require a sustained implementation process that evolves over decades.

IV. Definition of the Smart Grid

The Smart Grid described in this Special Issue is not "pie-in-the-sky" but a true global transformation for which hundreds of billions of dollar-equivalents will be spent within the next decade on real technologies that will provide intelligent management of the electric grid over the coming decades. However, some aspects of the Smart Grid system described herein may turn out not to be cost effective, and they then must wait until cheaper technologies are developed or societal benefits justify the expenditures. That is, the ultimate Smart Grid is a vision, keeping in mind that it requires cost justification at every step before implementation, then testing and verification before extensive deployment.

Considering the above, the Smart Grid is defined as an electric system that uses information, two-way, cyber-secure communication technologies, and computational intelligence in an integrated fashion across electricity generation, transmission, substations, distribution and consumption to achieve a system that is clean, safe, secure, reliable, resilient, efficient and sustainable. This definition covers the entire spectrum of the energy system from the generation to the end points of consumption of the electricity. The reader will note that many definitions proposed by other users are subsets of this system-of-systems definition; as for example, if defined as smart metering, it addresses the consumption and to some extent the distribution part of this definition but not the full spectrum of integration required to implement the Smart Grid.

Achieving a smart grid will be a gradual and evolutionary process that will take many decades to be fully realized. To qualify as a Smart Grid, it is neither necessary nor feasible to incorporate all features at one time, but rather incorporation of each new feature can be carried out independently. Each will require cost justification and reasonable pay back on investments. However, interoperability of open systems will allow each addition to "Plug-and-Play" into the Smart Grid once the technologies have been validated. Assuming fully realized, the Smart Grid will have the following characteristics that are not available in the conventional electric energy system:

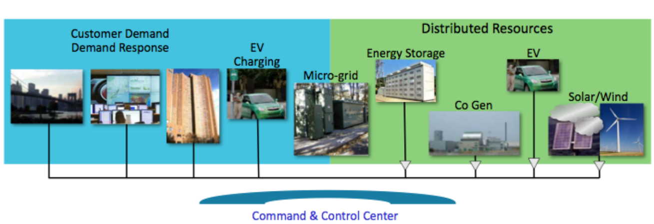
- Secure communications (two-way) covering the system from end-to-end,
- All main components are sensed and variances detected: cables, joints, terminations, transformers, consumer usage, power quality, etc. will be monitored in real time.

The above characteristics will provide massive amounts of incoming data that must be converted into situational awareness of the state of the grid. Controller technologies will then have to automate data and energy management so that information is streamlined, problems are diagnosed instantly, corrective actions are identified and executed dynamically in the field, and feedback loops provide metrics that verify that the work done is producing the desired effects. Such Smart Grid controllers will have the following characteristics:

- Self healing: automatic repair or removal of potentially faulty equipment from service before it fails, and reconfiguration of the system to reroute supplies of energy to sustain power to all customers,

- Flexible: the rapid and safe interconnection of distributed generation and energy storage at any point on the system at any time,
- Predictive: use of machine and reinforcement learning, weather impact projections, and stochastic analysis to provide predictions of the next most likely events so that appropriate actions are taken to reconfigure the system before next worst events can happen,
- Interactive: appropriate information is provided transparently regarding the status of the system not only to the operators but also to the customers to allow all key participants in the energy system to play an active role in optimal management of contingencies.
- Optimized: knowing the status of every major component in real or near real time and having control equipment to provide optional routing paths provides the capability for autonomous optimization of the flow of electricity throughout the system.
- Secure: considering the two-way communication capability of the Smart Grid covering the end-to-end system, the need for physical- as well as cyber-security of all critical assets is essential.

Figure 3. New equipment of the Smart Grid



V. Major New Components of the Smart Grid

As indicated by the above characteristics, the Smart Grid involves installation of much new, intelligent equipment at critical generation, transmission, distribution, and consumption points. For this equipment to become an effective part of the operations of an integrated Smart Grid, fundamental control technologies for communications, data management, diagnostic analysis, and work management are required. The Smart Grid must operate as an integrated machine: a system-of-systems. As shown in figure 3, the Smart Grid will change the conventional concept of energy management and operations since traditional "blind" demand will evolve to become controlled "visible" demand (such as with curtailable load). In some cases, demand will be convertable into supply (such as with electric vehicle and distributed battery storage). Excellent industry summaries are provided by Garrity (2008) and Some of these aspects of the Smart Grid are further described below.

Customer Demand, Demand Response and Curtailable Loads

Many people, especially in the public sector, consider the Smart Grid to be nothing if not Advanced Metering Infrastructure (AMI), including– Automatic Meter Reading (AMR). More advanced features of an integrated AMI includes a Distribution Management System with full control, monitoring and Geographic Information System (GIS) interfaces. In addition, AMI Smart Grid systems provide consumption control at the customer site, distributed load management, and 2-way communications (c.f.,Mahmood, Aamir, and Anis, 2008).

AMI and Home Area Networks (HAN) provide added Demand Response functionality such as automated control of refrigerators and/or air conditioners by the utility and curtailable load based on electronic communications only. Many conumer-utility intermediary companies provide automated curtailment programs through subscription services. Certain "Self Healing" capabilities more common to the Internet can be built into automated reconfiguration regimes, as for example demonstrated in Tsoukalas, and Gao, 2008).

Photovoltaics

PhotoVoltaics (PV) provide mostly local power generation that can provide significant load relief for the Smart Grid. However, the inherent unpredictability of the solar source caused by cloud cover and weather make the dispatching of fixed quantites of power impossible, unless distributed storage is coupled with the PV systems. That said, entire countries depend upon PV for hot water subsystems for homes such as Cyprus. PV is fundamentally a curtailment service, although small amounts of "Negawatts" are provided to the local grids surrounding PV arrays, especially in California (c.f., Profiting from negawatts, J Steinberger, J Van Niel, D Bourg - Energy Policy, 2009).

EV,Charging Stations and Microgrids

Electric Vehicles and Plug-in Hybrid Electric Vehicles (grouped as EVs here) present unique problems for the electric grid because they are mobile sinks for power in the day and fixed sinks at night. The perception for most needed intelligent interaction via the Smart Grid comes during the day in large urban areas, when large populations of EV vehicles are predicted to plug into the grid for recharging upon arrival at work, just as the electricity consumption of large urban cities is ramping up towards peak. A further homeland security need is that each EV must receive at least a 25% recharge so all vehicles can make it out of the city limits in case of an emergency. Thus, load transfer to storage facilities linked to EV charging stations is being considered in addition to grid charging. In addition, so called "Green Garages" are beginning to appear, that certify that the power used to charge the EV comes from renewable energy sources, even as that fact is hard to verify. However, EVs could represent a significant mobile source of emergency power in case of crisis situations such as blackouts. Then, the EVs may provide additional power to homes, assuming the vehicles made it back home safely. There will be much more on this topic as countries such as the United States introduce new laws like "The Electric Drive Vehicle Deployment Act" of 2010 that attempt to stimulate market penetration for EVs[4].

MicroGrids are small scale grids within the electric grid where distributed generation sources such as PV and wind are linked to distributed storage, and at least in concept, EV charging stations. They provide local electric distribution for a neighborhood, campus, manufacturing facility, etc. that can be independent of the grid itself. MicroGrids also include local load control, and often Heating Ventilation and Air Conditioning (HVAC) of large vertical buildings or groups of buildings. MicroGrids are designed to be able to stand alone from the electric grid (islanding) in times of crisis so that the power in the local area can be maintained via emergency generation. MicroGrids can also be used for significant curtailable load for utilities during peak load relief periods (c.f. M. Dicorato, et. al., 2009).

Actions between MicroGrids and the Smart Grid can then be coordinated to maintain optimal power flow, protection & switch coordination, while managing restoration plans and replacement options, all the while responding to financial and market variations. Pipattanasomporn and Rahman, 2009) discuss how software agents can be deployed by Smart Grid controllers to optimize just such a complex MicroGrid management scheme (also see Liu and Su, 2008, for another good example).

Energy Storage

A critical addition to the Smart Grid will be from the addition of significant energy storage capability. Intermittent power sources like PV, Solar Thermal, and Wind require someplace to store the electricity to fill needs during cloudy and/or windless times. The Electricity Storage Organization tracks the cost of both large and small scale energy storage systems, from Lithium-Ion, Nickle-Cadmium and Lead-Acid batteries, through fly wheels and super-capacitors, to various large scale battery storage devices, and finally to large scale cavern storage of compressed air and hydroelectric that involves pumping water back upstream during nights (Figure 4).

These technologies are all technologically viable, if affordable: a barrier that has not yet been passed. Until it is, large-scale deployment of alternative energy sources will be limited. Other electricity

[4] see for example: http://markey.house.gov/index.php?option=com_content&task=view&id=4006&Itemid=141).

storage devices that involve melting salt, heating vegetable oils, freezing ice for HVAC chiller operations, and the use of fuel cells have attained wider, though still limited, deployment (see below).

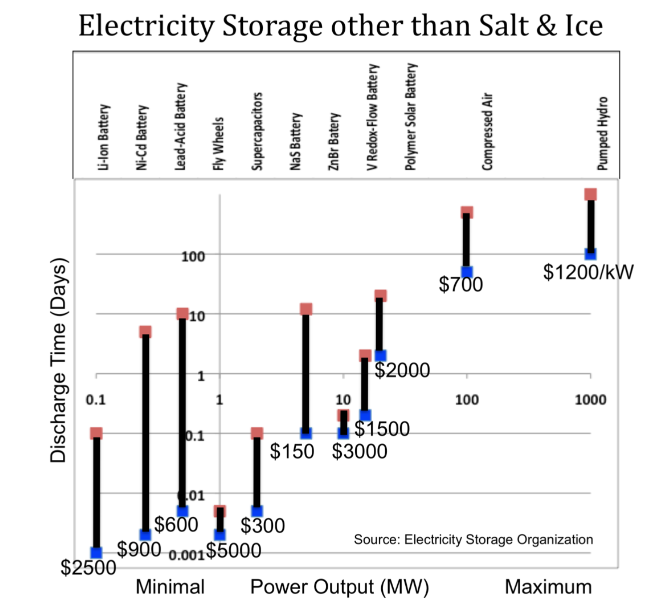


Figure 4. The Relative Power Output, Discharge Time, and cost per KWH for various Energy storage devices.

Distributed- and Co- Generation

The Smart Grid must be able to accommodate small-scale generation owned by customers such as combined heat and power co-generation facilities, as well as from the previously mentioned PV, EV and MicroGrid sources. Power management of distributed generation involving everything from Building Management Systems to solar generation depends on accurate weather forecasting, which adds to the uncertainties being optimized by smart grid control systems. New methods linking these erattic sources to storage are required to provide dispatchable loads (c.f., Jiang, 2006, and Chowdhury and Koval, 2005).

Massive Solar Thermal and Wind Farm Generation

Solar Thermal power generation, in particular, has been very successful in linking mirrors to a storage medium, usually a salt that is melted or vegitable oil that is heated. Both can be used to boil water for many hours afterwards. This combination has allowed the design of every large Solar Thermal power plants. It should be theoretically possible to build such plants that generate as much electricity as the other two largest alternative energy sources to burning hydrocarbons: nuclear and hydro electric. Arizona has begun construction of the first 280 MW of an intended 4300 MW Solar Thermal plant south of Phoenix (Figure 5).

The outlook for wind combines strong but erratic wind turbine generators such as those in West Texas with Compressed Air Energy Storage (CAES) in underground salt caverns or emptied natural gas reservoirs. Swider (2007) has demonstrated the economic market modeling needed to justify the combined investment of wind generators with CAES. Payback is minimized only if the laying of regional transmission lines needed to get the power to market is part of the up-front investment, a lesson learned the hard way by Texas. There as much as half of the 2000 MW+ of West Texas wind power is dormant at any time because of transmission limitations that are only now being alleviated, long after construction of the wind generators (Anderson, 2004). A similar German study by Lerch (2008) Demonstrated that CAES can be economic in the case of large-scale wind power deployment in European offshore waters.

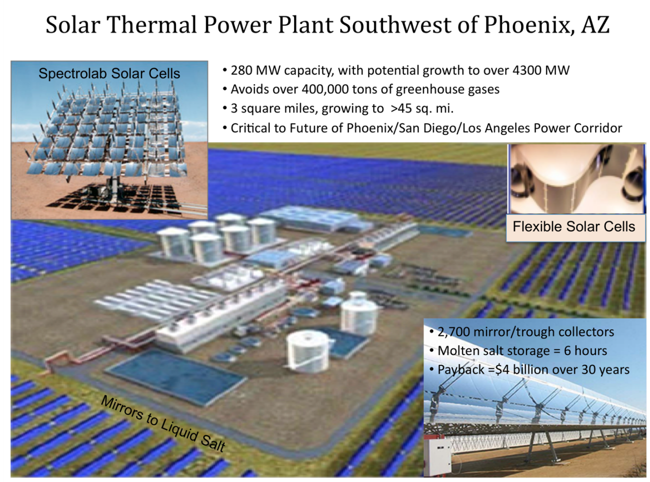


Figure 5. An artist's representation of the first 280 MW module of a Solar Thermal Power Plant complex southwest of Phoenix, Arizona, that will be selling power into the Western Interconnect and Southern California (image courtesy of Arizona State University).

Nanotechnologies and Power Generation and Storage of the Future

Above all, the Smart Grid must have the capacity to adapt to new technologies not yet invented or in long term development such as fusion nuclear, or more likely, nanotechnology breakthroughs. Examples of future Nanotechnologies that might be important energy sources or storage media within the next 10 years (Smalley, 2007) include (Figure 6):

- Photovoltaic materials that may drop cost by 100 fold or more
- Photocatalysts that reduce CO2 emissions to methanol
- Nano-materials that directly convert light and water to produce hydrogen via thermochemical catalysts that generate Hydrogen from water and that work efficiently at temperatures lower than 900 C
- Nano Fuel Cells that drop the cost by 10-100x and provide low temp starting capacity and are reversible
- Direct Hydrogen storage using lightweight Nanl materials for pressure tanks and/or a new lightweight, easily reversible hydrogen chemisorption system (called material X)
- Batteries, supercapacitors, and flywheels improved by 10-100x for automotive and distributed generation applications
- High current quantum wires (QW) that might rewire the transmission grid and enable continental, and even worldwide electrical energy transport; and also to replace aluminum and copper wires essentially everywhere -- particularly in the windings of electric motors and generators
- Nanoelectronics to revolutionize computers, sensors and devices.
- Nano Robotics with Artificial Intelligence to enable construction and maintenance of solar structures in space and on the moon; and to enable nuclear reactor maintenance and fuel reprocessing on Earth
- Super-strong, light weight materials to drop cost to launch solar arrays into space
- Thermochemical catalysts to generate H2 from water that work efficiently at temperatures lower than 900 C.
- Nanotech lighting to replace incandescent and fluorescent lights
- Nano-Photovoltaics -- new paints for the exterior of buildings that generate electricity

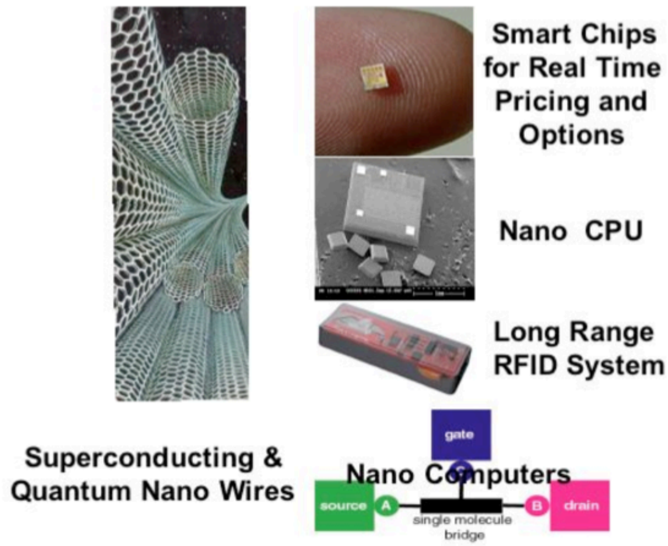


Figure 6. Plenty of room at the bottom, according to Richard Feynman, describing nanotechnology opportunities (c.f., Hey, J.G., Feynman and computation: exploring the limits of computers, Westview Press, 2002). Source: Baker Institute Study No. 30, Energy and Nanotechnology, Strategy for the Future, Rice University, April, 2005, accessable at: http://www.rice.edu/energy/publications/energynanotechnology.html .

Taking the most likely of these to first appear on the Smart Grid, Quantum wires (QW) have the electrical conductivity of copper at one-sixth the weight and it will be stronger than Kevlar. They can be spun into polypropylene-like "rope" and used for the transmission grid of the future. These Fullerene nanotude arrays form a "super-material" of extreme strength, lightness of weight, high temperature resistance, unidirectional thermal conductivity (electrons just fit into each tube, and so have only one place to go). The electrons quantum jump from inside one QW tube to the next (c.f., Yakobson and Smalley, (1997) and Anantram and Govindan, (,2000).

VI. Adaptive stochastic Control

A key to the implementation of the Smart Grid is to create the intelligent management of the margin between the ever-expanding demand for electricity and its efficient, safe, secure, and sustainable supply at all points along the distribution path. Electricity is no longer entering the grid exclusively at massive power plants on the transmission beginnings of the grid, but it will also be generated from distributed resources at customer sites throughout the distribution grid, and even from energy storage at consumer sites and substations. As indicated in Figure 7, intelligent controllers must receive, digest, and interpret all manner of new data coming from SCADA sources and send commands to manage contingencies, optimize power flows, initiate preventive maintenance, control switching and load, minimize capital investment, deal with erratic solar and wind generation, and optimize distributed storage, all the while dealing with potential and real equipment failures as well as weather and price variations.

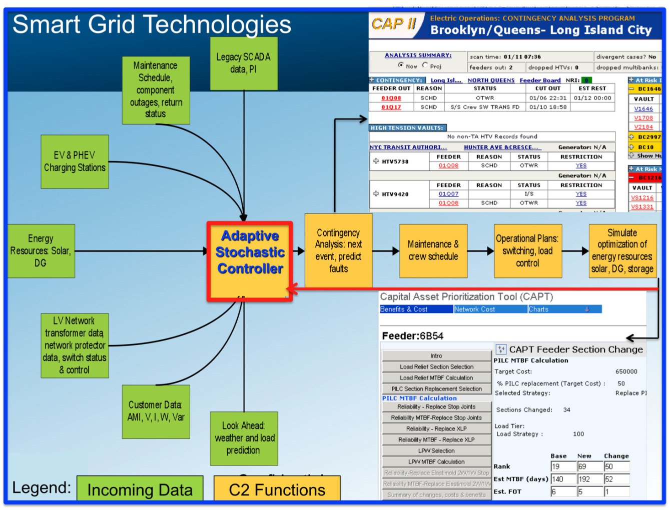


Figure 7. The Smart Grid must optimally interpret incoming data from many new sources (green) with new controls such as Contingency Analysis Programs (CAP in the upper right) and Capital Asset Prioritization Tools (CAPT in lower right).

This Smart Grid data and energy management system must be, by definition, adaptive and stochastic, meaning that it is prepared to respond to varying weather conditions, crew status, and equipment performance changes while optimizing supply to meet demand within economic constraints that simultaneously minimize costs for consumers, regulators and industry stockholders.

Some utilities now use complex, computational command and control systems similar to those used in petrochemical and nuclear plant management, such as decision support and portfolio management tools, activity based accounting, and preventive maintenance programs. However, the computational systems utilized in these controller calculations are generally policy-and-rules-based decision systems. Risk and variance are considered using linear programming algorithms. These systems are very good at identifying the “next worst” condition that can happen to the electric grid at any given time, but not so good at determining actions to prevent the “next most likely” condition to occur on the electric grid.

Controlling the new complexities of the Smart Grid is a multi-stage, time-variable, stochastic optimization problem to the Operation Research engineer and operator. The Adaptive Stochastic Controller (ASC) for the Smart Grid requires the import of Approximate Dynamic Programming (ADP) and Mixed-Integer, Nonlinear Programming solvers that are more familiar to the petrochemical and transportation industries. If the electricity industry successfully imports these intelligent controllers, economic benefits will be on the order of savings we have measured after transitions to such autonomous, adaptive controllers in these other industries (c.f. Anderson et al, 2008).

ADP Adaptive Stochastic Control optimizes by solving the Hamilton-Jacobi-Bellman equation using ADP interacting with the electric system model used by engineering to plan improvements in the grid today. Feedback loops and a critic function are critical to establish cause-and-effect, similar to the ways that models are used in Model Predictive Control (MPC) in other industries. The ADP Adaptive Stochastic Controller delivers these real-time feedback loops to Machine Learning Systems that enable simultaneous Load & Source Control and Dynamic Treatment Optimization to drive the Smart Grid to fewer and fewer emergency failures over time.

Momoh (2006) offers an excellent summary of the present state of the art in ADP Adaptive Stochastic Control and the technologies that it is replacing in Control Centers across the world (Table 1 is replicated below).

TABLE 1 LIST OF TYPICAL PROBLEMS AND OPTIMIZATION SOLUTIONS

Optimization Problems	Currently used Techniques	Next Generation Techniques
Unit Commitment / Hydro dispatch	Dynamic Programming (DP)	ADP & its variants
Control Coordination	Decomposition Optimization	ADP, AHP, and EP methods
Machine Controls and Stabilization	Optimal Control	ADP and Evolutionary Programming
Optimal Reconfiguration	Mixed Integer Programming	Dynamic Stochastic Optimal Power Flow (DSOPF) and its variants
Loss Minimization	NLP and Interior Point methods	
Economic dispatch for Large Systems	NLP, DP methods	
Locational Marginal Pricing	LP methods	ADP
Data Mining	State estimation (SE)	ADP and EP methods
Optimal Sensor Placement	IS methods such as ANN	ADP and DA

Werbos (2009) further describes the intelligence that must be mathematically managed using state-of-the-art computational control theory. Chuang and McGranaghan (2008), further develop the requirements for such intelligent controllers for Smart Grids to include distributed generation and storage devices and the interfaces needed connect to electricity market participation. Thusly, the ADP Adaptive Stochastic Controller coordinates generation, utility and customer response to actual system and market conditions in real-time.

Within the Adaptive Stochastic Controller, ADP is used as a mathematical decomposition strategy that breaks the problem of continuous grid management, with its long time horizons, into a series of shorter problems that the Mixed-Integer Nonlinear Programming solver can handle, thereby solving the 'curse-of-dimensionality' caused by the exponential increase in complexity as dimensionality of sources and loads increase as the Smart Grid is built-out. The ADP Adaptive Stochastic Controller framework also provides a way of treating uncertainty from both operational and financial standpoints, simultaneously. To achieve this, Anderson and Boulanger (2009) describe the mathematical combination of Real Options evaluation of the cost/benefit with operational policy and action optimization using the ADP algorithms within the Adaptive Stochastic Controller. The result is maximization of real option value as a control objective along with efficient and safe operations.

Current business plans for utilities are also based on risk/reward optimization algorithms, although these are usually Net Present Value (NPV) computations used in a portfolio management context. The future Smart Grid will be too dynamic and too complex for such linear methodologies. Real options optimization and autonomous control will be required throughout the grid, from consumer to utility to generation, as described by Ernst, et al, (2008).

Load & Source Control:

The control of distributed energy storage for the real time Load nad Source Control has been mostly limited to date to pumped hydro. However, recent demonstration projects are providing new opportunities to show the value of energy storage in the control of grid stabilization, operations support, power quality management, and load shifting applications. Candidate high value applications are:

- "Instantaneous" versus Ramp Rate Limited Generation Based Spinning Reserve as Bridge Power to Standby Generation in the Event of Loss of Generation or Transmission
- Cycling Power Supply and Load Arbitrage
- Regulation Control Support
- Reserve Power for System Power Reliability, Security and Quality
- Utility Load Shifting for Supply Infrastructure Asset Optimization and Emergency Response
- End-user Energy Management and Power Quality/Reliability Requirements
- Intermittent Renewable Power (e.g., Wind) Stability and Optimization

ADP Adaptive Stochastic Control for Load and Source management must exercise real options decisions in real time based on price and market condition information fed to the controller. The real time options include:

- option value of arbitrage,
- option value of peak shaving,
- option value of greater network reliability,
- option value of environmental benefits
- Dynamic Treatment

ADP Adaptive Stochastic Control also provides Dynamic Treatment optimization for maintenance operations. Machine Learning and statistical models for failure that use causal inference, propensity and survival analysis developed for the medical industry have been shown effective to arrive at treatment actions to prevent electric grid failures (Rudin, et al, 2011). The dynamic treatment output of Adaptive Stochastic Control is a prioritization of work needed and control actions to be taken, either discretely or continuously, to keep grid devices such as distributed generation and storage, sectionalizing switches, and load pockets within optimal performance bounds.

Adaptive Stochastic Control in Transmission

The Adaptive Stochastic Control functions for the Smart Grid also include static and dynamic security assessment capabilities along with self-checking of relay settings on critical transmission facilities. With the deployment of phasor measurement units to monitor grid performance across heavily loaded regional transmission interconnections, there will be advances in state estimators that are capable of real-time simulations for large networks that will need to be incorporated into the overall management of the Smart Grid. For example, mobilizing grid capacity reserves through active management to avoid overloads will enable operators to relieve bottlenecks and redeploy necessary generation and transmission assets from both the transmission and distribution grids to eliminate congestion points and load pockets in the integrated transmission and distribution grids.

VII. Challenges to Achieving a Comprehensive Smart Grid

A primary objective of the Smart Grid is to improve our capacity to use more, but cheaper, electricity to power the improvements in the standard-of-living of all people on Planet Earth. However, the transition must be cost effective, or we will never get there from here. The tracking of key performance metrics that continuously and automatically score improvements generated by the Smart Grid will be required if the effort is sustainable over the 20 to 30 years that will be required for a full conversion to a comprehensive Smart Grid in any country. Documenting these improvements requires the establishment of an initial baseline for all major components of the existing grid, and then continuous measurement of the impact of new construction and implementation against that baseline. A benefit from this documentation will be that Adaptive Stochastic Controllers of the Smart Grid will have been validated to redirect load around congestion, manage peak demand, weather and equipment problems that will eliminate the need for expensive new power plants and substations. Internationally, computers operating these Adaptive Stochastic Controllers managing every level of the new Smart Grid could eventually save the need to build Terra-watts of new generation worldwide.

It is expected that over time the Smart Grid will improve the capacity factor of the electric system through more optimal supply and demand management. It allows for the re-use of existing hardware infrastructure in a more efficient manner by adding modern controller intelligence to the existing system. Understanding the risks and consumer impact of using the available resources optimally should allow Smart Grid utilities to lower peak demand and reduce Capital and O&M costs by mitigating emergencies of all kinds during peak load periods. It is our joint task as an industry to maintain the tracking metrics worldwide to document that these predicted benefits are actually realized by the Smart Grid implementation we are all beginning. Best practices should be shared easily and efficiently.

Challenges to the future success of the smart grid come from many fronts, such as consumer buy-in: consumers have to see real savings and efficiency improvements; better regulation: governmental control must stay up to date technologically and in touch with consumers; cost justification; Smart Grid components must be individually as well as systemically cost effective; education: utilities, service companies and universities must produce educated consumers as well as a new generation of electrical engineer savvy in computer sciences and systems engineering; and new inventions and technologies must be easily adopted and adapted into the Smart Grid since it will evolve over the next 20 to 30 years.

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